

On-Chip Integrated UV Microplasma Source for Biophotonic Applications

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Doctor of Engineering Physics

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Yize Liu

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List of Acronyms

A

AC	Alternating Current
AlCl_3	Aluminium Chloride
ALD	Atomic Layer Deposition
AlF_3	Aluminum Fluoride
AlGaN	Aluminum Gallium Nitride
AlN	Aluminum Nitride
AlO_x	Alluminum Oxide
ArF	Argon Fluoride

B

BCl_3	Boron Trichloride
BBO	Beta Barium Borate

C

CH_4	Methane
Cl_2	Chlorine
CMOS	Complementary Metal Oxide Semiconductor

D

DBD	Dielectric Barrier Discharge
DC	Direct Current
DNA	Deoxyribonucleic Acid

DUV Deep Ultraviolet

E

EBL Electron-Beam Lithography
EDX Energy Dispersive X-ray Spectroscopy
ESP Electrostatic Precipitator

F

FDTD Finite Difference Time Domain
FDE Finite Difference Eigenmode
FL Focal Length

H

H₂ Hydrogen
He Helium

I

ICCD Intensified Charge-Coupled Device
ICP Inductively Coupled Plasma
InGaN Indium Gallium Nitride

K

KrF Krypton Fluoride

L

LBO Lithium Triborate

LED	Light-Emitting Diode
LiNbO ₃	Lithium Niobate
LPP	Laser-Produced Plasma

M

MEMS	Micro-Electro-Mechanical Systems
MgF ₂	Magnesium Fluoride
MHCD	Micro Hollow Cathode Discharge
MIE	Mean Initial Energy
MPD	Microcavity Plasma Device

N

N ₂	Nitrogen
NA	Numerical Aperture
ND	Neutral Density

P

PCSEL	Photonic Crystal Surface-Emitting Laser
PECVD	Plasma-Enhanced Chemical Vapor Deposition
PIC	Photonic Integrated Circuits
ptp	Peak To Peak

Q

QLED	Quantum Dot Light-Emitting Diode
QPI	Quantitative Phase Imaging

R

RF	Radio Frequency
----	-----------------

RIE	Reactive-Ion Etching
ROI	Region Of Interest
ROS	Reactive Oxygen Species

S

SEM	Scanning Electron Microscope
SEEC	Secondary Electron Emission Coefficient
SHG	Second Harmonic Generation
SNR	Signal-to-Noise Ratio
Si	Silicon
SiN _x	Silicon Nitride
SiO ₂	Silicon Dioxide

T

TMA	Trimethylaluminium
-----	--------------------

U

UV	Ultraviolet
UVA	Ultraviolet A
UVB	Ultraviolet B
UVC	Ultraviolet C
UV-POCS	Ultraviolet Plasma-On-Chip Sources

V

VUV	Vacuum Ultraviolet
-----	--------------------

W

WERS	Waveguide-enhanced Raman spectroscopy
------	---------------------------------------

X

XeCl

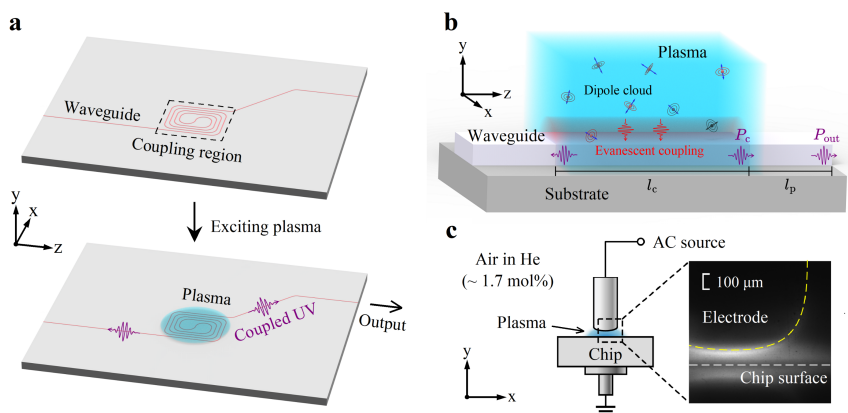
Xenon Chloride

Nederlandse samenvatting

Inleiding

De levenswetenschappen steunen steeds meer op optische technieken die in het ultraviolette (UV) golflengtegebied werken. Veel biomoleculen – zoals endogene chromoforen, DNA en tryptofaan – vertonen sterke absorptie en autofluorescentie bij UV-excitatie, wat labelvrije beeldvorming, sterilisatie en geavanceerde oxidatieprocessen mogelijk maakt [2–5]. Het vertalen van deze mogelijkheden naar praktische, geminiaturiseerde lab-on-a-chip apparaten wordt echter belemmerd door een kritische bottleneck: het ontbreken van compacte, efficiënte en integreerbare UV-lichtbronnen. Conventionele UV-zenders (kwiklampen, excimeerlasers, frequentie-verviervoudigde vastestoflasers) zijn omvangrijk, hebben een hoge étendue en zijn fundamenteel onverenigbaar met submicrometer fotonische geïntegreerde schakelingen (PIC's). AlGaN UV-LED's en laserdiodes hebben vooruitgang geboekt, maar hun externe kwantumefficiëntie blijft laag in het diepe UV, en hun emissie komt van grote oppervlakken (honderden micrometers tot millimeters), wat leidt tot een slechte koppeling in single-mode golfgeleiders [6, 7]. Kwantumstip-LED's bieden instelbaarheid maar zijn nog grotendeels beperkt tot het nabije UV [8, 9].

Dit proefschrift pakt deze lacune aan door een on-chip UV-bron te ontwikkelen die gebaseerd is op evanescente koppeling tussen een micro-gap diëlektrische barrièreontlading (DBD) plasma en een UV-transparante PIC, de UV-plasma-on-chip bron (UV-POCS). Het plasma wordt rechtstreeks in het evanescente veld van een single-mode golfgeleider geplaatst, waardoor de étendue-beperkingen van vrije-ruimte collectie worden omzeild. Een helium-lucht mengsel wordt gebruikt om zware-deeltjesreacties (Penning-ionisatie en ladingsoverdracht) te benutten die aangeslagen emitters genereren, zelfs in de plasmarandlaag waar de elektronendichtheid laag is. Het werk combineert een 1D transiënt plasmamodel met een dipool-golfgeleider koppelingsmodel en valideert experimenteel de detectiemogelijkheid op picowattniveau. Hoewel directe meting van de plasmagekoppelde uitgang werd verhinderd door koolstofgebaseerde contaminatie, blijft het onderliggende principe geldig en worden twee praktische oplossingen voorgesteld.



Figuur 1: Algemeen concept van de UV-POCS. (a) Werkingsprincipe – een microplasma gegenereerd boven een spiraalvormige golfgeleider koppelt zijn UV-emissie evanescent in de geleide mode. (b) Schematische voorstelling van de evanescente plasma-golfgeleider koppeling – alleen zenders binnen (~ 100 nm) van het golfgeleideroppervlak dragen bij. (c) De experimentele atmosferische DBD-opstelling met helium-lucht mengsel als achtergrondgas. De micro-gap wordt geregeld met een hoogspanningselektrode boven de spiraalgolfgeleider.

Concept en theoretisch kader

Het centrale concept van de UV-POCS wordt geïllustreerd in Fig. 1. Een micro-gap DBD-plasma wordt direct boven een spiraalvormige golfgeleider gecreëerd. Een deel van de UV-emissie van het plasma – voornamelijk het N_2^+ eerste negatieve systeem bij 391,4 nm – koppelt evanescent in de geleide mode van de golfgeleider en plant zich voort naar het uitgangsfacet. Dit evanescente koppelingsproces steunt op het feit dat het elektrische veld van de geleide mode ongeveer 100 nm in de bekleding doordringt; alleen plasma-emitters binnen deze regio kunnen optisch vermogen naar de mode overbrengen.

Een fundamentele uitdaging is dat de randlaag – de regio grenzend aan het chipoppervlak – een zeer lage elektronendichtheid heeft, waardoor conventionele elektron-impact excitatie inefficiënt is. Om dit te overwinnen wordt een helium-lucht mengsel gebruikt. In zo'n mengsel genereren zware-deeltjesreacties (Penning-ionisatie en ladingsoverdracht) aangeslagen emitters rechtstreeks in de randlaag, waardoor de noodzaak voor energetische elektronen wordt omzeild. Deze reacties produceren $N_2^+(B)$ moleculen, waarvan het stralingsverval de gewenste UV-emissie bij 391,4 nm oplevert.

Om het plasma kwantitatief te beschrijven, wordt een 1D transiënt model ontwikkeld. Het lost drift-diffusievergelijkingen op voor elektronen, ionen en metastabielen (zeven species in totaal), gekoppeld met een zelfconsistent elektrisch veld. Het model omvat de belangrijkste kinetische processen in het helium-stikstof

plasma en levert de emissiesnelheid r_{ems} . Voor het fotonische deel wordt het plasma behandeld als een willekeurige verdeling van stralende dipolen. Met behulp van Fermi's gouden regel en de toestandsdichtheid in een golfgeleider wordt een analytische uitdrukking voor de koppelingsefficiëntie afgeleid, die afhangt van de groepssnelheid v_g en een effectief oppervlak A_{eff} . Voor multimode golfgeleiders is de totale efficiëntie de som over alle geleide modes. Combinatie van het plasma- en fotonische model voorspelt een uitgangsvermogen in het picowattbereik (2.9–11.5 pW).

Ontwikkeling van het experimentele systeem

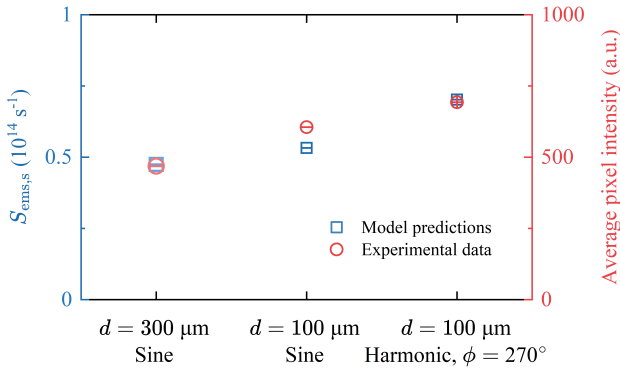
Een volledig geïntegreerd UV-plasma-on-chip experimenteel systeem werd ontwikkeld, bestaande uit drie hoofdcomponenten: een DBD-plasmabron, een chipstage met de fotonische chip en de aardings elektrode, en een optisch detectiesysteem (ICCD-camera, aspherische lenzen, optische behuizing). De ontwikkeling van een betrouwbare en contaminatievrije plasmabron op een fotonische chip was een pionierswerk, aangezien er geen kant-en-klare oplossing bestond. De plasmaconfiguratie onderging drie radicale iteraties. De initiële oppervlaktebarrièreontlading (SBD) in vacuüm leed onder smelting van de gouden elektrode, delaminatie van het substraat en parasitaire ontladingen. Een sandwich-achtige dubbel-diëlektrische DBD elimineerde direct elektrode-chip contact maar introduceerde ontladingspaden die de gaspleet omzeilden. De finale configuratie – een enkellaagse DBD werkend bij atmosferische druk – bleek stabiel en reproduceerbaar na optimalisatie van de elektrodetip (afgeplat, rond profiel) en gebruik van een gecontroleerde helium-gedomineerde gasachtergrond; hier fungeert de chip als enige diëlektrische barrière. Parallel werd de chipstage vier keer herontworpen, uiteindelijk met een Teflon-PVC combinatie om koolstofcontaminatie te minimaliseren. De hoogspanningselektrode werd geïsoleerd met kwartsbuizen (in plaats van PTFE-tape) en gemaakt van zuiver wolfram om kopersputteren te vermijden. Voor het fotonische deel werden laagverlies AlO_x golfgeleiders (~ 3 dB/cm bij UVA-golflengte) gebruikt, gefabriceerd via atomaire laagdepositie, een SiN_x hard masker en chloor-gebaseerd ICP-etsen. De integratie van deze plasmabron met de fotonische chip, samen met de aangepaste optische detectie, vormde de kern van het UV-POCS experimentele systeem.

Versterking van de plasma-UV-emissie aan het chipoppervlak

Het versterken van de emissie-intensiteit aan het chipoppervlak (~ 100 nm van de golfgeleider) is cruciaal om het golfgeleider-gekoppelde uitgangsvermogen naar een detecteerbaar niveau te tillen. Twee complementaire strategieën werden onderzocht om deze versterking te bereiken: ruimtelijke controle via afname van de ontladingszone en temporele controle via harmonische excitatie.

Ruimtelijke controle – optimalisatie van de gap. Het verkleinen van de ont-ladingszone van $400\ \mu\text{m}$ tot $80\ \mu\text{m}$ versterkt het elektrische veld in de kathode-randlaag. Wanneer de gap kleiner wordt dan tweemaal de randlaagdikte ($\sim 60\ \mu\text{m}$), overlappen de randlagen, wat de ionenflux en elektronendichtheid aan het chipoppervlak verhoogt. De emissie-intensiteit aan het chipoppervlak neemt significant toe en verzadigt beneden $100\ \mu\text{m}$. Het 1D-model reproduceert de experimenteel waargenomen overgang van een drielaags naar een éénzone emissieprofiel.

Temporele controle – harmonische excitatie. Het toevoegen van een tweede harmonische component (10 kHz fundamentele frequentie, amplitudeverhouding 0,5) met een faseverschil van 270° versterkt de piekspanningen over de gap met ongeveer 3% en herverdeelt de vermogensdissipatie asymmetrisch. Dit leidt tot randlaagverdunning ($\sim 4\ \mu\text{m}$) en preferentiële insluiting van het plasma aan de chip-zijde tijdens de halve cyclus waarin de chip als kathode fungeert. Positieve polariteit (270°) bevoordeelt het diëlektrische oppervlak; negatieve polariteit bevoordeelt de aangedreven elektrode.



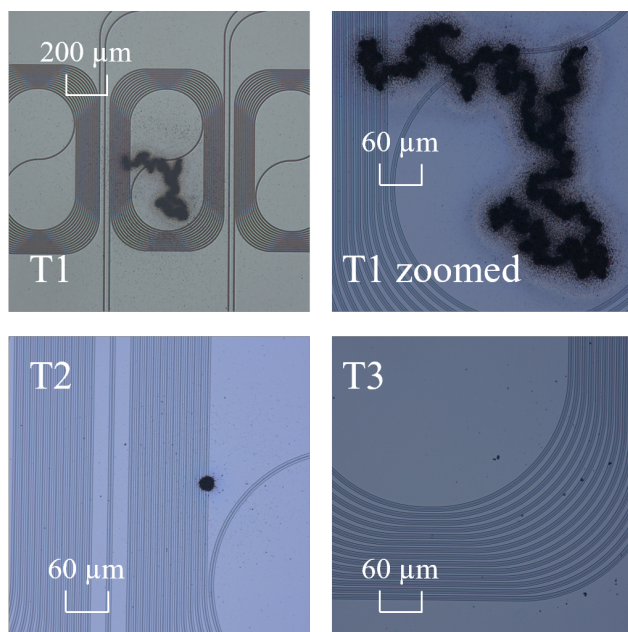
Figuur 2: Voorspelde en gemeten emissieversterking in de $3\ \mu\text{m}$ oppervlaktelaag. Gecombineerde ruimtelijke en temporele controle levert een toename van 48% ten opzichte van sinusvormige excitatie.

Toegepast in combinatie leveren deze technieken een versterking van 48% in de oppervlakte-emissie (Fig. 2), zoals bevestigd door zowel ICCD-metingen als het model.

Validatie en contaminatieproblemen

Alvorens plasmagekoppelde metingen uit te voeren, werd het detectiesysteem gevalideerd met een verzwakte 405 nm laser: neutrale dichtheidsfilters ($\text{OD4}+\text{OD2}$) reduceerden het signaal tot 0,39 pW, en de ICCD-camera detecteerde betrouwbaar de vlek na stapeling van vijf beelden, wat picowattgevoeligheid bevestigt, zelfs

in aanwezigheid van plasma-geïnduceerde ruis. Directe meting van de plasmagekoppelde golfgeleideruitgang werd echter niet bereikt vanwege koolstofgebaseerde contaminatie (Fig. 3). Deze contaminatie was afkomstig van polymeerbevattende componenten (3D-geprinte delen, PVC, vacuümvet) en stofdeeltjes uit de lucht die door het sterke elektrische veld naar het ontladingscentrum werden getrokken. Eenmaal gevangen werden stofdeeltjes verhit en verbrand in het zuurstofbevattende helium-lucht mengsel, waardoor verkoolde residuen achterbleven die het geleide licht sterk verstrooiden en volledig verlies van golfgeleiderfunctionaliteit veroorzaakten. Verschillende mitigatiemaatregelen (gelokaliseerde heliumstroom, kamerdoorspoeling, elektrostatische precipitator) verminderden de depositie maar elimineerden de contaminatie niet. De afwezigheid van een meetbaar signaal is daarom een technologische beperking, geen fundamenteel bezwaar: evanescente koppeling van incoherente dipolen is elders gevalideerd (bv. in golfgeleider-versterkte Ramanspectroscopie [10–12]), en de plasmadipolen bij 391,4 nm zijn analoog.



Figuur 3: Koolstofgebaseerde contaminatie na DBD-bedrijf: vezelachtig stof, grote deeltjes ($\sim 20\text{ }\mu\text{m}$), en deeltjes van enkele micrometers.

Perspectieven

Twee langetermijnoplossingen worden voorgesteld: (i) het verplaatsen van de opstelling naar een cleanroomomgeving met laag-uitgassende componenten, en (ii) het insluiten van het plasma in een microholte afgesloten met een diëlektrisch deksel.

Experimentele en simulaties tonen aan dat een gap van 20–100 μm stabiele DBD-bedrijf ondersteunt terwijl een verhoogde emissiesnelheid binnen de evanescente koppelingszone wordt gegarandeerd. Buiten het UVA-bereik kan het concept worden uitgebreid naar andere UV-banden door het gasmengsel te wijzigen (bv. Xe, Kr, Ar/F₂ voor excimeremissie). Een oppervlaktebarrièreontlading (SBD) biedt een nog compactere geometrie met lagere spanningsvereisten (tot enkele honderden volt). Uiteindelijk zou dezelfde architectuur een self-seeded on-chip gaslaser mogelijk kunnen maken, waarbij het microplasma zowel als spontane zender als als versterkingsmedium fungeert, wat coherente UV-emissie oplevert. Dit werk legt de basis voor volledig geïntegreerde UV-plasma-on-chip bronnen en adresseert een kritische bottleneck in lab-on-a-chip biosensing en bioimaging.

English summary

Introduction

The life sciences increasingly rely on optical techniques that operate in the ultraviolet (UV) spectral range. Many biomolecules – such as endogenous chromophores, DNA, and tryptophan – exhibit strong absorption and autofluorescence upon UV excitation, enabling label-free imaging, sterilization, and advanced oxidation processes [2–5]. However, translating these capabilities into practical, miniaturized lab-on-a-chip devices is hindered by a critical bottleneck: the lack of compact, efficient, and integrable UV light sources. Conventional UV emitters (mercury lamps, excimer lasers, frequency-quadrupled solid-state lasers) are bulky, have high étendue, and are fundamentally incompatible with sub-micrometer photonic integrated circuits (PICs). AlGaIn UV LEDs and laser diodes have made progress, but their external quantum efficiencies remain low in the deep UV, and their emission arises from large-area dies, leading to poor coupling into single-mode waveguides [6, 7]. Quantum-dot LEDs offer tunability but are still mainly confined to the near-UV [8, 9].

This thesis addresses this gap by developing an on-chip UV source based on evanescent coupling between a micro-gap dielectric barrier discharge (DBD) plasma and a UV-transparent PIC, the UV plasma-on-chip source (UV-POCS). The plasma is placed directly within the evanescent field of a single-mode waveguide, thereby bypassing the étendue limitations of free-space collection. A helium-air mixture is used to exploit heavy-particle reactions (Penning ionization and charge exchange) that generate excited emitters even in the plasma sheath where electron density is low. The work combines a 1D transient plasma model with a dipole-waveguide coupling model, and experimentally validates detection capability at the picowatt level. Although direct measurement of plasma-coupled output was prevented by carbon-based contamination, the underlying principle remains sound and two practical solutions are proposed.

Concept and theoretical framework

The central concept of the UV-POCS is illustrated in Fig. 1. A micro-gap DBD plasma is created directly above a spiral waveguide. A fraction of the UV emission from the plasma – primarily the N_2^+ first negative system at 391.4 nm – couples evanescently into the guided mode of the waveguide and propagates to the output

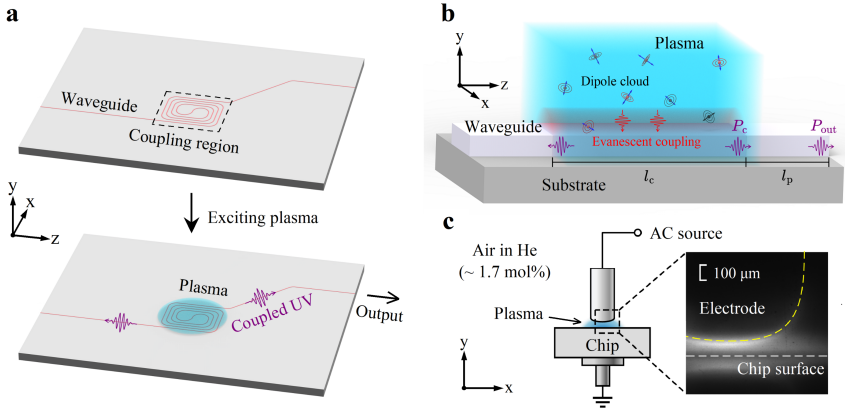


Figure 1: Overall concept of the UV-POCS. (a) Working principle – a microplasma generated above a spiral waveguide couples its UV emission evanescently into the guided mode. (b) Schematic of the plasma-waveguide evanescent coupling – only emitters within (~ 100 nm) of the waveguide surface contribute. (c) The experimental atmospheric DBD setup with helium-air mixture as the background gas. The micro-scale discharge gap is controlled with a high-voltage electrode positioned on top of the spiral waveguide.

facet. This evanescent coupling process relies on the fact that the guided mode's electric field extends about 100 nm into the cladding; only plasma emitters located within this region can transfer optical power to the mode.

A fundamental challenge is that the plasma sheath – the region adjacent to the chip surface – has a very low electron density, making conventional electron-impact excitation inefficient. To overcome this, a helium-air mixture is used. In such a mixture, heavy-particle reactions (Penning ionization and charge exchange) generate excited emitters directly within the sheath, bypassing the need for energetic electrons. These reactions produce $N_2^+(B)$ molecules, whose radiative decay yields the target UV emission at 391.4 nm.

To describe the plasma quantitatively, a 1D transient model is developed. It solves drift-diffusion equations for electrons, ions, and metastables (seven species in total) coupled with a self-consistent electric field. The model accounts for the key kinetic processes in the helium-nitrogen plasma and provides the emission rate r_{ems} . For the photonic part, the plasma is treated as a random distribution of radiating dipoles. Using Fermi's golden rule and the density of states in a waveguide, an analytical expression for the coupling efficiency is derived, which involves the group velocity v_g and an effective area A_{eff} . For multimode waveguides, the total efficiency is the sum over all guided modes. Combining the plasma and photonic models predicts an output power in the picowatt range (2.9–11.5 pW).

Experimental system development

A fully integrated UV plasma-on-chip experimental system was developed, comprising three main structural components: a DBD plasma source, a chip stage with the photonic chip and ground electrode, and an optical detection system (ICCD camera, aspheric lenses, optical enclosure). The development of a reliable and contamination-free plasma source on a photonic chip was a pioneering effort, as no off-the-shelf solution existed. The plasma configuration itself underwent three radical iterations. The initial surface barrier discharge (SBD) in vacuum suffered from gold electrode melting, substrate delamination, and parasitic discharges. A sandwich-like double-dielectric DBD eliminated direct electrode-chip contact but introduced discharge paths that bypassed the gas gap. The final configuration – a one-layer DBD operating at atmospheric pressure – proved stable and reproducible after optimizing the electrode tip (rounded flat profile) and using a controlled helium-dominant gas background; here the chip serves as the only dielectric barrier. In parallel, the chip stage was redesigned four times, finalized with a Teflon-PVC combination to minimize carbon contamination. The high-voltage electrode was insulated with quartz tubes (instead of PTFE tape) and made of pure tungsten to avoid copper sputtering. For the photonic part, low-loss AlO_x waveguides (~ 3 dB/cm at UVA wavelength) were employed, fabricated by atomic layer deposition, a SiN_x hard mask, and chlorine-based ICP etching. The integration of this plasma source with the photonic chip, together with the customized optical detection component, formed the core of the UV-POCS experimental system.

Enhancing plasma UV emission at the chip surface

Enhancing the emission intensity at the chip surface (~ 100 nm away from the waveguide) is crucial to lift the waveguide-coupled output power to a detectable level. Two complementary strategies were investigated to achieve this enhancement: spatial control via gap spacing reduction and temporal control via harmonic excitation.

Spatial control – gap spacing optimization. Reducing the discharge gap from $400\text{ }\mu\text{m}$ down to $80\text{ }\mu\text{m}$ intensifies the electric field in the cathode sheath. When the gap becomes smaller than twice the sheath thickness ($\sim 60\text{ }\mu\text{m}$), the sheaths overlap, increasing ion flux and electron density at the chip surface. The emission intensity at the chip surface increases significantly, saturating below $100\text{ }\mu\text{m}$. The 1D model reproduces the experimentally observed transition from a three-layer to a single-zone emission profile.

Temporal control – harmonic excitation. Adding a second harmonic component (10 kHz fundamental, amplitude ratio 0.5) with a phase difference of 270° amplifies the peak gap voltages by about 3% and redistributes power deposition asymmetrically. This leads to sheath thinning ($\sim 4\text{ }\mu\text{m}$) and preferential confinement of the

plasma on the chip side during the half-cycle when the chip acts as the cathode. Positive polarity (270°) favors the dielectric surface; negative polarity favors the powered electrode.

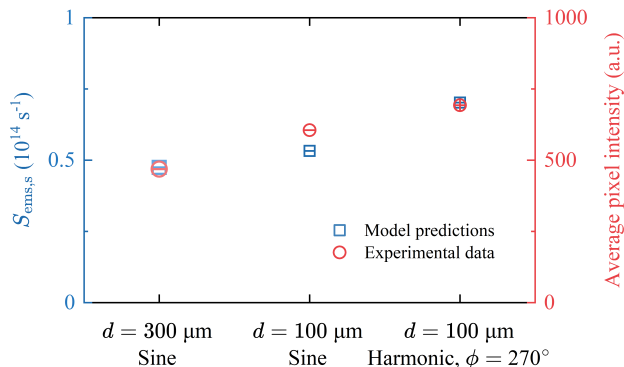


Figure 2: Predicted and measured emission enhancement in the $3 \mu\text{m}$ surface layer. Combined spatial and temporal control yields a 48% increase over sinusoidal excitation.

When applied in combination, these techniques yield a 48% enhancement in surface emission (Fig. 2), as confirmed by both ICCD measurements and the model.

Validation and contamination issues

Before attempting plasma-coupled measurements, the detection system was validated using an attenuated 405 nm laser: neutral density filters (OD4+OD2) reduced the signal to 0.39 pW, and the ICCD camera reliably detected the spot after stacking five images, confirming picowatt sensitivity even in the presence of plasma-induced noise. Direct measurement of the plasma-coupled waveguide output was not achieved, however, due to carbon-based contamination (Fig. 3). This contamination originated from polymer-containing components (3D-printed parts, PVC, vacuum grease) and airborne dust attracted to the discharge center by the strong electric field. Once trapped, dust particles were heated and combusted in the oxygen-containing helium-air mixture, leaving carbonized residues that strongly scattered guided light and caused complete loss of waveguide functionality. Several mitigation measures (localized helium flow, chamber flushing, electrostatic precipitator) reduced the deposition rate but did not eliminate contamination. The absence of a measurable signal is therefore a technological limitation, not a fundamental flaw: evanescent coupling of incoherent dipoles has been validated elsewhere (e.g., in waveguide-enhanced Raman spectroscopy [10–12]), and the plasma dipoles at 391.4 nm are analogous.

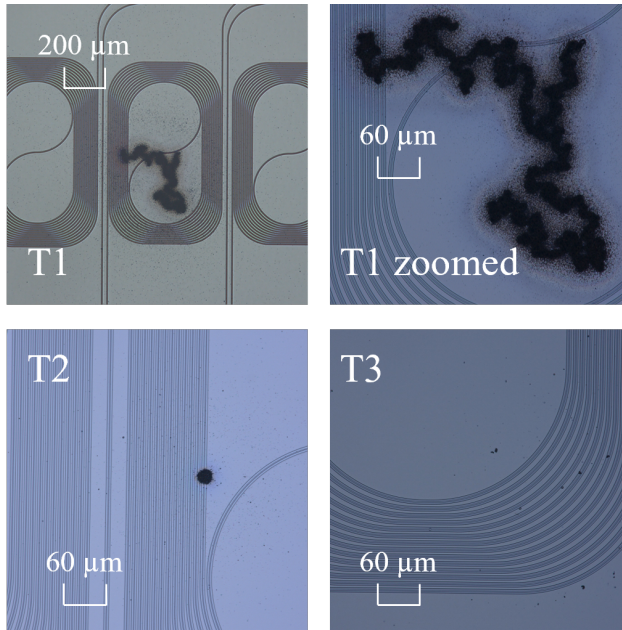


Figure 3: Carbon-based contamination after DBD operation: fibrous dust, large particles ($\sim 20 \mu\text{m}$), and micrometer-sized residues.

Perspectives

Two long-term solutions are proposed: (i) relocating the setup to a cleanroom environment with low-outgassing components, and (ii) encapsulating the plasma in a microcavity sealed by a dielectric lid. Experimental and simulation results show that a cavity height of $20\text{--}100 \mu\text{m}$ supports stable DBD operation while ensuring an increased emission rate within the evanescent coupling zone. Beyond the UVA range, the concept can be extended to other UV bands by changing the gas mixture (e.g., Xe, Kr, Ar/F₂ for excimer emission). Surface barrier discharge (SBD) offers an even more compact geometry with reduced voltage requirements (down to several hundred volts). Ultimately, the same architecture might enable a self-seeded on-chip gas laser, where the microplasma acts as both a spontaneous emitter and a gain medium, providing coherent UV emission. This work lays the foundation for fully integrated UV plasma-on-chip sources, addressing a critical bottleneck in lab-on-a-chip biosensing and bioimaging.

1

Introduction

The convergence of life sciences and photonic technologies has created a strong demand for miniaturized high-performance optical systems, particularly in the ultraviolet (UV) wavelength, where biomolecules exhibit intrinsic optical signatures. Despite remarkable progress in on-chip UV light manipulation technologies, the full potential of UV bio-sensing and bio-imaging remains constrained by a critical asymmetry: efficient integrated UV sources have yet to achieve comparable advancements. This introduction aims to review the state-of-the-art UV generation technology and discuss solutions to bridge this gap. This chapter begins by introducing the biophysical foundations that make UV techniques promising for biological applications. The realization of these techniques poses critical requirements on the generation and manipulation of UV light, leading to complex and usually bulky UV systems. Section 1.2 reviews the limitations of conventional bulky UV sources and surveys the landscape of emerging miniaturized alternatives. The interdisciplinary fusion of photonic integrated circuits (PICs) and UV-emitting microplasma is proposed as a possible solution worthwhile to explore in view of the lack of integrated UV sources. Section 1.3 gives a brief review of UV PICs, highlighting established platforms and biophotonic applications. Section 1.4 introduces dielectric barrier discharge (DBD) and other microplasma configurations as efficient, miniaturizable UV emitters. The research objective and outline of the thesis will be stated at the end of this chapter.

1.1 UV light in life sciences: bio-physical foundations

Ultraviolet radiation interacts with biological systems through several fundamental physical mechanisms that enable its broad application in life sciences. Direct absorption by nucleic acids induces DNA damage such as cyclobutane-pyrimidine dimers, which is exploited for sterilization and disinfection [2, 3]. UVA radiation excites endogenous chromophores, generating reactive oxygen species (ROS) that mediate oxidative damage and cellular signaling [13, 14]. Autofluorescence of intrinsic biomolecules (e.g., tryptophan) upon UV excitation enables label-free imaging, while photocatalysis and photolysis drive advanced oxidation processes for environmental remediation and pollutant degradation [4, 5, 15]. These physical mechanisms underpin a wide range of applications - from therapeutic dermatology and plant biology to quantitative molecular detection and solar-blind photodetection [16–19].

The diverse application of UV light in the life sciences is thus unified by well-characterized photophysical and photochemical processes. Realizing these capabilities outside well-equipped laboratories, however, demands a fundamental shift: the bulky, costly sources traditionally used for UV generation must be replaced by compact, mass-productive sources integrated directly with photonic circuits. Translating the rich interactions of UV with biomolecules into practical, miniaturized systems therefore requires a compact and efficient UV source that can be integrated with on-chip photonic circuits. The following sections examine the source technologies available for such integration, from conventional bulky systems to emerging miniaturized solutions.

1.2 UV sources: bulky vs. miniaturized

The critical bottleneck in realizing compact UV systems lies in the light source itself. While the biophysical advantages of UV light are clear, conventional sources that generate this light remain fundamentally incompatible with miniaturized photonic platforms. Over the past decades, UV emission has been dominated by macroscopic gas-discharge lamps and complex laser systems developed primarily for spectroscopy, lithography, and materials processing — not for chip-scale integration [20, 21]. Their optical, electrical, and geometrical characteristics were optimized for free-space delivery or fiber coupling, not for direct interfacing with sub-micrometer photonic integrated circuits (PICs). A PIC confines light in waveguides that support discrete electric field distributions – called modes – which propagate without changing their transverse shape. A single-mode waveguide supports only one such pattern, and this spatial coherence is favorable in biosensing as it offers better spectral resolution. Conventional UV sources radiate from large-area emitters (millimeters to centimeters) with high étendue, whereas a single-mode

PIC waveguide has a sub-micron cross-section and therefore small étendue. Consequently, a persistent mismatch in size and étendue exists between traditional UV sources and the waveguides and resonators of emerging integrated photonic architectures.

1.2.1 Conventional bulky UV sources

Historically, high-brightness coherent UV radiation has been provided by excimer lasers, nitrogen lasers, and frequency-converted solid-state lasers. Excimer systems such as ArF (193 nm), KrF (248 nm), and XeCl (308 nm) became workhorses for semiconductor lithography, micromachining, and materials processing owing to their high pulse energies, short wavelengths, and relatively broad gain bandwidths [22, 23]. However, these devices require high-voltage pulsed power supplies, large gas chambers with carefully controlled mixtures and pressures, and complex thermal management. Typical commercial excimer lasers occupy volumes of many tens to hundreds of liters, with wall-plug efficiencies typically ranging from 0.2% to 5% and significant maintenance requirements due to gas handling and window degradation [23, 24]. Frequency-quadrupled solid-state lasers - often based on Nd- or Yb-doped gain media combined with nonlinear crystals such as lithium triborate (LBO) or beta barium borate (BBO) - provide narrow-linewidth UV emission in the 200–400 nm range with excellent beam quality, but at the cost of multi-stage cavity designs, stringent alignment tolerances, and bulky packaging for mechanical and thermal stability [25, 26]. Nitrogen lasers operating at 337 nm offer simpler construction but still rely on high-voltage gas discharge in macroscopic cavities, with limited repetition rates and lifetimes [27]. Overall, these coherent UV sources remain large, expensive, and power-hungry, with limited wavelength flexibility compared with electronically tunable solid-state emitters.

Incoherent extended UV sources - including mercury, xenon, and deuterium lamps - have long been standard for spectroscopy, analytical chemistry, and biological imaging. Low-pressure mercury lamps provide strong line emission at 254 nm and additional lines in the near-UV and visible, while medium- and high-pressure mercury or mercury–xenon lamps offer broadband spectra across the UV to visible region with higher radiance [28]. Xenon arc lamps and deuterium lamps are widely used as quasi-continuum UV–visible sources; deuterium lamps emit smoothly down to about 180 nm, limited by window materials such as fused silica or MgF_2 [29, 30]. Despite their spectral usefulness, these lamps are inherently extended sources: the emitting plasma occupies volumes of millimeters to centimeters, enclosed in bulbs a few centimeters in size, with thermal loads that necessitate bulky housings and cooling [28]. Their spatial coherence is low, divergence is high, and lifetime and stability can be limiting factors, especially in precision metrology. More recently, UV LEDs based on AlGaN and related alloys have emerged as compact, electrically

driven incoherent sources spanning UVA, UVB, and parts of the UVC region [6, 31]. However, present devices typically exhibit external quantum efficiencies below 10% in the deep UV, and their emission still arises from large-area dies (hundreds of micrometers to millimeters), so they behave as extended, low-coherence emitters in most optical systems [7, 15].

The central difficulty in interfacing these conventional sources with integrated photonic circuits is rooted in the concept of *étendue* (optical phase-space volume). *Étendue* is conserved in passive optical systems and captures the joint spread of a beam in position and angle. Extended, incoherent sources such as lamps and large-area LEDs possess high *étendue*: they radiate from large emitting areas into wide angular distributions, filling many spatial and angular modes [32, 33]. In contrast, a single-mode PIC waveguide supports only one spatial mode with a small acceptance angle, corresponding to a vanishingly small *étendue*. No passive arrangement of lenses or mirrors can reduce the source *étendue* mismatch; at best, one can select a tiny fraction of the emitted power that happens to fall within the phase-space volume of the guided mode. For typical macroscopic UV lamps or LEDs placed in the far field of a chip, only an infinitesimal portion of the radiated power - often in the femtowatt range for milliwatt-level sources - can be coupled into a single-mode waveguide, even with high-numerical-aperture focusing optics and optimized alignment [33, 34]. Coherent laser sources mitigate some of these issues by providing lower *étendue* beams, but their macroscopic cavity geometries and packaging still complicate tight integration, and free-space coupling into sub-micrometer waveguides introduces alignment sensitivity and packaging overhead incompatible with truly compact, robust systems.

This fundamental mismatch between the macroscopic, high-*étendue* emission of conventional UV sources and the microscopic, low-*étendue* acceptance of integrated waveguides represents the primary bottleneck for fully integrated UV photonic systems. While careful optical design, micro-optics, and fiber interposer can incrementally improve coupling efficiency, they do not eliminate the underlying phase-space incompatibility. As UV photonic integrated circuits mature for applications in sensing, spectroscopy, and quantum technologies, there is a growing consensus that new classes of sources - engineered from the outset for on-chip operation and near-field coupling - are required to unlock the full potential of compact UV devices [6, 35]. The following subsection therefore turn to miniaturized, integrable emitters that seek to bridge this scale gap between the source and the photonic circuit.

1.2.2 Potential solutions for miniaturized UV sources

The limited availability of compact, efficient UV emitters remains a major bottleneck for integrated UV photonic systems. This subsection reviews the main

strategies to overcome this challenge – solid-state III–nitride emitters (LEDs, laser diodes, micro-LEDs, and nanostructures), colloidal quantum-dot emitters, non-linear frequency conversion in lithium niobate, and deep-UV photonic crystal surface-emitting lasers – and then introduces microplasma discharges as an alternative that addresses several of their inherent limitations.

Solid-state III–nitride emitters. Solid-state emitters based on III–nitride semiconductors have become the leading platform for compact UV light sources. By adjusting the composition of Al, In and Ga in (Al,In,Ga)N alloys, these devices cover wavelengths from the near-UV down to the deep-UV (DUV) [6]. Compared with bulky and fragile mercury discharge lamps, AlGaIn-based UV LEDs and laser diodes offer miniaturization, electrical drive, spectral tunability and long lifetimes, making them natural candidates for on-chip sources [6, 7, 36]. However, the UV range remains far less mature than the visible. State-of-the-art AlGaIn DUV LEDs typically exhibit external quantum efficiencies (EQEs) well below 10%, dropping to around 1% for emission below 250 nm. This poor performance arises from high threading dislocation densities, poor p-type doping, strong polarization fields and inefficient light extraction [6, 15, 31, 37]. Consequently, these devices require higher drive voltages, offer lower wall-plug efficiencies, and show reduced reliability compared with InGaIn blue or green LEDs [36, 37].

Beyond conventional LEDs, edge-emitting and vertical-cavity III–nitride UV laser diodes provide narrow linewidths and higher brightness, with recent demonstrations in the UVB–UVC range highlighting progress in material quality and cavity design [6, 38]. Recent advances have further extended this progress to UV-B laser diodes grown by molecular beam epitaxy on single-crystal AlN substrates, achieving electrically pumped lasing at 298.5 nm with a threshold current density of 3.4 kA/cm² and a spectral linewidth of 0.2 nm [39]. Nevertheless, UV laser diodes remain difficult to manufacture, exhibit high thresholds and limited lifetime, and their integration into dense photonic circuits is still at an early stage [6, 38]. In parallel, AlGaIn micro-LEDs have emerged as promising high-brightness, highly scalable UV sources. Deep-UV micro-LED arrays with pixel sizes down to a few micrometers can deliver optical power densities of 100–400 W cm^{−2} around 270–290 nm, with EQEs of 3–6% and resolutions exceeding 2500 pixels per inch [40, 41]. These devices are already being explored for maskless photolithography and as UV pumps for quantum-dot micro-displays, underscoring their potential for tightly integrated UV platforms [40, 41].

Nanostructured III–nitride emitters offer an additional route toward efficiency improvements. Core–shell AlGaIn nanorod LEDs can reduce dislocation densities, relax strain, mitigate the quantum-confined Stark effect, and improve light extraction, thereby addressing several intrinsic bottlenecks of c-plane quantum wells [31, 42]. Roadmap analyses point to nanostructuring, advanced band engi-

neering, and improved contacts as key directions to raise UV LED efficiencies toward those of visible devices [6, 31, 36]. Integration of III–nitride UV emitters with silicon photonics via micro-transfer printing further opens a pathway to fully on-chip light sources, avoiding fiber coupling and bulky external modules [6, 43].

Colloidal quantum-dot emitters. As an alternative to epitaxial III–nitrides, colloidal quantum-dot light-emitting diodes (QLEDs) provide a solution-processed route to miniaturized UV emitters. Carefully engineered CdZnS/ZnS nanocrystal LEDs have demonstrated “genuine” UV emission around 380 nm with high irradiance and minimal visible leakage [8]. QLEDs offer excellent spectral tunability, high color purity, and compatibility with printing and lithographic patterning. Recent reviews emphasize their potential for high-resolution, self-emissive displays and integrated optoelectronics [9]. However, most high-performance QLEDs currently operate in the visible; extending these architectures to shorter UV wavelengths while maintaining efficiency and stability remains an active challenge [8, 9]. Consequently, quantum-dot down-conversion driven by DUV micro-LED pumps has emerged as a pragmatic hybrid strategy: AlGaIn micro-LEDs in the 270–300 nm range efficiently excite visible quantum dots, enabling ultra-wide color gamuts while retaining a compact UV primary source [40, 44].

Nonlinear frequency conversion in lithium niobate. An alternative route to compact UV emission relies on second-harmonic generation (SHG) in lithium niobate (LiNbO_3). Recent advances have demonstrated efficient UV generation using both metasurface and waveguide platforms. Near-UV SHG at 394 nm in LiNbO_3 metasurfaces has been reported with a record absolute conversion efficiency of 1.36×10^{-3} [45]. Milliwatt-level UV emission at 390 nm in thin-film LiNbO_3 waveguides using sidewall poling has been achieved, with a normalized conversion efficiency of $5050\% \text{W}^{-1} \text{cm}^{-2}$ and an on-chip power of 4.2 mW [46]. These results confirm that SHG in LiNbO_3 can deliver bright, narrow-linewidth UV light suitable for on-chip integration. The approach relies on an external near-visible pump laser and requires careful quasi-phase-matching over centimeter-scale interaction lengths, but it benefits from the mature fabrication of LiNbO_3 photonic circuits and the coherence of the pump.

Photonic crystal surface-emitting lasers. Another emerging class of miniaturized UV sources is the photonic crystal surface-emitting laser (PCSEL). Deep-UV PCSELs operating at ~ 279 nm with single-mode emission and a beam divergence below 1° have recently been demonstrated [47]. This overcomes the poor beam quality and multi-mode issues typical of conventional deep-UV edge-emitting lasers. The approach exploits a two-dimensional photonic crystal in a wide-bandgap semiconductor gain medium to achieve large-area coherent surface emission with high

brightness. However, fabricating UV-transparent photonic crystals with sufficient index contrast and low scattering remains challenging, and material development in aluminum gallium nitride (AlGaN) and aluminum nitride (AlN) platforms is still ongoing. Despite these hurdles, deep-UV PCSELs offer a promising path to compact, high-beam-quality UV sources directly on chip.

The microplasma alternative. In summary, the landscape of miniaturized UV sources is defined by trade-offs between spectral reach, efficiency, fabrication complexity, and integrability. AlGaN LEDs and micro-LEDs provide the most mature route to electrically driven, chip-scale UV emission across UVC–UVA, but still suffer from low wall-plug efficiencies and challenging epitaxy. UV laser diodes offer superior coherence but are technologically demanding. Quantum-dot approaches excel in tunability and patternability, yet are so far largely confined to near-UV or down-conversion architectures.

Against this background, microplasma discharges offer a compelling alternative that overcomes several of these limitations. Unlike solid-state emitters, a microplasma generates a broad UV spectrum extending from the vacuum ultraviolet (VUV) to the infrared [48–50], with a high power density (often exceeding 100 W cm^{-3}) and a simple electrode-based structure that can be operated at atmospheric pressure [49, 51–53]. Electrical-to-optical conversion efficiencies as high as 20% have been reported for certain excimer-based microplasmas [54]. More importantly, the low refractive index of a plasma (close to unity) allows it to act as the top cladding of a high-index-contrast waveguide without perturbing the guided mode. A guided mode is not confined entirely to the core; its electric field extends into the cladding and decays exponentially – this is the evanescent field, with a characteristic penetration depth of about 100 nm at UV wavelengths. Because the plasma index is nearly that of vacuum, the evanescent tail decays into the plasma with the same short penetration depth. The plasma can therefore be placed directly within this evanescent field. This near-field coupling mechanism bypasses the étendue limitations inherent in free-space collection from a large-area source.

A key additional advantage is that, although the microplasma itself is an extended, incoherent emitter, its coupling to a single-mode waveguide effectively filters the spatial modes: only the portion of the plasma emission that overlaps with the fundamental mode of the waveguide is collected and guided. Consequently, the output of the chip behaves as a single-mode source with excellent spatial coherence, determined solely by the waveguide mode rather than by the plasma. This is a unique feature of the evanescent-coupling approach that cannot be achieved with conventional free-space collection from the same plasma. The detailed physics and generation methods of microplasmas are discussed later in Section 1.4.

1.3 UV photonic integrated circuits as miniaturization enablers

Photonic Integrated Circuits (PICs) have revolutionized optical system design by enabling the transition from bulky, discrete optical setups to monolithic, chip-scale platforms. By integrating essential optical components - such as waveguides, splitters, filters, and resonators - onto a single substrate using lithographic techniques, PICs offer significant advantages over traditional bulk optics in terms of stability, reduced footprint, and scalability. This monolithic approach eliminates alignment drift and drastically reduces system size and cost, which is fundamental to the lab-on-a-chip paradigm. As a result, PICs facilitate the translation of complex optical benches into portable and robust devices suitable for mass production, which has been pivotal in enabling high-performance biosensing and bioimaging outside conventional laboratory environments [55–58].

The extension of PIC technology into the ultraviolet (UV) spectral range has opened new avenues for miniaturized systems with enhanced spatial resolution and unique light–matter interactions, particularly relevant for label-free biosensing, autofluorescence imaging, and advanced microscopy [59, 60]. However, achieving low-loss UV photonic integration presents substantial challenges due to increased material absorption and scattering at shorter wavelengths. Overcoming these obstacles has required the development of wide-bandgap material platforms with high transparency in the UVA to UVC ranges and fabrication flows that remain compatible with CMOS or wafer-scale processing [1, 61, 62]. Recent progress demonstrates that UV-PICs can now deliver robust performance for advanced sensing and imaging tasks on chip-scale devices, including operation down to the UVC band [1].

1.3.1 UV photonic integration platforms

The realization of UV photonic integrated circuits relies on materials that combine wide bandgaps with compatibility for scalable fabrication and heterogeneous integration. Key platforms include silicon-on-insulator (SOI), silicon nitride (SiN_x), lithium niobate (LiNbO_3), AlN, AlGaIn, aluminum Oxide (Al_2O_3), and, more recently, suspended thermal SiO_2 for the deep UV [1, 61–63].

SOI has been foundational for visible-to-infrared photonics but suffers from strong absorption below $\sim 1.1 \mu\text{m}$, which limits its applicability in the UV regime despite its excellent maturity and high-index contrast [63]. SiN_x extends transparency into the visible and near-UV, and low-loss blue and near-UV waveguides and lasers have been demonstrated; nevertheless, material absorption and scattering significantly increase toward shorter wavelengths [62, 64].

AlN stands out due to its large bandgap ($\sim 6.2 \text{ eV}$), broad transparency window

from deep-UV to mid-infrared, sizable second-order nonlinearities, piezoelectricity, and compatibility with CMOS processes [65, 66]. AlN-on-sapphire and related structures support ultra-high-Q microring resonators in the near-UV with quality factors exceeding 10^5 , enabling nonlinear and quantum photonic functionalities in the UV [65]. AlGaIn/AlN heterostructures further exploit the tunability of the bandgap to cover the UV to visible spectral range with high index contrast and relatively low loss [67].

Al_2O_3 deposited by atomic layer deposition (ALD) provides excellent UV transparency and low propagation loss and can be monolithically integrated with SiN_x to realize broadband platforms spanning from the UV to the short-wave infrared [68]. This material has been used to realize low-loss waveguides and complex interferometric circuits at $\lambda = 360$ nm for on-chip structured illumination microscopy and quantitative phase imaging [59]. Lithium niobate on insulator (LNOI) offers strong electro-optic and nonlinear coefficients; while propagation losses increase at short wavelengths, efficient frequency conversion into the UV has been experimentally demonstrated using periodically poled LN waveguides [69, 70]. Finally, for the UVC band (200–280 nm), suspended thermal SiO_2 waveguides fabricated by under-etching the silicon substrate have recently achieved propagation losses below 3–4 dB/cm at 266 nm in air and water claddings, positioning TOX as a promising UVC PIC platform [1].

Each platform presents trade-offs between the transparency window, propagation loss, fabrication complexity, nonlinearity, and prospects for integrating active devices such as sources and detectors. Platform selection is therefore application-driven, spanning biosensing, quantum optics, nonlinear frequency conversion, lab-on-a-chip microscopy, and environmental or biochemical sensing.

1.3.2 UV integrated photonic systems for advanced sensing and imaging

The maturity of UV-PIC technology is evidenced by a growing number of functional lab-on-a-chip systems that exploit on-chip manipulation of UV light for advanced biosensing and bioimaging. A prominent example is the use of Al_2O_3 -based UV photonic integrated circuits for far-field structured illumination autofluorescence microscopy at 360 nm excitation wavelength [59]. These chips generate high-contrast structured illumination patterns directly FROM the photonic circuit, enabling super-resolved autofluorescence imaging of biological samples - such as yeast cells - without altering conventional sample handling protocols, revealing sub-diffraction features that remain unresolved in standard wide-field microscopy [59, 71, 72].

Beyond structured illumination, PIC-based quantitative phase imaging (QPI) has emerged as a powerful label-free modality in which photonic chips provide compact, stable beam shaping and interferometric functionality. A first demonstration of

QPI using a UV PIC as an add-on coherent illumination source to a standard wide-field microscope achieved diffraction-limited resolution and phase noise levels competitive with state-of-the-art bulk systems [73, 74]. This development connects the broader QPI community - where quantitative phase imaging is increasingly used in biomedicine for label-free assessment of cell morphology, biomass distributions, and drug response [75] - with UV integrated photonics.

More generally, integrated photonic biosensors based on Si, SiN_x, and hybrid platforms already support label-free, multiplexed, and highly sensitive detection of biomolecules, and are increasingly being combined with microfluidics into fully integrated lab-on-a-chip systems [55, 57, 58]. As UV-compatible platforms such as AlN, AlGaN, Al₂O₃, and TOX mature, these biosensing concepts can be translated toward shorter wavelengths to exploit stronger intrinsic absorption and autofluorescence signatures of biomolecules as well as improved spatial resolution. In parallel, UV-compatible PICs are being explored for robust, miniaturized systems relevant to defense and environmental monitoring, where PIC-based biochemical sensors can provide portable and highly accurate detection of chemical and biological agents [56]. Together, these demonstrations confirm that guiding and processing UV light on a chip is not only feasible, but also increasingly central to next-generation biosensing and bioimaging technologies.

1.4 UV-emitting microplasma

Plasma, the fourth state of matter, is the most abundant form of matter in the universe. Compared with the three well-known states of matter, it is the most energetic state on the particle scale, where atoms are stripped of their electrons in a process known as ionization. This results in a mixture of free electrons, positive ions, and neutral particles. Their collisional interactions make plasma a potent source of electromagnetic emission, particularly in the UV range. The presence of the unbound charged particles makes plasma highly electrically conductive and distinguishes it from the gas state by enabling collective behavior. This collective behavior is governed by long-range electromagnetic forces, meaning that the motion of each charged particle is influenced by the fields generated by all others. For example, while plasma is highly responsive to externally applied electromagnetic fields, it inherently strives to maintain quasineutrality - a state where positive and negative charge densities are nearly equal on a macroscopic scale. This is achieved through the space charge effect, where local charge imbalances create intense electric fields that rapidly redistribute the charged particles to restore bulk neutrality.

This bulk quasineutrality, however, must necessarily break down at any boundary, such as a solid wall, resulting in a non-neutral region known as a plasma sheath. The sheath forms because electrons, being much lighter than ions, have higher

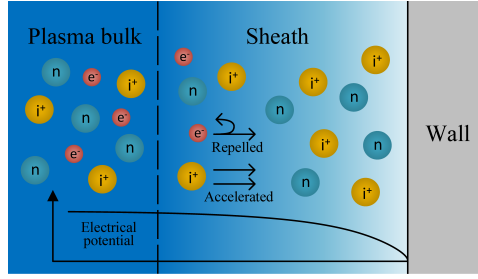


Figure 1.1: Plasma sheath acts as a balancer of the charge flux towards the wall.

thermal velocities and thus initially bombard the wall more frequently. This charges the wall negatively, creating an electric field that repels further electrons and accelerates positive ions toward the wall. The sheath is thus a thin layer (typically tens of micrometers at atmospheric pressure) where the electron density drops from its bulk value to nearly zero, while the ion density remains high, leading to a net positive space charge. That leads to a low emission rate from electron-impact excitation, which makes plasma-waveguide coupling difficult. This difficulty and the corresponding solution — introduction of heavy particle reactions — is discussed later in Subsection 1.4.2.

The thickness of the sheath is governed by the Debye length, which depends on electron density and temperature. In a DC glow discharge, the sheath is static and supports a large potential drop that accelerates ions. In an AC discharge (such as the 10 kHz DBD used in this work), the sheath oscillates with the driving frequency; during each half-cycle, the electrode that is momentarily cathodic develops a sheath that accelerates ions toward the surface. This dynamic behavior has a strong influence on ion energy distribution and surface heating. In the present DBD configuration, the chip surface alternates between cathode and anode roles; the sheath on the chip side is of particular interest because it determines the local electric field and the conditions for electron-impact excitation near the waveguide. The sheath thus functions as a dynamic, self-adjusting layer that ensures global charge conservation by equalizing the particle fluxes to the wall over time, as illustrated in Fig. 1.1.

1.4.1 Generation method of microplasma

Microplasmas are plasmas confined to submillimeter dimensions, where the characteristic device size - such as the electrode gap - becomes comparable to or even smaller than the plasma sheath [49, 76]. These systems are characterized by high electron densities (often exceeding 10^{20} m^{-3}), strong non-equilibrium between electrons and heavy particles, and the ability to operate stably at atmo-

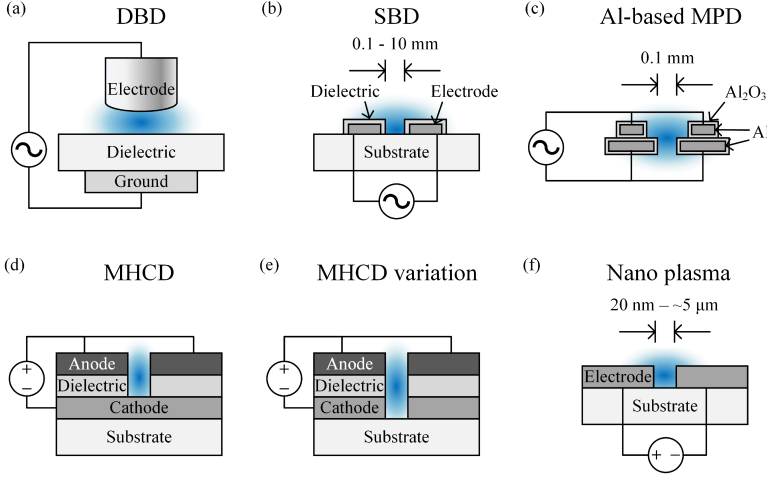


Figure 1.2: Schematics of various microplasma configuration suitable for integration with PICs: (a) dielectric barrier discharge (DBD), (b) surface barrier discharge (SBD), (c) Aluminum-based microcavity plasma device (MPD), (d) and (e) two types of micro hollow cathode discharge (MHCD), (f) nano plasma.

spheric pressure [49, 77]. Such properties enable unique plasma chemistries and efficient production of reactive species at near-room temperature, distinguishing microplasmas from conventional large-scale discharges [52, 78]. Microplasmas have found applications across material processing, chemical analysis, photonics, and biomedicine due to their compactness, energy efficiency, and compatibility with miniaturized devices [77, 79, 80]. The generation methods for microplasmas can be broadly classified by their excitation schemes: AC-driven, DC-driven, and emerging techniques. Fig. 1.2 shows several discharge configurations of microplasmas that can be integrated with PICs.

AC-driven microplasmas. AC-driven microplasmas are most commonly realized using dielectric barrier discharge (DBD) configurations. In DBDs, one or more dielectric layers are placed between electrodes; charge accumulation on these dielectrics self-terminates each discharge event within an AC cycle, resulting in transient filamentary microdischarges [53, 80]. Typical electrode gaps range from tens to hundreds of micrometers. The non-thermal nature of DBDs ensures that while electrons reach high energies necessary for ionization and excitation, the bulk gas remains near room temperature [76]. Surface barrier discharges (SBDs) represent a variant where both electrodes reside on the same side of a dielectric substrate; here, plasma propagates along the surface rather than through a bulk gap [53]. Advances in microfabrication have enabled large-area arrays of

microcavity DBDs with high packing densities, providing uniform plasma over extended surfaces for applications such as plasma displays and surface treatment [80,81]. Microcavity plasma devices (MPDs) take miniaturization a step further, with cavity dimensions down to a few micrometers. MPDs typically employ AC, RF, or pulsed excitation to minimize electrode sputtering. The tight confinement leads to high electric fields and efficient power coupling, making MPDs promising for on-chip UV emitters and integrated sensors in microfluidic platforms [81].

DC-driven microplasmas. A typical demonstration of DC-driven microplasmas is the micro-hollow cathode discharge (MHCD). Typical MHCD consists of a hollow cathode separated from an anode by a thin dielectric layer; typical aperture diameters range from 50–500 μm [82,83]. The geometry promotes pendulum electron motion between cathode walls, enhancing ionization efficiency and enabling high electron densities with intense radiation output. MHCDs can operate in continuous DC or pulsed DC modes and are widely used as sources for UV–VUV radiation or as plasma cathodes in advanced electronic devices [80,82]. At even smaller scales (gap < 100 nm), nanoplasma devices exploit quantum tunneling and field emission effects alongside traditional gas breakdown mechanisms. These systems achieve extremely localized ionization regions with ultrafast switching capabilities using only modest DC biases [84].

Emerging excitation methods. Emerging excitation methods further expand the versatility of microplasma generation. Triboelectric excitation utilizes mechanical stimuli - such as those produced by triboelectric nanogenerators - to generate high-voltage pulses capable of igniting atmospheric-pressure plasmas without external power supplies, enabling portable or self-powered plasma sources for point-of-care diagnostics or environmental sensing [85,86]. Laser-induced breakdown offers sub-micrometer spatial resolution by focusing intense laser pulses into solids, liquids, or gases; this technique is valuable for precision micromachining and spectroscopic analysis [87]. Integration with microfluidic platforms allows DBD or jet-based plasmas to be generated within chip-scale reactors for chemical synthesis or analytical chemistry, where precise control over gas–liquid interfaces enhances mass transfer and reaction selectivity [88,89].

1.4.2 Surface UV collection from microplasma: difficulty and solution

UV emission from plasmas primarily arises from electron-impact excitation of gas atoms or molecules, which then release UV photons upon decay. Particularly strong UV sources include molecular gases like nitrogen, noble gases such as helium and argon, and their mixtures with halogens, the latter forming energized excimer

or exciplex molecules that efficiently emit UV light upon dissociation. However, collecting UV emission at surfaces presents a fundamental challenge: the plasma naturally forms a sheath - a transitional layer from the plasma bulk to any solid wall - where electron density decays exponentially. That leads to an unfavorable condition for electron-impact excitation and the subsequent UV emission from de-excitation. The sheath typically extends over tens of micrometers, which is several orders of magnitude larger than the optimal evanescent coupling zone (~ 100 nm), as shown in Fig. 1.3.

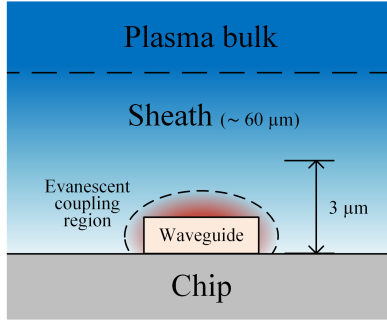


Figure 1.3: Major difficulty in achieving efficient evanescent plasma-waveguide coupling: the dimension mismatch.

To overcome this limitation, our approach utilizes carefully designed gas compositions that enable heavy-particle reactions, including charge exchange and Penning ionization. Since heavy particles remain abundant inside the sheath region, unlike electrons, the corresponding emitters can still be generated substantially. This strategy ensures strong surface emission despite the unfavorable conditions for electron-impact excitation, as detailed in Chapter 2.

1.5 Research objective

The primary objective of this thesis is to develop, optimize, and characterize an on-chip microplasma UV source enabled by enhanced plasma UV emission and efficient UV collection into PICs through evanescent plasma-waveguide coupling. The central hypothesis is that evanescent coupling between a micro-gap DBD plasma and a single-mode waveguide is feasible and can yield detectable output power, despite the intrinsic mismatch between the plasma sheath thickness and the evanescent field penetration depth. A critical step in realizing this hypothesis is the use of a gas mixture that promotes heavy-particle reactions (Penning ionization and charge exchange). These reactions generate excited UV emitters directly within the sheath, where the electron density is too low for electron-impact excitation, thereby overcoming the fundamental limitation of the plasma sheath. To test

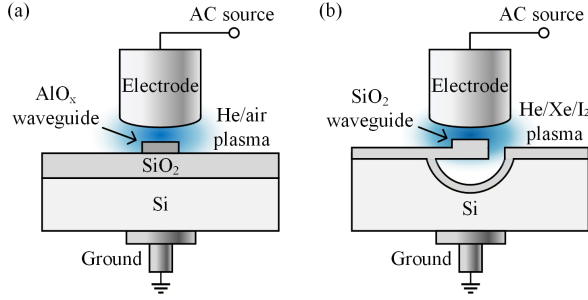


Figure 1.4: (a) UVA plasma-on-chip source structure studied in this thesis. (b) A showcase of plasma-on-chip source design in the UVC spectrum inspired by [1] (~ 253 nm).

this hypothesis, the research addresses the following question: Can UV emission be generated and enhanced within the narrow (~ 100 nm) evanescent coupling zone and efficiently coupled into a guided mode? To answer this question, a multi-physics theoretical framework combining a 1D transient plasma model with a dipole-waveguide coupling model was developed, experimental strategies for enhancing surface emission (gap spacing optimization and harmonic excitation) were investigated, and a prototype UV-POCS system was built and characterized. The schematic of the device is shown in Fig. 1.4 (a). Although both theoretical and experimental work of this thesis focus on the UVA spectrum (~ 391.4 nm), the fundamental methodology established here represents a universal approach that can be transferred to other wavelength regions, like the UVC platform shown in Fig. 1.4 (b).

The specific objectives of this research are:

1. To develop a multi-physics modeling framework that couples a 1D plasma discharge model with a dipole-waveguide coupling model. This integrated model will provide insights into the ionization dynamics, excited species generation, and efficiency of evanescent coupling into PIC waveguides.
2. To experimentally and numerically investigate strategies for enhancing local ionization and UV emission at the chip surface. This involves a detailed study of:
 - Spatial control: optimize the discharge gap spacing (down to $80\ \mu\text{m}$) to intensify the gap electric field and exploit the sheath dynamics in response to this geometric confinement.
 - Temporal control: implement harmonic excitation by customizing the applied voltage waveform to redistribute power deposition temporally and amplify peak ionization and emission rates.

3. To fabricate a prototype integrated UV plasma-on-chip source (UV-POCS) and experimentally characterize its performance by quantifying the UV output power and spectrum coupled from the waveguide, thereby validating the practical implementation of the proposed approach.

By achieving these objectives, this work aims to establish a comprehensive methodology for realizing high-performance, integrated UV light sources, thereby addressing a critical bottleneck in the development of fully integrated lab-on-a-chip systems for biosensing and bioimaging.

1.6 Thesis outline

This thesis is structured into five chapters that progressively address the research objectives:

Chapter 2 establishes the theoretical framework, presenting both the plasma discharge model and the dipole-waveguide coupling model used throughout this thesis.

Chapter 3 reviews the technical difficulties and solutions in the development of the UV-POCS device and the experimental system.

Chapter 4 investigates strategies for enhancing surface emission through geometric confinement and harmonic excitation, demonstrating a 48% emission enhancement at the chip surface.

Chapter 5 details the experimental characterization of the UV-POCS device and the final system-level optimization.

Chapter 6 summarizes the key contributions, discusses limitations, and outlines future research directions, including transferability to UVC spectrum through alternative designs.

1.7 Publications

1.7.1 Publications in international journals

1. Yize Liu, Nicolas Le Thomas, Christophe Leys, Anton Nikiforov, "Enhancing local ionization in micro-gap atmospheric discharge", *New Journal of Physics*, 27(7), p. 074302 (2025).

1.7.2 Publications in international conferences

1. Y. Liu, N. Le Thomas, C. Leys, A. Nikiforov, "Enhancing surface emission in micro-gap atmospheric discharge via harmonic excitation", *Plasma Thin Film International Union Meeting (PLATHINIUM)*, (2025) (poster).

2

Theoretical model of plasma-waveguide coupling

This chapter establishes a theoretical framework to model evanescent coupling between a micro-gap DBD plasma and an integrated waveguide, bridging the disciplines of plasma physics and photonics. Due to the difficulty in performing direct diagnostics on the micro-gap DBD plasma, 1D transient modeling with simplified helium/nitrogen chemistry has been chosen as an alternative approach to obtain the emission rate information. In the photonics part, the plasma is considered a dipole cloud source characterized by the dipole emission rate covering the waveguide as gas cladding. The evanescent coupling efficiency between dipoles and the waveguide is calculated using either finite difference eigenmode (FDE) or finite-difference time-domain (FDTD) numerical solvers. We also show that, under the thin strip waveguide assumption, the coupled power into multi-mode waveguides is proportional to the number of supported modes. By combining the plasma model with the photonic coupling calculation, a predictive estimate of the output power is achieved, yielding a power level on the order of 2.9–11.5 pW.

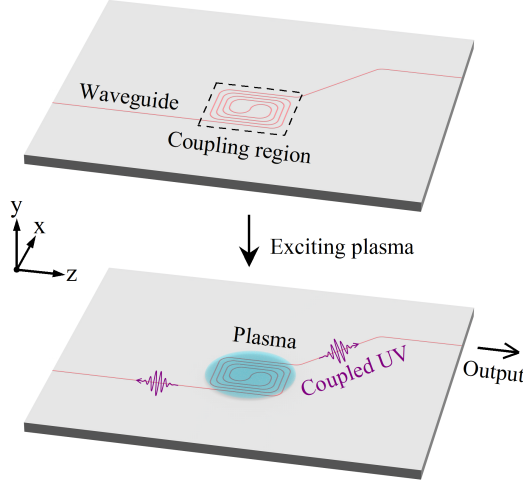


Figure 2.1: Principle of UV-POCS.

2.1 Theoretical framework

The overall operation of the UV-POCS device can be described by a set of equations that relate the plasma emission rate, the waveguide coupling efficiency, and the propagation loss. This section establishes the theoretical framework that links these quantities, starting from the definition of output power and the representation of the plasma as a random distribution of radiating dipoles. The key parameters are the local emission rate r_{ems} , obtained from the plasma model of Section 2.2, and the coupling efficiency η_c , calculated by the photonics model of Section 2.3. The resulting expressions for P_c and P_{out} form the basis for all subsequent power estimates and optimization discussions.

The working principle of UV-POCS is detailed as follows. A UV-emitting plasma is generated above the spiral-shaped coupling region of the waveguide, where a fraction of the free-space emission from the plasma is coupled evanescently into the guided mode, as illustrated in Fig. 2.1. The coupled light travels in both directions along the waveguide, but in the experiment, only the forward-propagating light to the output is measured. The output power of a specific light frequency ν is given by

$$P_{\text{out}} = P_c \times 10^{-\frac{\alpha l_p}{10}}, \quad (2.1)$$

where P_c is the coupled light power from the plasma to the waveguide, α is the loss rate in units of dB/cm, and l_p is the propagation length of the guided mode from the

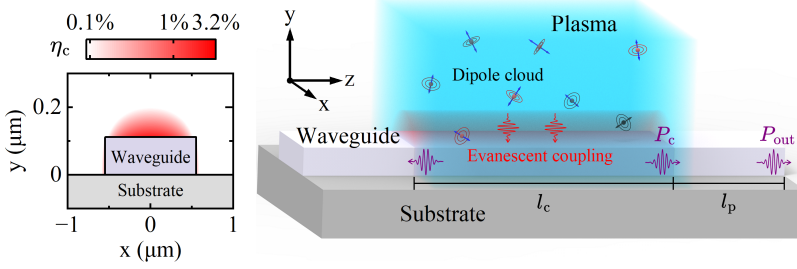


Figure 2.2: Left: a contour of the coupling efficiency showing the span of evanescent coupling around a single-mode waveguide. Right: schematic of the plasma-waveguide evanescent coupling.

exit of the coupling region to the output facet in cm.

The spontaneous emission of the ions and neutrals in their excited state (the emitters in the plasma) can be described with the dipole model. The plasma can therefore be considered a dipole cloud source with randomly distributed dipoles, characterized by the emission wavelength and the corresponding local emission rate r_{ems} , which is the product of the radiative decay rate of individual dipoles and the dipole number density. The overlap of the effective modal area with the surrounding dipole cloud is where evanescent coupling occurs, as shown in the red region in Fig. 2.2. The coupled power P_c at a specific light frequency ν is

$$P_c = l_{c,\text{eff}} r_{\text{ems},\nu} h\nu \iint_{A_{\text{tpclad}}} \eta_c(\mathbf{r}_0, \omega) dA, \quad (2.2)$$

$$l_{c,\text{eff}} = \int_0^{l_c} 10^{-\frac{\alpha(l_c-l)}{10}} dl, \quad (2.3)$$

where $l_{c,\text{eff}}$ is the effective coupling length in cm taking into account the propagation loss, and A_{tpclad} is the area in the top cladding over which the dipole cloud extends. This integral is restricted to the top cladding because only emitters in this region can overlap with the evanescent tail of the guided mode. Here η_c is the waveguide coupling efficiency of the emission from a dipole at a given position into a given propagation direction of the guided mode, averaged over all dipole orientations. It represents the total contribution from all guided modes; however, the contribution from a specific mode can also be extracted individually. Notice that r_{ems} is taken out of the integration. That is because the evanescent coupling is a sub-wavelength process, and within its span, the plasma density gradient is negligible, which means that r_{ems} used in Eq. (2.2) is spatially invariant. The calculation of r_{ems} and all the other plasma parameters, including particle densities, electron temperature, and reaction rates, is handled by the 1D transient plasma model, which will be detailed

in Section 2.2. The coupling efficiency η_c , on the other hand, is computed by the photonics model introduced in Section 2.3.

2.2 Model of atmospheric helium/nitrogen plasma

The local emission rate r_{ems} that drives the dipole-cloud model is not directly measurable in the micro-gap DBD configuration because of the extremely small gap and the presence of the dielectric chip, which prevents spatially resolved optical diagnostics. A numerical approach is therefore required. This section presents a one-dimensional transient plasma model that captures the essential kinetics of a helium/nitrogen mixture under AC excitation. The model solves the drift-diffusion equations for seven species, including electrons, ions, and metastables, with a self-consistent electric field. It provides the spatial and temporal distributions of the $\text{N}_2^+(B)$ excited state, from which the volume-averaged emission rate r_{ems} is derived. The model predictions are intended for direct comparison with experimental observations in Chapter 4.

2.2.1 Physical configuration and assumption

The model considers a simplified 1D structure in which plasma is generated in a helium flow with entrained nitrogen between the high-voltage electrode and the chip, with the ground electrode underneath the chip, as illustrated in Fig. 2.3. This is a typical DBD structure with just one layer of dielectric (the chip). The discharge is excited by an AC power supply. The breakdown occurs when the gap voltage reaches a certain threshold. In our experiments, the current peaks induced by microdischarge [51] are present, but they appear infrequently and contribute little to the net power consumption in all cases. Thus, the microdischarge is considered unimportant here, and the charge accumulation effect on the chip surface is considered negligible. The chip can then be simplified as an ideal parallel resistor-capacitor (RC) circuit (consideration of the leakage conductance is discussed in Appendix A). The total impedance and the phase angle of the RC circuit used in the model are calculated based on the result of a fast Fourier transform (FFT) analysis of the measured current-voltage (I-V) characteristic of the setup (see Fig. 4.4 for a representative I-V curve with a sinusoidal voltage waveform) under 3 kV peak-to-peak (ptp) applied voltage at 10 kHz.

The plasma is treated as a continuous fluid containing electrons, ions, and neutral particles. This assumption holds when the Knudsen number $\text{Kn} = \lambda_{\text{mfp}}/L \ll 1$, which means the mean free path λ_{mfp} of the particles is far smaller than the characteristic length scale of the system, and the plasma is collision-determined. Note that the system of particles does not reach thermodynamic equilibrium, so the species can have different temperatures. This is a typical condition in cold

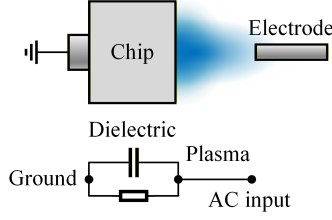


Figure 2.3: Schematic of the 1D transient plasma model.

plasma (also called non-thermal plasma), where the electron temperature is usually several eV or more, while heavy particles remain at almost the same scale as room temperature. In our experiments, the discharge is operated in pulses (~ 500 ms). The heating of heavy particles is negligible. Thus, all heavy particles are set to be at 300 K.

2.2.2 Governing equations

The plasma is described by a self-consistent set of equations accounting for the conservation of mass, momentum, energy, and charge. The motion of all species is described with the drift-diffusion approximation.

Conservation of mass. For each species k (electrons, ions, neutrals), the continuity equation is

$$\frac{\partial n_k}{\partial t} + \nabla \cdot \Gamma_k = S_k, \quad (2.4)$$

where n_k is the species density, Γ_k is the particle flux, and S_k is the net source term. The source terms couple all species through ionization, excitation, attachment, recombination, and other collisional processes.

Conservation of momentum. Under the drift-diffusion approximation, momentum conservation reduces to a flux expression that balances drift in the electric field against diffusion due to density gradients. For electrons,

$$\Gamma_e = -\mu_e n_e \mathbf{E} - D_e \nabla n_e, \quad (2.5)$$

with μ_e the electron mobility, D_e the diffusivity, and $\mathbf{E} = -\nabla V$ the electric field. For heavy species,

$$\Gamma_k = \text{sgn}(Z_k) \mu_k n_k \mathbf{E} - D_k \nabla n_k, \quad (2.6)$$

where Z_k is the charge number (zero for neutrals, for which the drift term vanishes). The mobility and diffusivity of each species will be discussed in Subsection 2.2.3.

Conservation of energy. Because electrons are not in thermal equilibrium with the heavy species, an additional equation is solved for the electron energy density $n_\varepsilon = n_e \varepsilon$ (with ε the mean electron energy in electronvolts). The equation is written in electronvolt units, so the elementary charge e does not appear explicitly. It reads:

$$\frac{\partial n_\varepsilon}{\partial t} + \nabla \cdot \mathbf{\Gamma}_\varepsilon = -\mathbf{E} \cdot \mathbf{\Gamma}_e - S_{\text{en}}, \quad (2.7)$$

where $\mathbf{\Gamma}_\varepsilon$ is the electron energy flux, $-\mathbf{E} \cdot \mathbf{\Gamma}_e$ is the Joule heating term (power gained by electrons from the electric field), and S_{en} represents energy losses due to inelastic collisions (positive loss). The energy flux is given by

$$\mathbf{\Gamma}_\varepsilon = -(\mu_\varepsilon \mathbf{E}) n_\varepsilon - D_\varepsilon \nabla n_\varepsilon, \quad (2.8)$$

with μ_ε and D_ε the energy mobility and diffusion coefficients.

Conservation of charge. The electric field is determined self-consistently from the space charge distribution via Poisson's equation:

$$\nabla \cdot (\varepsilon_0 \varepsilon_r \mathbf{E}) = \rho_{\text{sc}}, \quad (2.9)$$

where ε_0 is the vacuum permittivity, ε_r is the relative permittivity, and ρ_{sc} is the net space charge density.

2.2.3 Plasma kinetics

Seven species are considered in this study, electrons (e), helium ions (He^+), helium dimer ions (He_2^+), nitrogen molecular ions (N_2^+), nitrogen cluster ions (N_4^+), helium metastable atoms (He^*), and helium dimer metastable atoms (He_2^*). The reaction set considered in this study is given in Table 2.1. Note that the $\text{N}_2^+(B)$ ($B^2\Sigma_u^+$) species is not present in the computation process due to its rapid decay to the ground state through radiative decay R19 and collisional quenching R20.

As stated in the previous section, the drift-diffusion assumption is used to compute the number flux and energy flux of all 7 species. The electron mobility and diffusivity are calculated using the Boltzmann solver BOLSIG+ [102] with cross section data from the LXCat database [90, 103] as input. The local energy approximation is applied to compute the mean electron energy, which is used to parameterize the transport and reaction coefficients. The heavy particles have a fixed energy defined by room temperature (300 K) and an initial mole fraction calculated with fluid simulations (Appendix B). The mobility and diffusivity of the heavy particles, as well as the corresponding secondary electron emission coefficients (SEEC) [97] and the mean initial energy (MIE) of the secondary electron [104–106] are listed in Table 2.2.

Table 2.1: Reactions considered in the helium/nitrogen model

Index	Reaction	Rate constant ^a	$\Delta\epsilon^b(\text{eV})$	Ref.
Elastic, ionization, and excitation				
R1	$e + \text{He} \rightarrow e + \text{He}$	$f(\epsilon)$		[90]
R2	$e + \text{He} \rightarrow e + \text{He}^*$	$f(\epsilon)$	19.8	[90]
R3	$e + \text{He} \rightarrow 2e + \text{He}^+$	$f(\epsilon)$	24.6	[90]
R4	$e + \text{He}^* \rightarrow 2e + \text{He}^+$	$f(\epsilon)$	4.8	[91]
Three-body association, metastable pooling, and de-excitation				
R5	$\text{He}^* + 2\text{He} \rightarrow \text{He}_2^* + \text{He}$	2×10^{-46}		[92]
R6	$\text{He}^+ + 2\text{He} \rightarrow \text{He}_2^+ + \text{He}$	1.4×10^{-43}		[93]
R7	$\text{N}_2^+ + \text{N}_2 + \text{He} \rightarrow \text{N}_4^+ + \text{He}$	8.9×10^{-42}		[94]
R8	$2\text{He}^* \rightarrow e + \text{He}_2^+$	2×10^{-15}	-18.2	[93]
R9	$2\text{He}^* \rightarrow e + \text{He}^+ + \text{He}$	8.7×10^{-16}	-15.8	[93]
R10	$\text{He}^* + \text{He}_2^* \rightarrow e + \text{He}^+ + 2\text{He}$	5×10^{-16}	-13.5	[95]
R11	$\text{He}^* + \text{He}_2^* \rightarrow e + \text{He}_2^+ + \text{He}$	2×10^{-15}	-15.9	[95]
R12	$2\text{He}_2^* \rightarrow e + \text{He}_2^+ + 2\text{He}$	1.2×10^{-15}	-13.7	[95]
R13	$2\text{He}_2^* \rightarrow e + \text{He}^+ + 3\text{He}$	3×10^{-16}	-11.3	[95]
R14	$\text{He}_2^* + \text{He} \rightarrow 3\text{He}$	1.5×10^{-21}		[96]
Penning ionization and charge exchange				
R15	$\text{He}^* + \text{N}_2 \rightarrow e + \text{N}_2^+(B) + \text{He}$	5×10^{-17}	-4.2	[97]
R16	$\text{He}_2^* + \text{N}_2 \rightarrow e + \text{N}_2^+(B) + 2\text{He}$	5×10^{-17}	-2.7	[97]
R17	$\text{He}^+ + \text{N}_2 \rightarrow \text{N}_2^+(B) + \text{He}$	5×10^{-16}		[98]
R18	$\text{He}_2^+ + \text{N}_2 \rightarrow \text{N}_2^+(B) + 2\text{He}$	5×10^{-16}		[98]
Decay of the excited state				
R19	$\text{N}_2^+(B) \xrightarrow{\text{Radiative}} \text{N}_2^+ + h\nu$	A		[99]
R20	$\text{N}_2^+(B) \xrightarrow{\text{Collisional}} \text{N}_2^+$	κA		[99]
Electron-ion recombination				
R21	$e + \text{He}_2^+ + \text{He} \rightarrow 3\text{He}$	2×10^{-39}		[100]
R22	$e + \text{N}_2^+ \rightarrow \text{N}_2$	6×10^{-13}		[101]
R23	$e + \text{N}_4^+ \rightarrow 2\text{N}_2$	2×10^{-12}		[101]

^a Rate coefficients are in s^{-1} , m^3s^{-1} , and m^6s^{-1} , for single, two, and three body reactions, respectively. $f(\epsilon)$ stands for the rate constant as a function of mean electron energy calculated by a Boltzmann solver [102] with the corresponding cross section data as input. A is the Einstein coefficient of $\text{N}_2^+(B)$. κ is the quenching ratio defined as the ratio of collisional quenching rate to radiative decay rate A .

^b A positive sign indicates loss of electron energy, whereas a negative sign stands for energy gain.

Table 2.2: Mobility μ , diffusivity D , SEEC and MIE of heavy particles

Incident particles	$\mu(\text{m}^2/\text{V}\cdot\text{s})^a$	$D(\text{m}^2/\text{s})$	SEEC	MIE (eV)
He^*		1.89×10^{-3}	0	0
He_2^*		1.28×10^{-3}	0	0
He^+	$f(E/N)$		0.25	5
He_2^+	$f(E/N)$		0.25	5
N_2^+	$f(E/N)$		0.005	3
N_4^+	Estimated from N_2^+		0.005	3

^a $f(E/N)$ denotes measured μ as a function of reduced electric field.

In the experiments, the N_2^+ first negative system dominates the UV emission ($B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$), which means the local emission rate r_{ems} can be estimated with the reaction rate of reaction R19, r_{19} . Reaction R19 is a fast transient process, and its reaction rate is controlled by much slower preceding reactions through which $\text{N}_2^+(B)$ is produced, viz. Penning ionization, R15 and R16, and charge exchange, R17 and R18. Therefore, considering also the emission loss due to collisional quenching R20, r_{ems} can be derived from the conservation of $\text{N}_2^+(B)$ as

$$r_{\text{ems}} \approx r_{19} = \frac{r_{15} + r_{16} + r_{17} + r_{18}}{\kappa + 1}. \quad (2.10)$$

The quenching ratio κ is estimated to be 23.8 based on the simulated gas mole fraction and is used hereafter.

2.3 Model of dipole-waveguide coupling

The coupling efficiency η_c is the second essential ingredient of the theoretical framework, linking the plasma emission rate to the power that actually enters the waveguide. This section presents a photonics model that quantifies how efficiently a randomly oriented dipole (representing an excited molecule or ion in the plasma) transfers its energy into the guided modes of a strip waveguide. Starting from first principles (Fermi's golden rule and the density of states in a waveguide), an analytical expression for η_c is derived in terms of the mode group velocity and an effective area. The model is then extended to multimode waveguides, and numerical implementations using both eigenmode expansion and FDTD are described. The results are validated against each other, and the predicted output powers for single- and multimode chips are presented.

2.3.1 Calculation of coupling efficiency

The coupling efficiency $\eta_c = \gamma_{\text{wg}}/\gamma_0$ quantifies the fraction of spontaneous emission coupled into the waveguide modes. It is a function of the dipole position in the

transverse plane. The derivation of η_c for a randomly oriented dipole near a strip waveguide starts from Fermi's golden rule in the weak coupling regime [107]. The spontaneous emission rate near a waveguide is given by

$$\gamma_{\text{wg}}(\mathbf{r}_0, \omega) = \frac{2\pi}{\hbar^2} |g(\mathbf{r}_0, \omega)|^2 \rho(\omega), \quad (2.11)$$

where the coupling strength is $|g(\mathbf{r}_0, \omega)|^2 = \xi^2 |\mathbf{d} \cdot \mathbf{E}(\mathbf{r}_0, \omega)|^2$ and $\rho(\omega)$ is the density of states. The normalization constant ξ relates the field amplitude to the photon energy. For a mode carrying energy $\hbar\omega$ over length L ,

$$\frac{\hbar\omega}{2} = L\xi^2 \iint \langle W_{\text{EM}} \rangle d\mathbf{r}, \quad (2.12)$$

where $\langle W_{\text{EM}} \rangle$ is the time-averaged energy density. In a non-magnetic, weakly dispersive medium, the electric and magnetic contributions are equal, so

$$\iint \langle W_{\text{EM}} \rangle d\mathbf{r} \approx \iint \epsilon_0 \epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r}, \omega)|^2 d\mathbf{r}. \quad (2.13)$$

Solving for ξ^2 yields

$$\xi^2 = \frac{\hbar\omega}{2L \iint \epsilon_0 \epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r}, \omega)|^2 d\mathbf{r}}. \quad (2.14)$$

For a single-mode waveguide, the density of states is $\rho(\omega) = L/(\pi v_g)$, where v_g is the group velocity. Substituting into Eq. (2.11) and canceling L gives

$$\gamma_{\text{wg}}(\mathbf{r}_0, \omega) = \frac{\omega}{\hbar v_g} \frac{|\mathbf{d} \cdot \mathbf{E}(\mathbf{r}_0, \omega)|^2}{\iint \epsilon_0 \epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r}, \omega)|^2 d\mathbf{r}}. \quad (2.15)$$

In a homogeneous medium with a refractive index n , the total spontaneous decay rate is

$$\gamma_0 = \frac{n\omega^3 |\mathbf{d}|^2}{3\pi \hbar \epsilon_0 c^3}. \quad (2.16)$$

For a randomly oriented dipole, with $\langle \cos^2 \theta \rangle = 1/3$, the averaging of $|\mathbf{d} \cdot \mathbf{E}|^2$ over all angles leads to

$$\langle |\mathbf{d} \cdot \mathbf{E}(\mathbf{r}_0, \omega)|^2 \rangle = \frac{1}{3} |\mathbf{d}|^2 |\mathbf{E}(\mathbf{r}_0, \omega)|^2. \quad (2.17)$$

Substituting Eq. (2.17) into Eq. (2.15) and dividing by Eq. (2.16), the coupling efficiency becomes

$$\eta_c(\mathbf{r}_0, \omega) = \frac{\pi \epsilon_0 c^3}{n v_g \omega^2} \frac{|\mathbf{E}(\mathbf{r}_0, \omega)|^2}{\iint \epsilon_0 \epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r}, \omega)|^2 d\mathbf{r}}. \quad (2.18)$$

To highlight the physical mechanisms involved in the coupling efficiency, it is convenient to introduce an effective area defined as follow:

$$A_{\text{eff}}(\mathbf{r}_0, \omega) = \frac{\iint \epsilon_0 \epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r}, \omega)|^2 d\mathbf{r}}{\epsilon_0 \epsilon(\mathbf{r}_0) |\mathbf{E}(\mathbf{r}_0, \omega)|^2}. \quad (2.19)$$

For a dipole near the waveguide surface, the enhanced local field reduces A_{eff} , which in turn increases the coupling efficiency. With $\epsilon(\mathbf{r}_0) = n^2$ and $\omega = 2\pi c/\lambda$, Eq. (2.18) simplifies to

$$\eta_c(\mathbf{r}_0, \omega) = \frac{1}{4\pi} \frac{c\lambda^2}{n^3 v_g A_{\text{eff}}(\mathbf{r}_0, \omega)} = \frac{1}{2} \frac{n_g}{n} \frac{\sigma_{\text{max}}}{A_{\text{eff}}(\mathbf{r}_0, \omega)}, \quad (2.20)$$

where $\sigma_{\text{max}} = (\lambda/n)^2/(2\pi)$ is the diffraction-limited area of a dipole in the top cladding medium of index n , representing the smallest area to which a dipole's emission can be confined in the far field. The ratio $\sigma_{\text{max}}/A_{\text{eff}}(\mathbf{r}_0, \omega)$ therefore expresses the fraction of the dipole's available emission solid angle that is intercepted by the waveguide mode; a smaller $A_{\text{eff}}(\mathbf{r}_0, \omega)$ (due to stronger mode confinement or proximity to the waveguide surface) leads to a larger fraction and, thus, higher coupling efficiency. The factor n_g/n accounts for the enhancement of the local density of optical states in the vicinity of the waveguide, which is a manifestation of the Purcell effect in this geometry. It also indicates that the coupling efficiency can benefit from the slow-light effect when n_g becomes larger.

The area-integrated coupling efficiency over the top cladding, where the dipole cloud resides, is of particular interest because it determines the total power coupled from the plasma into the waveguide. Integrating Eq. (2.20) over the top cladding area A_{tpclad} gives

$$\iint_{A_{\text{tpclad}}} \eta_c(\mathbf{r}_0, \omega) dA = \frac{1}{2} \frac{n_g}{n} \sigma_{\text{max}} \frac{\iint_{A_{\text{tpclad}}} \epsilon_0 \epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r}, \omega)|^2 d\mathbf{r}}{\iint \epsilon_0 \epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r}, \omega)|^2 d\mathbf{r}}, \quad (2.21)$$

where the integral in the denominator is taken over the entire transverse cross-section of the waveguide. This expression shows that the area-integrated coupling efficiency is proportional to the fraction of modal energy residing in the top cladding, confirming the physical interpretation discussed in Section 2.3.2.

For a multimode waveguide supporting N guided modes, the total coupling efficiency becomes a sum over all modes:

$$\eta_c^{\text{total}}(\mathbf{r}_0, \omega) = \sum_{m=1}^N \eta_c^{(m)}(\mathbf{r}_0, \omega) = \frac{1}{4\pi} \frac{c\lambda^2}{n^3} \sum_{m=1}^N \frac{1}{v_g^{(m)} A_{\text{eff}}^{(m)}(\mathbf{r}_0, \omega)}, \quad (2.22)$$

where $v_g^{(m)}$ and $A_{\text{eff}}^{(m)}$ are the group velocity and effective area of the m -th mode, respectively. The total coupled power into the waveguide is the sum of the powers into each guided mode, as the modes are orthogonal and do not interfere.

The coupling efficiency can be computed numerically using electromagnetic simulations. Using an eigenmode expansion solver such as Lumerical MODE, one can obtain the mode profiles $\mathbf{E}^{(m)}(\mathbf{r}, \omega)$, effective indices $n_{\text{eff}}^{(m)}$, and group velocities $v_g^{(m)}$ for all guided modes supported by the waveguide. The effective area $A_{\text{eff}}^{(m)}(\mathbf{r}_0, \omega)$ for each mode is then computed by evaluating the integrals in Eq. (2.19) using the simulated field distributions. The total coupling efficiency is obtained by summing over all modes according to Eq. (2.22). This approach is computationally efficient, as it requires only a single frequency-domain simulation of the waveguide cross-section.

Another approach is to solve Maxwell's equations by discretizing space and time without further assumptions, also known as the FDTD method. The coupling efficiency is obtained by monitoring the normalized power at the output facet directly, without the need to solve Eq. (2.22). FDTD inherently accounts for radiation losses into the cladding and substrate, position-dependent coupling near the core-cladding interface, and coupling between guided and radiation modes. However, it is computationally expensive, especially with the need to perform parametric sweeps of the dipole position. The mesh needs to be sufficiently fine to enable a good prediction of the scattering loss, which, in turn, adds to the expense.

2.3.2 Model results and validation

The coupling efficiency obtained from the two numerical approaches described above is compared here. Both simulations use the same single-mode waveguide geometry. In the FDTD simulations, dipoles are positioned on the symmetry plane of the waveguide, with their height varied using a 10 nm mesh resolution. The MODE-based results, in contrast, are computed from the modal electric field using Eq. (2.22). Fig. 2.4 shows the comparison between the two methods. The results are in good agreement overall. However, a slight deviation appears when the dipole is positioned very close to the waveguide surface, where the FDTD simulation predicts a marginally higher coupling efficiency. This discrepancy arises because the effective area model in Eq. (2.22) assumes an unperturbed mode profile, whereas the presence of the dipole itself modifies the local density of optical states when it is in close proximity to the high-index-contrast interface - an effect fully captured by FDTD but not by the simple effective area approximation.

The computed result of coupling efficiency from FDTD simulation in single-mode and multi-mode cases is presented in Fig. 2.5. The waveguide geometry and the dipole emission wavelength $\lambda = 391.4$ nm is chosen to match the experimental conditions. The waveguide material is AlO_x ($n \approx 1.68$) on a SiO_2 substrate

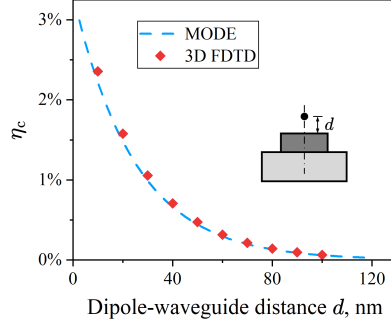


Figure 2.4: Mutual validation of the two approaches for computing coupling efficiency.

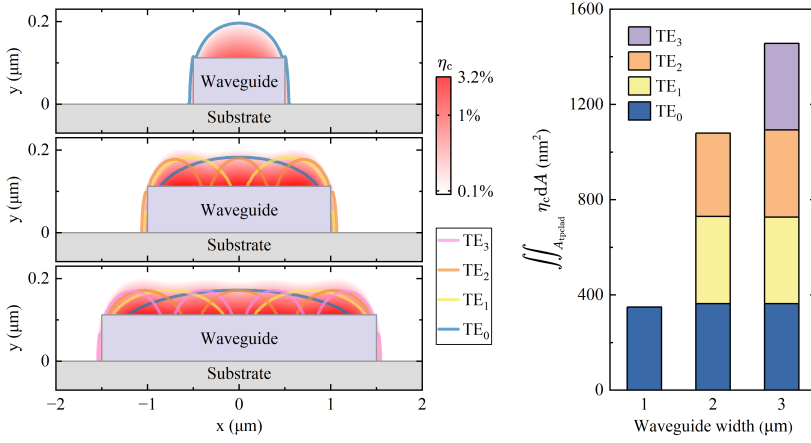


Figure 2.5: Coupling efficiency computed using the FDTD solver at $\lambda = 391.4$ nm. Left: contour plots of the coupling efficiency (red) for single-mode ($1 \mu\text{m}$ width) and multi-mode ($2 \mu\text{m}$ and $3 \mu\text{m}$ widths) waveguides; the colored lines indicate the effective coupling region for each guided mode. The waveguide height is fixed at 110 nm. Right: area-integrated coupling efficiency for each mode as a function of waveguide width. This quantity represents the fraction of modal energy residing in the top cladding, where the dipole cloud is located.

($n \approx 1.48$), with the waveguide height fixed at 110 nm. The waveguide width is swept from $1 \mu\text{m}$ to $2 \mu\text{m}$ and $3 \mu\text{m}$, and the corresponding number of guided modes increases from 1 to 3 and 4, respectively. The effective coupling region, delineated by the red contour, is confined to the top surface of the waveguide and extends approximately 90 nm into the cladding. Widening the waveguide broadens this effective coupling region laterally due to the emergence of higher-order modes, while the vertical extent remains unchanged.

The right panel of Fig. 2.5 shows the coupling efficiency to each individual

mode integrated over the cross-sectional plane. Physically, this area-integrated quantity $\iint_{A_{\text{tclad}}} \eta_c dA$ represents the fraction of the modal energy available to the dipoles that resides in the top cladding, where the dipole cloud is located. The near-equal contribution from each mode in the multimode waveguides can be understood from the thin-waveguide geometry. Since the waveguide height (110 nm) is fixed and much smaller than the width, the vertical field profile is nearly identical for all guided modes. With the dipole cloud spanning the entire top cladding, each guided mode presents an independent, orthogonal channel for the dipoles to radiate into, and the normalized mode energy ensures that each channel collects a similar fraction of the total radiated power. As the waveguide width increases from 2 μm to 3 μm , the TE₀ mode expands laterally, but its peak intensity decreases accordingly due to the fixed power normalization; the area-integrated coupling efficiency therefore remains essentially unchanged. When the width is reduced to the single-mode regime (1 μm), however, the mode approaches its transverse cutoff. The effective index drops and the mode field spreads more toward the substrate, reducing the fraction of modal energy residing in the top cladding where the dipoles are located. Consequently, the area-integrated coupling efficiency of the TE₀ mode decreases slightly at the transition from multimode to single-mode operation.

Now, with the local emission rate r_{ems} from the plasma model and the coupling efficiency η_c from the photonics simulations, Eq. (2.2) and Eq. (2.1) can finally be solved. To estimate the power output that can be expected from the experiment, a series of parameters are adopted based on the actual experimental conditions, as listed in Table 2.3. The local emission rate r_{ems} used in the calculation is taken from the baseline operating condition described in Section 4.2 of Chapter 4. For the single-mode waveguide with a 1 μm width and a 110 nm height, the power output is expected to be 2.88 pW. For the 2 μm and 3 μm wide multi-mode waveguides with the same height, the results are 8.64 and 11.52 pW, respectively.

Table 2.3: Parameters used for the estimation of P_{out} .

Variable	Value
r_{ems}	$1.3 \times 10^{24} \text{ m}^{-3} \text{ s}^{-1}$
λ	391.4 nm
α	3 dB/cm
l_c	3 cm
l_p	1 cm
$P_{\text{out, SM}}$	2.88 pW

2.3.3 Optimization strategies for power output

Equation (2.1) suggests three general strategies for maximizing output power. The most direct approach is to increase the effective coupling length $l_{c,\text{eff}}$. However,

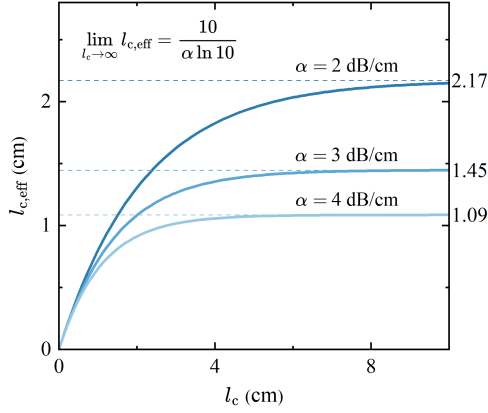


Figure 2.6: Effective coupling length as a function of physical coupling length for three different propagation loss values.

as indicated by Eq. (2.3), the enhancement achievable through extending the physical coupling length l_c is ultimately constrained by propagation loss. Figure 2.6 illustrates this limitation: the maximum attainable $l_{c,eff}$ is inversely proportional to the loss rate α in dB/cm. For the chip used in the experiments, the typical loss rate is 3 dB/cm, corresponding to an upper limit of $l_{c,eff} \approx 1.45$ cm. Under these conditions, a coupling length not exceeding 4 cm is preferable for optimizing output power.

The second strategy involves maximizing the pump source, specifically the plasma emission rate r_{ems} . Since the coupling region extends only ~ 90 nm from the waveguide surface, enhancing r_{ems} requires controlling the emission processes occurring at the interface between the plasma and the chip surface, where spatial charge effects dominate. Optimizing surface emission therefore demands a detailed understanding of sheath dynamics, which will be discussed thoroughly in Section 4.

The third approach focuses on improving the waveguide design to increase the coupling efficiency η_c . For instance, introducing a slot opening at the waveguide center creates a so-called slot waveguide, which can enhance the area-integrated coupling efficiency (as in the right panel of Fig. 2.5) and therefore the output power by approximately 25%. However, any design modification aimed at improving coupling must not induce excessive propagation loss. If the additional loss outweighs the gain in coupling efficiency, the net output power will be reduced rather than enhanced. Thus, the optimization must carefully balance improved light collection against increased attenuation.

2.4 Conclusion

This chapter has developed a comprehensive theoretical framework for modeling evanescent coupling between a micro-gap DBD plasma and an integrated optical waveguide. The framework consists of two components: a 1D transient plasma model that provides the emission characteristics of the UV source, and a photonics model that quantifies the coupling efficiency between randomly oriented dipoles and the waveguide modes.

The plasma model, based on the drift-diffusion approximation with a simplified helium/nitrogen chemistry set, captures the essential kinetics governing the production of $\text{N}_2^+(B)$ emitters. Through analysis of the reaction pathways, the local emission rate r_{ems} was derived from the balance between $\text{N}_2^+(B)$ production (via Penning ionization and charge exchange) and its loss through radiative decay and collisional quenching. This approach circumvents the need for direct measurement of the reaction rates in the micro-gap discharge, providing a practical means to estimate the source emission intensity for the coupling calculation.

The photonics model established an analytical expression for the coupling efficiency η_c of a randomly oriented dipole to a waveguide mode, starting from Fermi's golden rule. The derivation began with the single-mode case and was subsequently extended to multimode waveguides by summing over all guided modes. Two numerical approaches for computing η_c were evaluated and mutually validated: eigenmode expansion (MODE) offers computational efficiency for parametric studies, while FDTD provides greater accuracy near interfaces by capturing local density of states modifications. A key finding is that for waveguides with height much smaller than width, the integrated coupling efficiency scales linearly with the number of guided modes, with each mode contributing nearly equally to the total coupled power.

Combining the two models, the baseline output power for the experimental configuration is estimated to be 2.88 pW for a single-mode waveguide, and 11.52 pW for a 3 μm wide multi-mode waveguide. Three optimization strategies were analyzed: increasing the effective coupling length (limited by propagation loss), maximizing the plasma emission rate near the interface (governed by sheath dynamics), and improving waveguide design (e.g., slot waveguides) while maintaining low propagation loss. These trade-offs must be carefully balanced to maximize the detectable output power.

The theoretical framework established in this chapter provides a solid foundation for interpreting experimental results and guiding future device optimization. The plasma model will be employed to investigate strategies for enhancing surface UV emission together with experimental efforts (Chapter 4), while the photonics model will direct the chip design and aid in the device measurements in Chapter 4.

3

Development of UV-POCS experimental system

This chapter reviews the development of the UV-POCS experimental system from its initial conception to its final state. The system comprises two primary components: a DBD plasma setup that generates a microplasma on the chip surface and an optical detection system that monitors the plasma emission and measures the output signal from the chip. The principal challenges encountered throughout this development stem from the fundamentally conflicting requirements of these two subsystems. Plasma operation typically involves harsh conditions characterized by sputtering, deposition, dust attraction, heat generation, and mechanical vibration. In contrast, the chip and its associated optical system demand a clean, stable environment free from mechanical and optical noise. The complexity of integrating the two disparate systems adds to the difficulty of identifying and resolving issues, making the development process lengthy and iterative.

Section 3.1 reviews the design evolution and improvements made to the plasma setup. The overall discharge configuration is described in Subsection 3.1.1, while the chip stage and high-voltage electrode assembly are detailed in Subsections 3.1.2 and 3.1.3, respectively. Section 3.2 addresses the challenges encountered in building the optical detection system, with Subsection 3.2.1 covering the overall optical configuration and Subsection 3.2.2 detailing the chip alignment issue. Finally, Section 3.3 introduces the design and fabrication of the chip itself.

3.1 Plasma setup

The development of a reliable and reproducible plasma source on the chip surface is the cornerstone of the UV-POCS system. The plasma must be confined to a well-defined coupling region of the waveguide, generate sufficient UV emission, and avoid any contamination or damage to the chip. Achieving these goals required an iterative process of design, testing, and refinement, guided by both experimental observations and the physical constraints of dielectric barrier discharges at reduced and atmospheric pressures. This section traces the evolution of the plasma setup from an initial surface barrier discharge (SBD) configuration in vacuum, through a sandwich-like double-dielectric DBD, to the final on-chip one-layer DBD operating in helium-rich atmospheric pressure. Each stage is described along with the specific problems encountered - such as electrode melting, substrate delamination, parasitic discharge paths, and carbon-based contamination - and the corresponding solutions that led to the final established design. The chip stage and high-voltage electrode assembly are discussed in detail, as their material choices and mechanical design proved critical for maintaining both electrical insulation and a clean plasma environment.

3.1.1 Discharge configuration

As previously introduced in Section 1.4, there is a variety of well-established microplasma configurations that are compatible with the semiconductor platform. Yet, for the purpose of developing the UV-POCS device, extensive exploration of the discharge configuration is still needed, as the pioneering nature of the device and the integration of the experimental systems pose new challenges that are rarely discussed. Considering the potential for miniaturization, fabrication, and integration with other PIC components, dielectric barrier discharge (DBD) and its variation, surface barrier discharge (SBD), are selected from the discharge configurations. The exploration starts from a simple SBD structure. Two major shifts in the design are made later to tackle the practical issues observed in the experimental attempts, which lead to the final state of the configuration: an on-chip DBD microplasma operated in atmospheric pressure.

SBD in vacuum. The first prototype of the UV-POCS device starts from a simple idea. Inspired by waveguide-enhanced Raman spectroscopy (WERS), which excites and collects the Raman signal using the evanescent field of a waveguide, if the air cladding itself becomes UV-emitting (in the plasma state), then a certain amount of the free-space UV light can also be collected into waveguide mode. The easiest way to create a microplasma around a waveguide would be the SBD configuration, which involves depositing a patterned metal layer in the vicinity of the waveguide as a high-voltage electrode. By connecting the backside of the chip to ground

and powering the metal layer electrode with an external AC supply, plasma can therefore be formed on top if the gas can be sufficiently ionized.

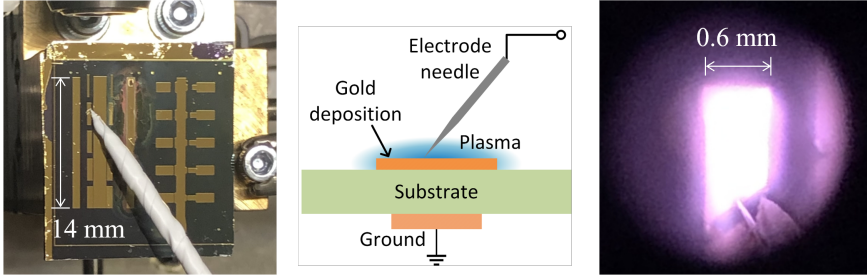


Figure 3.1: Testing of the SBD configuration. Left: picture of the discharge setup before the test. Center: schematic drawing of the setup. Right: plasma emission during the test in vacuum state.

The SBD setup is shown in Fig. 3.1. The metal layer is connected to an external power supply via a tungsten needle. The needle is insulated with polytetrafluoroethylene (PTFE) tape, leaving only the tip exposed. The needle tip is positioned with a probe stage (Fig. 3.2). The tested chip sample features a series of gold deposits patterned in a rectangular shape with varied areas. The substrate of the chip is 525 μm silicon with 3 μm silicon oxide on top. A brass stand is used as both the chip holder and the ground electrode. The setup is inside a plastic vacuum chamber that can be pumped down to 10^{-3} mbar. The chamber is later refilled with helium as the discharge medium.

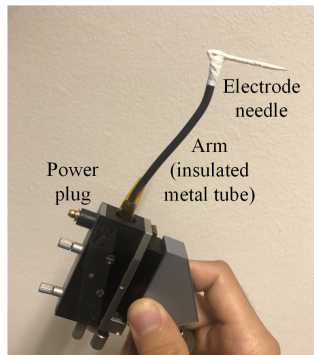


Figure 3.2: The initial design of the high-voltage assembly.

The first problem encountered in the test is with the insulation of the setup. To ensure a localized plasma at the desired gold electrode, the entire high-voltage side needs to be fully insulated, especially around the probe stage and the electrode needle. It has been observed that plasma can be generated around the long arm of

the probe stage at a low helium pressure of 20 mbar. This problem can be solved either by improving the insulation or by increasing the chamber pressure. The latter approach limits the discharge current by inducing a higher collision rate between the electrons and the background heavy particles, and eventually avoids undesired discharges. The modification of the high-voltage assembly, including the electrode and the probe stage, is reviewed later in Subsection 3.1.3.

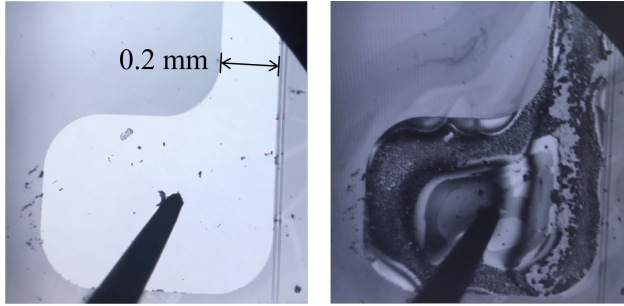


Figure 3.3: Gold electrode layer melted after plasma test. Left: picture of the gold layer and the electrode tip before test. Right: the melted gold layer after test.

The increase in working pressure is also proven to be a possible solution for two other issues that cause the failure of the chip. The first issue is the melting of the gold layer (Fig. 3.3). It is observed that the heat generated during the discharge is so high that the electrode gold deposit eventually melts. This problem occurs when the current density through the electrode layer exceeds a certain level. It can be a result of using an electrode area that is too small or of having a discharge current that is too high. The second issue is the delamination of the silicon oxide substrate around the electrode layer. As presented in Fig. 3.4, significant cracks in the silicon oxide layer are observed to deteriorate along with the operating duration. It is assumed that micro arcs are formed around the electrode, which causes severe heat deposition and damage to the substrate. By increasing the refilled helium pressure from 20 mbar to 300 mbar, the melting issue is addressed, but delamination around the margin of the electrode remains. This eliminates the current SBD configuration from being a candidate for realizing the UV-POCS concept, as the effective coupling distance of the waveguide in UV wavelength is less than 100 nm, and the waveguide at this distance scale from the electrode will inevitably be destroyed along with the substrate. The only way to solve this is to cover the electrode with a dielectric layer, just as the classical SBD configuration illustrated in Fig. 1.2 (b). However, integrating such an insulation layer with sufficient thickness (at least several hundred microns) into the fabrication of a chip with UV waveguides is difficult and time-consuming. The SBD configuration is thereby aborted.

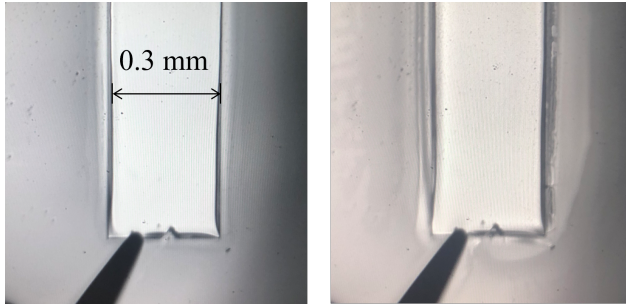


Figure 3.4: Delamination issue found in the SBD tests. Left: picture of the rectangular gold electrode layer after 5 min of plasma operation. Right: substrate delamination around the gold layer after 20 min of plasma operation.

Sandwich-like DBD in vacuum. To avoid arcing found in the SBD test, a general idea is to avoid using features that are too narrow for the electrode (like the edge of the electrode layer) and to add dielectric in between the electrodes to block direct breakdown. That leads to the second optional discharge configuration, the sandwich-like DBD with two layers of dielectric. The chip itself serves as one dielectric layer, whereas an additional quartz glass is introduced on top of the chip with a certain gap spacing (Fig. 3.5). The high-voltage electrode layer is now transferred to the top surface of the glass. A long-strip brass ground electrode is buried inside the plastic chip stage and touches the backside of the chip. The plasma is expected to be generated in the gas gap between the glass and the chip, right on top of the waveguide. Two silicon chips are used as spacers on both sides to control the gap spacing.

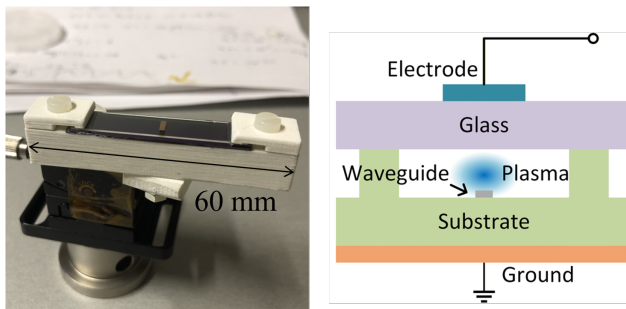


Figure 3.5: Sandwich-like DBD configuration. Left: picture of the chip stage used in the test. Right: schematic drawing of the setup.

Yet the plasma does not behave as expected. As shown in Fig. 3.6, the discharge channel, which is the visually bright part connected to the electrode, does not pass through the gas gap to reach the chip surface and therefore the waveguide;

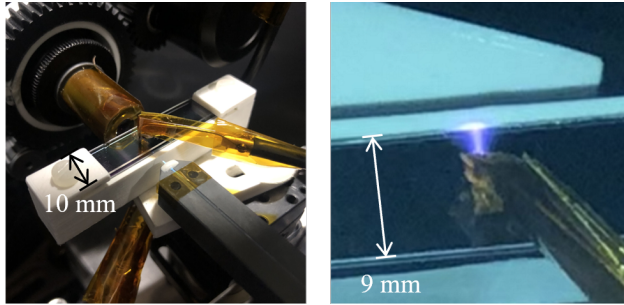


Figure 3.6: The discharge channel bypasses the chip. Left: the sandwich-like DBD setup with electrode connected. Right: bright visible emission across the top glass indicating the plasma is excited outside the gas gap.

instead, it goes across the upper surface of the glass, creating a shortcut through the gas medium. The solution to address this problem is straightforward and already well-applied in the industry: either increase the relative area of the dielectric barrier, which is the ratio of the chip and glass overlap area to the area of the electrode, or add extra dielectric to block the undesired discharge channel. The former approach poses a strict requirement on the chip area and is therefore not suitable for future miniaturization. Regarding the second approach, efforts such as adding additional walls and a sheath tube onto the quartz glass have been made but have turned out to be unhelpful. Thinning the top glass or shrinking the gap spacing is expected to help, but it is also technically impractical, as the glass can easily break when the electrode tip approaches. In a word, the DBD with two dielectric layers is not the most promising solution for the job.

One-layer DBD in atmospheric pressure. Since keeping the top glass as an additional dielectric layer inevitably excites discharge pathways directly through the gas medium, a reasonable shift in mindset is to remove it and leave the electrode tip exposed, as illustrated in Fig. 3.7. Doing so will solve the undesired discharge pathways, but arcing will again be a concern. Increasing the operating pressure can sufficiently suppress arcing. According to Paschen's law [108], if the background gas pressure is increased to atmospheric pressure for a given gap spacing of a few hundred microns, there will be a significant rise in the breakdown voltage of helium. At such high pressures, electrons suffer frequent collisions with heavy particles and lose energy rapidly, making it more difficult to initiate and sustain an arc.

Apart from the need to confine the plasma, being able to work in atmospheric pressure is also a huge advantage for future applications of the UV-POCS. The major drawback will be the collisional quenching of the UV emission from plasma, as the short-lived emissive species, for instance, $N_2^+(B)$ ($B^2\Sigma_u^+$) in the helium-air plasma, lose more energy through collisions with heavy particles, as already

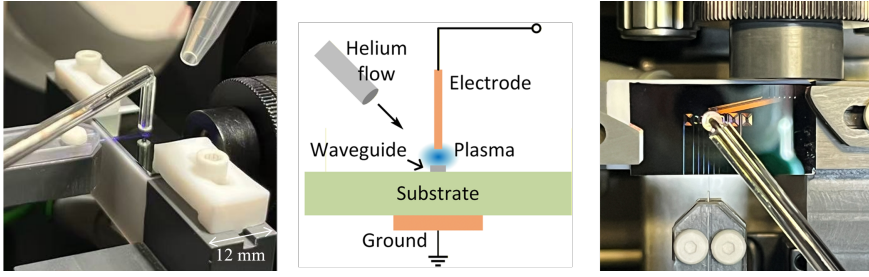


Figure 3.7: DBD configuration with chip as the only one dielectric layer. Left: picture of the chip stage aligned and ready for testing. Center: schematic drawing of the setup. Right: top view of the setup.

discussed in Subsection 2.2.3. Still, to balance the needs from a systematic point of view, the practical advantages of atmospheric pressure operation outweigh the disadvantage of extra quenching loss in UV emission.

It needs to be pointed out that shifting the environment directly to atmospheric air is not a good solution, as the air is a mixture of molecular gases with high electron affinity and low breakdown voltage, which would promote arcing and reduce the UV emission efficiency, especially for a discharge gap of a few hundred microns. A good alternative approach is to introduce a controlled helium flow and direct it onto the chip surface to form a helium-air mixture with helium as the dominant component (Fig. 3.7). Helium, being a noble gas with a high ionization threshold and excellent thermal conductivity, enables a stable diffuse discharge at atmospheric pressure. A helium-rich background greatly facilitates the formation of $N_2^+(B)$ through Penning ionization and charge exchange (Subsection 2.2.3), producing the N_2^+ first negative system as the target UV emission.

The resulting plasma emission profile under atmospheric pressure is shown in Fig. 3.8. At a small discharge gap of $100\ \mu\text{m}$, the plasma is generated stably

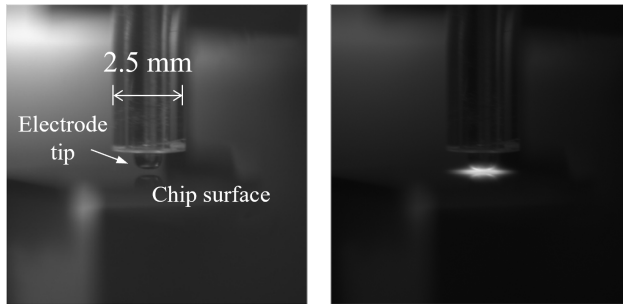


Figure 3.8: Left: One-layer DBD setup with a discharge gap of $100\ \mu\text{m}$ (electrode tip to chip surface) from side view. Right: visible plasma emission profile in atmospheric pressure.

in diffuse state with controlled expansion on the chip surface, without arcing. It is an ideal condition to continue the following research on the plasma-waveguide evanescent coupling. The study on enhancing plasma emission via geometrical and temporal control will be detailed in Section 4.

3.1.2 Chip stage

During the development of the plasma setup, the chip stage, which serves not only as a holder but also as the ground electrode, has undergone multiple key improvements in design. Fig. 3.9 reviews the four major versions of the chip stage that have been employed. The first stage is the brass holder used in the SBD test. As the design of

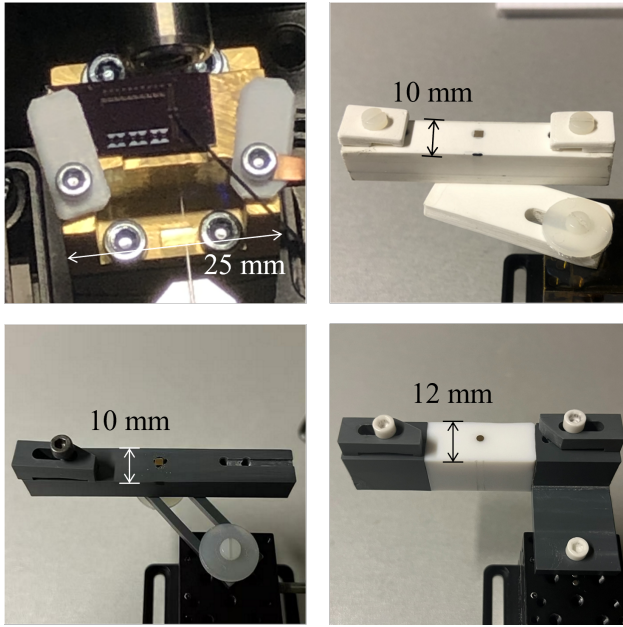


Figure 3.9: Versions of the chip stage. Top left: the first chip stage used in early tests. Out of brass. Top right: the second version, 3D-printed plastic stage. A square brass ground electrode is fixed in the center with vacuum glue. Bottom left: the third edition, machined polyvinyl chloride (PVC) with ground electrode fixed by screws. Bottom right: the last design, a chip stage with Teflon as the insulation material and PVC as the supporting structure. The shape of the ground electrode changes to round.

the discharge configuration shifts to DBD, the projected area of the electrode must be smaller than the area of the dielectric to ensure sufficient dielectric blocking. Since the chip, which is the bottom dielectric in contact with the ground electrode, is not visibly transparent, aligning the ground electrode with the coupling region on the chip and the high-voltage electrode becomes tricky. In the second design of the

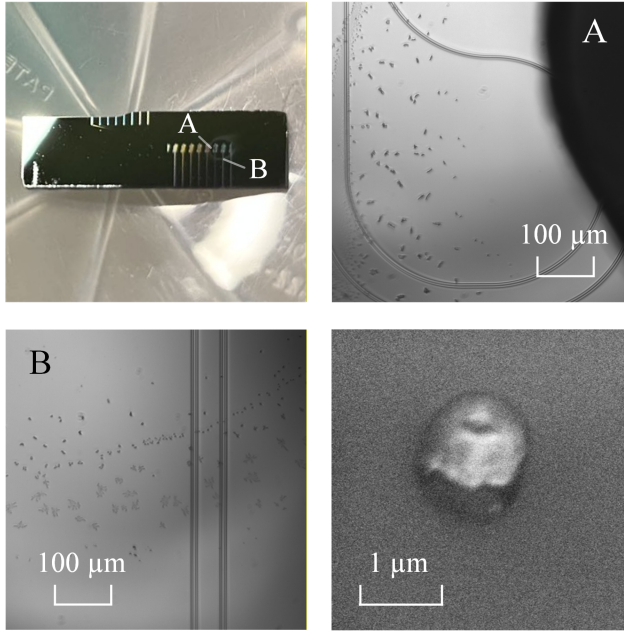


Figure 3.10: Carbon contamination observed on the chip after the plasma test. Top left: contamination around the target waveguide in a ring-like pattern. Top right: zoomed view at point A, the adjacent waveguide spiral. Bottom left: zoomed view at point B, the input of the target waveguide. Bottom right: SEM image of a contamination particle.

chip stage, the ground electrode is set to be a 2 mm square. This is a compromised result, balancing both the needs of electrode insulation and the operability of the alignment. The third edition maintains the same ground electrode design with only a small modification to its fixing. The ground electrode is fixed in the center hole with screws, and instead of filling the hole with glue, a gas channel that allows the gas to be removed from the bottom of the chip stage while pumping is left. This is a specific solution to the problem of chip fixing in the vacuum environment. Due to the imperfect surface contact between the backside of the chip and the stage, air can be trapped in the gaps and cause unwanted discharge around the ground electrode (assumed based on the deposition stain on the ground electrode). Opening these gaps to the chamber leads to the effective removal of the residual air.

An essential issue with the second and third designs is carbon-based contamination originating from the polymer materials used in the setup (Fig. 3.10). In the second design, the chip stage and clamps are 3D-printed, and vacuum glue (resin mixed with ceramic powder) is applied to fix the ground electrode; in the third version, the material is changed to PVC, and vacuum glue is no longer used. Although the ion energy in atmospheric-pressure DBD is relatively low, these

polymer components are in close proximity to the discharge and are continuously exposed to energetic ions, electrons, and reactive radicals. This leads to sputtering, etching, or decomposition of the polymer, releasing carbon-containing fragments into the gas phase that are subsequently transported to the chip surface, where they condense and form a ring-like pattern around the waveguide, as illustrated in Fig. 3.10. An energy dispersive X-ray spectroscopy (EDX) analysis enabled with scanning electron microscopy (SEM) confirmed the presence of carbon, along with silicon and oxygen, which originated from the chip. Such contamination strongly scatters guided light, causing temporal failure of the chip.

To minimize contamination, Teflon is considered a good alternative material for the chip stage, as the carbon-fluorine (C-F) bond is one of the strongest single bonds in organic chemistry and is therefore resistant to plasma etching. The only drawback of Teflon for this application is its softness; specifically, it is not a good option for making threaded holes. In the last version of the chip stage, a combination of two materials is used, where PVC holds the structure and Teflon handles the contact with the chip and insulates the ground. The screws fixing the chip clamps are changed to ceramic ones, which helps both with insulation and contamination control.

3.1.3 High-voltage electrode assembly

As another essential component of the discharge setup, the high-voltage assembly affects the confinement of the plasma profile and therefore plays a critical role in the study of plasma-waveguide coupling. The development of the high-voltage assembly encounters similar difficulties to those introduced in the previous subsection about the chip stage, but with greater challenges in the insulation design. As previously explained, in the initial design of the high-voltage assembly (Fig. 3.2), PTFE tape is used around the tungsten electrode needle for insulation, with only the tip exposed. However, PTFE tape is not the most ideal option for the job. Although PTFE itself is chemically inert and resistant to plasma degradation, the tape form introduces practical limitations: it can loosen over time, compromising insulation reliability, and its surface may carry residual contaminants or accumulate dust that can be released into the discharge.

From a plasma physics and contamination perspective, using a quartz tube to insulate the high-voltage electrode is generally preferable to PTFE tape. Quartz (fused silica) is a high-purity, inorganic material with excellent dielectric strength, thermal stability, and resistance to plasma erosion. It does not outgas significant organic compounds and remains chemically inert even under long-duration exposure to energetic ions and UV radiation. Fig. 3.11 shows the final version of the high voltage assembly, which uses quartz tubes for the arm and tip insulation.

A special tungsten electrode with a 90-degree turn is used at the tip of the high-

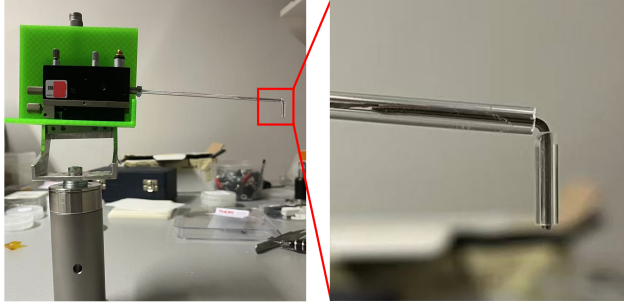


Figure 3.11: The final version of the high-voltage assembly. The enlargement view on the right details the electrode tungsten tip sheathed by quartz glass tubes.

voltage assembly. It features a flat tip with a rounded edge. This profile has been optimized through multiple plasma tests to guarantee a stable and diffused plasma that evenly covers the coupling region on the chip surface. Fig. 3.12 provides a comparison of the emission profile with a pointy needle tip, which is an early-stage design, and the rounded flat tip. Under the same discharge gap distance ($200\text{ }\mu\text{m}$), applied voltage (ptp 3 kV, 10 kHz, sinusoidal waveform), and background gas environment, the rounded flat tip offers more evenly-distributed emission over a wide span. The discharge in the pointy needle tip also exhibits unstable discharge characteristics such as flickering of the emission or the constant shift of the plasma attach region on the electrode, which is not seen in the rounded flat tip case.

It is essential to use only metal that is resistant to plasma etching (such as tungsten) to avoid metal-based contamination, which can cause permanent damage to the waveguides on the tested chip. It has been observed that using alloy materials containing copper on the high-voltage side results in copper contamination on the chip, as confirmed by SEM-EDX results. The combination of quartz tubes and tungsten electrodes is one of the few options that offer both the insulation and contamination-free environment required by the experiment. However, since tungsten cannot be welded using normal procedures, making electrical connections inside the quartz tube becomes technically difficult. The final design of the assembly uses an interference fit between the inner tip of the tungsten electrode and the quartz tube, enabled by precise control of the sizes. The brass wire connected to the external power supply is pressed against the tungsten tip, as shown in Fig. 3.11. The connection point is designed to be far enough from the external environment to avoid copper contamination.

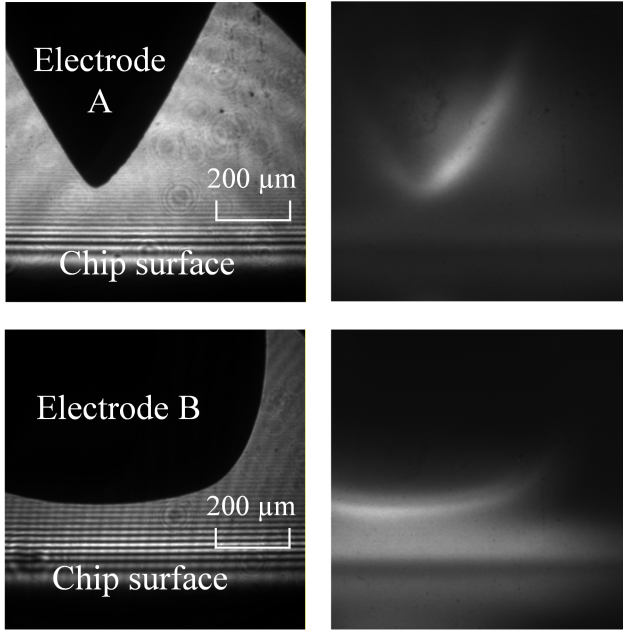


Figure 3.12: Plasma emission profiles with two electrode tip designs. Top left: profile of the electrode A, the pointy needle tip, illuminated by a background laser source. Top right: unstable emission covering mainly the needle tip. Bottom left: profile of the electrode B, the rounded flat tip. Bottom right: stable even emission covering the discharge gap.

3.2 Optical detection system

3.2.1 Optical configuration

The optical detection system consists of three parts: the laser input (405 nm) coupled to a single-mode UV fiber for optical alignment of the photonic chip; the illumination light path for top-view imaging of the chip; and the output light path that collects and directs the chip output to the detector via spatial coupling. The initial and final designs of the optical configuration are shown in Fig. 3.13.

In both designs, the input laser beam is launched from outside the chamber, passes through a VPCH42-UV UV-transparent window, and is collected inside by an RC04APC-F01 UV-enhanced reflective collimator before being guided to the chip via the single-mode fiber. The fiber is secured in a custom mount made of plastic and ceramic screws to avoid creating unintended discharge pathways. Its position during alignment is precisely controlled by a Luminos I6000 six-axis XYZ/RYP positioner. Top-view illumination for imaging is provided by a blue LED. A removable Thorlabs MicroSpot UV microscope objective ($5\times$) is mounted above the chip stage, focusing and collecting light that eventually reaches a laboratory

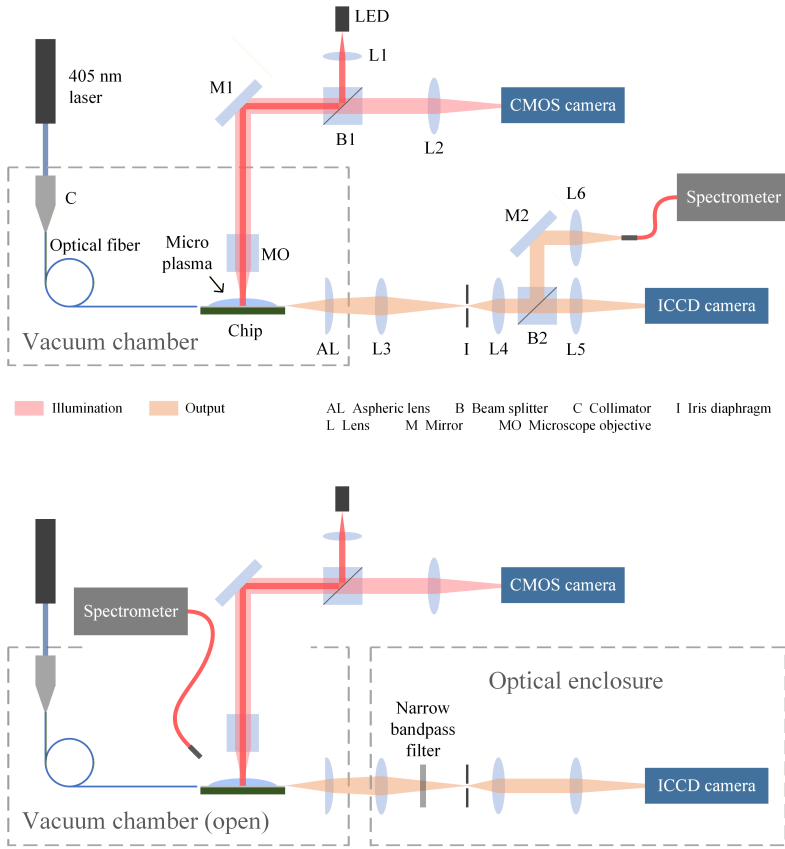


Figure 3.13: Schematics of the optical detection system. Top: initial design. Bottom: final design.

camera with a complementary metal-oxide-semiconductor (CMOS) sensor. Light emitted from the waveguide facet is collected by a UV aspheric lens and guided through an optical zoom path to an intensified charge-coupled device (ICCD) camera, which offers exceptional sensitivity suitable for detecting signals at the photon-counting level. An iris diaphragm placed in the zoom path blocks unwanted background and stray light, improving the signal-to-noise ratio (SNR).

As noted in Subsection 3.1.1, a major shift in the designed operating pressure occurred from low-pressure to atmospheric pressure conditions. In the prototype setup, the optical system was designed to work with a vacuum chamber, meaning that parts of the light path (LED illumination, input laser beam, and chip output) had to pass through the chamber while it was evacuated. Maintaining optical alignment under those conditions was technically difficult (discussed in the next subsection). This limitation disappears at atmospheric pressure as the chamber can be left open

during experiments.

In the initial design, the output was split by a beam splitter: one half went to a spectrometer, the other half to the ICCD camera, incurring a 50% signal loss on each path. According to the device performance predicted by the model (Section 2), the expected output power is on the picowatt scale. The spectrometer is insufficiently sensitive for such weak signals, especially when using the same exposure time as the ICCD camera. To improve the SNR, the beam splitter and the spectrometer branch were therefore removed. An alternative method to obtain the emission spectrum is to insert narrow-bandpass filters in the output path and measure the signal intensity from the ICCD images. By applying filters corresponding to each strong plasma emission line, the device output spectrum can be reconstructed. Moreover, because the plasma now operates at atmospheric pressure, its emission spectrum can be measured directly by placing the collection fiber of the spectrometer inside the chamber, in the vicinity of the discharge.

Noise in the ICCD images originates from two main sources: ambient stray light and direct plasma free-space emission captured by the aspheric lens. In the final design, an optical enclosure (Fig. 3.14) was added to block ambient light. The enclosure covers the entire output light path, including the ICCD camera. Tests confirmed that the experiments are conducted in a near-ideal dark environment with minimal background noise, even when the ICCD camera operates at maximum gain and an exposure time of 100 ms.

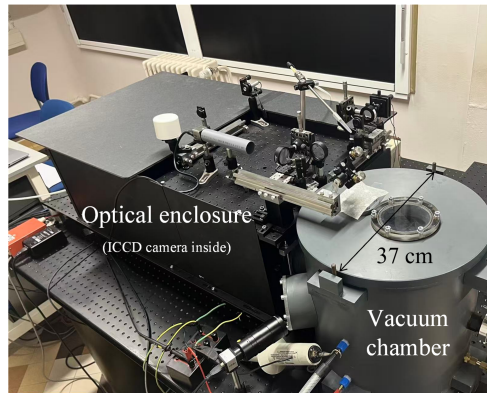


Figure 3.14: Photograph of the optical enclosure.

Multiple aspheric lenses were used depending on the measurement scenario. For collecting the chip output signal, a lens with a high numerical aperture (NA), a short focal length (FL), and a small diameter is preferred. The NA determines the acceptance angle: a high NA collects more photons from the output facet, yielding a higher SNR. A lens with a short FL and small diameter collects less direct free-space emission from the plasma - the dominant noise source - thereby

further improving SNR. An aspheric lens (10 mm diameter, NA = 0.63, FL = 2.52 mm, supplied by Edmund Optics) is mounted in a custom plastic lens tube that moves with the lens positioner. When focused, the tip of the tube is located about 1 mm away from the chip edge. To minimize the influence of plasma free-space emission, the plasma center - determined primarily by the designed position of the coupling spiral region on the chip - should be located sufficiently far from the waveguide end at the output facet in the transverse direction (horizontal direction in Fig. 3.7). The chip design strategy is detailed in Section 3.3. For observing the plasma emission profile (Chapter 4), however, a much longer FL is required because the lens must focus not on the chip edge but on the plasma center at the electrode tip.

3.2.2 Chip alignment

As mentioned in the previous subsection, the alignment of the chip in the optical path is achieved via fiber edge coupling at the input and via spatial coupling at the output. Fig. 3.15 shows the setup in the aligned state inside the vacuum chamber. The edge coupling is done by bringing the fiber tip (the coating needs to be stripped

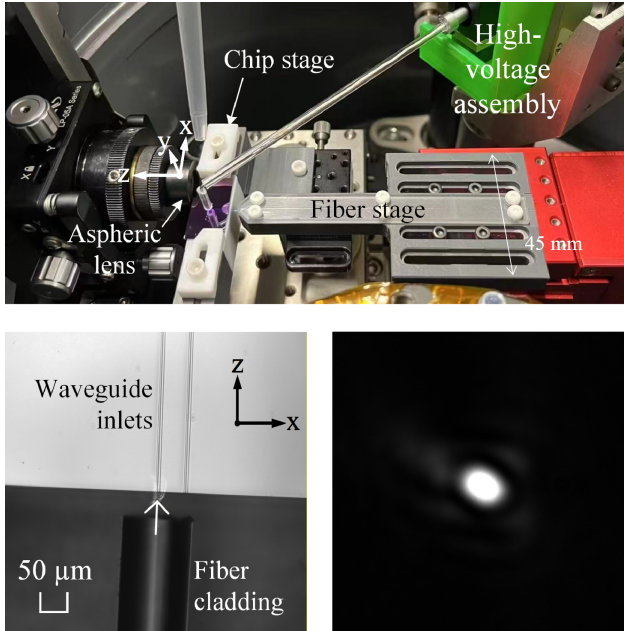


Figure 3.15: Top: optical alignment inside the vacuum chamber. Bottom left: fiber edge coupling at the chip input side. Bottom right: mode profile at the output facet of a single-mode waveguide retrieved with the aspheric lens using a CMOS camera (replacing the ICCD camera).

off) to the input facet of the waveguide. Once aligned, a clear line that corresponds to the scattered light from the waveguide should be visible from the top view. The spatial coupling at the output side is more difficult, as the focal point is not a visible entity in the camera view. To achieve ideal spatial coupling, the alignment between the lens and the output facet of the waveguide needs to be done in 5 degrees of motion, namely the three translation axes (X transverse, Y vertical, and Z focus), yaw, and pitch. A practical technique for spatial coupling is to first perform a coarse alignment of the three translation axes with the bare eye or a cell phone camera. If done correctly, there should be a visible round pattern on a paper screen (preferably placed before the iris first). Then, try to place the bright pattern at the center of the aperture and focus the lens. Upon finishing the translational alignment, one should adjust the yaw together with the transverse position x , or the pitch together with y . The correct yaw and pitch should yield an Airy pattern on the output camera, as shown in the bottom right of Fig. 3.15. It is worth mentioning that during the alignment process, it is better to use a CMOS camera instead of the ICCD camera, which has fewer pixels, as the former offers better resolution for the laser signal.

The optical alignment is very sensitive to mechanical positioning. Any drift in the fiber position or lens focus - caused by material deformation under mechanical or thermal stress, as well as shock or vibration from external factors like the vacuum pump - will result in the loss of optical alignment. For experiments that require vacuum operation, the loss of alignment cannot be corrected in real time with the chamber sealed. Efforts such as introducing de-vibration designs to the vacuum pump and improving the mechanical connection of the stages inside the chamber have been made to maintain the alignment in the vacuum state. However, despite the above-mentioned improvements, the loss of alignment was still observed as the fiber was pulled away from the chip edge while the chamber was pumped down to vacuum. Investigations have been performed on every component in the chamber, which took two months, until it was found that the alignment issue had something to do with the aluminum breadboard placed on the bottom of the chamber, where all the components are fixed. Note that there are threaded holes at a fixed spacing on the breadboard, and when some optical component is fixed on top, a series of tiny gas chambers is created, where the outside is vacuum and the inside is atmospheric pressure. These tiny chambers together contribute to a force that causes a slight displacement of the fiber positioner on top, which eventually results in the loss of alignment. This is also consistent with the experimental observations; the process of losing the alignment is pressure-dependent, and the alignment can be recovered by refilling the chamber to atmospheric pressure. With the knowledge of the root cause, the solution is simple; put spacers underneath the breadboard to lift it up, and the tiny chambers disappear. No displacement of the fiber tip is observed while operating in vacuum afterward.

As the discharge design changes to atmospheric pressure, maintaining the

optical alignment can be performed in real-time. Due to the influence of the helium flow, a small perturbation in the fiber position has been observed, but it is a slow process and can be amended in time without losing the alignment instantaneously. In fact, the alignment needs to be constantly checked during the experiments to ensure the camera is capturing the correct output from the waveguide facet.

3.3 Chip design and fabrication

3.3.1 Layout design

The layout of the chip defines the relative position of the plasma center with regard to the input and output facets. Fig. 3.16 shows the basic layout of the waveguide. As previously demonstrated in Fig. 2.1 at the beginning of Chapter 2, the coupling region, which will be aligned with the high-voltage and ground electrodes, takes a spiral form to maximize the coupling length l_c at the center of the discharge. The width and height of the coupling region are determined by two parameters, namely the bend radius and the spacing of the spiral. To minimize bending loss to a negligible extent, the bend radius should not be less than $200\text{ }\mu\text{m}$. With a bend radius of $200\text{ }\mu\text{m}$, to match the coupling region with the cross section of the high-voltage electrode (a circle with a diameter of 1 mm) in size, the spiral spacing is chosen to be $10\text{ }\mu\text{m}$. At such a spacing, the scattered light from each turn can be clearly distinguished from one another in the top view captured by the CMOS camera. This is a crucial condition for the measurement of the waveguide loss rate based on scattered light.

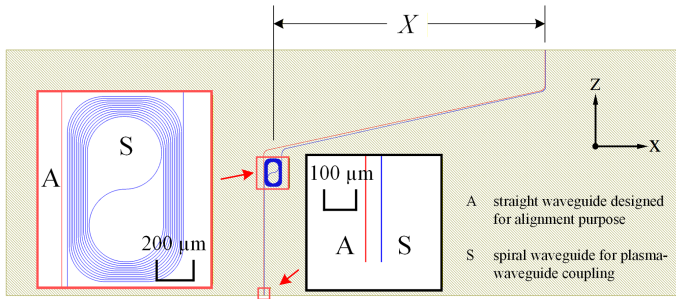


Figure 3.16: Layout design of the chip.

During the early-stage plasma-waveguide coupling tests with straight waveguides, it was noted that the plasma emission flooded the entire view of the ICCD camera with its brightness, and the expected output signal was too weak to compete with it. Since the output light originates from the plasma emission, it is impossible to use filters or polarizers to filter it out from the bright background. The only

solution is to shift the discharge center away from the output facet in the transverse direction x . To determine a proper value for this transverse shift, a series of experimental tests was conducted focusing on measuring the noise intensity, which comes from the plasma free-space emission, as a function of the x coordinate. The results are presented in Fig. 3.17. It is observed that for the given plasma condition, a transverse shift of at least 8 mm is necessary to minimize the impact from the plasma free-space noise. To ensure an ideal SNR, the transverse shift is finally chosen to be 10 mm for the following study.

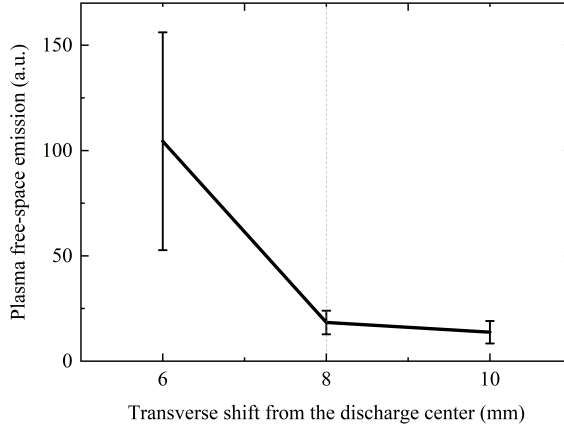


Figure 3.17: Plasma free-space emission intensity versus transverse offset (on x axis) of the focal point from the discharge center. The plasma setup works under the same operating condition as in Section 4.2. The intensity is obtained by area-averaging the pixel intensity of the ICCD images. The error bar data is processed from 5 tests for each x offset value.

According to the deduction of the effective coupling length $l_{c,eff}$ in Subsection 2.3.3, and considering a loss rate level of 3-4 dB/cm (based on the measurements of the tested single-mode waveguides), the coupling length l_c , which is the length of the spiral in the coupling region, should not exceed 4 cm. Further increasing l_c will not result in an active enhancement of $l_{c,eff}$ and therefore the output power, but will surely introduce more propagation loss throughout the waveguide and make the chip alignment more difficult. In the finalized chip design, 12-turn and 14-turn spirals are used in the coupling regions, corresponding to coupling lengths of 3.1 and 3.7 cm, respectively. At such a waveguide length, the chip-lens spatial coupling becomes difficult, as the coarse alignment process, which is the crucial initial step, suffers from an attenuated signal intensity. It will be almost impossible to find the right focal position if one cannot visually see any patterns from the laser on the paper screen. To assist the chip alignment, an additional short waveguide is introduced next to each spiral waveguide, as depicted in Fig. 3.16. The input and output of this auxiliary waveguide are designed to be in close proximity to the spiral waveguide

with a $50\ \mu\text{m}$ shift. Since the total length of these additional waveguides is less than 2 cm, a bright laser spot can be seen on the paper screen while performing the coarse alignment with these short waveguides, which makes spatial coupling much easier. The alignment of the spiral waveguides can be simplified by aligning with the auxiliary waveguide first and then shifting the entire chip stage by $50\ \mu\text{m}$. That yields a visible pattern on the paper screen even with the strong propagation loss in the spiral waveguides.

3.3.2 Fabrication of the chip

The fabrication of the UV photonic integrated circuits follows the process flow illustrated in Fig. 3.18. Starting from a thermally oxidized silicon wafer with

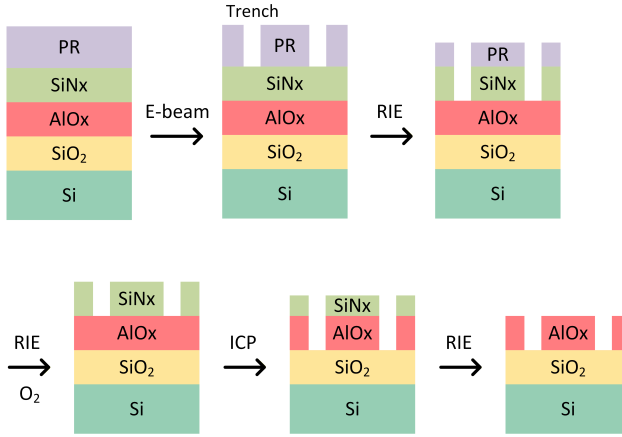


Figure 3.18: Fabrication flow of the AlO_x waveguide using SiN_x as hard mask.

a $3\ \mu\text{m}$ thick buried oxide layer (SiO_2 on Si), a 110 nm-thick AlO_x layer is deposited by atomic layer deposition (ALD) using trimethylaluminium (TMA) and water precursors at $300\ ^\circ\text{C}$. This deposition temperature is critical for minimizing carbon and hydrogen impurities, which otherwise cause strong UV absorption. To transfer the waveguide pattern into the AlO_x layer, a hard mask is required because a conventional photoresist mask is etched much faster than AlO_x when using chlorine-based chemistry, leading to mask deformation before the AlO_x is fully etched. Silicon nitride (SiN_x) deposited by plasma enhanced chemical vapor deposition (PECVD) is chosen as the hard mask for two main reasons: first, it exhibits a high etching selectivity ($\gg 1$) with respect to AlO_x in the chlorine-based inductively coupled plasma (ICP) etching process; second, it remains mechanically stable and does not deform under the plasma conditions, preserving the pattern fidelity. After depositing a 100 nm-thick SiN_x layer, the waveguide pattern is defined by electron-beam lithography (EBL) in a positive photoresist (ARP6200.09

supplied by Allresist). The pattern is first transferred into the SiN_x hard mask by reactive ion etching (RIE) using a CF_4/H_2 gas mixture. The remaining photoresist is then removed by oxygen plasma, leaving the SiN_x mask ready for the AlO_x etching step.

The AlO_x layer is etched with ICP using a $\text{BCl}_3/\text{Cl}_2/\text{Ar}$ gas mixture. This chlorine-based chemistry is essential because the fluorine-based gasses produce non-volatile AlF_3 , which redeposits on the sidewalls and halts the etching. The chlorine mixture, by contrast, generates volatile AlCl_3 , enabling a high etching rate and smooth sidewalls. The ICP power (1250 W) controls the plasma density, while the RF power (50 W) determines the ion energy, balancing anisotropic etching with minimal sidewall roughness. After the AlO_x is fully etched, the SiN_x hard mask is removed in an RIE step using a CF_4/H_2 mixture, leaving the AlO_x strip waveguides on the SiO_2/Si substrate.

3.4 Conclusion

This chapter has presented the iterative development of the UV-POCS experimental system, from the initial design concept to a fully operational setup. The development process was driven by the need to reconcile two inherently conflicting requirements: the harsh, contaminating, and mechanically unstable environment of a DBD plasma, and the clean, vibration-free, and optically stable conditions demanded by a PIC and its associated detection system.

The plasma setup underwent three major evolutionary stages. The initial SBD configuration in vacuum suffered from electrode melting, substrate delamination, and parasitic discharges, which could not be fully resolved even by increasing the operating pressure. The subsequent sandwich-like double-dielectric DBD eliminated the direct electrode-chip contact but introduced unwanted discharge paths bypassing the gas gap, making it impractical for reliable coupling. The final configuration - a one-layer DBD operating at atmospheric pressure with a controlled helium flow - proved to be the final solution. It suppresses arcing, avoids parasitic discharges by removing the top glass, and maintains a stable, diffuse plasma on the chip surface. The chip stage and high-voltage electrode assembly were iteratively refined to address material-induced carbon contamination and insulation reliability. The use of Teflon in combination with PVC, ceramic screws, and quartz-insulated tungsten electrodes proved essential to achieve a contamination-free and electrically stable plasma environment.

The optical detection system was adapted from a vacuum-compatible design to a simpler atmospheric-pressure configuration. Key improvements included the removal of the beam splitter to avoid 50% signal loss, the introduction of an optical enclosure to suppress ambient stray light, and the use of a high-NA aspheric lens with a short FL to maximize collection from the waveguide facet while

minimizing direct plasma background. The critical issue of maintaining optical alignment under vacuum was traced to trapped air pockets under the breadboard; the solution - lifting the breadboard with spacers - allowed stable alignment during low-pressure operation. At atmospheric pressure, real-time alignment adjustment became possible, greatly simplifying experiments.

The chip design incorporated a spiral coupling region to maximize the effective coupling length, with a transverse offset of 10 mm to move the output facet away from the intense plasma free-space emission. Short auxiliary waveguides were added to facilitate spatial coupling. The fabrication process, based on ALD- AlO_x waveguides with a SiN_x hard mask and chlorine-based ICP etching, reliably produced waveguides with propagation losses of 3–4 dB/cm at UVA wavelength.

Collectively, the developments described in this chapter evolved an unstable and irreproducible test setup towards a robust, contamination-controlled, and optically optimized experimental system for the UV-POCS concept. The established plasma and optical configurations, together with the validated chip design and fabrication protocol, provide a solid experimental foundation for the plasma emission studies in Chapter 4 and Chapter 5.

4

Enhancing plasma UV emission on the chip surface

In the fourth chapter, the methods for enhancing the plasma emission rate r_{ems} are investigated experimentally and numerically. The enhancement of local ionization and UV emission in the micro-gap atmospheric plasma near the dielectric surface of the photonic chip is achieved by controlling the geometric confinement and using harmonic excitation. The plasma model introduced in Section 2.2 is employed here to provide insight into the ionization enhancement mechanism under controlled external conditions. This chapter is organized as follows. Section 4.1 describes the experimental setup. Section 4.2 discusses the pre-test results that determine a baseline operating condition used in both the experiment and simulation. Section 4.3 explores the impact of discharge gap spacing on ionization dynamics, with Subsection 4.3.1 presenting the variation of measured emission intensity profiles along the gap spacing (80–400 μm), and Subsection 4.3.2 providing theoretical interpretations through time-averaged and time-sampling analyzes. Section 4.4 further examines the harmonic excitation strategies in which a second-order harmonic component is introduced to the sinusoidal voltage input with specific phase differences. Subsection 4.4.1 experimentally investigates the phase-difference-dependent emission enhancement, while Subsection 4.4.2 analyzes these findings based on the transient results of the simulation. Finally, Section 4.5 summarizes the key insights and discusses their implications for UV-POCS and other applications that benefit from enhanced ionization at a dielectric surface.

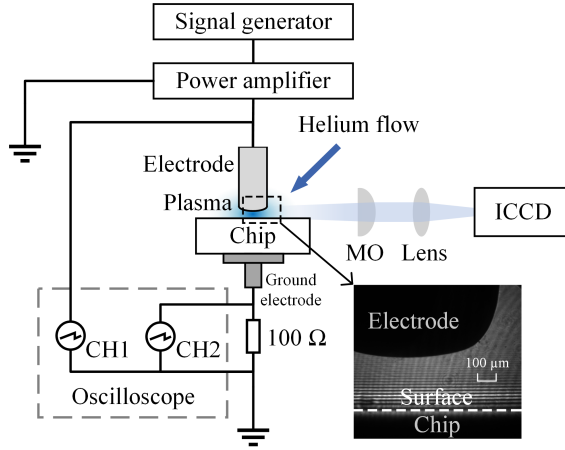


Figure 4.1: Experimental setup. The enlarged view is an ICCD image that shows the electrode tip profile outlined by a background laser emission at a wavelength of 405 nm.

4.1 Experimental setup

Following the work in Chapter 3, a whole set of discharge and detection system for the UV-POCS concept is available for the experimental study of plasma emission and plasma-chip coupling. As discussed in Chapter 3, the implementation of UV-POCS will utilize helium-air DBD plasma at atmospheric pressure. The experimental setup consists of three main components: the high-voltage electrode assembly connected to an AC power supply, the chip stage that holds the chip and ground electrode, and the optical detection instrumentation, as shown schematically in Fig. 4.1.

The high-voltage electrode assembly features a tungsten electrode with a diameter of 1 mm, powered by a combination of a B&K precision 4045B signal generator and a power amplifier delivering arbitrary waveform excitation at 10 kHz. The electrode tip is flat with rounded edges to avoid point discharge, as shown in the enlarged view in Fig. 4.1. The electrode is mounted on a vertical translation stage that allows precise control of the gap spacing d between electrode tip and the chip. The zero position ($d = 0$) is determined by bringing the electrode tip into contact with the chip surface. The applied voltage is measured with a high-voltage probe, while the current is monitored across a $100\ \Omega$ sampling resistor. Both signals are recorded by a PicoScope 3204A oscilloscope. The signal generator is triggered by a TGP110 pulse generator, operating the discharge in pulsed mode with a 500 ms on-time to minimize dust accumulation and carbon-based deposition on the chip surface, which were observed under continuous AC excitation.

The chip is fabricated with a $525\text{-}\mu\text{m}$ -thick undoped silicon substrate and a 3

μm oxide layer on top, as detailed in Section 3.3. The chip is mounted on a special stage (Subsection 3.1.2) where the ground electrode is fixed and insulated at the center. The grounded electrode is connected to the backside of the chip, completing the dielectric barrier discharge configuration. A gas pipe (4 mm inner diameter nozzle) positioned 3 cm above the discharge gap at an angle supplies a constant helium flow to the discharge region, where it mixes with ambient air upon reaching the chip surface, creating the helium/air mixture in which the discharge operates.

The optical detection system collects discharge emission with a UV-compatible microscope objective, which is then focused through a UV-compatible lens onto an intensified charge-coupled device (ICCD) camera (Hamamatsu C8484-05G) with a fixed gain factor of 1. The ICCD camera is triggered by a second TGP110 pulse generator and gated with a 100 ms exposure window, delayed by 200 ms after the onset of each discharge pulse to ensure measurement during the stabilized portion of the discharge. The pixel coordinates of the captured ICCD images are calibrated to real-world positions using the known vertical displacement of the electrode translation stage, enabling quantitative spatial analysis of the emission profile.

4.2 Baseline operating condition

Before the study on enhancing the plasma emission, a baseline operating condition needs to be properly selected. The operating parameters that determine the discharge characteristic are the gap spacing between the electrode tip and the chip, the waveform, amplitude, and frequency of the applied voltage on the electrode, and the helium flow rate that controls the gas concentration. The effects of gap spacing and voltage waveform will be investigated and discussed in the following two sections. A generally good starting point for this experiment will be a 300 μm discharge gap spacing and a 10 kHz sinusoidal voltage input with a peak-to-peak (ptp) amplitude of 3 kV applied to the high-voltage electrode. The reasons are as follows. A 300 μm discharge gap spacing allows for the observation of the full visual structure of the plasma (sheath-bulk-sheath), as the sheath, a relatively darker region at the plasma boundary, is usually tens of microns thick. And under 3 kV ptp voltage amplitude, the plasma is stable and localized in the coupling region without being too spread out or even arcing. The power supply, or, say, the power amplifier, is optimized around 10 to 15 kHz. Deviating too much from this frequency range will cause a severe reduction in the amplification factor.

With the other two conditions determined, the only parameter that needs to be decided is the helium flow rate. Choosing a flow rate that is too low will fail to support the establishment of the discharge. A flow of helium that is too strong is also not desired, as the plasma emission can be too spread out over the chip surface, leading to strong background noise from the plasma. Dust can also be

blown away, charged, and attracted towards the chip by the electrostatic force, leaving contamination that causes the failure of the waveguides.

A pre-test is conducted to determine the helium flow rate used in the experiment. During the test, the gap spacing is fixed at $300\text{ }\mu\text{m}$, and a 10 kHz, 3 kV ptp sinusoidal voltage input is fed to the electrode. The flow rate is swept from 2 SLM to 6 SLM. The percentage of helium in the gas mixture can be increased by using a higher flow rate. The correlation between helium mole fraction and helium flow rate is estimated based on CFD simulations (Appendix B). The longitudinal emission profile along the centerline of the discharge gap, taken by the ICCD camera, is observed while varying the helium flow rate Q . Figure 4.2 shows the evolution of these emission profiles with increasing Q . The pixel intensities represent horizontally averaged results over a span of $323\text{ }\mu\text{m}$, as indicated in the inset of Fig. 4.2. The overall emission intensity increases monotonically with Q . The intensity drops observed at both ends of each profile correspond to the sheath regions forming adjacent to the chip surface and the electrode surface, as explained in Subsection 1.4.2.

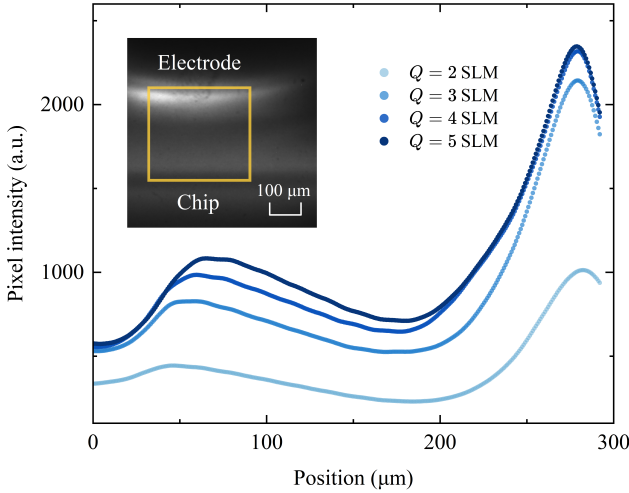


Figure 4.2: Variation of longitudinal light intensity profile with helium flow rate. The region of interest (ROI) is located at the center of the discharge setup, marked by the yellow frame. Position 0 corresponds to the chip surface.

It is notable that the emission intensity in both sheath regions saturates when Q reaches 4 SLM. This saturation behavior can be attributed to the diminishing response of the helium mole fraction to further increases in flow rate beyond 4 SLM (Appendix B). To avoid dust accumulation resulting from the flow turbulence, a flow rate higher than 4 SLM is therefore unnecessary. Now, all the operating parameters of the baseline condition are settled: gap spacing of $300\text{ }\mu\text{m}$, excitation frequency of 10 kHz, sinusoidal input voltage of 3 kV ptp, and helium flow rate of

4 SLM.

The emission characteristic under the baseline operating condition is also examined. The spectrum is measured horizontally with a 6 mm diameter collimated UV lens placed 3 cm away from the discharge and is analyzed with an AvaSpec 2048 spectrometer. The measured spectrum is presented in Fig. 4.3. The first negative system of N_2^+ ($B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$) and the second positive system of N_2 ($C^3\Pi_u \rightarrow B^3\Pi_g$) contribute to the majority of light emission in the UVA region. The strongest spectral line appears at 391.4 nm, originating from the first negative system of N_2^+ . This is also the experimental basis for considering only the emission of $N_2^+(B)$ ($B^2\Sigma_u^+$) in the simplified model (Section 2.2).

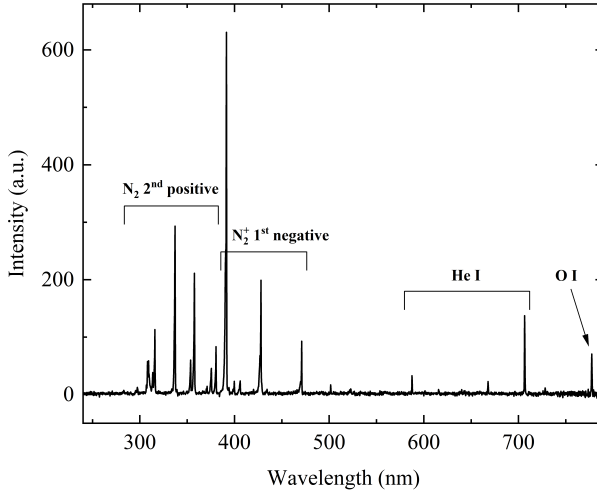


Figure 4.3: Emission spectrum measured in baseline condition.

The electrical characteristics of the discharge under the baseline condition are also characterized. Figure 4.4 shows the current-voltage (I-V) curves measured at the baseline gap spacing of 300 μm under sinusoidal excitation at 10 kHz and 3 kV ptp. The I-V curve exhibits the characteristic hysteresis of a dielectric barrier discharge, with the discharge current peaking near the zero crossings of the applied voltage. This phase relationship arises because the current in a DBD is displacement-current-dominated: the applied voltage charges the dielectric surfaces, and the discharge ignites when the voltage across the gas gap (rather than the applied voltage) reaches the breakdown threshold. Since the gap voltage is approximately the derivative of the applied voltage, the discharge current maximizes near the zero crossings.

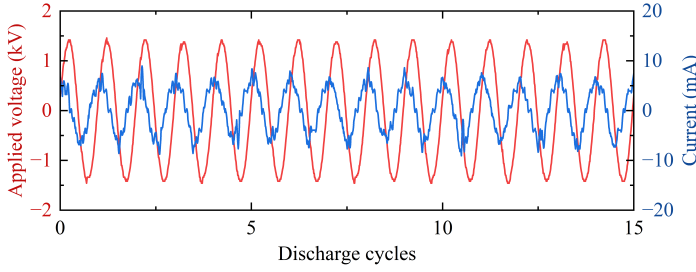


Figure 4.4: Current-voltage (I-V) characteristics of the DBD under the baseline condition ($d = 300 \mu\text{m}$, 10 kHz sinusoidal excitation, 3 kV ptp).

4.3 Effect of gap spacing

Having established a baseline operating condition in Section 4.2, this section investigates the influence of gap spacing on plasma emission characteristics. The gap spacing between the electrode and the chip surface is a critical geometric parameter that governs the electric field distribution, the sheath formation, and ultimately the spatial profile of UV emission available for waveguide coupling. Understanding how emission intensity at the chip surface varies with gap spacing is essential for optimizing the evanescent coupling discussed in Chapter 2. This section presents experimental measurements of emission profiles across a range of gap spacings, followed by numerical modeling that discusses the underlying physical mechanisms.

4.3.1 Experimental results

To identify the optimal geometry that provides enhanced ionization at the chip surface, the emission characteristics of the on-chip plasma are investigated as a function of gap spacing. The evolution of the emission intensity profile for gaps ranging from $80 \mu\text{m}$ to $400 \mu\text{m}$ is shown in Fig. 4.5. The ROI is identical to that used in Fig. 4.2 and described in Section 4.1.

As the gap decreases, the light intensity profile undergoes a distinct morphological transition. At $400 \mu\text{m}$, a three-layer structure is observed, consisting of two near-electrode regions with elevated intensity separated by a central region of lower intensity. When the gap is reduced to 300 and $200 \mu\text{m}$, the profile collapses into a two-layer structure. For gaps below $200 \mu\text{m}$, the profile further simplifies to a single emission region. Throughout these transitions, the current-voltage characteristics maintain similar shapes across all gap spacings, indicating that no fundamental change in discharge mode occurs.

Importantly, the emission intensity localized at the chip surface increases monotonically as the gap becomes thinner. This enhancement saturates when the gap

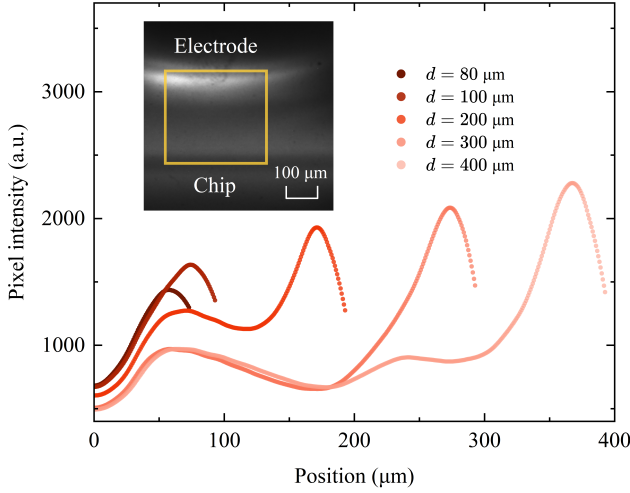


Figure 4.5: Longitudinal emission intensity profiles for four different discharge gap spacings. Position 0 denotes the chip surface. The ROI corresponds to that used in Fig. 4.2, as shown in the inset.

spacing falls below $100\ \mu\text{m}$. Conversely, the peak emission intensity within the gap exhibits the opposite trend, decreasing as the gap narrows. Consequently, the fraction of total optical power emitted near the chip surface increases substantially with decreasing gap spacing, a favorable trend for evanescent coupling to the waveguide.

4.3.2 Model results and discussion

The plasma model described in Section 2.2 is employed to interpret the experimental observations presented above. As established in Fig. 4.3, the N_2^+ first negative system dominates the UV emission at $391.4\ \text{nm}$. The total emission rate r_{ems} can therefore be estimated from the reaction rate of radiative decay R19 (Eq. (2.10)), as previously stated in Subsection 2.2.3. Figure 4.6 presents the time-averaged profiles of electron density and emission rate r_{ems} for gap spacings ranging from 100 to $400\ \mu\text{m}$. The model successfully reproduces the experimentally observed transition in emission profile (Fig. 4.5): a three-layer structure at $400\ \mu\text{m}$ evolves into a single-zone profile as the gap narrows to $100\ \mu\text{m}$.

The peak electron density remains relatively constant for gaps of $200\ \mu\text{m}$ and above, but begins to decrease when the gap becomes thinner than $200\ \mu\text{m}$. This behavior is consistent with the leftward movement on the helium Paschen curve as the gap narrows, entering a regime where sustaining the discharge becomes increasingly difficult [108]. The electron density at the chip surface, however, exhibits a different trend, increasing significantly as the gap is reduced from 200 to

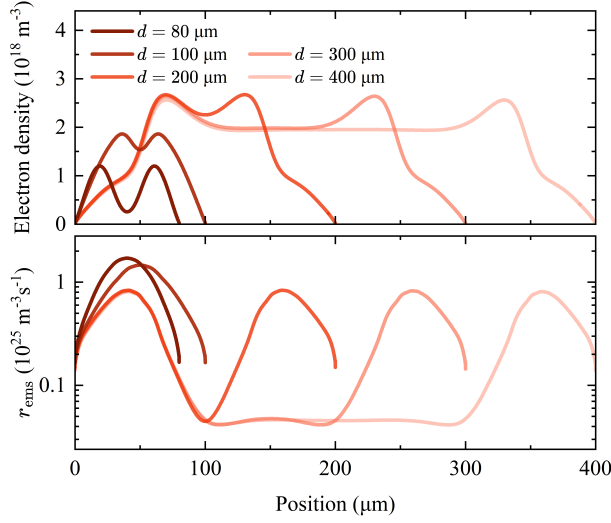


Figure 4.6: Simulated time-averaged profiles of electron density and emission rate r_{ems} for different gap spacings. Position 0 denotes the chip surface. The transition from three-layer to single-zone structure with decreasing gap reproduces experimental observations.

100 μm . This enhancement correlates directly with the increased surface emission observed experimentally, although the electron density and emission rate are not directly proportional, as the latter depends on excited state populations rather than electron density alone.

A notable discrepancy between the model and experiment is the symmetry of the simulated profiles, whereas the experimental profiles in Fig. 4.5 show some asymmetry. This difference arises from the simplified one-dimensional geometry employed in the model, which assumes perfectly symmetric electrodes. In the actual configuration, the powered electrode is exposed whereas the ground electrode is covered by the chip. The ground electrode (2 mm diameter) is set to be larger than the powered electrode (1 mm diameter) to insure alignment. That leads to a non-zero transverse electric field component that enhances plasma expansion toward regions of higher electric field, breaking the perfect symmetry.

A more detailed comparison of the time-averaged charged particle distributions for the 100 μm and 300 μm cases is provided in Fig. 4.7. In the 300 μm case, a quasi-neutral plasma bulk occupies the central region, flanked by two ion-rich sheaths adjacent to each electrode. For the 100 μm case, however, the time-averaged result deviates significantly from quasi-neutrality, with the entire gap exhibiting a net positive charge. This increased time-averaged ion density correlates with the enhanced emission observed in Fig. 4.6, driven by more efficient charge exchange from helium to nitrogen ions (R17 and R18). It is important to note that time-

averaged charge separation does not imply a complete absence of quasi-neutrality in the instantaneous, spatially resolved sense; this distinction will be clarified through transient modeling results below.

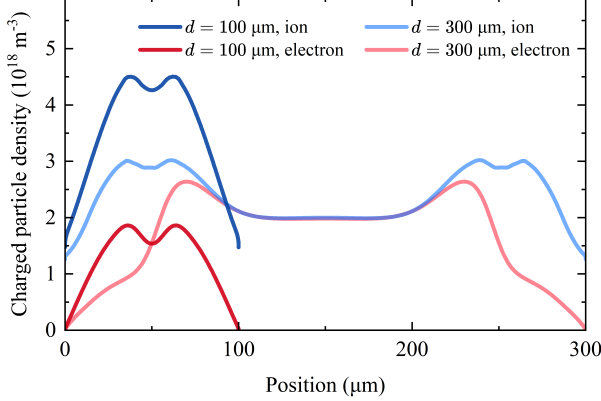


Figure 4.7: Time-averaged charged particle density profiles for $d = 100 \mu\text{m}$ and $d = 300 \mu\text{m}$ cases. Red lines represent electron densities, blue lines represent ion densities. Position 0 denotes the chip surface.

To understand the mechanism underlying the collapse of the layered structure, time-resolved analysis within a single discharge cycle is necessary. Figure 4.8 presents the spatiotemporal evolution of electron density for the $300 \mu\text{m}$ gap case. The structure bears a strong resemblance to DC glow discharge [106], comprising a cathode sheath characterized by a steep electron density gradient, a positive column with a relatively flat profile occupying most of the gap, and a transition region (pre-sheath) connecting them. This analogy is reasonable given the 10 kHz excitation frequency, which is substantially lower than the characteristic collision frequencies in the discharge.

The electron density peak appears at the sheath edge (within the pre-sheath) on the cathode side, accompanied by a low-density region inside the cathode sheath where electrons have not yet gained sufficient energy from the electric field to initiate significant ionization. Electrons exiting the sheath are subsequently driven by the electric field toward the temporary anode, forming the positive column with its moderate density gradient.

Figure 4.9 shows the instantaneous distributions at the current peak phase ($\tau = 0.2$ in Fig. 4.8), when the chip surface functions as the cathode (position 0). These transient results differ markedly from the time-averaged profiles in Figs. 4.6 and 4.7, as expected. The majority of the potential drop (approximately 170 V) occurs across the cathode sheath, where electrons (both primary and secondary) acquire sufficient energy to ionize neutral particles, creating an ionization zone encompassing the sheath and part of the pre-sheath. The potential drop across the

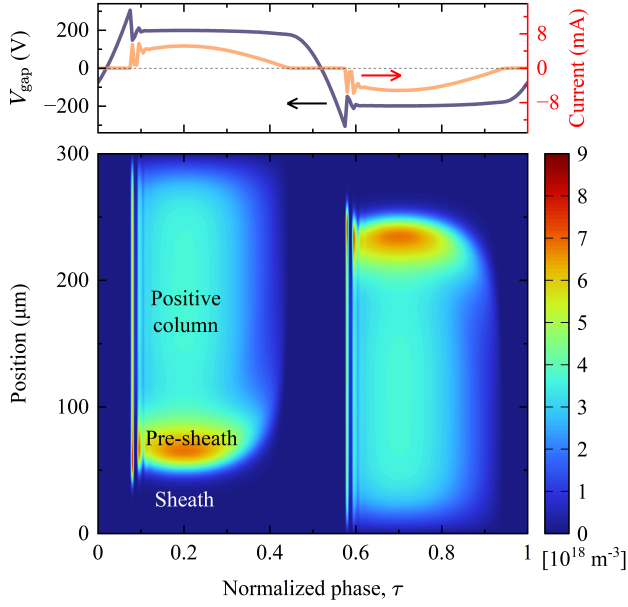


Figure 4.8: Spatiotemporal distribution of electron density over one discharge period for $d = 300 \text{ } \mu\text{m}$. The gap voltage and discharge current waveforms are provided as phase references. Position 0 denotes the chip surface; the powered electrode is at $300 \text{ } \mu\text{m}$. The phase has been adjusted for clarity.

bulk plasma is only about 30 V, consistent with quasi-neutrality requirements.

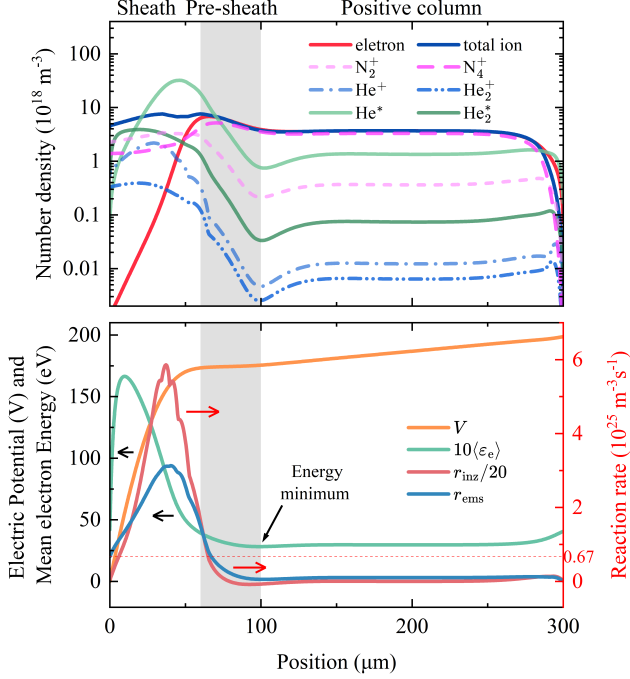


Figure 4.9: Transient simulation results for $d = 300 \mu\text{m}$ at phase $\tau = 0.2$: number densities, electric potential V , mean electron energy $\langle \varepsilon_e \rangle$, net ionization rate r_{inz} , and emission rate r_{ems} . Values of $\langle \varepsilon_e \rangle$ and r_{inz} are rescaled for clarity. Position 0 denotes the chip surface; the red dashed line marks r_{ems} at the chip surface.

The He^+ and He_2^+ ions produced in the ionization zone become trapped within the sheath potential barrier. These ions contribute significantly to light emission at the chip surface through charge exchange reactions R17 and R18, which are more efficient than Penning ionization (R15 and R16) in producing N_2^+ . Intense ionization within the cathode sheath is accompanied by strong excitation of helium atoms to the metastable He^* state (R2), which subsequently forms He_2^* (R2 + R5). These metastable species contribute to N_2^+ production and the subsequent 391.4 nm emission through Penning ionization (R15 and R16).

Upon leaving the ionization zone, N_2^+ rapidly converts to N_4^+ via three-body association R7, which becomes efficient at atmospheric pressure. Ions within the sheath maintain the discharge by producing secondary electrons, analogous to DC glow discharge where ionization occurs primarily within or at the edge of the cathode sheath [106]. The cathode sheath thickness is approximately $60 \mu\text{m}$, with no discernible sheath structure on the anode side.

The minimum mean electron energy appears between the pre-sheath and the

positive column, approximately $100\ \mu\text{m}$ from the chip surface, producing a corresponding minimum in r_{ems} at the same location. Time averaging of these transient emission profiles yields the three-layer structure observed experimentally when the gap is sufficiently large that the pre-sheath regions from opposite half-cycles do not overlap. This condition holds for $d > 200\ \mu\text{m}$, explaining the transition from two-layer to three-layer structures observed in Fig. 4.6.

Figure 4.10 presents the corresponding analysis for the $100\ \mu\text{m}$ gap case. In contrast to the $300\ \mu\text{m}$ case, the positive column - characterized by flat density profiles - is entirely absent, leaving only the cathode sheath and pre-sheath within the gap. The mean electron energy minimum now occurs at the anode surface. The peak emission rate r_{ems} is located near the gap center, resulting in the single-peak time-averaged structure observed experimentally (Fig. 4.5).

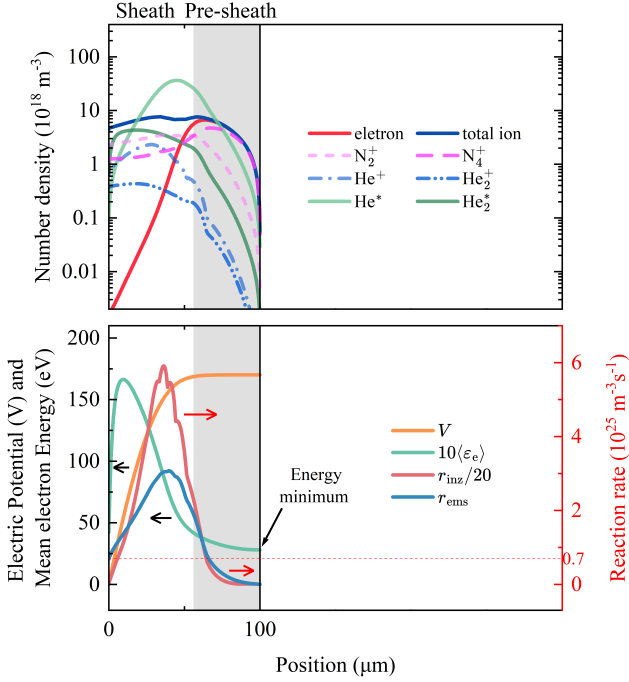


Figure 4.10: Transient simulation results for $d = 100\ \mu\text{m}$ at phase $\tau = 0.2$: number densities, electric potential V , mean electron energy $\langle \varepsilon_e \rangle$, net ionization rate r_{inz} , and emission rate r_{ems} . Values of $\langle \varepsilon_e \rangle$ and r_{inz} are rescaled for clarity. Position 0 denotes the chip surface; the red dashed line marks r_{ems} at the chip surface.

The sheath thickness decreases only slightly (by approximately $4\ \mu\text{m}$) compared to the $300\ \mu\text{m}$ case, but now occupies most of the gap volume. This explains the non-quasi-neutral time-averaged results in Fig. 4.7, as the sheaths from opposite half-cycles begin to overlap spatially when the voltage polarity reverses. The sheath

potential drop remains nearly unchanged at approximately 170 V, while the reduced sheath thickness increases the average electric field by about 25%. This enhanced reduced electric field E/N elevates the mean electron energy, increasing ionization cross sections and reaction rates [109] through their exponential dependence on electron energy [110].

Importantly, the emission rate at the chip surface increases as a result of enhanced ionization and charge exchange reactions (R17 and R18). A quantitative evaluation of this emission enhancement at small gap spacing is shown in Fig. 4.11. It is noticeable that the experimental and theoretical trends diverge at a gap spacing below 80 μm , as the experimental result presents a more modest increase as the gap spacing decreases. This divergence indicates the failure of the 1D assumption at a gap spacing small enough to be comparable to the sheath thickness. It is observed that the plasma tends to be more visibly spread-out as the gap spacing drops below 80 μm .

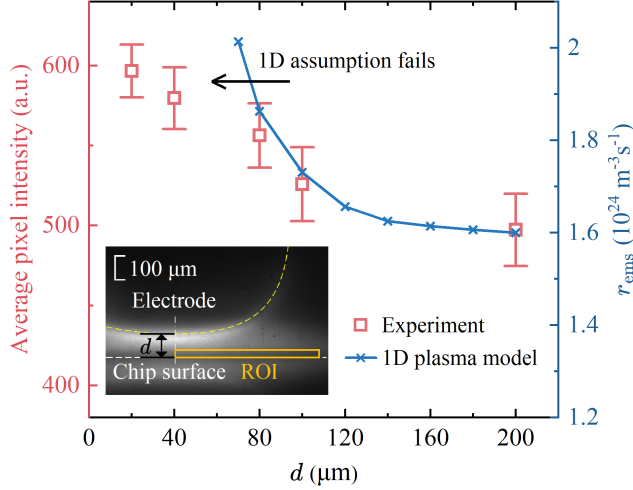


Figure 4.11: Variation of predicted emission rate r_{ems} and experimental measured emission intensity at the chip surface along with the gap spacing d ranging from 20 to 200 μm . The ROI for acquiring the emission intensity is illustrated in the inset.

4.4 Harmonic excitation and effect of phase difference

The previous section demonstrated that reducing the gap spacing enhances ionization near the chip surface by increasing the electric field within the cathode sheath. This spatial optimization, however, represents only one approach to controlling

the discharge characteristics. An additional degree of freedom of the research lies in the temporal distribution of the applied voltage - specifically, the waveform shape. This section investigates harmonic excitation, where a second-order harmonic component is superimposed on the fundamental frequency, to modulate the temporal evolution of the electric field and thereby influence the emission profile. Understanding this temporal control mechanism is essential for maximizing the UV emission available for waveguide coupling.

4.4.1 Experimental results

Building on the understanding of discharge structure as a function of gap spacing developed in Section 4.3, a gap of $d = 300 \mu\text{m}$ is selected for the harmonic excitation study. This spacing provides sufficient distance between the electrode and chip surface to allow the transient response of the discharge to the driving waveform to be clearly observed, avoiding the spatial overlap of sheaths that occurs at smaller gaps.

Harmonic excitation is implemented by adding a second harmonic component to the fundamental sinusoidal waveform while maintaining the same peak-to-peak voltage amplitude as the pure sinusoidal case. The second harmonic is attenuated by a factor of two to compensate for the difference in capacitive reactance arising from the frequency dependence of the impedance. The input voltage waveform is given by

$$V_{\text{in}}(t) = \frac{V_0}{C(\phi)} \left[\sin(2\pi f_0 t) + \frac{1}{2} \sin(4\pi f_0 t + \phi) \right], \quad (4.1)$$

where ϕ is the phase difference between the fundamental and second harmonic components, $f_0 = 10 \text{ kHz}$ is the fundamental frequency, and $C(\phi)$ is a scaling coefficient that ensures the peak-to-peak voltage equals $2V_0$, matching the amplitude used in the sinusoidal reference case. The waveforms investigated in this study are illustrated in Fig. 4.12.

A clarification regarding the phase convention is necessary here: adding 180° to ϕ (for example, changing from 90° to 270°) is equivalent to flipping the waveform across the horizontal axis, representing a polarity reversal. This operation differs from simply negating ϕ , which would flip the waveform across both axes, resulting in reversal of both polarity and temporal phase. In the $\phi = 240^\circ$ and $\phi = 270^\circ$ cases, the powered electrode experiences a more positive bias, whereas in the $\phi = 60^\circ$ and $\phi = 90^\circ$ cases, the polarity is reversed.

Corrections on the amplitude and phase are done before feeding the waveform to the signal generator. This is to compensate for the gain differences and phase delays introduced by the power amplifier. To verify that the capacitive reactances of the two frequency components are properly balanced, the current-voltage characteristic of the setup is measured at a peak-to-peak voltage below the discharge onset

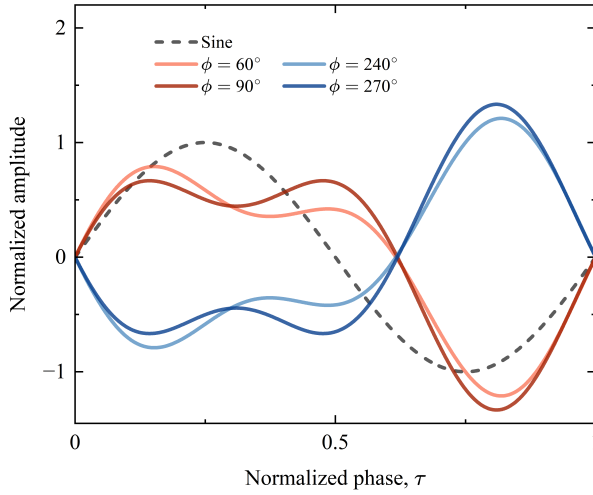


Figure 4.12: Harmonic excitation waveforms for different phase differences ϕ between the fundamental and second harmonic components. Amplitudes are normalized by V_0 , and the phases of each waveform are shifted to align at the origin for clear comparison.

threshold and analyzed using fast Fourier transform (FFT). The results confirm that the coefficient of $1/2$ has been successfully applied to the second harmonic term (Eq. 4.1) and the frequency-dependent impedance has been appropriately compensated.

Figure 4.13 presents the emission intensity profiles measured for different phase differences, compared to the sinusoidal reference case at the same fundamental frequency. The response of the emission profile to the input waveform variation reveals several key findings:

1. Across the entire range of ϕ investigated, harmonic excitation consistently produces higher overall emission intensity than the pure sine wave;
2. The polarity of the waveform exhibits clear spatial selectivity: positive polarity waveforms ($\phi = 240^\circ$ and $\phi = 270^\circ$) enhance emission predominantly on the chip surface, while negative polarity waveforms ($\phi = 60^\circ$ and $\phi = 90^\circ$) favor the powered electrode side;
3. Among all cases examined, the $\phi = 270^\circ$ phase difference yields the most intense emission at the chip surface.

It is noteworthy that all four harmonic excitation cases maintain a three-layer emission profile structure, similar to that observed in Fig. 4.5 for the $300\ \mu\text{m}$ gap. As discussed in Section 4.3, the presence of an additional intensity peak in the center indicates that the cathode sheaths on both sides are spatially separated, implying

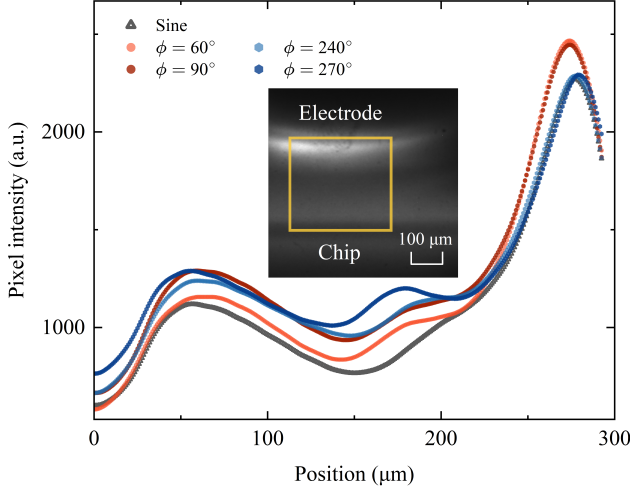


Figure 4.13: Longitudinal emission intensity profiles for different phase differences under harmonic excitation, compared with the sinusoidal case at the same fundamental frequency (10 kHz, shown as a dashed line). Positive polarity cases ($\phi = 240^\circ$ and $\phi = 270^\circ$) are shown in blue; negative polarity cases ($\phi = 60^\circ$ and $\phi = 90^\circ$) are shown in red. Position 0 denotes the chip surface. The ROI is identical to that used in Fig. 4.2.

that the sheath thickness relative to the gap spacing is reduced under harmonic excitation. This observation is consistent with the enhanced surface emission seen on both electrodes: the chip surface in the $\phi = 90^\circ$, 240° , and 270° cases, and the powered electrode surface in the $\phi = 60^\circ$ and 90° cases.

4.4.2 Model results and discussion

The experimental trends are reproduced by the plasma model, as shown in Fig. 4.14, which presents the time-averaged electron density and emission rate for each waveform. Within the range of ϕ studied, the introduction of a second harmonic component consistently results in sheath thinning, effectively pushing the plasma closer to either the anode or cathode depending on the waveform polarity. Positive polarity waveforms (240° and 270°) preferentially enhance ionization in the vicinity of the chip surface, while negative polarity waveforms (60° and 90°) favor the powered electrode side. The $\phi = 270^\circ$ case yields the greatest enhancement on the chip surface, consistent with experimental observations.

The mechanism underlying this enhancement can be understood by examining the phase-resolved discharge dynamics. Figure 4.15 compares the gap voltage, total discharge current, and ionization source term S_{inz} - defined as the total net electron production rate integrated across the entire gap - for the sinusoidal reference case and the $\phi = 270^\circ$ harmonic excitation case. While the sinusoidal case produces

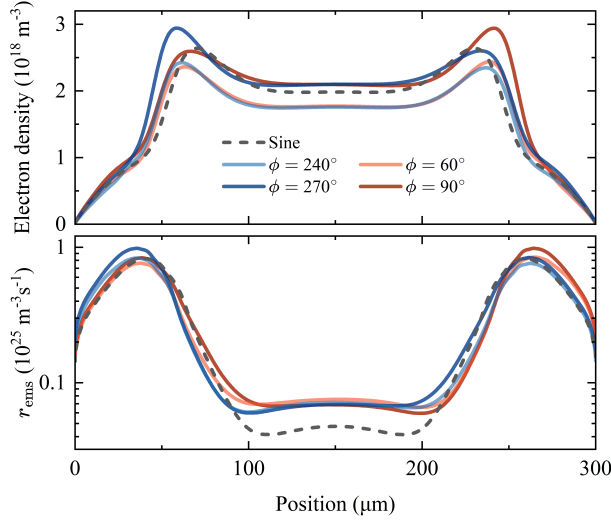


Figure 4.14: Time-averaged electron density profiles predicted by the model for different harmonic excitation waveforms. Position 0 denotes the chip surface. The results reproduce the experimentally observed polarity-dependent enhancement.

symmetric positive and negative half-cycles, harmonic excitation with $\phi = 270^\circ$ yields asymmetric peak gap voltages: approximately 205 V on the positive half-cycle compared to 199 V on the negative half-cycle, both slightly higher than the 199 V peaks of the sine wave case. The insets in the top right image provide enlarged views of these peak voltage differences.

This asymmetry in gap voltage leads to correspondingly unbalanced discharge currents, with a higher positive peak occurring at $\tau = 0.3$ compared to the negative peak at $\tau = 0.7$. The ionization source term S_{inz} follows a similar trend, as charge carrier production through ionization is positively correlated with discharge current magnitude. These results indicate that harmonic excitation redistributes power deposition temporally within the discharge cycle, preferentially enhancing ionization during the half-cycle when the gap is positively biased.

The uneven temporal distribution of power deposition also manifests in the spatial distribution of the plasma. Figure 4.16 presents the spatiotemporal evolution of electron density for the $\phi = 270^\circ$ case. Compared to the sinusoidal case shown in Fig. 4.8, the overall electron density increases unevenly across the gap. The most pronounced enhancement occurs around $\tau = 0.3$, when the chip surface functions as the cathode, with peak electron density exceeding $1.2 \times 10^{19} \text{ m}^{-3}$ in the cathode layer. The enhancement during the opposite half-cycle ($\tau \approx 0.7$) is comparatively weaker, with peak electron density reaching only $9.6 \times 10^{18} \text{ m}^{-3}$. This spatially selective enhancement gives rise to the asymmetric time-averaged profiles observed

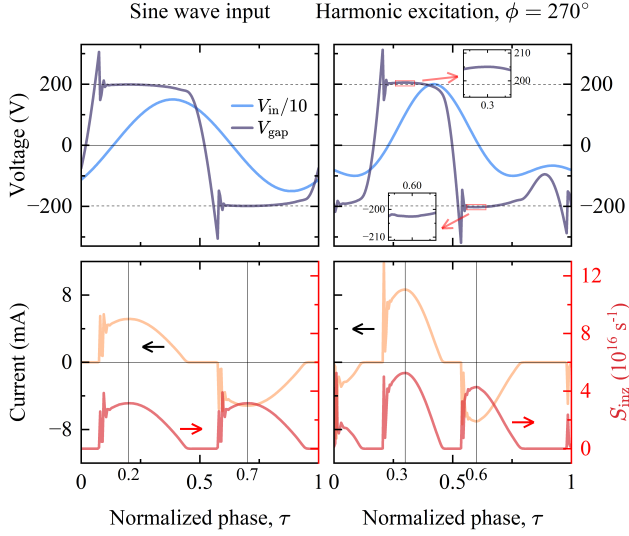


Figure 4.15: Phase-resolved gap voltage, total discharge current, and ionization source term S_{inz} for the sinusoidal reference case (left column) and the $\phi = 270^\circ$ harmonic excitation case (right column). The scaled input waveforms are shown as references. Dashed lines indicate the peak gap voltages of the sine wave case. Insets in the top right image show enlarged views of the peak gap voltages. Phases are adjusted for clarity.

in Fig. 4.14.

To quantitatively assess the combined effect of gap spacing optimization and harmonic excitation, Fig. 4.17 evaluates the emission enhancement within a surface layer defined as the region within $3 \mu\text{m}$ of the chip surface, with cross-sectional area matching that of the powered electrode. This region corresponds to the zone where plasma-wall interactions - including evanescent coupling to the waveguide - predominate. The model predicts that reducing the gap spacing alone increases the total emission rate $S_{\text{ems},s}$ - the volume integral of r_{ems} within this layer - by 12%. Combining gap optimization with $\phi = 270^\circ$ harmonic excitation yields a 48% enhancement, a prediction that is corroborated by experimental measurements of the average pixel intensity in the same region.

4.5 Conclusion

This chapter has demonstrated that localized ionization enhancement in micro-gap atmospheric pressure DBD plasmas can be achieved through two complementary approaches: spatial control via gap spacing optimization and temporal control via harmonic excitation of the driving waveform. When applied in combination, these techniques yield a 48% enhancement in surface emission intensity relative to the

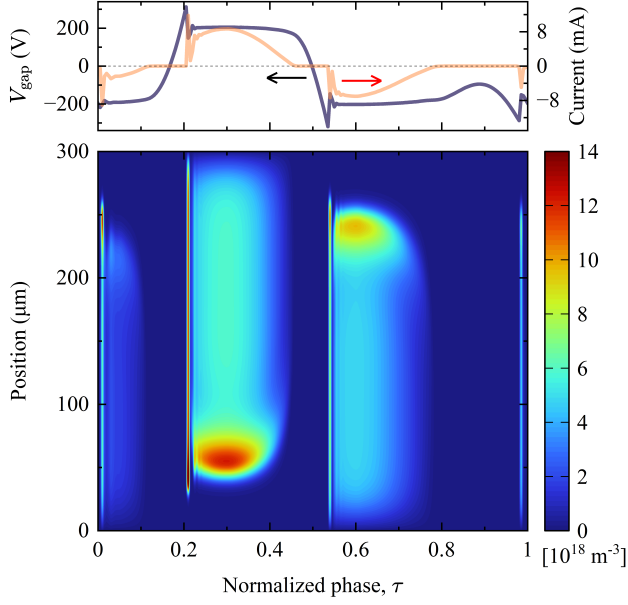


Figure 4.16: Spatiotemporal distribution of electron density for the $\phi = 270^\circ$ harmonic excitation case with $d = 300 \mu\text{m}$. Gap voltage and discharge current waveforms are provided as references. Position 0 denotes the chip surface; the powered electrode is at $300 \mu\text{m}$. Phases are adjusted as in Fig. 4.15.

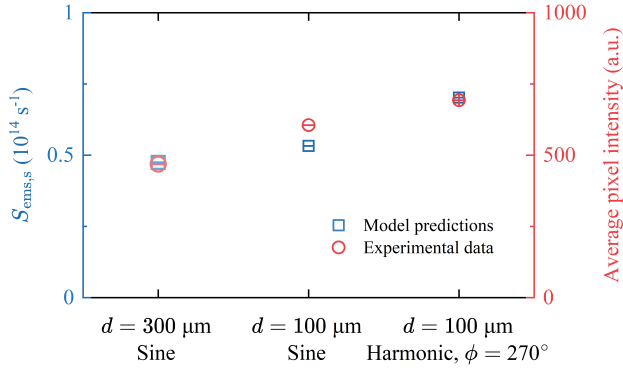


Figure 4.17: Enhancement of emission within the surface layer ($3 \mu\text{m}$ adjacent to the chip surface) predicted by the model and observed experimentally. Blue bars represent the model-predicted total emission rate $S_{\text{ems},s}$; red bars represent the experimentally measured average pixel intensity in the same region.

baseline sinusoidal excitation at the same peak-to-peak voltage.

The experimental and modeling results establish that reducing the gap spacing intensifies ionization and emission near the chip surface through two mechanisms: the enhancement of the electric field within the cathode sheath, and the spatial overlap of sheaths when the gap becomes smaller than twice the sheath thickness. The model successfully reproduces the transition in emission profile morphology observed experimentally and confirms that decreasing the gap below this threshold leads to increased surface emission.

Harmonic excitation, particularly with a phase difference of 270° , further enhances surface emission by amplifying the peak gap voltages and redistributing power deposition asymmetrically within the discharge cycle. This temporal modulation results in sheath thinning and preferential confinement of the plasma on the chip side during the half-cycle when it functions as the cathode. The polarity-dependent spatial selectivity of this enhancement - positive polarity favoring the dielectric surface while negative polarity favoring the powered electrode - provides an additional degree of control for tailoring the emission profile.

The one-dimensional plasma model employed throughout this investigation has proven capable of reproducing the qualitative trends observed experimentally, offering insights into the underlying ionization kinetics, emission characteristics, and sheath dynamics. These findings establish a robust methodology for optimizing atmospheric-pressure microplasmas for UV-POCS applications and provide practical guidance for other technologies requiring localized ionization control, including surface activation, chemical synthesis, and biomedical device fabrication.

5

Validation of the UV-POCS concept

Having established the theoretical framework for plasma-waveguide evanescent coupling (Chapter 2) and developed the experimental system (Chapter 3) together with strategies to enhance surface UV emission (Chapter 4), this chapter aims to validate the UV-POCS concept by detecting the waveguide-coupled output from a micro-gap DBD plasma. The first critical step is to confirm that the detection system can reliably measure picowatt-scale optical signals – the predicted power level from the theoretical model – in the presence of plasma-induced background noise. Following this validation, direct measurements of the plasma-coupled output are attempted. When these measurements fail to produce a detectable signal, the cause is traced to contamination. The nature of the contamination, its sources, and the efforts to mitigate it are examined in detail. Finally, two long-term solutions are proposed to eliminate contamination and enable future successful demonstration of the UV-POCS device.

5.1 Validation of detection capability for picowatt-scale optical power

Before proceeding to the measurement of the device output, it is critical to validate the detection limitation of the experimental system. As previously predicted with the theoretical model (Chapter 2), the output power is expected to be on the picowatt scale. To guarantee a successful detection of the chip output, the signal-to-noise-ratio (SNR) becomes critical. Section 3.2 has introduced a series of works regarding the design of the chip and detection system in an effort to reach a higher SNR. In this subsection, the established system will be tested with the input laser with proper attenuation to simulate the plasma-coupled light output. Specifically, the 405 nm laser used for optical alignment will be coupled into the waveguide. Since their wavelengths are close to each other (405 nm and 391.4 nm), with attenuation, the light output from this laser-pumped waveguide should resemble that from the plasma-waveguide coupling.

The attenuation is achieved with a set of neutral density (ND) filters placed before the ICCD camera. The attenuation factor of the ND filters is described by the optical density (OD), i.e., how much it reduces the optical power of an incident beam. OD is related to the transmission T with $T = 10^{-OD}$. To reach the picowatt level, OD4, OD2, and OD1 filters optimized in a spectral range of 350-700 nm are used in the test. The transmission of each ND filter is measured with a Shimadzu UVmini-1240 spectrophotometer. At the laser wavelength (405 nm), the OD4 filter yields a transmission of 4.07×10^{-4} , whereas OD2 gives 2.64×10^{-3} and OD1 gives 6.53×10^{-2} . The final output is first measured with a Thorlabs S140C photodiode power sensor to obtain an exact number for the output power, and it is then captured by the ICCD camera. A 100 μm pinhole is introduced in place of the iris diaphragm to block the surrounding rings of the Airy pattern, allowing an ideal single spot to be visible on the ICCD images. The resulting images are shown in Fig. 5.1. With the combined usage of OD4 and OD1 filters, the output is attenuated to 9.57 pW. At this power level, the spot is easily visible with a moderate gain factor (50). With OD4 and OD2 filters, the output is further reduced to 0.39 pW. To acquire a clear visible spot structure in this situation, the stack of multiple images has proven to be necessary, even with the maximum gain factor (64).

However, it is not a good option to stack too many images without a good SNR, as the background noise, mainly from the plasma free-space emission, will also accumulate. With the simulated output using the laser pump verified, the next step is to add the plasma noise and assess the systematic SNR. It needs to be pointed out that triggering the discharge with the input laser on will cause the plasma to expand more, and the camera will measure a higher level of background noise. This is due to the fact that the laser photons can assist in the ionization and excitation processes and contribute to the onset of the discharge. It is similar to the laser-produced

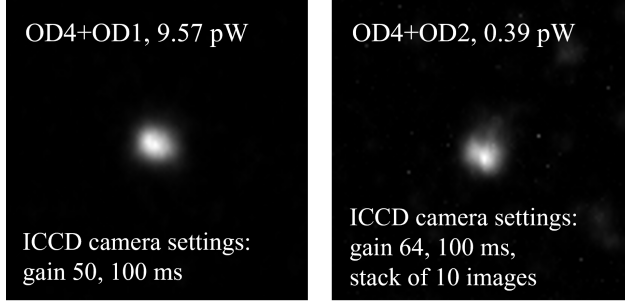


Figure 5.1: ICCD images of the laser-pumped chip output under two sets of ND filters. Left: a combination of OD4 and OD1 which yields 9.57 pW output. Right: OD4 and OD2, 0.39 pW.

plasma (LPP), except that here the laser is just assisting instead of sustaining the discharge. To avoid this issue, the plasma-induced noise is measured in separate tests under the same optical configuration (only the pinhole is switched back to the adjustable iris diaphragm). The results are compared in Fig. 5.2. It is found that using a stack of 5 images can enhance the SNR compared to a single image, as the randomly distributed noise being averaged. Considering that the expected plasma-coupled light output is less stable than the simulated signal from the laser, the SNR will be overpredicted, especially with a high stack number. In conclusion, a stack number of 5 is chosen for the subsequent experiments.

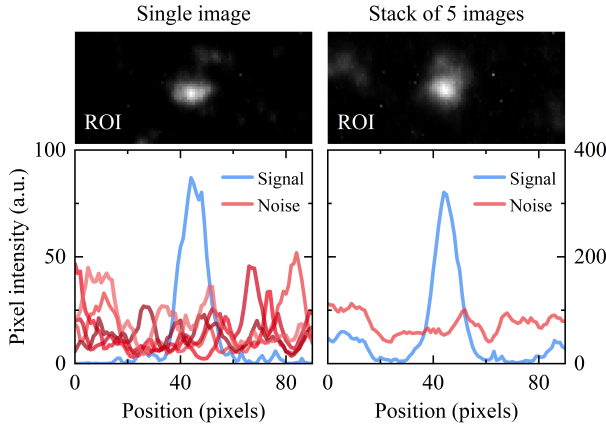


Figure 5.2: Comparison of the simulated SNR of a single image or a stack of 5 images, shown in two columns. The region of interest (ROI) is illustrated on top of the intensity profile for each case. In the single image case the simulated laser signal is compared with 5 measurements of the plasma free-space noise, whereas the 5-image-stack case the noise is the sum of 5 measurements.

5.2 Validation on device output

Despite the proven detection capability, direct measurement of the plasma-coupled waveguide output was not achieved. This section demonstrates that this limitation does not invalidate the plasma-waveguide evanescent coupling principle — which remains theoretically sound — but instead stems from unavoidable contamination introduced by the DBD environment.

5.2.1 Sample failure due to contamination

As previously introduced in Chapter 2, contamination during DBD operation has been a dominant obstacle in the development of the UV-POCS experimental system. The contamination is traced to copper from the material of the high-voltage electrode and carbon-based components from either the experimental setup or airborne dust from the environment. Copper contamination is induced via ion sputtering on the electrode surface and can be simply addressed by switching the electrode material to pure tungsten, which has a high threshold energy for sputtering. Carbon-based contamination, on the other hand, comes from a much greater variety of sources distributed over a wider spatial span, and is therefore more difficult to eliminate. During DBD operation, dust particles in the vicinity become electrically charged and are drawn toward the discharge center by the strong electric field, which is located directly above the coupling spiral waveguide. Once trapped in the plasma, the dust is subjected to ion and electron bombardment, UV radiation, and reactive oxygen species from the helium-air mixture. This leads to heating and combustion of the organic matter, leaving behind carbonized residues that adhere firmly to the chip surface. Similar dust attraction issue is also a known practical nuisance that appears in the plasma processing field, which also involves high-voltage discharge [111, 112]. Fig. 5.3 illustrates three cases in which the tested samples are contaminated by dust of different sizes. The samples are observed to be contaminated by a variety of dust types, including common airborne fibrous dust, large dust particles from the setup ($\sim 20\ \mu\text{m}$ diameter), and small particles of a few micrometers that are invisible to the naked eye.

The presence of dust on the waveguide will scatter the propagating light away; therefore, it will make it impossible to detect any output from the plasma-waveguide coupling. During the experiment, the optical alignment needs to be constantly checked to ensure the waveguide is still functional, and this is done by validating the laser-pumped output to the ICCD camera. In the contaminated case, the signal intensity from the waveguide mode should drop drastically to almost zero. Direct evidence of the contamination-induced scattering can be visualized from the top view of the spiral. Fig. 5.4 compares the scattered light from the spiral coupling waveguide before and after the DBD test. With contamination on chip the waveguide becomes lossy, and most of the light has been scattered out in the spiral region.

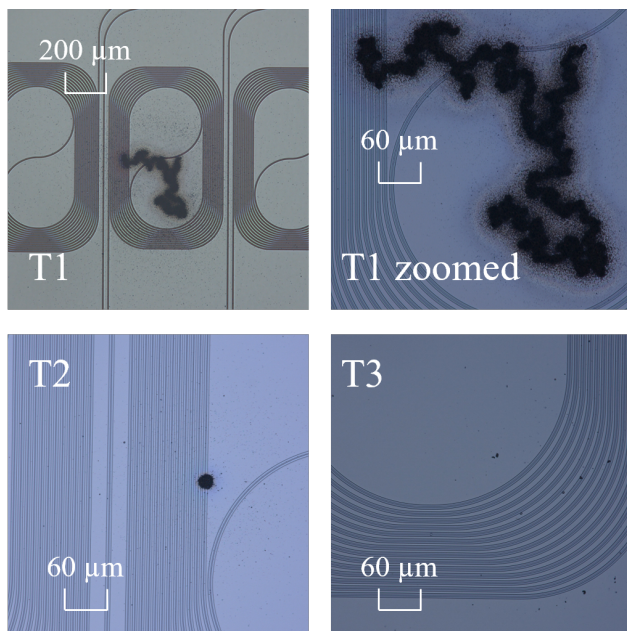


Figure 5.3: Chip contamination after three separate tests. Top left: large fibrous dust burnt dry on the coupling spiral. Top right: zoomed view of top left. Bottom left: dust particle with a diameter of about 20 μm . Bottom right: small particles of a few micrometers.

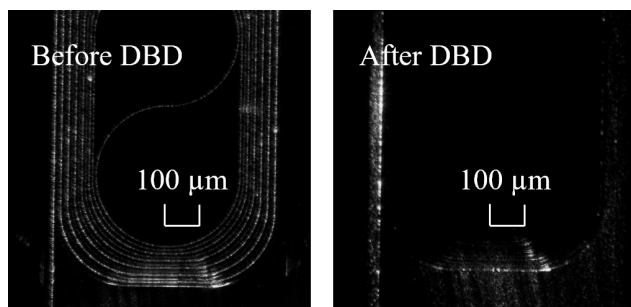


Figure 5.4: Waveguide failure due to strong scattering induced by contamination during DBD operation.

There are limited ways of performing effective cleaning on the contaminated samples. Wet cleaning with acetone has been proven ineffective for the carbonized residues. Ultrasonic acetone bath can help with the situation by physically loosening their attachment to the chip surface, but it can break the fragile waveguide as well. Immersion in piranha solution is an established approach to cleaning silicon wafers, but it will react with AlOx and damage the waveguide structure. Dry etching, specifically oxygen plasma cleaning, has been observed to remove a small fraction of the residues after long-period etching (hours in total), but it is inefficient at completely removing them.

5.2.2 Attempts at mitigating contamination

Having contamination as the dominant obstacle, efforts have been made to explore effective measures to reduce its effect on the experiment. The first approach is to improve the flow of helium gas. In Chapter 4 a baseline condition has been established at 4 SLM helium flow, delivered by a 4 mm diameter nozzle positioned about 3 cm away from the discharge gap. To minimize the spatial span of turbulent flow, which blows and carries dust, the nozzle is placed closer to the discharge gap (~ 1.5 cm), and the flow rate is correspondingly reduced to 2 SLM. The nozzle diameter is reduced to 2 mm to compensate for the drop in inlet velocity with the reduced flow rate. Together with CFD simulation validation, the helium flow is confirmed to be more localized, while the helium gas concentration remains in the same level.

Another effective way to reduce the amount of dust in the vicinity of the setup is chamber flushing, which is pumping the chamber while having gas flow in at the same time. By using a high flow rate of nitrogen or leaving the gas inlet open for ambient air, the strong gas flow inside the chamber can serve to ventilate the loose dust towards the pump. However, this approach cannot guarantee complete removal of the dust, and since the experiment is conducted in atmospheric air with the chamber open, the airborne dust can still contribute to the contamination. After months of testing samples and improving the cleaning procedures, the waveguide failure during DBD is still inevitable.

Given the circumstances, the introduction of an electrostatic precipitator (ESP) was proposed as the last resort. An electrostatic precipitator cleans the gas by using a high-voltage corona discharge to electrically charge dust particles, which are then pushed by the electric field onto the collection plates [113, 114]. In order to perform in-situ cleaning of the setup (having the chip in an aligned, ready-for-experiment state), a simple needle-to-plate negative corona discharge structure was designed, as shown in Fig. 5.5. This ESP can be mounted above the UV-POCS setup and removed before the experiment. A 30 kV DC power supply is used to power the device. To avoid arcing, the electrical connections of the DBD setup through the

chamber need to be removed during ESP cleaning. Due to the fact that atmospheric corona discharge creates ozone as an unwanted byproduct, the duration of ESP cleaning needs to be limited to avoid a high ozone concentration around the DBD setup. In a test, 5 min of ESP cleaning is used. Despite the contamination being lowered and only small dust present on the chip (Fig. 5.3, from T2 to T3), the waveguide still becomes dysfunctional.

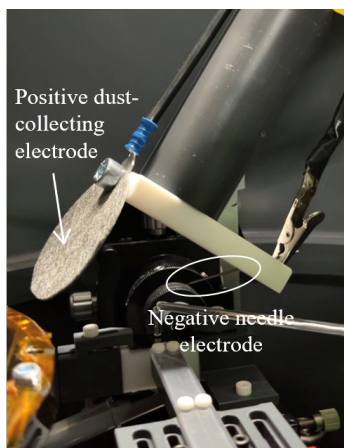


Figure 5.5: The electrostatic precipitator (ESP) used for dust removal. It is in principle a needle-to-plate negative corona discharge.

5.2.3 Why evanescent coupling remains plausible

Despite the fact that direct experimental evidence of plasma-waveguide coupling has not yet been obtained due to contamination, the underlying physical principle of dipole-waveguide evanescent coupling is well established in other fields. A particularly relevant analogy is waveguide-enhanced Raman spectroscopy (WERS). In WERS, analyte molecules are placed in the cladding of a high-index-contrast waveguide. The evanescent tail of the guided mode excites molecular vibrations, and the resulting Raman dipoles (incoherent, isotropic emitters) couple back into the waveguide mode. The coupling efficiency for such dipoles has been both theoretically derived and experimentally verified using the same analytical formalism presented in Chapter 2 Subsection 2.3.1, with effective areas A_{eff} and coupling efficiencies that match predictions within experimental uncertainty [12].

The only difference between a Raman dipole and a plasma dipole is the origin of the excitation and the emission wavelength. In both cases, the emitter is a randomly oriented electric dipole located in the near field of the waveguide. The evanescent coupling process is governed solely by the dipole's position, orientation, and wavelength, not by whether the dipole is excited optically or collisionally.

Consequently, the coupling efficiency η_c derived in Chapter 2 applies equally to $N_2^+(B)$ dipoles ($B^2\Sigma_u^+$) emitting at 391.4 nm. Since WERS has been successfully demonstrated at visible and UV wavelengths with signal levels far below the picowatt range, the predicted picowatt-scale output from the plasma is well within the reach of the same coupling mechanism [10, 11].

Thus, the absence of a measurable signal in the present work is not due to a failure of evanescent coupling – the principle remains plausible and has been validated in different fields – but rather due to the technological limitation of contamination control. Once the contamination issue is addressed, the coupling should become observable.

5.3 Possible solutions for contamination control

There are two promising strategies proposed to eliminate or isolate contamination sources in the UV-POCS experimental system. The first approach mitigates external dust by relocating the entire setup to a cleanroom environment. The second, a more radical approach, eliminates both dust and polymer sources by encapsulating the plasma directly on the chip, isolating it from the external surroundings altogether.

Transfer to a cleanroom environment Moving the entire DBD setup into a dedicated cleanroom (ISO 5 or better) would drastically reduce airborne particles. However, the existing chamber, gas lines, and electrical feedthroughs must be redesigned to avoid introducing new contaminants (e.g., outgassing from polymers). A cleanroom-compatible high-voltage probe and a sealed gas circulation system are essential. This approach would retain the established electrode-gap geometry and optical detection system, but at the cost of a complete system rebuild.

On-chip gas encapsulation A more radical solution is to confine the gas discharge within a microcavity directly fabricated on the chip, using a dielectric lid (e.g., glass or SiN membrane) that seals the helium-air mixture. This is already a well-established approach applied in the micro-electro-mechanical systems (MEMS) field [49, 81, 115]. This encapsulated microplasma approach would physically isolate the plasma from the external environment and thus prevent dust attraction. The lid will act as an integrated dielectric barrier with the electrode patterned on top. The contactless electrode design simplifies the material requirements, allowing for the use of a standard semiconductor-compatible metal deposition approach, such as plasma-enhanced chemical vapor deposition (PECVD) of gold. The established work in Chapter 4 on the effect of gap spacing proves — confirmed by both experimental and simulation results — that a cavity height of 20–100 μm still permits stable DBD operation while enhancing the plasma emission rate within the evanescent coupling zone.

5.4 Conclusion

This chapter has validated that the experimental detection system can reliably measure picowatt-scale optical signals, even in the presence of plasma-induced background noise. Using calibrated neutral density filters, the ICCD camera successfully captured waveguide-coupled laser light attenuated to 0.39 pW, and a stack of five images was determined to provide an optimal signal-to-noise ratio for subsequent experiments.

Direct measurement of plasma-coupled waveguide output was not achieved. The primary obstacle was identified as carbon-based contamination originating from polymer-containing components in the setup and from airborne dust attracted to the discharge center. Once deposited on the waveguide, these carbonized residues strongly scatter guided light, leading to a dramatic increase in propagation loss and, in most cases, complete loss of waveguide functionality. Copper contamination from the high-voltage electrode was also observed, but this can be eliminated by switching to pure tungsten.

Several measures to mitigate contamination were explored: localized helium flow, chamber flushing, and an electrostatic precipitator. While these efforts reduced the deposition rate, they could not prevent eventual waveguide failure. Wet cleaning with acetone was ineffective, ultrasonic baths risked damaging the fragile waveguides, and oxygen plasma cleaning removed only a fraction of the residues after many hours.

Despite the lack of direct experimental evidence, the underlying principle of evanescent coupling remains physically sound. The same theoretical formalism has been experimentally validated in waveguide-enhanced Raman spectroscopy (WERS), where weak, incoherent dipoles couple efficiently into guided modes. The plasma dipoles ($N_2^+(B)$ at 391.4 nm) are analogous to Raman dipoles; only the excitation mechanism differs. Therefore, the absence of a measurable signal is a technological limitation – contamination – not a fundamental refutation of the concept.

Two long-term solutions have been proposed. The first is to relocate the entire DBD setup into a cleanroom (ISO 5 or better) with redesigned, low-outgassing components. The second, more radical approach is to encapsulate the plasma directly on the chip within a micro-cavity sealed by a dielectric lid, which would isolate the discharge from external dust and eliminate the need for polymer-containing parts. Preliminary simulations indicate that a cavity height of 20–100 μm still permits stable DBD operation while keeping the plasma within the evanescent coupling zone. With these improvements, the UV-POCS device is expected to achieve its first successful experimental demonstration of evanescent plasma-waveguide coupling.

6

Conclusion and Perspectives

6.1 Conclusion

This thesis developed, optimized, and characterized an on-chip microplasma UV source based on evanescent coupling between a micro-gap dielectric barrier discharge (DBD) and a UV-transparent photonic integrated circuit (PIC). The work addressed a critical bottleneck in integrated UV photonics: the lack of compact, efficient, and integrable UV emitters. A fundamental challenge is that in the plasma sheath adjacent to the chip surface, electron density is intrinsically low, making conventional electron-impact excitation inefficient. To overcome this, a key novelty of this work is the use of a helium-air mixture, where heavy-particle reactions – specifically Penning ionization and charge exchange – generate excited emitters directly within the sheath, drastically increasing the emission rate at the chip surface and making the UV-POCS concept feasible. A theoretical framework was established by combining a 1D transient plasma model that captures these reaction pathways with a dipole-waveguide coupling model, linking plasma emission kinetics to the power coupled into a single-mode waveguide. The model predicts an output power on the order of 2.9–11.5 pW for the experimental configuration.

To put this figure in context, the total UV power available from the plasma is estimated at 1–3 mW based on energy flux measurements from similar surface barrier discharges [116]. Combining this with the predicted coupled power of 2.9–11.5 pW yields a plasma-to-waveguide efficiency on the order of 10^{-9} to 10^{-8} . This extremely low efficiency is not a failure of the evanescent coupling

principle, but a direct consequence of the geometry: the evanescent coupling depth (~ 100 nm) is three orders of magnitude smaller than the plasma sheath thickness (~ 50 μ m), with additional reductions from collisional quenching ($\kappa \approx 23.8$) and low dipole-to-mode overlap. These results underline the need for engineering solutions—slow-light or slot waveguides to extend the evanescent field, and encapsulated SBD designs (Subsection 6.2.2) to reduce voltage, plasma dimension, and loss.

The experimental system was developed through a lengthy, iterative process that addressed numerous practical challenges. The plasma setup evolved from an initial surface barrier discharge (SBD) in vacuum, which suffered from electrode melting, substrate delamination, and parasitic discharges despite pressure adjustments. A sandwich-like double-dielectric DBD eliminated direct electrode-chip contact but introduced discharge paths that bypassed the gas gap. The final configuration – a one-layer DBD (chip as the dielectric barrier) operating in a helium-air mixture at atmospheric pressure – proved stable and reproducible. The chip stage was redesigned four times, transitioning from brass to 3D-printed plastic, then to PVC, and finally to a Teflon-PVC combination to minimize carbon-based contamination. The high-voltage electrode assembly was similarly refined: PTFE tape insulation was replaced by quartz tubes, and the electrode was optimized from a copper-containing alloy to pure tungsten with an optimized rounded flat tip profile to ensure a stable, diffuse plasma. For the photonic part, the low-loss UV platform based on atomic-layer-deposited AlO_x waveguides on a SiO_2/Si substrate was employed. These waveguides, fabricated using a SiN_x hard mask and chlorine-based ICP etching, provide single-mode propagation with losses of about 3 dB/cm at the UVA wavelength. The integration of this plasma setup with the photonic chip, together with a customized optical detection system and a dedicated alignment procedure, formed the core of the UV-POCS experimental system.

Two complementary strategies were experimentally and numerically investigated to enhance plasma UV emission at the chip surface. Spatial control via reduction of the discharge gap (down to 80 μ m) intensifies the electric field within the cathode sheath. When the gap becomes smaller than twice the sheath thickness, the sheaths overlap spatially. Both mechanisms increase surface emission. Temporal control via harmonic excitation with a phase difference of 270° amplified the peak gap voltages and redistributed power deposition asymmetrically, leading to sheath thinning and preferential confinement of the plasma on the chip side during the half-cycle when it functions as the cathode. The polarity-dependent spatial selectivity (positive polarity favoring the dielectric surface, negative polarity favoring the powered electrode) provides an additional degree of control. When applied in combination, these techniques yielded a 48% enhancement in surface emission relative to baseline sinusoidal excitation.

The detection system was validated to reliably measure picowatt-scale opti-

cal signals, even in the presence of plasma-induced background noise. Using calibrated neutral density filters, the ICCD camera successfully detected attenuated laser-pumped output down to 0.39 pW. However, direct measurement of plasma-coupled waveguide output was not achieved. The primary obstacle was identified as carbon-based contamination from polymer-containing components and airborne dust attracted to the discharge center. Once deposited on the waveguide, the carbonized residues strongly scattered guided light, leading to loss of waveguide functionality. Several mitigation measures (localized helium flow, chamber flushing, electrostatic precipitator) reduced but did not eliminate contamination. The underlying evanescent coupling principle remains sound; it has been validated in analogous systems such as waveguide-enhanced Raman spectroscopy. Two long-term solutions were proposed: relocation to a cleanroom environment and on-chip gas encapsulation in a microcavity sealed by a dielectric lid. Preliminary simulations indicate that a cavity height of 20–100 μm supports stable DBD operation while keeping the plasma within the evanescent coupling zone.

Thus, this thesis provides a comprehensive methodology for realizing high-performance, integrated UV plasma-on-chip sources. The theoretical framework, experimental system, and enhancement strategies lay the foundation for a fully functional UV-POCS device, addressing a key bottleneck in lab-on-a-chip biosensing and bioimaging.

6.2 Perspectives

6.2.1 Microplasma as light source

The microplasma concept demonstrated in this thesis is not confined to the UVA range. The helium–air DBD’s intense emission at 391.4 nm from the N_2^+ first negative system ($B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$), driven by efficient He metastable Penning ionization and He- N_2 charge exchange, exemplifies the spectral selectivity accessible in microscale discharges. By substituting the Penning gas mixture with excimer-forming compositions (e.g., Xe, Kr, Ar/ F_2), the output can be shifted across the UVB, UVC, and VUV regions, providing narrow-band sources at predetermined wavelengths. Electrode geometries, such as microcavity plasma devices and micro-hollow cathode discharges, further lower the voltage requirement and raise power density while remaining compatible with standard microfabrication processes. Direct monolithic or hybrid integration of these plasma cells with UV photonic integrated circuits would eliminate external optics and yield compact, electrically driven, multi-wavelength on-chip light sources for fluorescence excitation, photochemical synthesis, and quantum-state control, establishing a scalable pathway to chip-scale ultraviolet photonic systems.

6.2.2 Surface barrier discharge as on-chip plasma light source

Surface barrier discharge (SBD) – where both electrodes are placed on the same side of a dielectric layer – offers an even more compact geometry for on-chip plasma generation. Unlike the earlier SBD attempt described in Chapter 4, the present approach covers the electrodes with a dielectric layer to prevent arcing. The plasma propagates along the surface, potentially providing a sheet-like emitter directly above the waveguide core. In the SBD setup, the voltage requirement is greatly lowered (from several kilovolts to several hundred volts), as the AC field doesn't have to pass through the chip. SBD would also eliminate the need for a separate high-voltage electrode tip and simplify alignment. Combining SBD with the encapsulated microcavity approach could yield a fully planar, lithographically defined plasma source integrated directly with the PIC, as illustrated in Fig. 6.1. Further research into electrode design, dielectric materials, and power supply schemes is required to stabilize SBD at atmospheric pressure and maximize UV emission within the evanescent coupling zone.

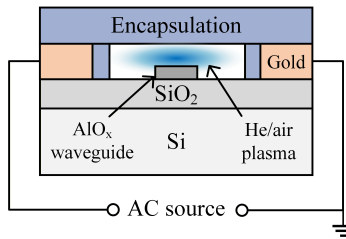


Figure 6.1: The schematic of UV-POCS with encapsulated SBD structure.

6.2.3 Miniaturized gas laser

The core of this thesis is the evanescent coupling of spontaneous UV emission from a microplasma into a waveguide mode. A logical, far-reaching extension is to exploit that same plasma not only as a photon source but simultaneously as a gain medium, thereby realizing a plasma-driven, self-seeded on-chip laser. In this concept, the plasma evanescently couples its spontaneous emission into the waveguide, providing the seed light. As that light propagates along the waveguide, it passes back through the same microplasma region that is maintained in a state of population inversion; the plasma then amplifies the propagating mode via stimulated emission, acting as a distributed gain section. No external laser pump is required—the plasma is at once the lamp, the gain medium, and, when embedded in a cavity, the active element of the oscillator.

To assess the feasibility of such a device, it is instructive to first examine the gain levels achievable in gas-phase UV media. Rare-gas-halide (RGH) excimer

lasers represent the most extensively studied class of gas-phase UV gain media. Small-signal gain coefficients in these systems typically range from 0.01 to 0.3 cm^{-1} depending on the specific gas mixture, pump scheme, and operating pressure. For example, KrF (248 nm) and XeCl (308 nm) lasers have reported gain coefficients of 0.02–0.22 cm^{-1} and 0.07–0.3 cm^{-1} , respectively, while ArF (193 nm) systems typically achieve 0.15–0.17 cm^{-1} under discharge pumping [117–119]. These values confirm the feasibility of substantial optical gain in UV gas discharges. However, conventional RGH lasers rely on high-voltage pulsed excitation, corrosive halogen gases (F_2 , Cl_2 , HCl), and macroscopic gas chambers, making them fundamentally incompatible with PIC integration. Alternative gas mixtures that offer gain potential with improved compatibility for on-chip integration include the He/Xe/ I_2 system. In this mixture, glow and capacitive discharges pump several UV-emitting species, including the atomic iodine resonant line at 206 nm, the XeI^+ excimer band at 253 nm, and the $\text{I}_2(\text{B-X})$ molecular band around 342 nm [120–122]. The emission spectrum can be tailored by adjusting the gas pressure and mixture composition [121]. For example, in a He/Xe/ I_2 glow discharge at $P(\text{He})/P(\text{Xe}) = 400/120$ Pa, the spectral distribution was found to be $\text{I}(206 \text{ nm})/\text{I}(253 \text{ nm})/\text{I}(342 \text{ nm}) = 54/9/37\%$ [120]. These discharges can be efficient, with reported UV powers of 5–7 W and efficiencies of 5%–12% depending on the discharge type and operating conditions [120, 121]. The XeI^+ excimer formation proceeds through ion-ion recombination and harpoon reactions, leading to population inversion on the $\text{B}_{1/2} \rightarrow \text{X}_{1/2}$ transition at 253 nm [122]. While specific small-signal gain coefficients for the He/Xe/ I_2 system are not explicitly reported in the literature, the demonstrated efficiencies and narrow-band emission suggest that gain coefficients comparable to the lower end of the RGH range (0.01–0.05 cm^{-1}) are plausible. Importantly, iodine is significantly less corrosive than chlorine or fluorine, and sealed-off operation with lifetimes exceeding 1000 hours has been demonstrated [121]. These properties, combined with compatibility with dielectric barrier or capacitive discharge geometries, make He/Xe/ I_2 and related gas mixtures promising candidates for future chip-scale plasma-based UV lasers.

With this gain landscape in mind, the photon budget for a plasma-driven on-chip laser can now be assessed. To close the round-trip gain (gain exceeding total losses), three missing pieces must converge. First, a high-gain plasma medium must be engineered to reach the levels discussed above—the microplasma’s high electron density (10^{18} – 10^{21} m^{-3}) and strong thermal non-equilibrium ($T_e \gg T_g$) can, in principle, provide intense pumping of an upper laser level while suppressing collisional quenching and Doppler broadening, but the small-signal gain per unit length must be pushed to levels sufficient to compensate for realistic waveguide losses. Second, low-loss UV waveguides are essential. With a typical propagation loss of 3 dB/cm of AlO_x waveguide in the UVA range, corresponding to an attenuation coefficient of approximately 0.69 cm^{-1} , the present waveguide loss is already an

order of magnitude larger than the upper end of the RGH gain range. To make the plasma-on-chip laser concept viable, the waveguide loss must be reduced to the sub-0.1 cm⁻¹ level, equivalent to less than 0.5 dB/cm, so that plasma gain can dominate. Third, for the evanescent coupling architecture demonstrated in this thesis, high mode overlap between the plasma gain volume and the waveguide mode is critical—only the evanescent tail of the modal field overlaps with the plasma, and the effective gain coefficient scales with this confinement factor. Engineering the waveguide core to be more exposed to the microplasma is therefore key.

Integrating a distributed plasma gain–seed structure, a low-loss waveguide (with loss well below 0.5 dB/cm), and an optical cavity (e.g., distributed Bragg reflectors or high- Q micro-ring resonators) on the same chip would yield a coherent, narrow-linewidth UV source with brightness far exceeding that of an LED or spontaneous microplasma, while remaining chip-scale. Recent advances in low-loss UV waveguide fabrication [62, 123, 124] and high- Q resonator design [64, 125, 126] make this self-seeded plasma laser a challenging but scientifically viable long-term objective. Moreover, the 253 nm emission of XeI⁺ falls within the UVC band, where emerging low-loss waveguide platforms such as suspended thermal SiO₂ [1] could provide the necessary optical confinement for evanescent coupling and feedback.

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Effect of dielectric consideration

The consideration of the leakage conductance of the dielectric in the model is crucial in determining the correlation between waveform polarity and the spatial selectivity of the localized discharge enhancement. Fig. A.1 shows the variation in the time-averaged electron density as a result of considering the chip differently (with or without leakage conductance). By neglecting the leakage conductance of the chip (from an RC circuit to an ideal capacitor, fixed impedance magnitude), the plasma can still be pushed towards both sides with the introduction of harmonic wave excitation ($\phi = 270^\circ$). However, the spatial selectivity of the ionization enhancement is suppressed, leaving a symmetrical profile from the time-averaged perspective. This difference can be explained by the temporal distribution of the electric field (Fig. A.2). In the ideally insulated case, the peak gap voltages become symmetric to the x-axis, resulting in identical responses of the ionization source term ($t = 0.3$ and $t = 0.6$). This is consistent with the symmetrical profile of the time-averaged electron density in Fig. A.1. In this sense, it can be concluded that the ideal insulation assumption can lead to a distorted prediction of the discharge enhancement effect when harmonic excitation is applied to DBD plasma.

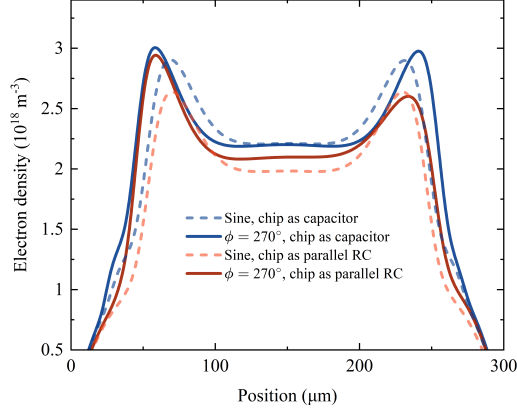


Figure A.1: Comparison of the time-averaged electron density profile under harmonic excitation with $\phi = 270^\circ$ in situations where the chip is considered as a capacitor or as a parallel RC circuit. The results of the sine input cases are also given as a reference. Position 0 denotes the chip surface.

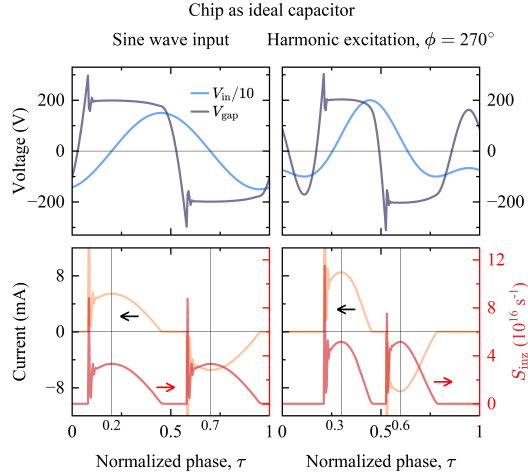


Figure A.2: Phase-resolved model result of gap voltage, total discharge current, and ionization source term S_{inz} in both sine input and harmonic excitation cases when the chip is considered as an ideal capacitor. The scaled input waveforms are given as references. The phases are adjusted for clarity.

B

Calculation of helium mole fraction

The correlation between helium mole fraction and helium flow rate is estimated with CFD simulations using the realizable $k-\varepsilon$ turbulent model. Since the plasma covers a relatively small region with respect to the flow field, the geometry considered in the simulation can be simplified to a 2D axisymmetric structure, namely a jet of helium impinging onto the chip surface in atmospheric air. The results are shown in Fig. B.1.

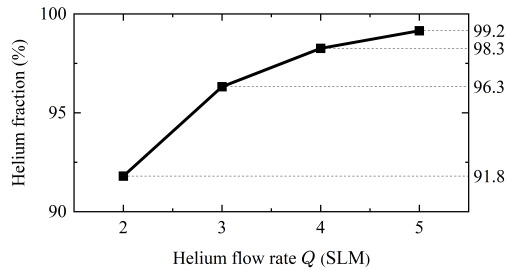


Figure B.1: Helium fraction versus helium flow rate.

