



ON-CHIP INTEGRATED UV MICROPLASMA SOURCES FOR BIOPHOTONIC APPLICATIONS

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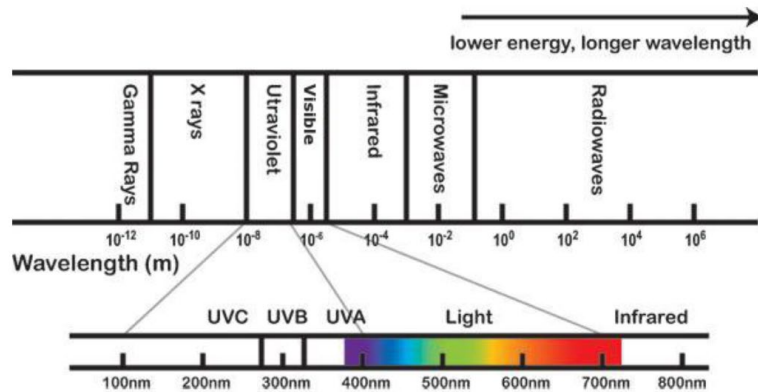
Promoters: Prof. Christophe Leys, Prof. Nicolas Le Thomas, Dr. Anton Nikiforov

INTRODUCTION

UV LIGHT: THE INVISIBLE KEY TO BIOLOGY

What is UV?

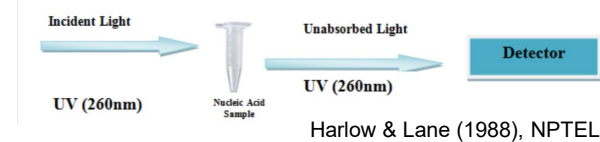
Ultraviolet light (UV) is a type of radiation found naturally in sunlight.



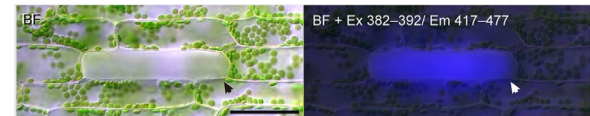
The electromagnetic spectrum. Ultraviolet (UV) can be divided into UVA, UVB, and UVC bands.

Why Biology Cares?

- UV Absorption

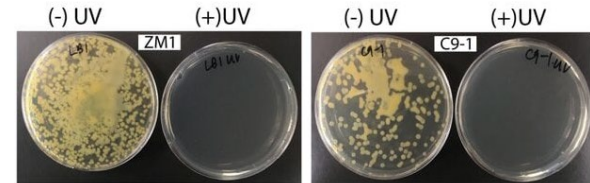


- Autofluorescence



Hara et al. (2015)

- Sterilization



Morella et al. (2019)



THE BOTTLENECK - COMPACT UV SOURCE

UV photonics for biosensing demands a source that is simultaneously compact, integrable, efficient, and wavelength-flexible.

UV SOURCE SOLUTIONS

UV Lamp

High-power broadband
UV source.
Bulky; toxic.



UV LED

Compact, good QE.
Deep-UV QE collapses;
high étendue.



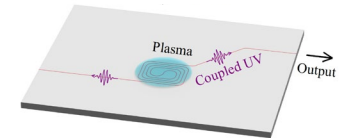
UV Laser

Low étendue, good
beam. Fixed wavelength.
Difficult to integrate.



UV-POCS

Compact, Integrable, and
wavelength-adjustable



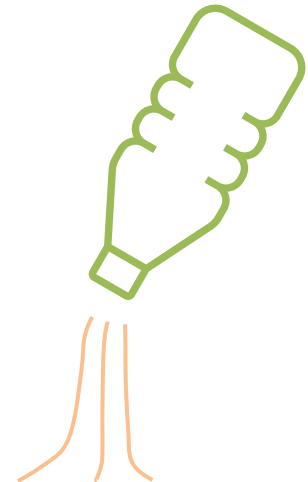
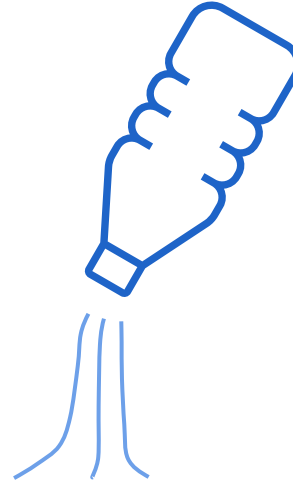
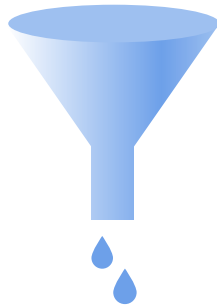
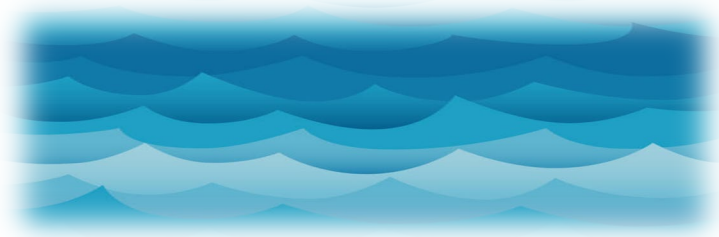
Chip



WHY MAKING A COMPACT UV SOURCE IS HARD?

Etendue mismatch: funnel water from a sea, very inefficient

Wavelength adjustability: different drinks in the bottle, instead of just water

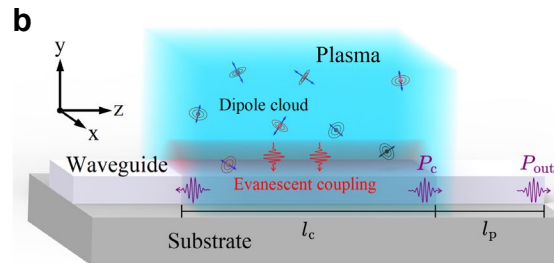
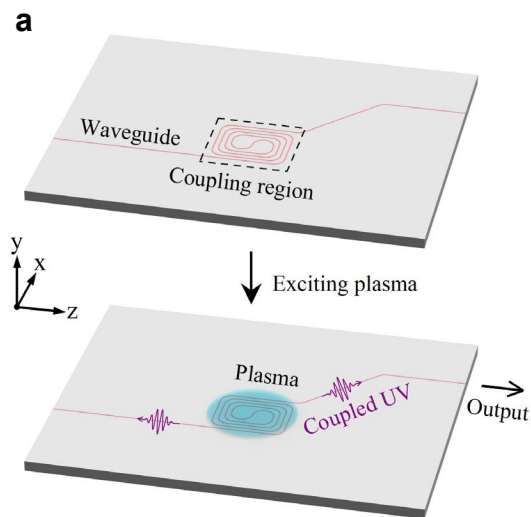


UV-POCS: EVANESCENT CAPTURE OF PLASMA UV

Basic idea: UV-emitting plasma above a spiral AIOx waveguide.

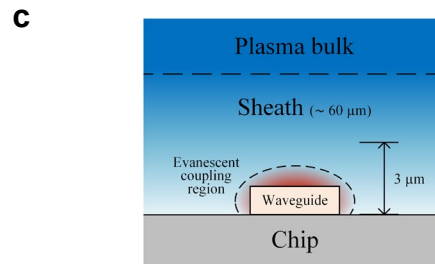
Advantages: wavelength-adjustable (by changing gas); Single-mode output available.

Challenges: low overlap



a: Device schematic.

b: Zoom of plasma-waveguide evanescent coupling.



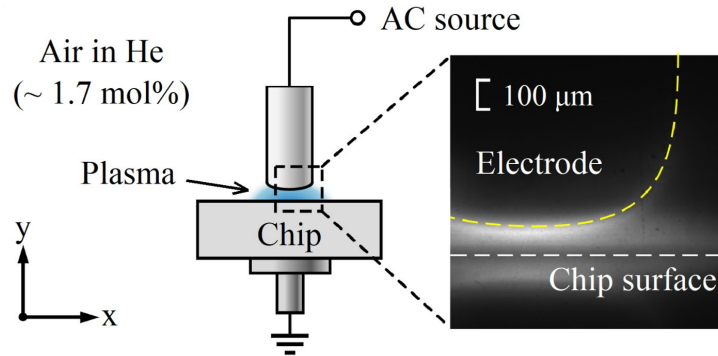
c: Overlap of the evanescent tail with the plasma sheath (penetration depth ~ 100 nm for UV).

THEORETICAL MODELLING

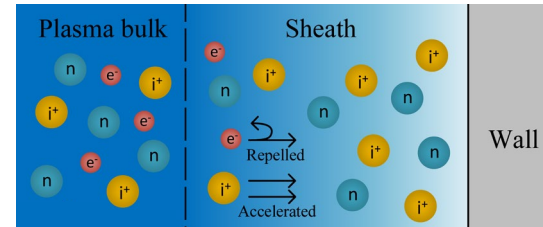
PLASMA MODEL – PLASMA KINETICS AND EMISSION

1D fluid model of dielectric barrier discharge (DBD) to predict plasma emission.

Enhancing surface emission: introducing helium-nitrogen heavy-particle reactions.



Schematic of the on-chip DBD.



The sheath is usually a low-emission zone.

Index	Reaction	Rate constant ^a
Penning ionization and charge exchange		
R15	$\text{He}^* + \text{N}_2 \rightarrow \text{e} + \text{N}_2^+(B) + \text{He}$	5×10^{-17}
R16	$\text{He}_2^* + \text{N}_2 \rightarrow \text{e} + \text{N}_2^+(B) + 2\text{He}$	5×10^{-17}
R17	$\text{He}^+ + \text{N}_2 \rightarrow \text{N}_2^+(B) + \text{He}$	5×10^{-16}
R18	$\text{He}_2^+ + \text{N}_2 \rightarrow \text{N}_2^+(B) + 2\text{He}$	5×10^{-16}

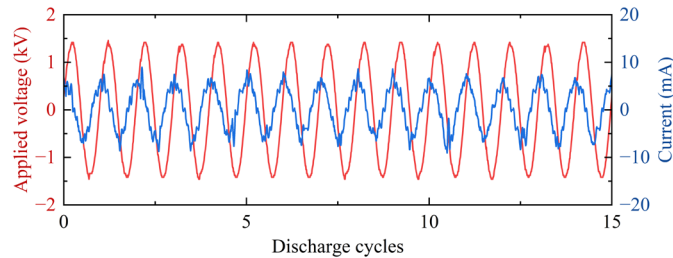
Heavy particle reactions promoting sheath emission at 391.4 nm.



PLASMA MODEL – EXTERNAL INPUT

The dielectric layer (the chip) is considered an RC circuit, where R and C come from experiments.

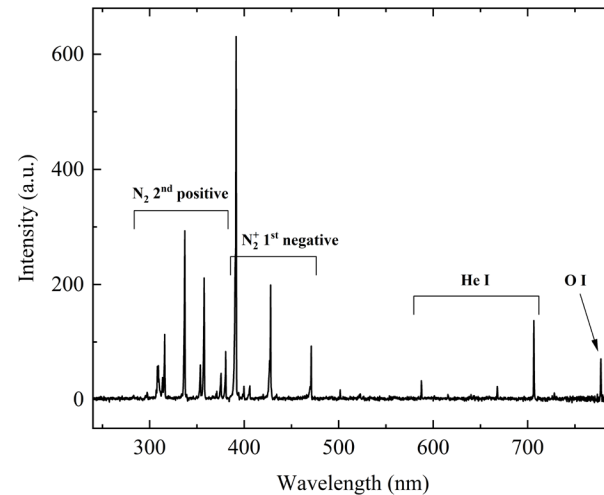
The emission spectrum gives the fraction of the 391.4 nm line to the whole first negative system of N_2^+ .



IV curves are used to calculate the dielectric impedance.

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

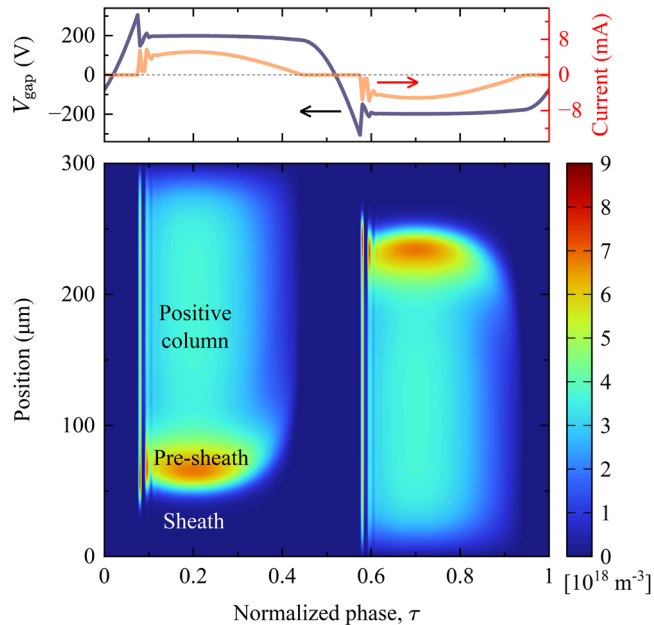
Boundary condition parameters (SEEC, MIE).



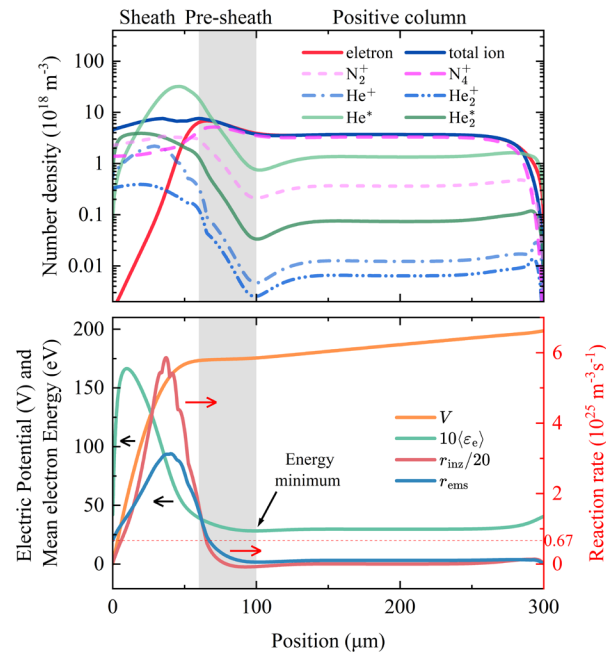
Emission spectrum.

PLASMA MODEL – RESULTS

With the transient population densities, the time-averaged r_{ems} at the 391.4 nm line can be obtained.



Spatiotemporal distribution of electron density at $d = 300 \mu\text{m}$



Transient population density, electric potential, and reaction rates at $\tau = 0.2$

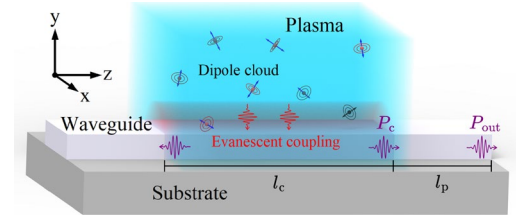
PHOTONICS MODEL – PLASMA-WAVEGUIDE COUPLING

The plasma is treated as a dipole cloud while calculating coupling efficiency η_c .

η_c can be expressed as two spontaneous rates $\eta_c = \gamma_{wg}/\gamma_0$, where

$$\gamma_{wg}(\mathbf{r}_0, \omega) = \frac{\omega}{\hbar v_g} \frac{|\mathbf{d} \cdot \mathbf{E}(\mathbf{r}_0, \omega)|^2}{\iint \epsilon_0 \epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r}, \omega)|^2 d\mathbf{r}} \quad \gamma_0 = \frac{n\omega^3 |\mathbf{d}|^2}{3\pi \hbar \epsilon_0 c^3}$$

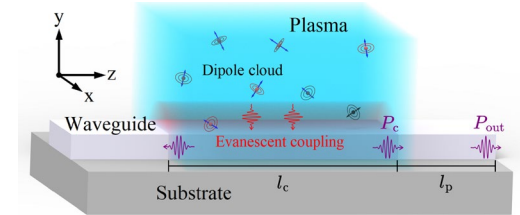
$$\Rightarrow \eta_c(\mathbf{r}_0, \omega) = \frac{\pi \epsilon_0 c^3}{n v_g \omega^2} \frac{|\mathbf{E}(\mathbf{r}_0, \omega)|^2}{\iint \epsilon_0 \epsilon(\mathbf{r}) |\mathbf{E}(\mathbf{r}, \omega)|^2 d\mathbf{r}}$$



PHOTONICS MODEL – PLASMA-WAVEGUIDE COUPLING

To highlight the physical mechanisms involved in the coupling efficiency, it is convenient to introduce an A_{eff} as

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



η_c therefore becomes

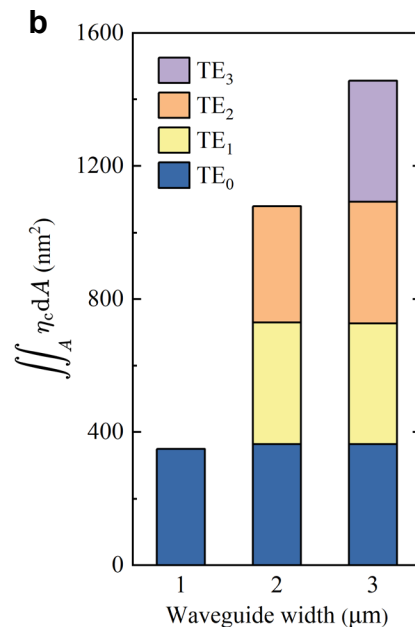
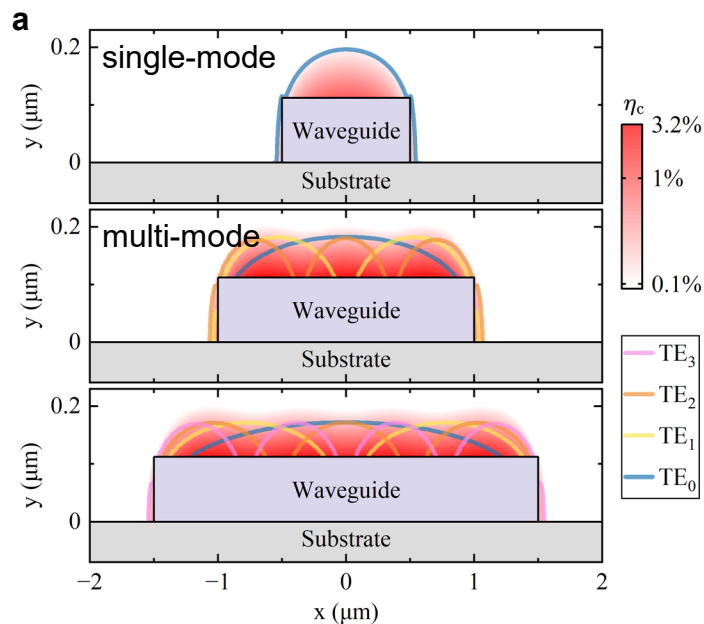
$$\eta_c(\mathbf{r}_0, \omega) = \frac{1}{4\pi} \frac{c\lambda^2}{n^3 v_g A_{\text{eff}}(\mathbf{r}_0, \omega)} = \frac{1}{2} \frac{n_g}{n} \frac{\sigma_{\text{max}}}{A_{\text{eff}}(\mathbf{r}_0, \omega)}$$

Index match Geometry overlap

Here $\sigma_{\text{max}} = (\lambda/n)^2 / (2\pi)$ is the diffraction-limited area of a dipole in the top cladding medium of index n

PHOTONICS MODEL – RESULTS

Computed output power: single-mode (1 μm width) 2.9 pW; multi-mode (3 μm width) 11.5 pW.



a: Contour of effective η_c at the target wavelength 391.4 nm.

b: Contribution of each mode, namely the area integration of η_c .

Under a thin-waveguide approximation, η_c is proportional to the number of supported modes.

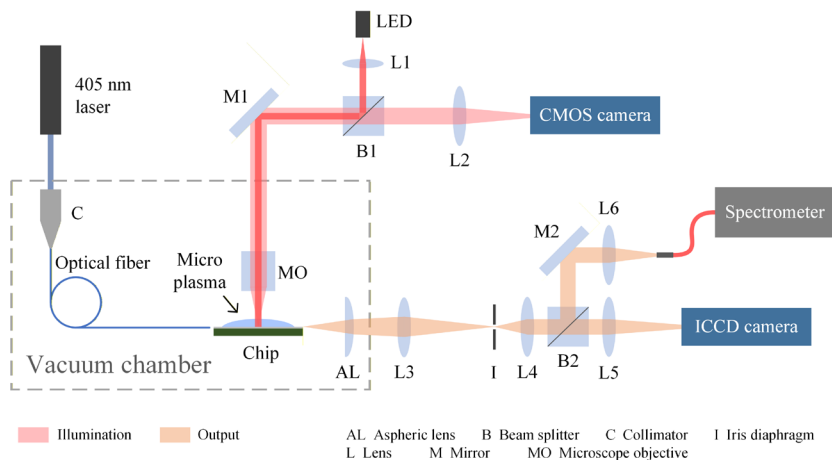
EXPERIMENTAL SYSTEM



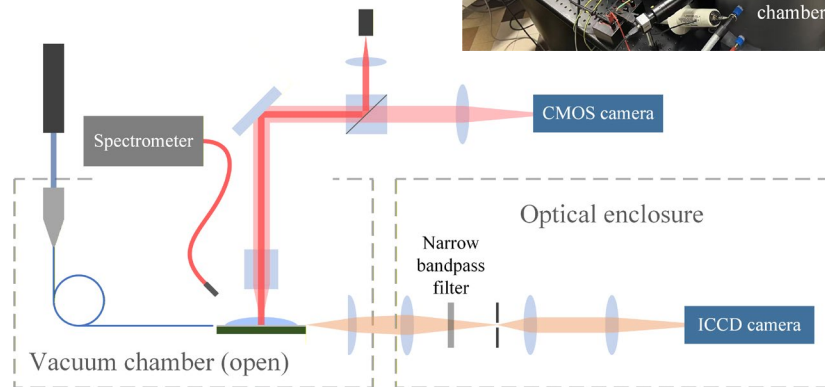
OPTICAL PATH

A 405 nm laser is used to align the optical path.

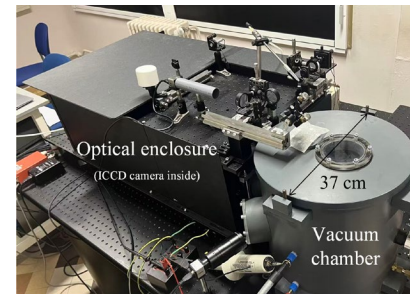
In: fiber edge coupling; Out: free-space coupling via aspherical lens.



Original design. Operated in vacuum.



Final design. Operates at atmospheric pressure. With optical enclosure.

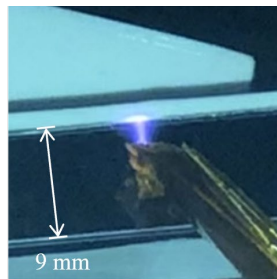
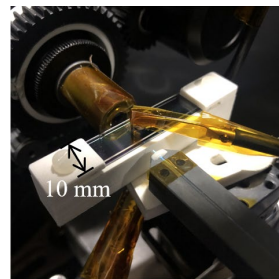
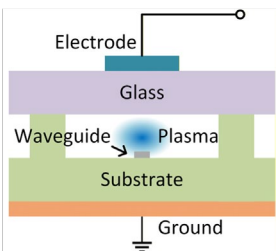
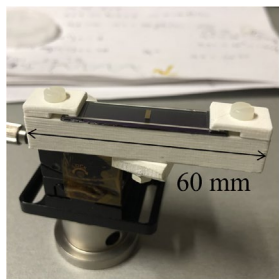
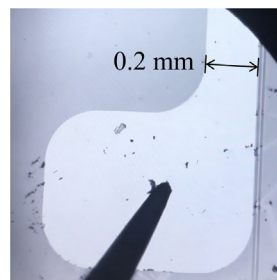
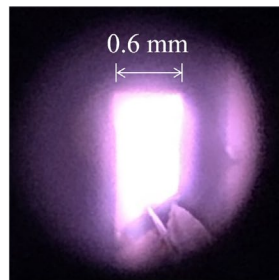
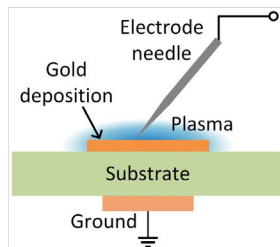
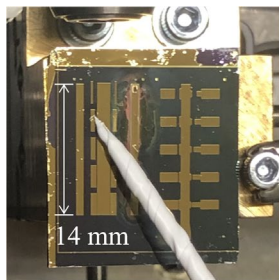
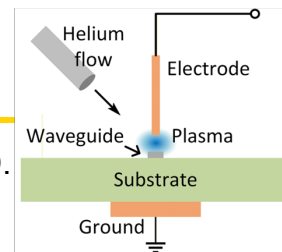


EARLY DESIGNS OF THE DISCHARGE SETUP

The SBD approach (with metal exposed) has the arcing issue;

In the two-layer DBD, plasma tends to form on top of the glass.

Final design, 1L DBD.



Top: SBD setup.
Suffering from arcing.

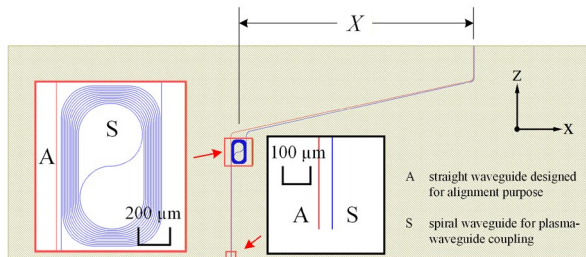
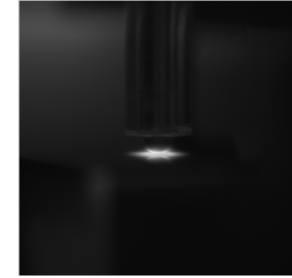
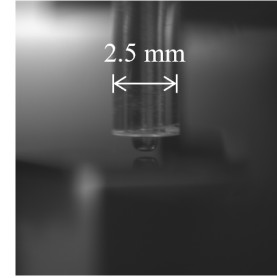
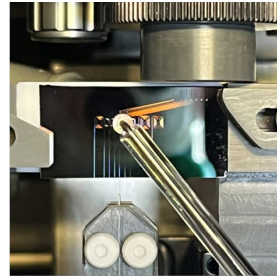
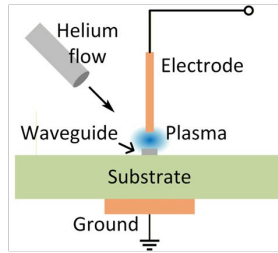
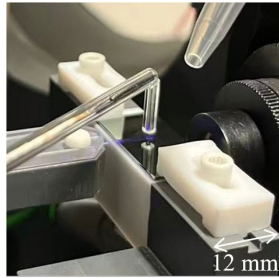
Bottom: 2L DBD.
Discharge leakage.



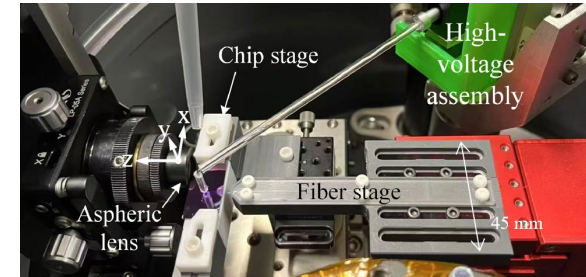
OPTICAL ALIGNMENT

From vacuum to atmospheric pressure, alignment becomes much more easier.

The output facet is shifted away from the discharge center (spiral) in the x-direction to reduce noise.



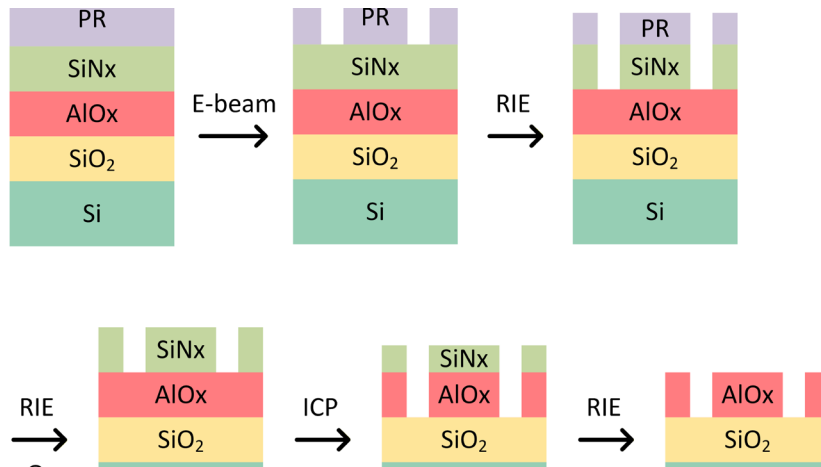
Design of the on-chip DBD setup, emission profile, chip layout design, and the in-and-out optical alignment.



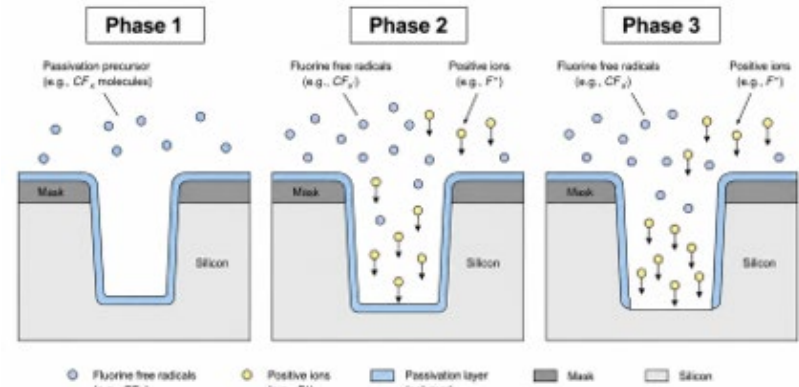
CHIP FABRICATION AND PROCESS IMPROVEMENT

SiNx is used as a hard mask for etching AlOx.

ICP recipe has been improved for smoother sidewalls and less propagation loss.



Original design. Operated in vacuum.



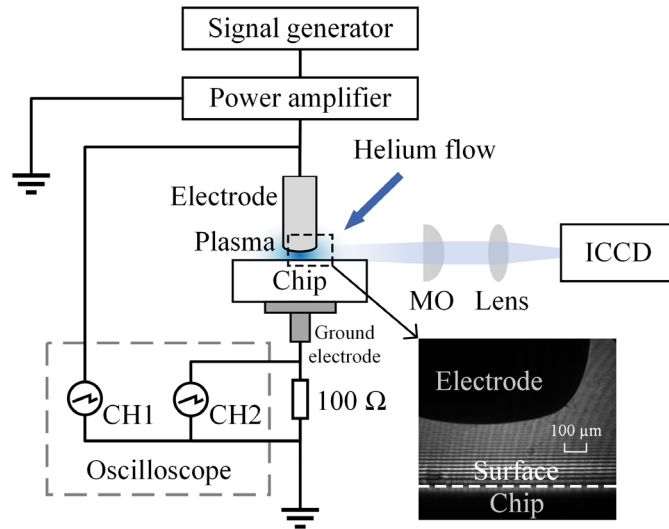
Final design. Operates at atmospheric pressure. With optical enclosure

EMISSION ENHANCEMENT

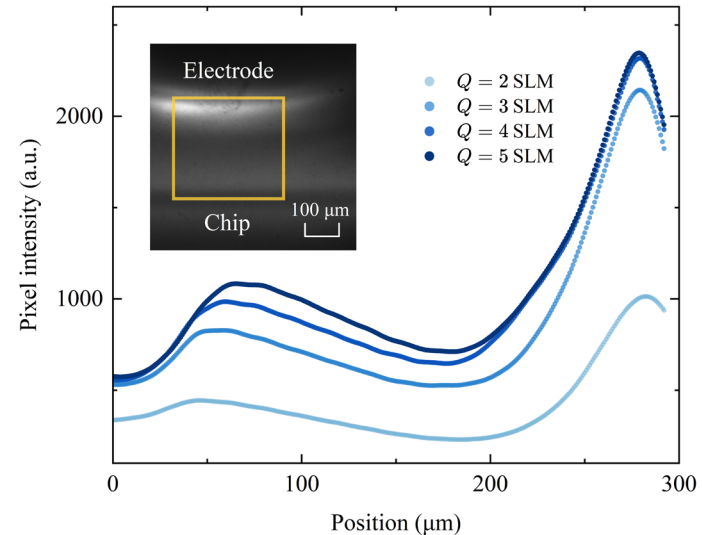
BASELINE OPERATION CONDITION

A baseline condition is established first as a control group.

3 kV ptp, 10 kHz sinusoidal wave, 4 SLM helium flow, 300 μm discharge gap.



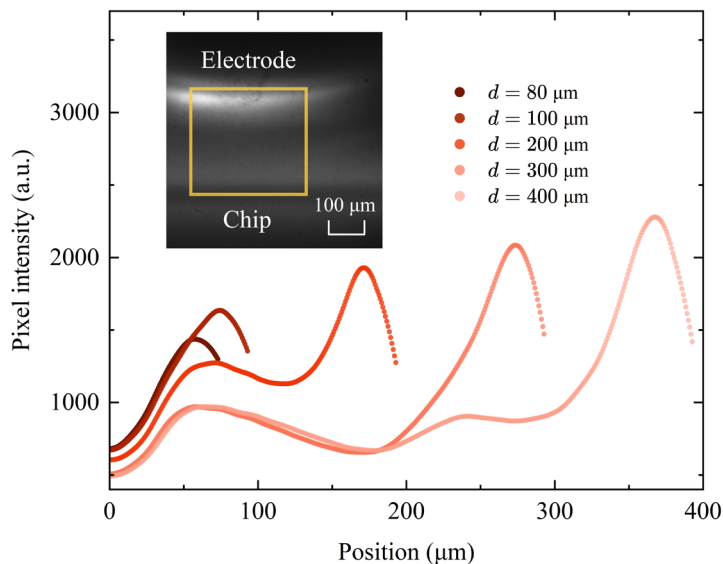
Experimental setup.



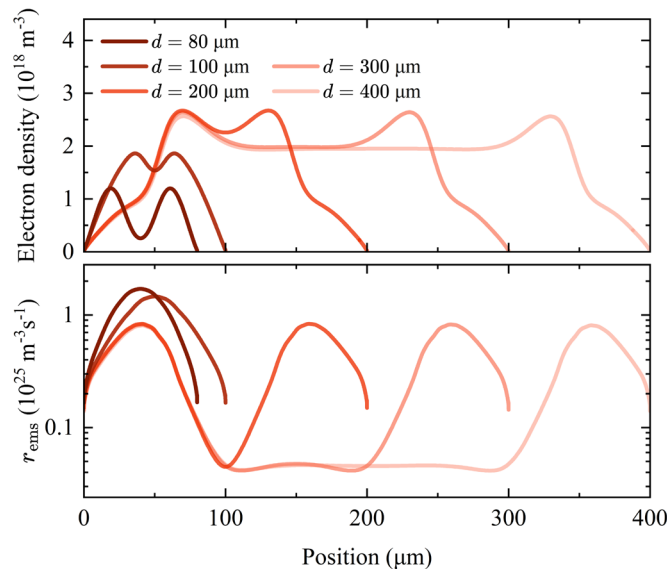
Flow rate is set to 4 SLM to ensure a helium-rich environment.

EMISSION ENHANCEMENT – SPATIAL CONTROL

Spatial control via reducing gap spacing d (between the electrode tip and the chip surface) enhances surface emission.



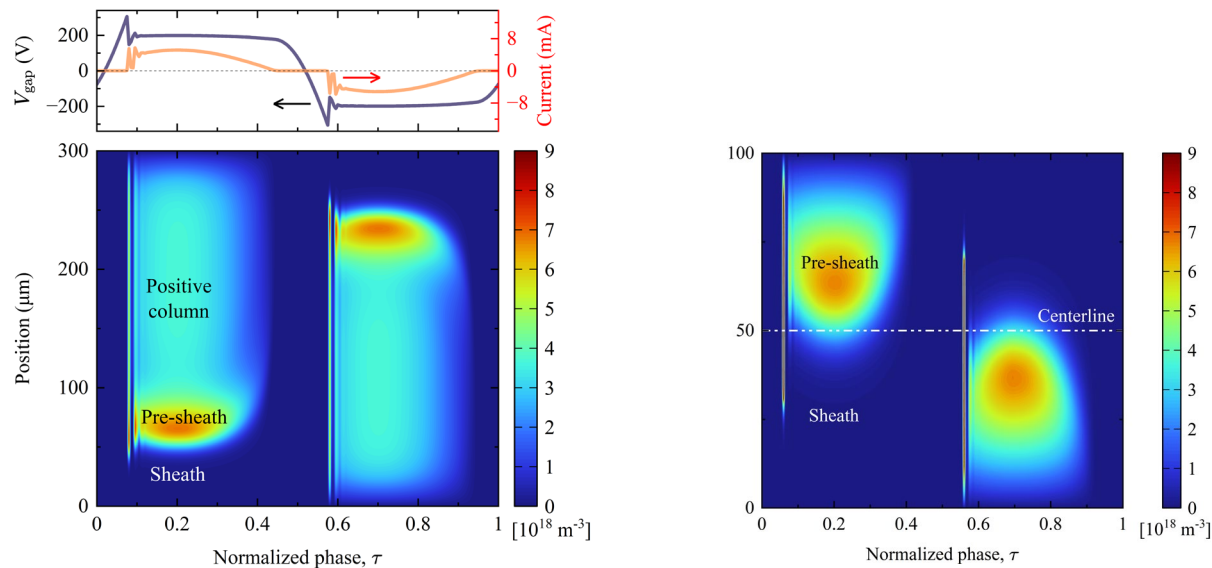
Measured emission profile varied with gap spacing d .



Model results. Top: electron density profile; Bottom: emission rate profile.

MODEL INSIGHT – SPATIAL CONTROL

By reducing the discharge gap d , a spatial-temporal overlap of the sheaths occurs, leading to an enhanced emission and the transition of the emission profile to a single peak.

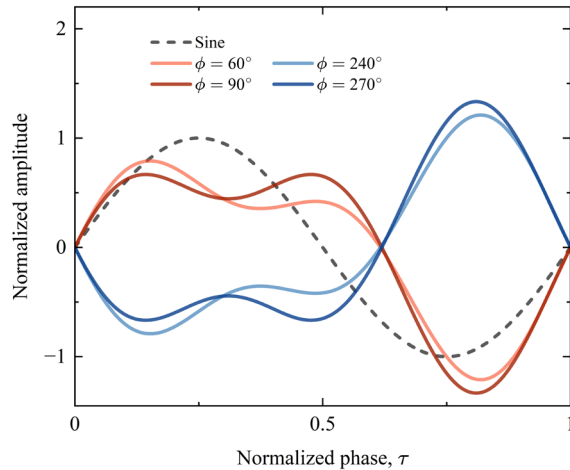


Spatiotemporal distribution of electron density at $d = 300 \mu\text{m}$ and $d = 100 \mu\text{m}$.

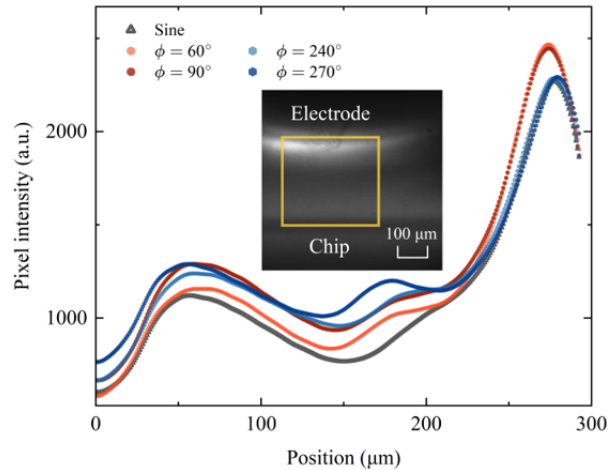


EMISSION ENHANCEMENT – TEMPORAL CONTROL

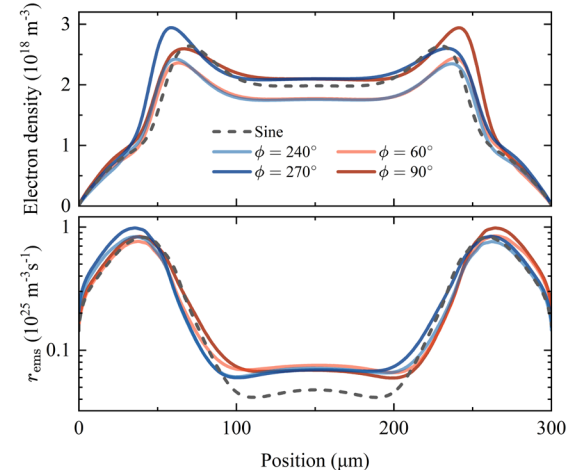
Temporal control by adding a second-order harmonic to the sinusoidal applied voltage enhances surface emission with a spatial preference.



Waveform variations under temporal control.



Measured emission profile varied with the applied voltage waveform.

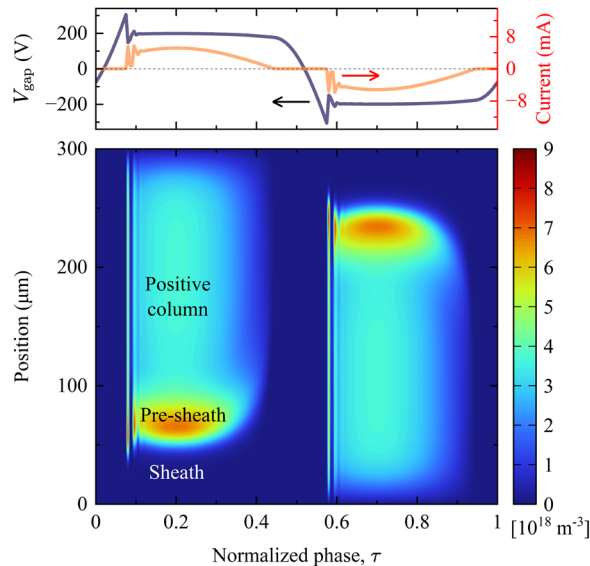


Model results. Top: electron density profile; Bottom: emission rate profile.

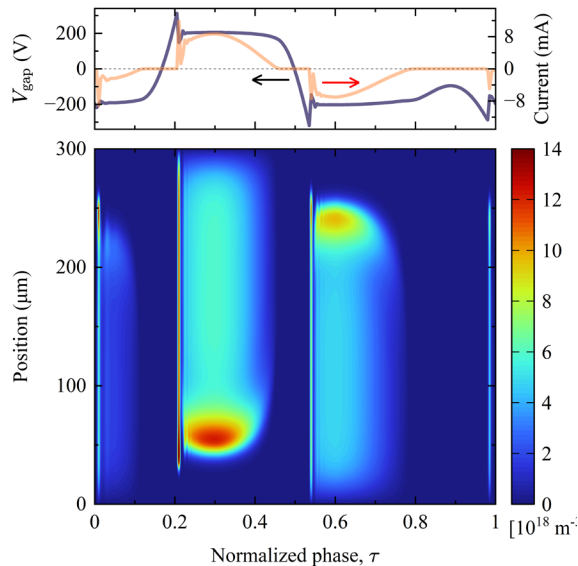
MODEL INSIGHT— TEMPORAL CONTROL

By temporal control, the power is redistributed during a discharge cycle.

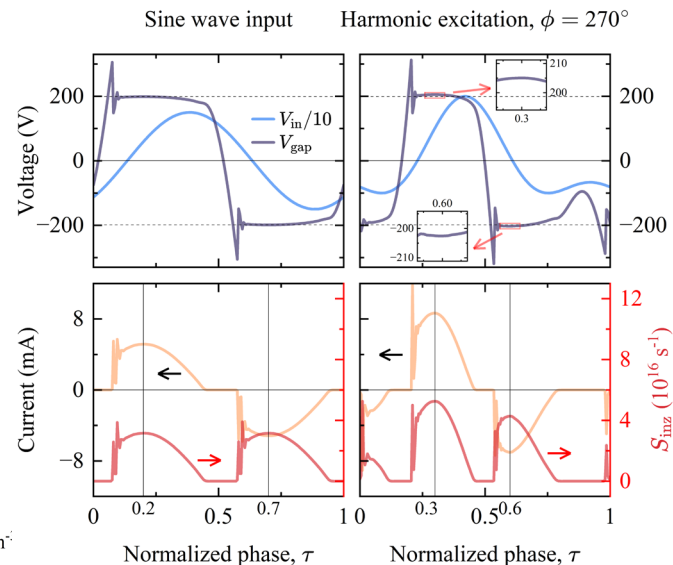
The peak voltage and current increase, as does the ionization source term.



Spatiotemporal distribution of electron density with sine wave.



Spatiotemporal distribution of electron density with harmonic excitation, $\phi = 270^\circ$.

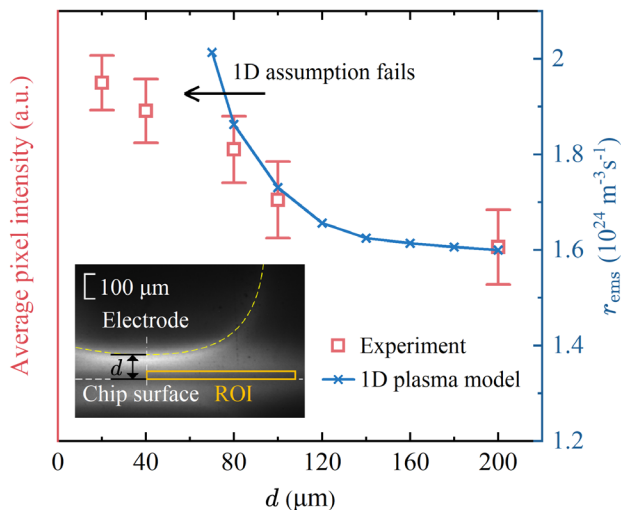


Applied voltage, gap voltage, current, and ionization source term in the two conditions.

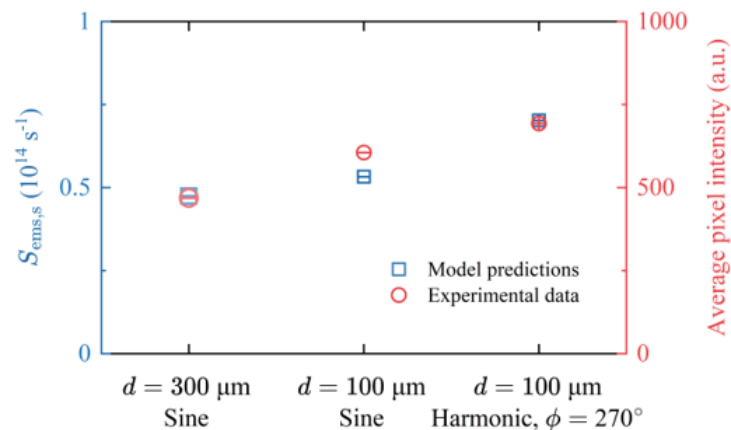
EMISSION ENHANCEMENT – CONCLUSION

The 1D assumption starts to fail at $d < 100\ \mu\text{m}$.

48% surface emission enhancement was achieved by combining the two approaches.



Experiment-simulation deviation at
sub-100 μm gap



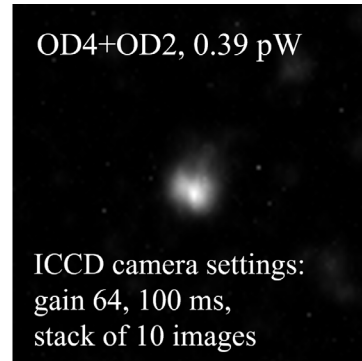
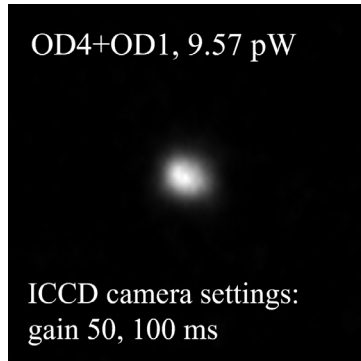
Overall emission enhancement
combining both techniques

DETECTION VALIDATION

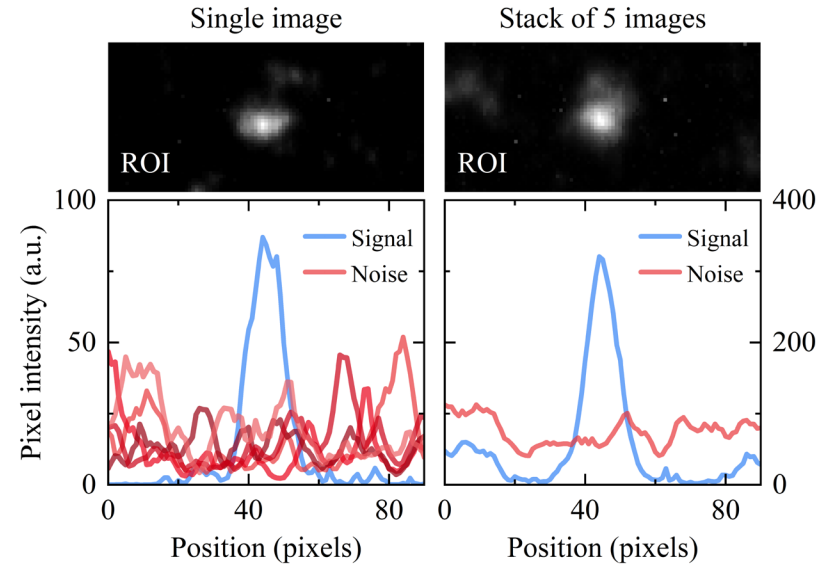


TECHNICAL OBSTACLE: BACKGROUND NOISE

A set of neutral density filters was used to reduce the laser-pumped output to simulate the desired coupled light from the plasma. A good signal-to-noise ratio can be obtained.



The output of the laser-pumped single-mode waveguide.



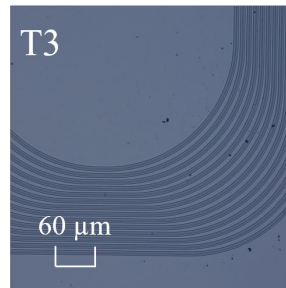
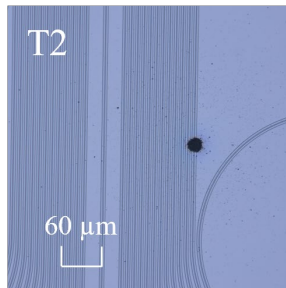
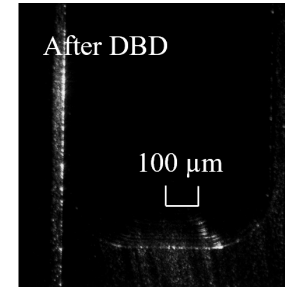
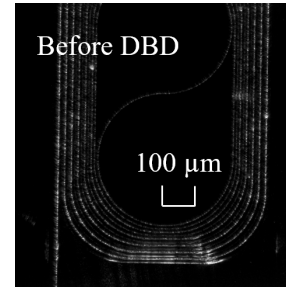
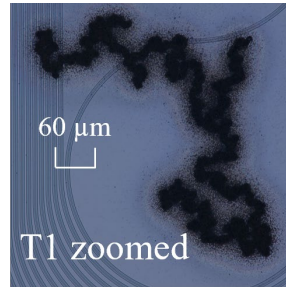
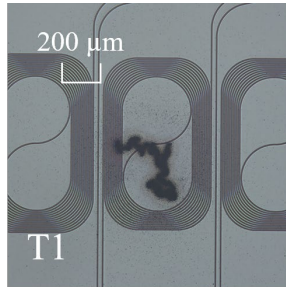
Single exposure vs. stack of 5 exposures.



TECHNICAL OBSTACLE: CONTAMINATION

Direct plasma-coupled measurement was blocked by carbon contamination.

Unavoidable due to their airborne nature.



Design of the on-chip DBD setup,
emission profile, chip layout design,
and the in-and-out optical alignment.

CONCLUSION & PERSPECTIVE



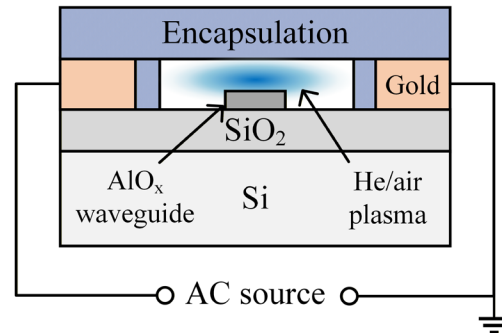
CONCLUSION

- Developed a coupled theoretical framework and functional prototype; the model predicts a power output of 3–11 pW at 391.4 nm
- Achieved 48% surface emission enhancement via gap optimization and harmonic excitation
- Validated picowatt detection capability, yet direct plasma-coupled measurement was blocked by carbon contamination



PERSPECTIVE

- **Contamination control:** surface barrier discharge (SBD) in a microcavity (20–100 μm height) with a dielectric lid
- **Spectral extension:** change gas mixture (Xe, Kr, Ar/ F_2) to access UVB, UVC, and VUV
- **On-chip gas laser:** exploit plasma as both spontaneous emitter and gain medium—self-seeded, pump-free, coherent UV source



Future design of UV-POCS: encapsulated SBD

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