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Heterogeneous Integration of Multi-Band Mode-Locked and Single-Mode Lasers on an Extended Commercial SiN Platform

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ABSTRACT

Integrated silicon nitride (SiN) waveguides offer ultra-low propagation loss across a broad transparency window, enabling large-scale photonic integrated circuits (PICs) for applications from LiDAR to quantum photonics. However, integrating lasers on SiN PICs remains challenging due to the large refractive-index contrast between SiN and high-index III-V gain materials. We address this by extending Ligentec's commercial bi-layer SiN platform with a polycrystalline silicon (Poly-Si) layer and demonstrate heterogeneous integration of GaAs- and InP-based amplifiers via a scalable process called micro-transfer printing. Multi-section adiabatic tapers ensure efficient coupling from the SiN to Poly-Si layer and onward to the printed III-V devices. In a single fabrication run, we realize a diverse set of lasers, including the first O-band GaAs-on-SiN mode-locked laser (5.1 GHz repetition rate, 5.4 ps pulse width), a C-band mode-locked laser delivering >1 mW optical power per output, and multiple single-mode sources (ring-filter and distributed Bragg reflector cavities) with side-mode suppression ratio up to 51 dB and intrinsic linewidth down to 1 kHz. These results demonstrate how combining micro-transfer printing with an extended SiN platform enables versatile, multi-wavelength laser integration, establishing a practical route to complex light sources for advanced photonic systems.

1 | Introduction

Silicon photonics has evolved dramatically over the past four decades, becoming a cornerstone for technologies ranging from optical communications and biosensing to LiDAR and spectroscopy [1]. While silicon-on-insulator (SOI) has been the dominant platform, SiN has recently emerged as a compelling complementary technology owing to its superior passive optical properties. Its broad transparency window, negligible two-photon

absorption (TPA), and ultra-low propagation losses (< 0.04 dB/m [2]) make it the ideal fabrication platform for large-scale photonic integrated circuits (PICs) required in artificial intelligence, quantum computing, and precision timekeeping [3–5]. Furthermore, the ability to handle watt-levels of optical power makes this material platform suitable for demanding nonlinear devices, examples of which are Kerr frequency combs and supercontinuum generation, which are difficult to achieve in silicon due to nonlinear losses [6, 7]. However, despite these advantages, SiN's

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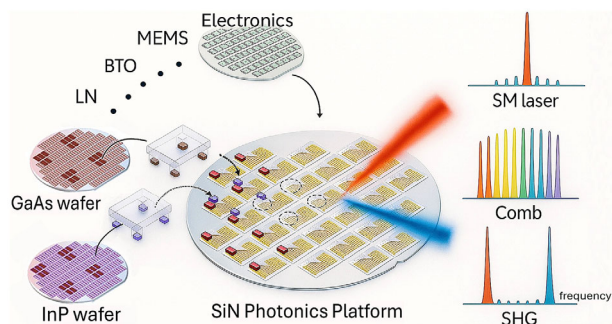


FIGURE 1 | Overview of the developed silicon nitride platform with various heterogeneously integrated materials for multi-type laser sources and nonlinear devices. (LN: lithium niobate; BTO: barium titanate; SM: single-mode laser; SHG: second-harmonic generation).

insulating nature and indirect bandgap present a fundamental challenge: it cannot efficiently generate or amplify light.

To realize fully integrated photonic systems on a chip, active III–V semiconductor materials must be integrated onto the passive SiN platform. Since III–V materials typically have a high refractive index (> 3.2) compared to SiN (around 2.0), evanescent coupling between the two layers is technically unfeasible. The most viable solution to enable this transition is through multilayer integration, where an intermediate layer serves as a bridge to couple the optical mode between the high-index gain medium and the low-loss and low-index SiN waveguide [8, 9]. This co-integration results in the ability to both use the active components presented in the III–V semiconductor materials, as well as leveraging the low-loss SiN waveguide to extend the photon lifetime within the laser cavity, which enhances the coherence and spectral purity [10, 11]. While previous demonstrations have validated this approach, they have often relied on amorphous silicon intermediate layer, which suffers from a limited thermal budget, and have only been demonstrated for indium phosphide (InP)-based amplifiers operating in the C-band [12, 13]. Emerging applications increasingly require integrated sources across multiple wavelength bands. In the O-band range, gallium arsenide (GaAs)-based quantum dot (QD) gain media are attractive because QD lasers typically exhibit small linewidth enhancement factors and high damping rates, which have been shown to improve tolerance to optical feedback [14]. Therefore, a versatile integration platform is needed to host multiple material systems, such as GaAs and InP, on a single chip using scalable integration methods.

In the proposed method in this paper, we overcome these limitations using micro-transfer printing (μ TP) for the scalable, heterogeneous integration of diverse III–V materials onto a commercial SiN photonic platform. Unlike traditional bonding techniques, μ TP allows for the parallel placement of pre-processed devices, or “chiplets”, from different native substrates (e.g., GaAs, InP, GaSb, LN, BTO) onto a common target wafer with high throughput and yield [15, 16]. As schematically illustrated in Figure 1, μ TP relies on the kinetically controlled adhesion of an elastomeric polydimethylsiloxane (PDMS) stamp to pick up devices and place them onto SiN wafer. To resolve the refractive index mismatch between SiN and the amplifying material while maintaining low coupling loss, we incorporated a polycrystalline silicon (Poly-

Si) layer onto a bi-layer SiN platform to act as the intermediate bridging layer between the low-index SiN and high-index III–V layers. This Poly-Si material offers advantages in thermal stability and high-power handling capability compared to amorphous silicon, as it can withstand higher process temperature and avoids some light-induced metastable degradation mechanisms [17, 18].

In this work, we demonstrate the versatility of this new SiN platform by integrating both InP-based quantum well (QW) and GaAs-based QD gain materials onto a single chip. As a proof of concept, we realize the first O-band GaAs-on-SiN passive mode-locked comb lasers, achieving a repetition rate of 5.1 GHz and optical pulses of 5.4 ps. In parallel, we demonstrate C-band mode-locked lasers with output powers exceeding 1 mW. Leveraging the ultra-low-loss SiN platform, our single-mode lasers achieve side-mode suppression ratio (SMSR) up to 51 dB and intrinsic linewidths as low as 1 kHz. The primary focus of this work is to demonstrate the versatility of the SiN platform for multi-material, multi-wavelength, and multifunctional heterogeneous laser integration. In parallel, work is ongoing to transfer the developed O- and C-band micro-transfer-printing processes onto 100 mm SiN wafers, establishing μ TP as a robust and scalable path toward complex heterogeneous photonic integrated circuits.

2 | Results

2.1 | SiN Platform Extension Using Poly-Si

The large refractive index mismatch between SiN (~ 2.0) and III–V materials (> 3.2) hinders direct evanescent coupling, as efficient phase matching would require taper tip widths below 100 nm with etched depths exceeding 1 μ m, which is typically out of reach for III–V fabrication. To overcome this, we developed a multilayer platform extension in collaboration with Ligentec on a commercial dual-layer SiN stack. As illustrated in Figure 2a, the platform incorporates three device layers: an 800-nm-thick SiN layer (X1), a 200-nm-thick SiN layer (X2), and a 360-nm-thick Poly-Si layer, allowing low-loss evanescent coupling between the SiN and Poly-Si layers. This architecture allows for few-micron-thick III–V membranes or pre-fabricated amplifiers to be heterogeneously integrated on top via micro-transfer printing using a thin (40-nm-thick) divinylsiloxane-bisbenzocyclobutene (DVS-BCB) adhesive layer. A detailed description of the integration process is provided in the Materials and Methods section.

Figure 2b details the three-stage adiabatic taper which was designed for efficient optical coupling in the O-band between the X1 and Poly-Si layers. To suppress reflections, the taper tip widths for Poly-Si and X2 waveguides are set to 180 nm and 200 nm, respectively. In the first stage, the X1 waveguide linearly narrows from 2 to 1.3 μ m while X2 widens, pulling the optical mode upward. In the second stage, the X1 waveguide tapers down to 200 nm, resulting in full mode transfer into the Poly-Si layer. In the final stage, the optical mode is fully contained in the 3 μ m wide Poly-Si layer, and the X2 is expanded to function as a supportive layer.

The bridging function of the layer X2 enables the taper to achieve a theoretical transmission efficiency of 97.9% within a compact 180 μ m length. Minimizing the length of this transition

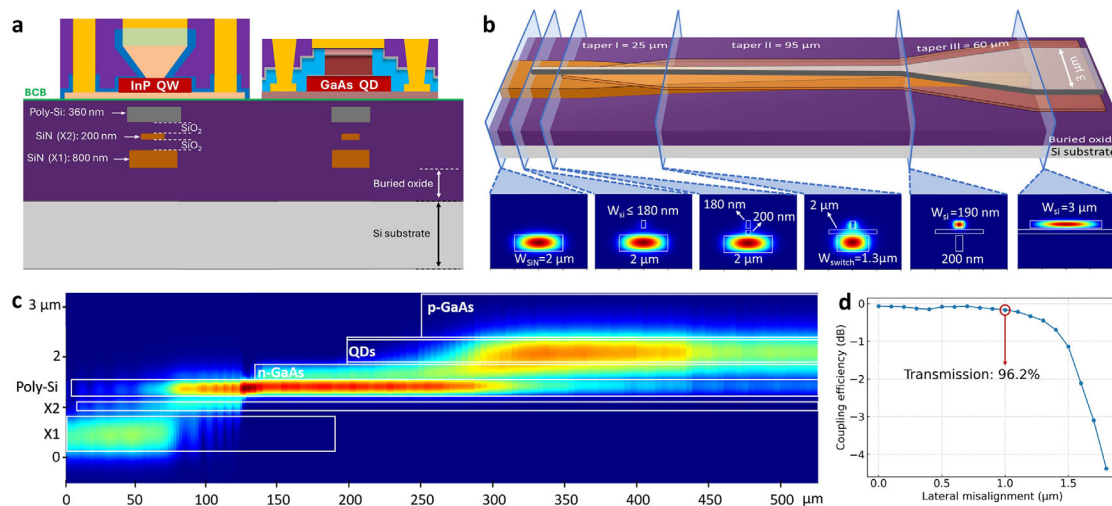


FIGURE 2 | Commercial SiN photonics platform. (a) Schematic layer stack of developed platform. (b) Fully coupled taper design from X1 to Poly-Si layer. (c) Cross-section view of the fundamental TE mode propagation through the SiN/Poly-Si/GaAs escalator. (d) Simulated coupling efficiency as a function of lateral misalignment between the GaAs and SiN layers.

is critical to mitigate the impact of optical attenuation within the polycrystalline silicon. Propagation-loss evaluation on separate Poly-Si test structures shows C-band losses of 10–20 dB/cm, with higher losses expected in the O band. For the SiN-to-Poly-Si transition used here, this corresponds to an additional Poly-Si loss contribution of approximately 0.4 dB. The full SiN/Poly-Si/GaAs coupling escalator was simulated using Ansys Lumerical MODE (Figure 2c), showing an adiabatic transition for the fundamental TE₀ mode. The weak ripples observed in the Poly-Si waveguide are attributed to minor interference effects caused by back-reflections from the III–V taper tips. On the III–V coupon side, the waveguide is tapered using a linear adiabatic design similar to that of the underlying Poly-Si waveguide. The detailed geometry and simulated mode evolution are provided in Note S1. Figure 2d presents the simulated coupling efficiency ($|S_{21}|^2$) as a function of lateral misalignment between the GaAs coupon and SiN layer. Even under misalignments of $\pm 1 \mu\text{m}$, which is within the typically reported 3σ misalignment of micro-transfer printing tools, the coupling efficiency remains above 96%. Given that modern wafer-scale μTP tools offer alignment specifications of even $\pm 0.5 \mu\text{m}$ (3σ), this design provides sufficient alignment tolerance to support manufacturing at scale. For the SiN/Poly-Si/InP escalator implementation in the C-band, we employed a conventional multi-section coupling architecture [19], resulting in a simulated coupling efficiency of 99.1%. While the SiN X2 layer is still utilized in the optical transition, the dimensions of the SiN waveguides remain constant in this configuration. Instead, adiabatic coupling between the SiN and Poly-Si layers is achieved solely by varying the width of the Poly-Si waveguide.

2.2 | Mode-Locked Lasers

The mode-locked lasers are based on a ring-type extended-cavity topology, in which two counter-propagating pulses collide in a central saturable absorber (SA) [13, 20]. As schematically illustrated in Figure 3a, the laser comprises two spiral delay lines in the thick SiN layer X1 and a printed III–V amplifier with a SA positioned at the center of the cavity. A directional coupler

is used to couple light out of the cavity in the O-band, and an 85:15 multimode interferometer (MMI) is employed for the C-band. The directional coupler was included to offer a highly compact footprint with minimal excess loss, whereas the MMI provides enhanced fabrication tolerance and a broader operational bandwidth which is advantageous for comb generation. To simplify experimental testing during initial prototype evaluation, integrated grating couplers (GCs) were used for rapid out-of-plane light extraction. While these standard foundry GCs exhibit approximately –20 dB of back-reflection, accounting for the double-pass loss through the $\approx 15\%$ laser outcoupler suppresses the effective cavity feedback to below –35 dB. For practical packaged implementations, utilizing edge couplers will eliminate these grating-induced reflections and enhance the overall fiber-coupling efficiency. Optical microscope images of the fabricated O- and C-band devices are shown in Figure 3b,c. The GaAs and InP coupons, including the taper-transition sections on both sides, have total lengths of 1660 and 2500 μm , respectively. The SA lengths are 170 μm for the O-band laser and 100 μm for the C-band laser, each isolated by two electrical isolation trenches. The SA lengths were chosen by considering the absorber–gain balance of the laser cavity, since the SA ratio strongly affects the mode-locking regime and pulse dynamics in mode-locked lasers [21]. For a fixed physical geometry, the SA reverse bias provides an additional tuning degree of freedom by modifying the absorber loss and carrier recovery dynamics [22]. The lateral misalignment between the printed III–V coupons and the SiN chip is typically below 1 μm . By carefully fine-tuning the alignment during printing, it can be further reduced to a few hundred nanometers, as shown for a representative device in Figure 3d. Further details on the III–V material composition and coupon fabrication are provided in the Materials and Methods section.

The chip was mounted on a temperature-controlled chuck maintained at 18°C, chosen as a practical trade-off to keep the amplifier temperature as low as possible while avoiding on-chip water condensation. Electrical injection was provided by a custom radio-frequency (RF) probe, while the optical output was collected via on-chip grating couplers into a cleaved SMF-28 fiber

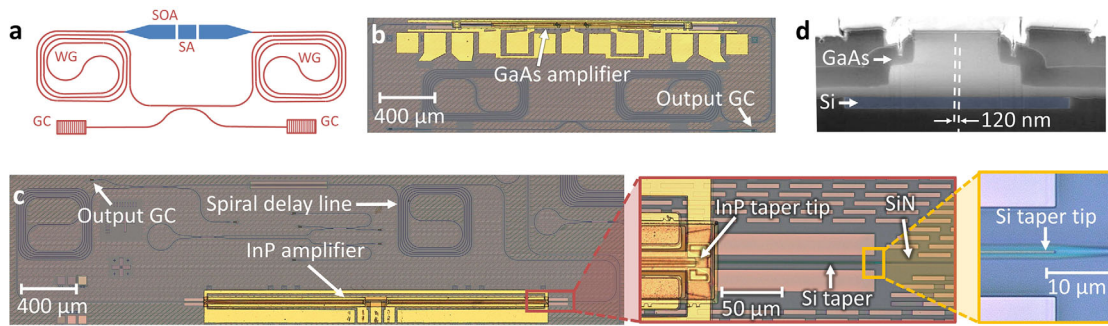


FIGURE 3 | Mode-locked comb lasers. (a) Schematic layout of mode-locked laser cavity. (b,c) Optical microscope images of the micro transfer printed GaAs-on-SiN and InP-on-SiN laser. (d) FIB cross-section view of the printed coupon with respect to the underlying poly-Si.

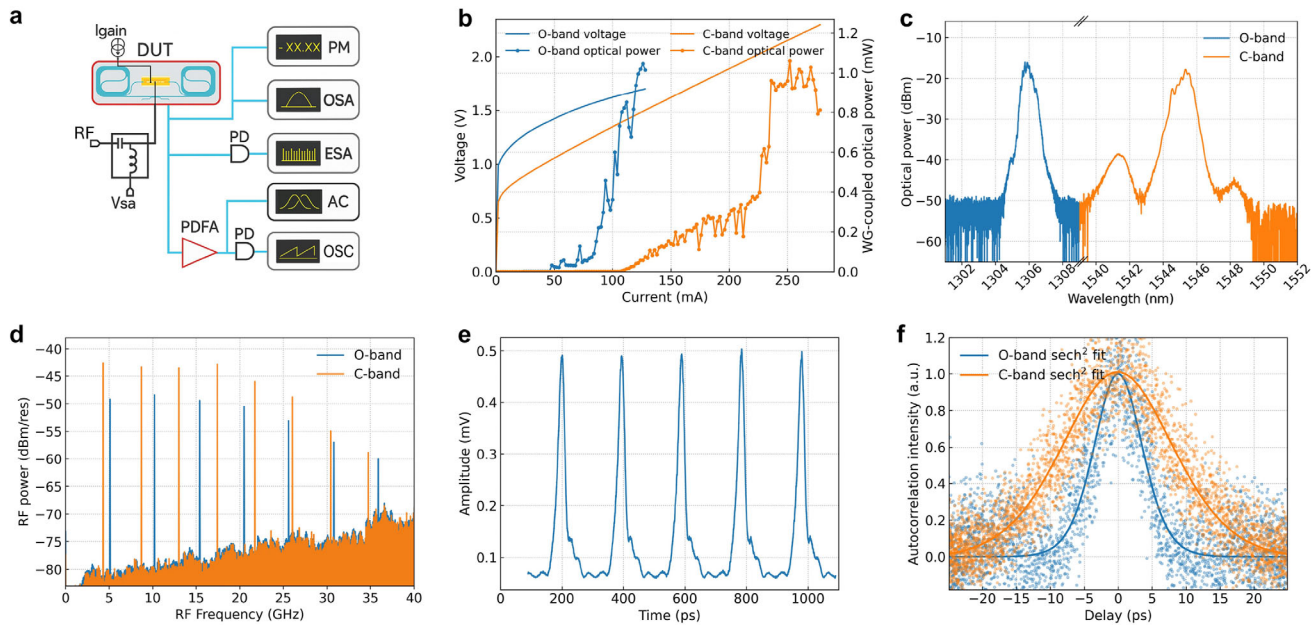


FIGURE 4 | Experimental setup and results of mode-locked comb lasers. (a) Measurement setup. PDFA: praseodymium doped fiber amplifier; PD: photodetector; PM: power meter; OSA: optical spectrum analyzer; ESA: electrical spectrum analyzer; AC: autocorrelation; OSC: oscilloscope. (b) Light-current-voltage (L-I-V) curves of both lasers with SA left open circuit. (c) Optical spectra of both lasers obtained at mode-locking point. (d) RF spectra of the generated pulse train for a RBW of 100 kHz. (e) Recorded pulse train of the O-band laser by an oscilloscope. (f) Measured autocorrelation trace with sech^2 fits of both lasers.

(setup schematic in Figure 4a). It is important to note that the symmetric ring-cavity geometry results in bidirectional emission. Consequently, the reported power levels, measured from a single output port, represent half of the total generated light. Figure 4b illustrates the light-current-voltage (LIV) characteristics with the SA section electrically floating for both the O- and C-band devices. From the slope of the I-V curves, the differential resistances are extracted to be 3Ω at 110 mA for the O-band GaAs device and 8Ω at 270 mA for the C-band InP device. The 3Ω for the GaAs coupon is comparable to values reported for GaAs QD lasers [23]. For the InP devices, the slightly higher resistance reflects a deliberate heterogeneous design trade-off, where the bottom n-contact layer is kept thin and moderately doped to minimize free-carrier absorption in the hybrid optical mode. The kink observed in the C-band LI curve is attributed to a mode-hopping effect, likely induced by localized self-heating shifting the gain spectrum.

As the reverse bias on the SA is increased, the optical spectrum transitions from discrete multimode lasing peaks to a broadband envelope, indicating the onset of mode-locking. To confirm this regime, the output light was coupled to a high-speed photodetector, and the generated RF beat note was analyzed using an electrical spectrum analyzer (ESA). Stable mode-locking is observed for both O-band and C-band devices over a broad operating window, specifically when the semiconductor optical amplifier (SOA) current exceeds twice the threshold and the SA reverse bias ranges between -1.8 V and -3 V . Representative optical and RF spectra at the optimal mode-locking operating points (O-band: 120 mA/ -2.6 V and C-band: 290 mA/ -2.4 V) are presented in Figure 4c,d. Each laser delivers more than 0.4 mW of waveguide-coupled optical power per output port. The current output power is limited by the overall gain-loss balance of the heterogeneous cavity, including Poly-Si-related propagation loss, the finite effective III-V gain length, and localized self-

heating caused by the high thermal resistance of the thick buried oxide layer [24]. For scenarios requiring higher optical power, an additional on-chip amplifier can be integrated following the mode-locked laser (MLL) to boost the output [25]. Both combs contain over 40 optical laser lines, corresponding to 10-dB optical bandwidths of approximately 1 and 2 nm for the O-band and C-band devices, respectively. Although the individual comb lines are not fully resolved in the optical spectra due to the finite resolution of the OSA, they generate an RF beat note on a photodetector with an electrical signal-to-noise ratio (SNR) exceeding 30 dB. The observation of the fundamental repetition frequency and its harmonics, corresponding to the cavity round-trip time, confirms stable mode-locking and strong phase coherence between the optical modes [26]. This establishes a direct mapping between the optical and RF domains, which in future work could enable frequency synthesis, coherent detection, and precision metrology using integrated mode-locked lasers. Future iterations involving cavity engineering, such as dispersion management and optical confinement tuning, are expected to further increase the comb bandwidth [27].

Figure 4e displays the pulse train of the O-band MLL, recorded using a high-speed photodetector and a sampling oscilloscope (OSC). A stable periodic pulse train is observed without satellite pulses, confirming stable mode-locked operation. The minor trailing oscillations following the main pulses are attributed to ringing in the photoreceiver's impulse response and are not intrinsic to the optical waveform. Given that the pulse duration is significantly shorter than the combined impulse response of the detection system, intensity autocorrelation (AC) measurements were performed to resolve the temporal profile. The measured autocorrelation traces, fitted with a sech^2 profile, are presented in Figure 4f. The deconvoluted pulse durations are calculated to be 5.4 ps for the O-band laser and 12.5 ps for the C-band laser.

To evaluate the frequency stability of the generated pulse-train, single-sideband phase-noise (SSB-PN) measurements were performed on the fundamental RF repetition tone of the mode-locked laser [28]. By applying a Voigt fit to the measured phase noise data, we were able to deconvolve the Gaussian technical noise from the intrinsic Lorentzian line shape. This analysis yields intrinsic Lorentzian linewidths of 50 Hz for the O-band device and 120 Hz for the C-band device. The corresponding phase-noise data and Voigt fits are provided in Note S4. While the passively mode-locked laser already shows stable operation, applications requiring precise comb-spacing control benefit from locking the repetition rate to an external reference. We experimentally demonstrated this via hybrid mode-locking, where the SA section is modulated by a low-noise electrical synthesizer at the passive repetition frequency. With an RF drive power of 10 μ W, the repetition-rate tone follows the external reference and the low-offset phase noise is strongly suppressed. Detailed comparison and related measurements are provided in Note S5.

2.3 | Single-Mode Lasers

To achieve compact, frequency-stable single-mode continuous-wave (CW) lasers, we investigated two distinct cavity architectures: a ring-filter geometry and a distributed Bragg reflector (DBR) design (schematics in Figure 5a,b).

The ring-filter laser features a symmetric cavity incorporating two long spiral delay lines (2×6.8 cm) to extend the photon lifetime, and a central add-drop ring resonator (free spectral range of 30–40 GHz) for mode selection. Single-mode operation in this architecture relies on a Vernier effect between the resonances of the microring and the longitudinal modes of the laser cavity. Due to strong mode competition, the specific longitudinal cavity mode that optimally aligns with a microring resonance reaches threshold first and starts lasing. This dominant mode clamps the optical gain, effectively suppressing lasing at adjacent ring resonances despite the broad emission spectrum of the gain medium. The measured Q factors of the ring filters are approximately 3×10^5 in the O-band and 1×10^6 in the C-band. The CW laser cavity is entirely confined in the thick low-loss SiN layer X1, and the waveguide dimensions support only the fundamental mode. A representative microscope image of the fabricated O-band device is shown in Figure 5c.

The DBR laser employs a Sagnac loop mirror for a simulated 100% reflection on one end and a wavelength-selective DBR grating on the other. Crucially, the DBR grating is defined in the 200-nm-thick SiN layer X2 (1.2 μ m width). By defining the grating in the thinner layer X2, the optical confinement is reduced compared to X1, thereby enhancing the interaction with the etched posts while ensuring compliance with foundry-set design rules. A 40- μ m-long adiabatic taper transitions light between the main cavity implemented in X1 and the reflector implemented in X2. The grating consists of circular posts (330 nm diameter) with 9700 periods having an 860 nm pitch optimized for 1550 nm. This architecture is inherently scalable and can be fabricated within Ligentec's design rules. Furthermore, by individually adjusting the grating period of each laser, multi-channel laser arrays with well-defined channel spacing (e.g., 100 GHz) can be realized in parallel. Figure 5d shows a printed laser array, highlighting the scalability of the μ TP approach.

Characterization was performed at 18°C. Figure 6a,d,g display the LIV curves of the three laser designs, revealing threshold currents of 89, 120, and 95 mA, respectively. Pronounced kinks and dips in the L–I–V curves of the ring-filter lasers are attributed to cavity-mode detuning between the lasing mode and the ring resonance, driven by thermal and carrier-induced refractive-index changes in the gain section. Conversely, for the DBR architecture, these fluctuations stem from the longitudinal cavity modes sequentially entering and exiting the reflection band of the DBR mirror. The C-band DBR laser yields a waveguide-coupled output of 3.8 mW, while the O-band variant (GaAs) is limited to sub-milliwatt levels, which is a constraint that can be addressed in future iterations by enhancing the QD gain, increasing the coupon length and reducing the Poly-Si loss. Optical spectra (Figure 6b,e,h) confirm high spectral purity, with SMSR reaching 43, 51, and 47 dB.

While the ring-filter cavity exhibits mode hopping, the DBR-laser maintained lasing at a single-wavelength set by the DBR grating. Frequency noise spectral density was measured to extract the intrinsic Lorentzian linewidth (Figure 6c,f,i) based on the Schawlow–Townes relation [29]. The C-band ring-filter laser achieved a record-low intrinsic linewidth of 1 kHz for micro-transfer printed lasers. The broader linewidth of the O-band ring-filter laser is attributed to the lower Q factor of the microring and higher Poly-Si-related loss, which reduce the cavity photon

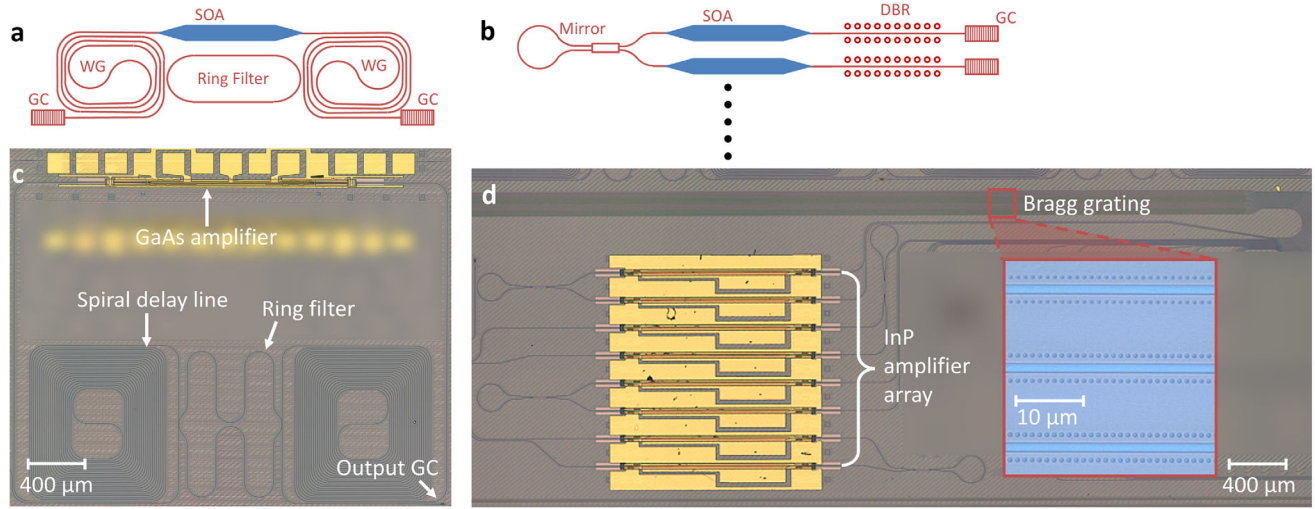


FIGURE 5 | Single-mode CW lasers. (a,b) Schematic layouts of ring-filter and DBR laser cavities. (c,d) Optical microscope images of the micro transfer printed GaAs-on-SiN laser and InP-on-SiN laser array.

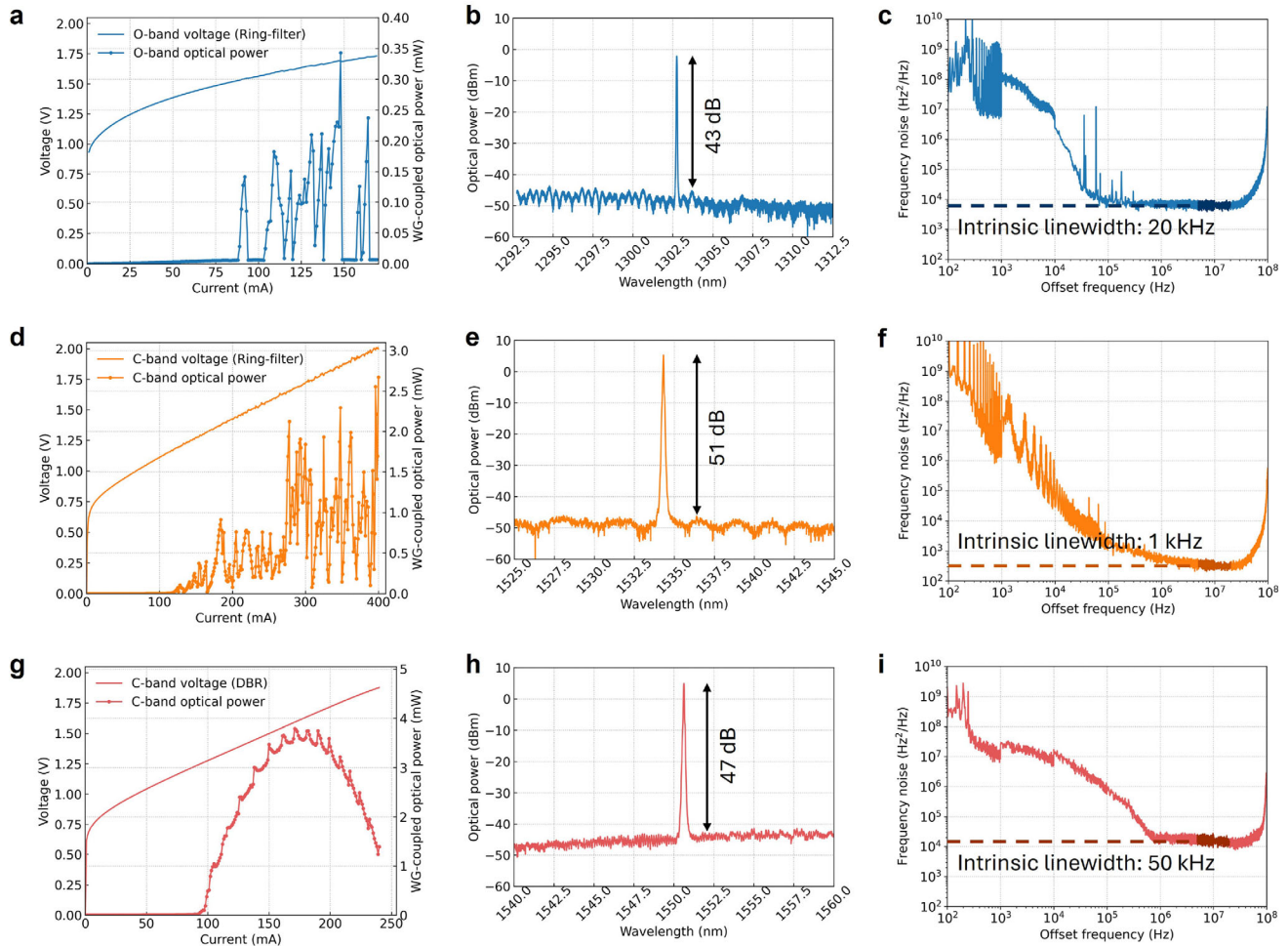


FIGURE 6 | Characterization results of single-mode CW lasers. (a,d,g) Light–Current–Voltage (L–I–V) curves of the devices. (b,e,h) Optical spectra measured at forward bias currents of 130, 300 and 180 mA. (c,f,i) Frequency-noise spectra recorded at the corresponding operating points.

lifetime and intracavity photon number. The DBR design offers the highest output power and the most robust single-mode operation, but also exhibits the broadest linewidth, reflecting the inherent design trade-offs between the two cavity architectures. Note that the rise in frequency noise near 5×10^7 Hz is an instrument artifact.

3 | Discussion

The results presented here establish micro-transfer printing as a robust and versatile pathway for the heterogeneous integration of diverse III–V gain materials onto a low-loss SiN photonic platform. The central focus of this work is the platform capability: the same SiN/Poly-Si circuit and μ TP process can support different active material systems, wavelength bands, and laser architectures. By extending this commercial SiN platform with an intermediate Poly-Si bridging layer, we successfully overcame the fundamental refractive index mismatch that otherwise hinders efficient optical coupling under CMOS-compatible materials and fabrication constraints. This architecture enables the integration of multiple material systems, as exemplified here by InP- and GaAs-based materials, at densities and topological complexities that are challenging to achieve with traditional wafer bonding techniques. The demonstration of passive mode-locked ring lasers highlights the distinct advantages of combining high-gain III–V amplifiers with thick, low-loss SiN delay lines, which in the future could be designed for dispersion compensation. The generation of optical combs, clean RF beat notes, and short optical pulses confirms that the heterogeneous cavity supports efficient colliding-pulse mode locking. Notably, our O-band devices represent, to the best of our knowledge, the first report of GaAs-on-SiN passively mode-locked lasers [30], unlocking the near-infrared spectrum for integrated frequency metrology. Although the present GaAs QD devices show more modest performance than the InP-based C-band lasers, their performance is expected to improve by increasing the effective gain length, reducing Poly-Si losses, and optimizing the GaAs QD coupon and heterogeneous cavity design.

For single-mode operation, the ring-filter architecture leverages the high Q of the SiN platform to achieve kHz-level intrinsic linewidths, albeit with susceptibility to mode hopping. This instability can be mitigated in future designs through active thermal stabilization or Vernier-effect wavelength filters [31]. Conversely, the DBR architecture offers a more robust single-mode operation and milliwatt-level output powers, making it ideal for practical communications transmitters where stability is important. Together, these results further show that the same integration platform can support different wavelength bands and laser architectures.

Looking beyond lasers, this commercial SiN platform is inherently extensible to a broader library of functional materials. Examples of these are to micro-transfer-print lithium niobate or lithium tantalate thin films, which could enable high-speed electro-optic modulators and fast-tunable lasers on the same chip [32, 33]. Furthermore, the successful parallel integration of SOA arrays underscores the throughput potential of μ TP, positioning it as a scalable solution for dense wavelength-multiplexed transmitters. Crucially, because μ TP is a back-end-compatible

process, it allows for the introduction of non-CMOS materials without contaminating front-end fabrication lines. Future efforts will focus on implementing active thermal tuning, depositing top oxide cladding for environmental protection, and scaling the assembly process to full wafer-level automation.

4 | Materials and Methods

4.1 | III–V Materials and Coupon Fabrication

The III–V epitaxial layer structures used for fabricating the coupons are summarized in Table 1. Unlike conventional III–V epitaxial stacks, μ TP requires the inclusion of a dedicated release layer, which can be selectively etched to free and suspend the coupon prior to transfer. For the GaAs-based structures, the stack begins with a 300-nm GaAs buffer layer, followed by a 1- μ m AlGaAs release layer. Above this, the functional device layers are grown, consisting of a 350-nm heavily doped n-GaAs contact layer, a 70-nm n-AlGaAs cladding layer, an active region with 12 periods of InAs quantum dots embedded within GaAs barriers, a 1.18- μ m p-AlGaAs cladding layer, and a 200-nm heavily doped p-GaAs contact layer. The 12-layer QD stack with 35 nm GaAs spacer was chosen to increase the effective dot density and modal gain, compensating for the relatively small active volume and typically lower modal gain per layer of self-assembled QDs [34, 35]. The resulting optical confinement factor in the QD active region is 66%, as detailed in Note S1. The epitaxy is capped with a 40/70 nm GaAs/AlGaAs sacrificial bilayer, which protects the wafer surface during transportation. The InP-based epitaxial stacks start with a 150-nm InP buffer layer, followed by a dual-layer GaInAs/AlInAs release structure (50/500 nm). Above the release layers, the device structure comprises a 200-nm heavily doped n-InP contact layer, a pair of 25-nm AlGaInAs transition layers, a pair of 25-nm AlGaInAs separate confinement heterostructure (SCH) layers, and an active region with 6 AlGaInAs quantum wells sandwiched by barriers. This 6-QW architecture was chosen to optimally balance optical gain, active-region thickness, carrier transport, and optical confinement (yielding a 1.44% confinement factor within the QWs themselves). This is followed by a 25-nm GaInAsP etch stop layer, a 1.7- μ m p-InP cladding layer, a 20-nm GaInAsP transition layer, and a 200-nm heavily doped p-GaInAs contact layer. The epitaxy is finalized with a 100-nm InP cap layer and a 20-nm GaInAs sacrificial layer for surface protection.

Figure 7a presents the schematic process flow for GaAs coupon fabrication, similar to that developed in our previous GaAs-on-SiN Fabry–Pérot laser demonstration [36]. First, the top GaAs/AlGaAs sacrificial layers were removed by a two-step wet-etch process ($\text{C}_6\text{H}_8\text{O}_7/\text{H}_2\text{O}_2$ followed by $\text{HCl}/\text{H}_2\text{O}$). After the removal of the sacrificial layers, a 350-nm SiN hard mask was deposited by plasma-enhanced chemical vapor deposition (PECVD). This SiN layer was subsequently patterned by electron-beam lithography (EBL) using the AR-P 6200.13 positive resist, followed by reactive-ion etching (RIE) with a CF_4/H_2 gas mixture. The p-AlGaAs mesa was then defined by inductively coupled plasma (ICP) etching using a BCl_3/N_2 chemistry (Figure 7a(i)). A 100-nm SiN layer was then deposited on the patterned p-cladding mesas to serve as a hard mask for defining the QDs active region. The same ICP etching was implemented to pattern the active region (Figure 7a(ii)). The n-contact metal stack

TABLE 1 | III-V epitaxial layer stacks.

a. GaAs-based QDs layer stack					
Layer	Layer type	Material	Thickness	Dopant	Doping type
14	Sacrificial	GaAs	40 nm	None	U/D
13	Sacrificial	Al _{0.85} Ga _{0.15} As	70 nm	None	U/D
12	Contact P	GaAs	200 nm	C	P
11	Cladding P	Al _{0.8} Ga _{0.2} As	1180 nm	C	P
10 × 12 repeats	Barrier	GaAs	10 nm	None	U/D
9 × 12 repeats	Barrier	GaAs	10 nm	C	P
8 × 12 repeats	Barrier	GaAs	15 nm	None	U/D
7 × 12 repeats	Barrier	In _{0.15} Ga _{0.85} As	/	None	U/D
6 × 12 repeats	QDs	InAs	/	None	U/D
5	Barrier	GaAs	30 nm	None	U/D
4	Cladding N	Al _{0.8} Ga _{0.2} As	70 nm	Si	N
3	Contact N	GaAs	350 nm	Si	N
2	Release layer	Al _{0.95} Ga _{0.05} As	1000 nm	None	U/D
1	Buffer layer	GaAs	300 nm	None	U/D
0	Substrate	N ⁺ GaAs 3 inch			
b. InP-based QW layer stack					
Layer	Layer type	Material	Thickness	Dopant	Doping type
18	Sacrificial	Ga _{0.47} In _{0.53} As	20 nm	None	U/D
17	Cap P	InP	100 nm	Zn	P
16	Contact P	Ga _{0.47} In _{0.53} As	200 nm	Zn	P
15	Transition P	Ga _{0.2} In _{0.8} As _{0.43} P _{0.57}	20 nm	Zn	P
14	Cladding P	InP	1200 nm	Zn	P
13	Cladding P	InP	500 nm	Zn	P
12	Etch stop	Ga _{0.2} In _{0.8} As _{0.43} P _{0.57}	25 nm	Zn	P
11	Transition	Al _{0.42} Ga _{0.05} In _{0.53} As	25 nm	None	U/D
10	SCH	Al _{0.33} Ga _{0.21} In _{0.46} As	25 nm	None	U/D
9 × 6 repeats	Barrier	Al _{0.22} Ga _{0.34} In _{0.44} As	10 nm	None	U/D
8 × 6 repeats	QW	Al _{0.07} Ga _{0.26} In _{0.67} As	6 nm	None	U/D
7	Barrier	Al _{0.22} Ga _{0.34} In _{0.44} As	10 nm	None	U/D
6	SCH	Al _{0.33} Ga _{0.21} In _{0.46} As	25 nm	None	U/D
5	Transition	Al _{0.33} Ga _{0.21} In _{0.46} As	25 nm	Si	N
4	Contact N	InP	200 nm	Si	N
3	Release layer	Ga _{0.47} In _{0.53} As	50 nm	None	U/D
2	Release layer	Al _{0.48} In _{0.52} As	500 nm	Si	N
1	Buffer layer	InP	150 nm	None	U/D
0	Substrate	N ⁺ InP 2 inch			

(GeAu alloy/Pd/Au/Ti/Au, 80/40/100/40/150 nm) was deposited by electron-beam (E-Beam) evaporation and patterned by lift-off process (Figure 7a(iii)). The entire structure was subsequently passivated with an additional SiN layer, which again served as a hard mask to etch the first coupon mesa down through the release layer into the GaAs substrate (Figure 7a(iv)). The coupon mesa was then encapsulated with a SiN/SiO_x (600/75 nm) dielectric

bilayer (Figure 7a(v)), and the topography was planarized with a thick BCB layer. After BCB etch-back (Figure 7a(vi)), the heavily doped p-GaAs layer was exposed. A photoresist mask with 45°-inclined trenches was used for ICP etching to locally remove the p-GaAs contact layer, thereby defining the saturable absorber and suppressing parasitic reflections caused by discontinuities in the layer stack. The p-contact metal stack (Ti/Au, 40/300

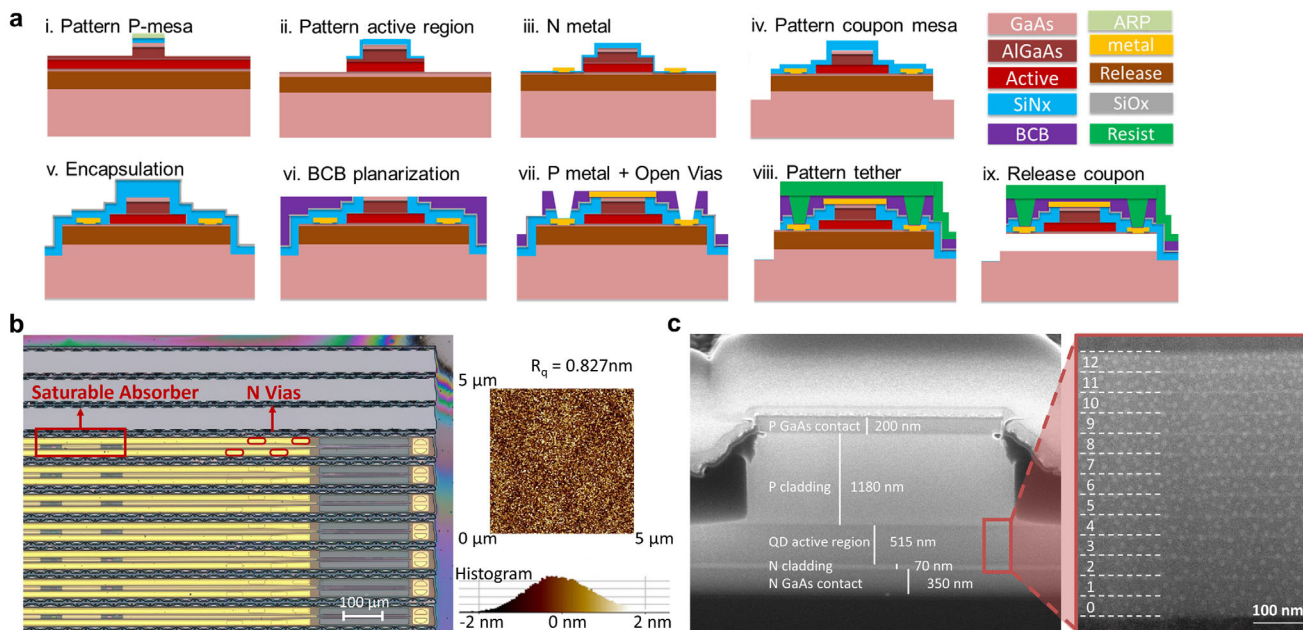


FIGURE 7 | Transfer-printable GaAs coupon fabrication. (a) Schematic illustration of the fabrication process flow. (b) Optical microscope image of the fabricated coupons, and atomic force microscope scan of the coupon backside. (c) Cross-section SEM image and TEM zoom-in of the QDs active region.

nm) was deposited by E-Beam evaporation, and N vias were opened by RIE using a photoresist mask (Figure 7a(vii)). The tether structures were patterned by contact lithography and RIE (Figure 7a(viii)). Details of the tether geometry and pick-up inspection are provided in Note S2. The final release was performed by selective wet etching in a 1:1 37% HCl:H₂O solution at 20°C. After release, the GaAs coupons were suspended and ready for μ TP (Figure 7a(ix)).

Figure 7b shows an optical microscope image of the fabricated GaAs coupons on the native substrate. Three empty sites indicate successful coupon pick-up, and the exposed substrate surfaces appear clean. Atomic force microscope (AFM) inspection of the coupon backside reveals an atomically smooth surface with a root-mean-square (RMS) roughness of 0.827 nm. The N vias are staggered along the cavity to avoid creating mechanical weak points. The cross-sectional scanning electron microscopy (SEM) image in Figure 7c confirms accurate etch-depth control throughout the fabrication sequence. We note that the top mesa edges experienced slight undercut during dry etching, which may lead to a marginal increase in optical loss. This can be mitigated by optimizing the etch recipe in future process runs. The white dots in the zoomed-in transmission electron microscopy (TEM) image are artifacts introduced during sample preparation rather than actual InAs QDs. Note S3 summarizes the InP coupon fabrication process, which builds upon the workflows established in our prior work [37, 38].

4.2 | Micro-Transfer-Printing Integration

Prior to printing, a thin adhesive layer of BCB:mesitylene (1:5) was spin-coated on the SiN target chip at 4000 rpm for 60 s and soft-baked at 150°C for 10 min. The resulting BCB was approximately

40 nm thick and was required to improve adhesion between the μ TP-integrated coupons and the SiN chip. After baking, the target chip was cooled slowly to avoid bubble formation in the deposited BCB. Transfer printing was carried out using the X-Celeprint μ TP-100 tool at room temperature. Although our integration was executed at the die level, the process is scalable to wafer-level printing using wafer-scale equipment that provides $\pm 500 \text{ nm}$ (3σ) alignment accuracy for large arrays. Following transfer, the encapsulation layer was removed by 90-min O₂ plasma, and the BCB was fully cured at 280°C. Electrical contacts were formed by depositing 1 μm Au with a 40 nm Ti adhesion layer.

4.3 | Laser Characterization

All devices were characterized on a customized temperature-controlled chuck consisting of an aluminium block mounted on a Peltier element and regulated by a Thorlabs TH10K thermistor together with a TED200C controller. The chuck temperature was maintained at 18 °C for all measurements. A simplified schematic of the measurement setup is shown in Figure 4a. Optical coupling from on-chip waveguides to single-mode fibers was achieved via SiN grating couplers. The lasers were biased using Keithley 2400 source-meter units. Optical spectra were acquired with an Anritsu MS9740A OSA with a resolution of 30 pm at the O-band, and a Yokogawa AQ6375 for the C-band measurements. The optical power was measured using an Agilent 81532A power meter. The optical output was sent to a Discovery photo-receiver (DSC-R409) equipped with a transimpedance amplifier (TIA), where optical beating generated RF comb that was recorded using an Agilent N9010A ESA with a frequency operation range of 10 Hz–44 GHz. To measure the repetition rate frequency, the ESA was used in FFT mode with a RBW of 1 kHz and a frequency span of 400 kHz. The pulse train was recorded

by detecting the electrical signal from the photo-receiver using a Tektronix DSA8300 digital serial analyzer. The optical pulse widths of the mode-locked lasers were measured using an APE pulseCheck intensity autocorrelator. The frequency noise and intrinsic linewidths of single-mode lasers were measured using an OEwaves OE4000 noise analyzer.

Author Contributions

D.W. and B.K. conceived the project idea. D.W., T.R., and C.B. designed and simulated the SiN components and circuits. D.W., L.T., and J.Z. prepared the III-V layout and performed the GaAs coupon fabrication. J.C., C.B., and S.C. developed the Poly-Si process. J.Z. and G.R. supported the μ TP integration. M.B. organized the InP coupon manufacturing. D.W., T.R., L.T., and S.P. carried out the experimental measurements. D.W. and T.R. wrote the manuscript. All authors reviewed the manuscript. M.G., D.T., G.R., and B.K. supervised the project. All authors contributed to discussions and interpretation of the results.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All the data supporting this study are available in the article. Additional data related to this article are available from the corresponding author upon request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: lpor71990-sup-0001-SuppMat.pdf.