Thermally Tuned High-Performance III-V/Si$_3$N$_4$ External Cavity Laser

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Yuyao Guo
Ruiling Zhao
Gangqiang Zhou
Liangjun Lu
Anton Stroganov
Muhammad Shemyal Nisar
Jianping Chen
Linjie Zhou

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Abstract: Silicon nitride ($\text{Si}_3\text{N}_4$) has a higher nonlinear threshold compared to silicon, which reduces the effect of two-photon absorption. However, the low thermo-optic coefficient and the reduced refractive index contrast of thin $\text{Si}_3\text{N}_4$ waveguides lead to a low thermal tuning speed and low thermal efficiency. This paper demonstrates a widely tunable III-V/$\text{Si}_3\text{N}_4$ hybrid-integrated external cavity laser with a relatively faster switching time. The $\text{Si}_3\text{N}_4$ external feedback circuit is based on 800-nm-thick $\text{Si}_3\text{N}_4$ waveguides with an optical confinement factor of 87%. It allows the reduction of the oxide under-cladding layer thickness to 4 $\mu$m and the oxide upper-cladding layer to 1.7 $\mu$m without additional loss. The switching time between two non-adjacent lasing wavelengths is 60.7 $\mu$s. The maximum output power is 34 mW under 500 mA injection current. The side mode suppression ratio is more than 70 dB over the tuning range of 58.5 nm. The laser intrinsic linewidth is 2.5 kHz.

Index Terms: Semiconductor laser, silicon photonics, hybrid integration, integrated photonics.

1. Introduction

Silicon photonics has attracted immense research interests due to its complementary metal-oxide-semiconductor (CMOS) compatibility, low cost, and high refractive index contrast. The primary materials for silicon photonic devices are silicon (Si), silicon nitride ($\text{Si}_3\text{N}_4$), silicon dioxide ($\text{SiO}_2$), and germanium (Ge). While germanium is mainly used for light detection, silicon is suitable for high-density photonic integration and high-speed modulation, and $\text{Si}_3\text{N}_4$ is attractive for passive devices because of its low propagation loss and high nonlinearity threshold. Various silicon photonic devices have been demonstrated, such as wavelength filters, arrayed waveguide gratings, electro-optic modulators, optical switches, photodetectors, etc. [1]–[3]. These devices have been widely employed for diverse applications such as telecommunication [4], optical interconnect [4],
microwave photonics [5], and light detection and ranging (LiDAR) [6]. Some silicon photonic devices have even been commercialized, such as 100-GHz and 400-GHz transmitters [7].

However, due to the indirect bandgap material property of silicon, efficient lasers cannot be made directly on silicon. Although some efforts have been made by resorting to nanostructures [8]–[10], erbium doping [11]–[13], and Raman effects [14], [15], there is still a long way for real-world applications. A viable method for silicon light sources is the integration of external III-V materials with silicon photonics. There are mainly three approaches to combine III-V materials with silicon photonic integrated circuits (PICs) [16]. These are epitaxial growth, heterogeneous integration, and hybrid integration. Epitaxial growth is a monolithic integration solution. So far, it has been demonstrated primarily for the O-band (around the 1310 nm wavelength). Moreover, optical coupling with silicon waveguides is still a problem [17]. Heterogeneous integration is a more mature method than epitaxial growth and can achieve wafer-scale photonic integration, but the yield still needs improvement [18]. Hybrid integration is the most straightforward and easy integration method. The laser/gain chips and the silicon PICs are produced on separate wafers and optimized for high performance after hybrid integration. Moreover, the separation of active and passive chips makes thermal management easier. Though a critical issue in hybrid integration is the mode mismatch between the active chip and the passive chip, the coupling loss can be reduced to below 1 dB by carefully designing a box-like spot size converter (SSC) on the passive chip [19], [20] or designing inverse tapers on both the active and passive chips [21], [22]. The photonic wire bonding technique [23] can also be used to further reduce the coupling loss.

For the hybrid lasers, various external cavity structures including Fabry-Perot (FP) cavities [24], distributed feedback (DFB) gratings [25], Bragg gratings [26], [27], sampled grating distributed Bragg reflectors (SG-DBR) [28], interferometric structures [29], and Vernier microring resonators (MRRs) have been demonstrated on the silicon or Si$_3$N$_4$ platforms [20], [30]–[32]. Among them, the Vernier MRRs-based hybrid external cavity lasers (ECLs) have attracted lots of attention due to the merits of narrow passband response with a large free spectral range (FSR) and a small footprint.

Silicon chip-scale LiDARs have attracted intense interest due to their critical application in autonomous driving vehicles. The laser source should provide high output power and a narrow linewidth to achieve a long detection range. One issue with silicon-based hybrid lasers is that silicon shows strong two-photon absorption (TPA) effect at the near-infrared wavelengths, inhibiting high optical power in silicon photonic circuits. When MRRs are used in the laser cavity, the TPA-limited optical power is even lower. For a typical 500 nm × 220 nm silicon straight waveguide, although the TPA threshold power is around 100 mW, the power enhancement caused by MRR resonance significantly reduces the on-chip optical power to about 20 mW [20], [33]–[35]. As Si$_3$N$_4$ has a much higher nonlinear threshold, the hybrid lasers based on Si$_3$N$_4$ photonic circuits are more favorable. Moreover, the relatively low refractive index contrast of Si$_3$N$_4$ waveguides makes the waveguide propagation loss lower and coupling between the III-V gain chip and the Si$_3$N$_4$ PIC easier, thereby guaranteeing good laser performances. A Si$_3$N$_4$ hybrid laser has been demonstrated with a 40-Hz linewidth and 20-mW output power [32]. A 100-mW high power Si$_3$N$_4$ hybrid laser with a 320-Hz intrinsic linewidth has also been reported [36]. The Si$_3$N$_4$ waveguide used in the previous demonstrations typically has a thickness of 100-400 nm.

Although the static performance of the Si$_3$N$_4$ hybrid laser is better than that of the silicon hybrid laser, the wavelength tuning power consumption is higher and the speed is much lower. The time required to switch between two adjacent and non-adjacent wavelength channels is typically 200 μs [37], [38] and 1 ms [39], respectively. The long switching time hinders the applicability of Si$_3$N$_4$ hybrid laser in LiDAR. For example, the frequency-modulated continuous-wave (FMCW) laser in the vehicle LiDAR system requires a frequency sweep bandwidth of at least 1 GHz and modulation speed of 10-100 kHz [40], [41]. Three factors cause the thermal tuning speed of Si$_3$N$_4$ to be one order of magnitude lower than that of silicon. First, the thermo-optic (TO) coefficient of Si$_3$N$_4$ is close to one-seventh of silicon [42], imposing a much higher temperature to get the same phase shift. Second, because of the lower refractive index contrast of the thin Si$_3$N$_4$ waveguide, the optical confinement is lower, and a significant amount of optical power is distributed in the silica cladding, which further reduces the effective TO coefficient [42]. Third, a thick cladding silica layer is required.
to separate the optical mode from the metallic heater on the top and the silicon substrate on the bottom. Therefore, heat transfer from the metallic heater to the waveguide and dissipation through the substrate needs longer time. All these aspects result in a much slower tuning speed of Si$_3$N$_4$ waveguides than silicon waveguides.

To improve the thermal tuning performance of the Si$_3$N$_4$ waveguides, a feasible method is to increase the optical confinement factor of the waveguide by utilizing a thicker Si$_3$N$_4$ waveguide. A thick Si$_3$N$_4$ waveguide improves the waveguide effective TO coefficient and reduces the silica cladding layer thickness. For example, LIGENTEC has achieved a tuning speed of 25 kHz using 800-nm-thick Si$_3$N$_4$ waveguides [3], comparable to that of silicon waveguides. Hybrid lasers based on the thick Si$_3$N$_4$ platform can benefit from its high tuning speed. The previous work has proved the feasibility of a hybrid laser based on the thick Si$_3$N$_4$ platform [43]–[48]. However, most of them focus on the Rayleigh backscattering in the Si$_3$N$_4$ ring resonator for feedback or injection locking of a hybrid laser [43]–[47], similar to the injection locking used in MgF$_2$ whispering gallery mode (WGM) resonators [49], [50]. Though a Vernier-filter-based tunable hybrid laser used as the pump source for the Kerr soliton generation has also been reported [48], to the best of our knowledge, there is no report on the improved thermal tuning performance benefiting from the thick Si$_3$N$_4$ platform.

Here we demonstrate a hybrid ECL incorporating a Vernier-ring filter on the 800-nm-thick Si$_3$N$_4$ platform. The laser shows a higher thermal tuning speed and a lower thermal tuning power compared to the thin Si$_3$N$_4$-based hybrid lasers. Compared with ECLs with a similar configuration, our laser also shows improved output power and side mode suppression ratio (SMSR), while maintaining a comparable wavelength tuning range and a narrow linewidth.

2. Device Structure and Principle

Fig. 1(a) shows the device structure of our hybrid ECL, consisting of an InP reflective semiconductor optical amplifier (RSOA) butt-coupled with a Si$_3$N$_4$ feedback PIC. The RSOA chip consists of five AlGaInAs quantum wells with a gain spectrum centered in the C-band. The rear side of the RSOA
acting as a mirror of the laser has a high reflection (HR) coating with a reflectivity of about 90%. The RSOA waveguide at the coupling facet is tilted at an angle of 8° to the normal and coated with an anti-reflection (AR) film. A Sagnac loop reflector forms the other mirror of the laser cavity in the Si$_3$N$_4$ PIC. Two add-drop MRRs with slightly different circumferences are inserted in the Sagnac loop acting as the laser longitudinal mode filter. At the coupling facet of the Si$_3$N$_4$ PIC, an inverse taper with a tilting angle of 17.7° to the normal is designed to match the waveguide mode of the RSOA. The inset illustrates the cross-section of the Si$_3$N$_4$ waveguide with an aluminum (Al) heater on top [51]. The Si$_3$N$_4$ waveguide has a thickness of 800 nm and a width of 1 μm. The thickness of the under-cladding layer is 4 μm. The separation distance between the heater and the waveguide is 1.7 μm. It should be noted that the oxide upper- and under-cladding layers are thinner than those used in the 100-nm-to-400-nm-thick Si$_3$N$_4$ platform [30], [52], [53].

Fig. 1(b) shows the working principle of the hybrid laser. The two cascaded MRRs work as a Vernier filter to select a single longitudinal mode with the highest net gain. A slight change in the laser cavity round-trip phase (including RSOA, phase shifter, or MRRs) will result in a continuous shift of the lasing wavelength until it jumps to the adjacent longitudinal mode. Tuning one of the MRRs to shift the Vernier filter wavelength causes the lasing wavelength to hop by an MRR FSR.

3. Simulation

3.1. Laser Cavity

We first simulated the device with the parameters set the same with the design. The length and the waveguide group index of the RSOA are 1.5 mm and 3.6, respectively. The length of the Si$_3$N$_4$ photonic circuit excluding the MRRs is 2.74 mm and the waveguide group index is 2.117. The MRRs have a circumference of 565 μm and 583 μm. Fig. 2(a) shows the normalized reflective spectrum of the Si$_3$N$_4$ circuit obtained from the transfer matrix simulation. The Vernier filter has an FSR of 60 nm, which is consistent with the desired tuning range. Fig. 2(b) shows the calculated full width at half maximum (FWHM) of the Vernier filter passband and the longitudinal mode spacing of the laser FP cavity as a function of the power coupling coefficient of the MRRs. Decreasing the power coupling coefficient of the MRRs increases the effective length of the Si$_3$N$_4$ feedback circuit due to the increased photon lifetime in the MRRs. Although the linewidth benefits from a long external cavity, the small longitudinal mode spacing makes the control of lasing wavelength difficult. In our design, the coupling coefficient is set to be 0.07. The corresponding longitudinal mode spacing is 5.4 GHz and the intrinsic linewidth is estimated to be 3 kHz according to the formula in [54].
3.2. **Si$_3$N$_4$ Waveguide Mode**

We used Lumerical MODE Solutions to simulate the electric field distribution in the Si$_3$N$_4$ waveguide and the confinement factor ($\Gamma$) [55]. As shown in Fig. 3(a), due to the large cross-sectional dimensions of the waveguide, the confinement factor is up to 87%. This helps reduce the oxide cladding thickness without inducing significant substrate leakage loss and absorption loss by the heater. Fig. 3(b) shows the electric field profile in the vertical direction. We adopt a thick under-cladding layer to guarantee negligible substrate leakage loss at the spot size converter (SSC). With the substrate under-cutting technology for the SSC, the under-cladding thickness can be reduced. This would further improve the heat dissipation rate and thereby the heater tuning speed at the cost of reduced thermal sensitivity.

3.3. **TO Phase Shifter**

We used the Lumerical DEVICE to simulate the thermal tuning efficiency and tuning speed [55]. The structural dimensions are set up according to the inset of Fig. 1. The boundary condition is set to a constant temperature (300 K) at the bottom of the substrate. As shown in Fig. 4(a), nearly...
122 mW heating power is required to achieve a $\pi$ phase shift. Fig. 4(b) shows that the temperature transient response. The rising time (10%-90%) and falling time (90%-10%) are both around 47 $\mu$s.

4. Experimental Results

4.1. Basic Laser Performance

The ECL was formed by butt-coupling the RSOA and the $\text{Si}_3\text{N}_4$ PIC chips. The RSOA was attached to an aluminum nitride chip carrier with the P-side down. The carrier was positioned on top of a thermoelectric cooler (TEC) and fixed with silver epoxy. During the measurement, the TEC temperature was controlled at 20 °C. A lensed fiber was aligned with the output port of the $\text{Si}_3\text{N}_4$ circuit. An isolator and an optical attenuator were inserted between the lensed fiber and the optical power meter. Fig. 5(a) shows the measured L-I-V curve. To measure the threshold current, we first aligned the MRRs and increased the RSOA current in small steps while turning on the phase shifter for longitudinal phase compensation. The resulted threshold current is approximately 53 mA. The maximum output power is about 34 mW under the pump current of around 500 mA. The output power can be further improved by optimizing the coupling efficiency between the $\text{Si}_3\text{N}_4$ chip and RSOA chip (~2 dB in the current device), decreasing the internal loss of the RSOA chip, and increasing the power coupling coefficient of the MRRs. We also tested the output power when the TEC temperature was set to 60 °C. As shown in Fig. 5(b), the maximum output power reaches about half of that at 20 °C.

Fig. 6(a) shows the superimposed lasing spectra over a wavelength range of 58.5 nm (1516.5 nm - 1575 nm) by tuning one of the MRRs. The spectra were measured with a high-resolution spectrum analyzer (APEX, AP2040A, resolution of 0.16 pm). Due to the limited measurement range, the spectra at the long-wavelength end were measured by another spectrum analyzer (YOKOGAWA, AQ6370D-12). The increased noise floor on the long-wavelength side was caused by the equipment. The laser wavelength tuning range is consistent with the simulation results in Fig. 2(a).

Fig. 6(b-d) present traces of the single lasing spectrum. No side modes were observed. The optical signal to noise ratio (OSNR) is 75 dB at around 1554 nm wavelength. The OSNR on the short and long wavelength sides slightly reduce to 70 dB and 72 dB, respectively. It indicates that SMSR exceeding 70 dB is achieved over the whole tuning range. The high SMSR benefits from the low parasitic reflection, the high SMSR of the Vernier filter, and the low waveguide loss of the $\text{Si}_3\text{N}_4$ circuit. To the best of our knowledge, an SMSR of 70 dB in a 58.5 nm wavelength range is a record for the III-V/$\text{Si}_3\text{N}_4$ and III-V/Si ECLs.
We measured the laser frequency noise using an optical noise analyzer (SYCATUS, A0040A). To avoid parasitic reflection, an optical isolator was connected to the laser output. Fig. 7 shows the power spectral density (PSD) in the frequency range from 100 Hz to 20 MHz for a pump current of 254 mA. The laser wavelength is 1537 nm. At about 6 MHz, the frequency noise levels off at
800 Hz²/Hz. Based on the relationship between the intrinsic linewidth and the white noise level [52], the intrinsic linewidth was calculated to be 2.53 kHz.

We used the model in [56] to fit the frequency noise spectrum:

\[ S_v(f) = \frac{\delta \nu}{\pi} + \frac{k_f}{f} + \frac{k_r}{f^2} \]

where \( S_v(f) \) is the optical frequency noise at the Fourier frequency \( f \), \( \delta \nu \) is the Lorentzian linewidth of the laser and \( k_f \) and \( k_r \) are two fitting parameters to characterize the magnitude of the flicker and random walk noises, respectively. From fitting, we obtained \( k_f \approx 3.46 \times 10^8 \text{ Hz}^2 \) and \( k_r \approx 8.54 \times 10^{11} \text{ Hz}^3 \).

4.2. Thermal Tuning Performance

Fig. 8 shows the lasing wavelength changing as a function of the thermal tuning power on MRR1 and MRR2. A nearly linear relationship was observed. In the measurement, only one MRR was tuned, while the other MRR and the phase shifter remain unchanged. Therefore, the lasing wavelength is not exactly in the center of the Vernier filter passband, leading to the small kinks. The thermal tuning efficiency is 0.24 nm/mW. The power consumption is 240 mW to shift one Vernier FSR (equal to \( 2\pi \) phase shift). The power required for thermal tuning is reduced by more than half compared with the thin Si₃N₄ waveguides [31].

Fig. 9(a) shows the setup for the wavelength switching speed measurement. The wavelength switching was obtained by adjusting the heating power on the MRR2. A rectangular electrical switching signal was generated by an arbitrary waveform generator (AWG, KEYSIGHT 81150A). Two optical bandpass filters (BPFs, Santec OTF-970) with a bandwidth smaller than one MRR FSR were used to select the original and shifted lasing modes, respectively. Light after the BPFs was detected by high-speed photodetectors (PDs, u2t XPDV2120R) before it was measured by a real-time oscilloscope (OSC, Tektronix DPO 5054B). A synchronous signal from the AWG was also sent to the OSC as a reference. The switching time was calculated as the time difference between the switching starting point and the end point when the detected signal reaches 90% (10%) for the shifted (original) mode.

In this measurement, the switching power was set to about 100 mW, corresponding to a lasering wavelength shift of ten channels (about 20 nm) in Fig. 6(a). As shown in Fig. 9(b-c), the wavelength switching durations on temperature rise and fall are 24.1 \( \mu \text{s} \) and 60.7 \( \mu \text{s} \), respectively. The reason for the shorter switching time in Fig. 9(b) is that the wavelength passes the shifted MRR resonance peak (with power overshoot) before stabilization. The time to reach final stabilization in the two scenarios is close. Therefore, we use the switching time in Fig. 9(c) to characterize the tuning speed of the laser. The thermal tuning speed is faster than that of the reported Si₃N₄-based ECLs.
based on the thin- Si$_3$N$_4$-platform [37], [38] and comparable with that of the Si-based thermal-tuning ECLs [57].

For the FMCW ranging, the frequency modulation speed is an important factor. We characterized the laser wavelength scanning performance. Fig. 10(a) shows the experimental setup. Optical signals from the hybrid laser and a commercially available tunable laser source (TLS, Agilent 8164A) were combined through a directional coupler (DC). The wavelength of the TLS was set close to the wavelength of the hybrid laser. An electrical triangular-wave signal with an amplitude of 1.8 V was applied onto the phase shifter to change the ECL wavelength within a longitudinal mode spacing. The beating signal was detected by a high-speed photodetector and recorded by an electrical spectrum analyzer (ESA, KEYSIGHT N9010B). We changed the repetition rate of the electrical driving signal and measured the frequency sweeping range of the RF beating signal.

Fig. 10(b) shows the measured RF spectrum at the modulation speed of 20 kHz. The laser frequency sweeping range was obtained by measuring the spectral width of the dynamic RF beating signal. Fig. 10(c) shows the extracted frequency sweeping range varying with the modulation speed. The frequency sweeping range is 2.68 GHz and 1.5 GHz at the 10 kHz and 20 kHz modulation speed, respectively. A 1.5 GHz frequency sweeping range corresponds to a theoretical ranging resolution of 10 cm, which can meet the resolution requirement for long-range detection. It should be noted that the sweeping range (or modulation speed) should be evaluated in combination with the laser longitudinal mode spacing. As for a fixed phase shift (or driving signal amplitude),
the laser frequency shift is proportional to the longitudinal mode spacing [31]. In this study, the measured longitudinal mode spacing is 4.5 GHz, slightly smaller than the simulation. The sweeping range of 1.5 GHz at the 20 kHz modulation speed corresponds to one-third of the FSR. It should be noted that since the longitudinal mode shifts within the passband of the Vernier filter, there is slight power variation during the sweep. If the electrical signals are applied to both the MRRs and the phase shifter, a wider frequency tuning range without power variation can be obtained [31].

5. Discussions and Conclusion

Table 1 compares the performance of this work with other Si$_3$N$_4$ and silicon ECLs with a similar configuration reported in the literature. Our ECL shows the highest SMSR and optical output power, while the intrinsic linewidth is comparable with the state-of-the-art [31]. The 120 nm tuning range in [31] is obtained by using a broadband gain chip with a tunable MZI structure in the external cavity. We can follow this design to expand the tuning range of our device. The tuning power consumption in our work is less than half compared with the thin-Si$_3$N$_4$ based ECLs [31]. Regarding the switching speed, our laser is faster than the reported thin-Si$_3$N$_4$-based ECLs [37], [38] and comparable with the Si-based thermal-tuning ECL [57].
TABLE 1
Performance Comparison with Other Si₃N₄-ECLs and Si-ECLs

| References | [31] | [48] | [30] | [37] | [38] | [57] | This work |
|------------|------|------|------|------|------|------|-----------|
| External cavity material | Si₃N₄ | Si₃N₄ | Si₃N₄ | Si₃N₄ | Si₃N₄ | Si | Si₃N₄ |
| Waveguide thickness (nm) | 340 (DS) | 730 | 300 | 340 (DS) | 340 (DS) | 220 | 800 |
| Tuning range (nm) | 120 | - | 46 | 50 | 44 | 35 | 58.5 |
| SMSR (dB) | 63 | 60 | 52 | 50 | 50 | 30 | 70 |
| Optical power (mW) | 24 | 9.5 | 6 | 10 | 1 | 0.45 | 34 |
| Intrinsic linewidth (kHz) | 2.2 | 40 | 18 | 80 | 25 | - | 2.5 |
| Switching time (μs) | - | - | - | 100(R)/230(F) | 200±40 | 55 | 60.7(F) |
| MRR π-phase-shift power (mW) | 380 | - | 132 | - | - | - | 120 |

DS: double strip Si₃N₄ thickness; R: temperature rising; F: temperature falling.

In summary, this paper has demonstrated a widely tunable III-V/Si₃N₄ hybrid ECL with the Vernier-MRRs-based Si₃N₄ circuit formed on a thick Si₃N₄ platform. The hybrid ECL has an output power of 34 mW, a narrow linewidth of 2.5 kHz, a wavelength tuning range of 58.5 nm, and an SMSR exceeding 70 dB. The thick Si₃N₄ waveguide allows a thin oxide cladding layer, leading to an improved thermal tuning performance. The 2π-phase-shift tuning power for the MRRs is 240 mW. The rising and falling time for switching two wavelengths is 24.1 μs and 60.7 μs, respectively. The frequency sweeping ranges is measured to be 2.68 GHz and 1.5 GHz at the modulation speed of 10 kHz and 20 kHz, respectively. Our ECL can be potentially used in FMCW coherent LiDAR system owing to its combined high performances.

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