

Widely tunable III-V/silicon lasers for spectroscopy in the short-wave infrared

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(Invited Paper)

Abstract—Silicon photonics can provide ultra-compact and high-performance building blocks for integrated laser sources, such as micro-ring resonators, beam combiners and gratings. Integrating III-V gain material with silicon photonic integrated circuits enables the realization of advanced laser sources and fully integrated photonics systems for optical communication and sensing applications. The availability of III-V/silicon laser sources operating in the 2-2.5 μm short-wave infrared (SWIR) wavelength range is very valuable for spectroscopic sensing since many important industrial gases and blood glucose have absorption bands in this wavelength range. In this paper, first we present our latest results on heterogeneously integrated III-V-on-silicon distributed feedback (DFB) laser arrays. A III-V-on-silicon DFB laser array covering the 2.27-2.39 μm wavelength range with 6 nm wavelength spacing is reported. This DFB laser array is employed as the light source for tunable diode laser absorption spectroscopy of different gases. A four-channel DFB laser array integrated with a beam combiner is used to perform spectroscopic sensing over a 7nm spectral range without mode hopping at room temperature. Finally, we present our recent advances in widely tunable Vernier lasers based on heterogeneous integration and butt-coupling of the gain section. Continuous tuning near the absorption lines by thermally adjusting the laser cavity length enable high-resolution TDLAS measurements together with wide wavelength coverage.

Index Terms—Semiconductor lasers, laser array, laser tuning, silicon photonics, mid-infrared

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I. INTRODUCTION

The development of silicon photonics in recent years has enabled low-cost and high-speed integrated optical transceivers used in short-distance data communication and long-haul optical transmission [1]. Integrating III-V materials or prefabricated III-V gain chips with silicon photonic integrated circuits (ICs) provides a practical solution to implement laser sources for silicon photonics applications [2]-[5]. This III-V/silicon hybrid approach also can be used to make advanced laser sources for optical communication and sensing applications since the silicon photonics platform can provide ultra-compact and high-performance photonic components, such as low-loss spiral waveguides, high-Q micro-ring resonators (MRRs) [6], low-loss on-chip beam combiners [7], and widely tunable filters [8]. For example, Z. Wang *et al.* demonstrated a passively mode-locked laser operating at 1.6 μm wavelength with a record-low repetition rate of 1 GHz by heterogeneously integrating a III-V-on-silicon semiconductor optical amplifier (SOA) with a 3.7 cm long silicon-on-insulator (SOI) spiral waveguide (propagation loss ~ 0.7 dB/cm) [9]. T. Kita *et al.* realized a III-V/silicon hybrid laser with a very wide wavelength tuning range that can cover the C-band (1530–1565nm) and L-band (1565–1625nm) of the optical communications window by using two silicon MRRs and an asymmetric Mach-Zehnder interferometer as the wavelength tuning filter [10]. Besides, the integration of III-V/silicon lasers with silicon photonic ICs enables fully integrated spectroscopic sensors for applications such as gas sensing [11] and bio-sensing [12]. In order to realize on-chip silicon photonic spectroscopic sensors, many efforts have been devoted to develop silicon waveguide-based components to probe the

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analyte [13]-[15]. However, in these on-chip silicon photonic sensors, the light from an external laser source is coupled to the chip for the absorption spectroscopy measurement, instead of using an integrated light source [11]-[15]. In order to realize a compact spectroscopic sensor, a chip-scale laser source should be integrated with the probe components. Therefore, realizing a III-V/silicon laser source is also a critical step towards on-chip silicon photonic spectroscopic sensors.

Tunable semiconductor lasers operating in the 2-2.5 μm wavelength range are very relevant for trace gas sensing since many important industrial gases (e.g., CO_2 , CO , CH_4 , NH_3 , C_2H_2) have strong absorption lines in this spectral region [16]. Compared with the near infrared region, the stronger absorption cross section of the molecules enable optical gas sensors to operate in this wavelength range with higher sensitivity. Although the mid-infrared spectral region ($> 2.5 \mu\text{m}$) offers even stronger absorption, in the 2-2.5 μm wavelength range the cheaper photonic components and low-noise photodetectors enable low-cost and miniaturized optical sensors without e.g. an extra cooling system. Among different semiconductor lasers, InP-based and GaSb-based distributed feedback (DFB) lasers and vertical cavity surface emitting lasers (VCSELs) have shown very good performance in the 2-2.5 μm wavelength range [17]-[20]. However, the tuning range of a single DFB laser and VCSEL is limited around 3-5 nm. The development of widely tunable InP-based and GaSb laser sources operating in this spectral region would allow to simultaneously detect different gases. It is also very valuable for bio-sensing considering the broad absorption features of bio-molecules. For example, blood glucose has a strong combination absorption band in the 2-2.3 μm wavelength range [21]. In this wavelength range, GaSb-based gain chips coupled to a diffraction grating used for wavelength selection have shown wide tunability [22]. However, the bulky optic system and mechanical controller used in these widely tunable lasers make it less suitable for portable, low-cost optical sensing.

For the 2-2.5 μm wavelength range, semiconductor lasers based on InP-based type-I, type-II and GaSb-based type-I heterostructures have shown high performance [17]-[20]. Among these material systems, laser diodes based on the GaSb-based type-I quantum wells exhibit the best performance and can lase above 3 μm wavelength [23]. However, the heterogeneous integration processes of GaSb-based materials are not as well-established as for InP-based materials, which results in a low process yield and poor device performance so far [24]. Heterogeneously integrated InP-type-I Fabry-Perot lasers on silicon operating at 2.0 μm wavelength have been demonstrated [25]. However, the emission wavelength of InP-based type-I quantum well lasers is limited to around 2.3 μm [26]. In recent years, InP-based type-II quantum well laser diodes with emission wavelength up to 2.7 μm wavelength have been realized by employing “W”-shaped InGaAs/GaAsSb quantum wells as the active region [27]. In this paper, we present three different types of chip-scale widely tunable lasers based on the heterogeneous integration of InP-based type-II materials on silicon or by butt-coupling a prefabricated a GaSb gain chip with silicon photonic ICs. The paper is organized as

follows. Section II introduces the heterogeneous integration process of InP-based type-II materials and the design of the optical coupling between the III-V waveguide and silicon waveguide. Section III discusses our recent results on InP-based type-II DFB laser arrays on silicon and their application in gas sensing. Section IV focuses on heterogeneously integrated widely tunable Vernier lasers, while Section V is devoted to the widely tunable GaSb/silicon external cavity laser. Finally, the paper is concluded in Section VI.

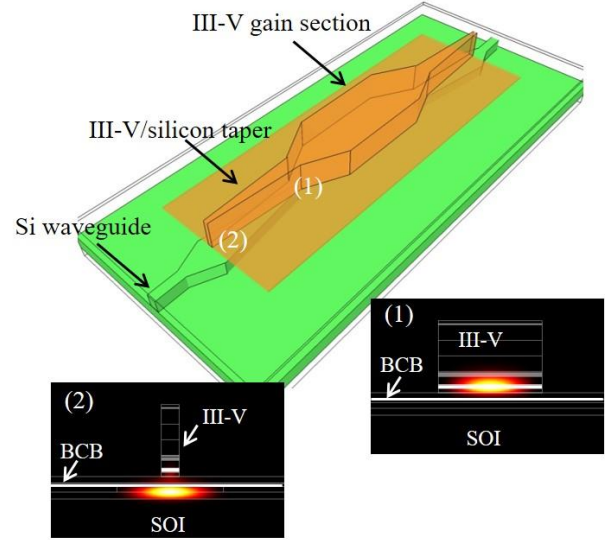


Fig.1. Schematic of the III-V-on-silicon semiconductor optical amplifier. The mode intensity distribution in the III-V/silicon hybrid waveguide at two positions is shown as an inset.

II. HETEROGENEOUSLY INTEGRATED III-V-ON-SILICON LASERS

A heterogeneously integrated InP-based type-II quantum well laser consists of a III-V-on-silicon semiconductor optical amplifier (SOA) and silicon waveguide-based feedback circuit. Figure 1 shows the schematic of the III-V-on-silicon SOA. The SOA is adhesively bonded on a silicon rib waveguide with an etch depth of 180 nm in a 400 nm silicon device layer and consists of a gain section in the center and two III-V/silicon spot size converters (SSCs) on both sides. In the gain section, the optical mode is strongly confined in the III-V waveguide to ensure a high modal gain. The III-V epitaxial layer stack consists of a 200 nm thick n -InP contact layer, an active region sandwiched between a 130 nm thick GaAsSb and a 250 nm thick AlGaAsSb separate confinement heterostructure layer, a 1.5 μm thick p -InP cladding layer and a 100 nm thick $p+$ -InGaAs contact layer. The active region contains six periods of a “W”-shaped quantum well structure, each separated by a 9 nm tensile strained $\text{GaAs}_{0.58}\text{Sb}_{0.42}$ layer. Every quantum well structure consists of a 2.9 nm thick $\text{GaAs}_{0.33}\text{Sb}_{0.67}$ layer surrounded by two 2.6 nm thick $\text{In}_{0.68}\text{Ga}_{0.32}\text{As}$ layers. The calculated confinement factor of the TE polarized fundamental mode in the quantum wells is around 10%. An efficient light coupling between the silicon waveguide and III-V waveguide is achieved by the III-V/silicon SSCs. The SSCs have two tapered section as shown in Fig.1. In the first section, the III-V

waveguide is linearly tapered from 5 μm to 1.2 μm over a length of 50 μm . In the second section, the III-V waveguide is linearly tapered to a very narrow tip where the silicon waveguide is tapered from 0.2 μm to 3 μm . The second section is an adiabatic inverted taper coupler, where the optical mode is gradually transferred from the III-V waveguide to silicon waveguide (and vice versa) as shown in Fig.1. The simulated coupling efficiency of the III-V/silicon SSC is around 90% when the III-V taper tip is 0.5 μm wide. Detailed information on the design of the III-V/silicon SSC can be found in Ref. [28].

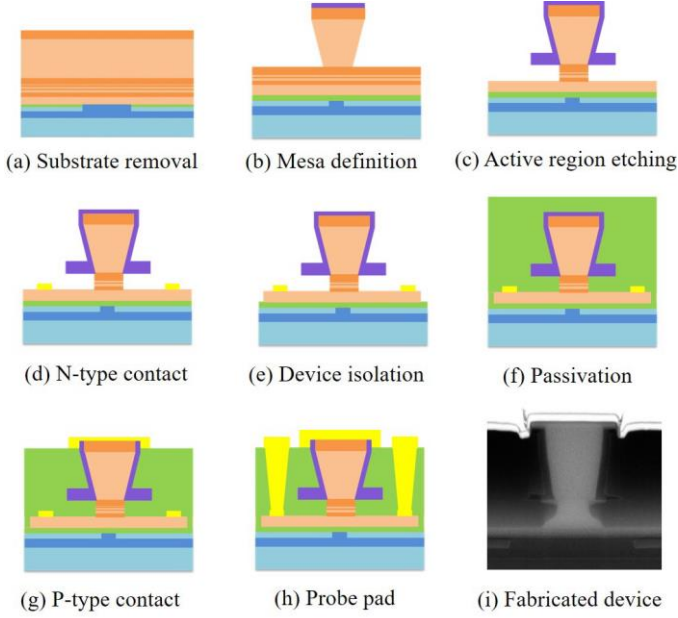


Fig.2. Process flow for the fabrication of III-V-on-silicon lasers.

The fabrication process of heterogeneously integrated InP-based type-II quantum well lasers can be divided in two parts: firstly the silicon waveguide circuits are processed in a CMOS pilot line on 200 mm SOI wafers, then the laser sources are fabricated in a III-V-on-silicon device platform developed for optical communication and sensing applications. In the CMOS pilot line, the waveguides are etched 180 nm deep in the 400 nm thick silicon device layer. To achieve a high-yield and uniform bonding, the silicon wafer is planarized by SiO_2 deposition followed by a chemical mechanical polishing down to the silicon device layer. Then the III-V epitaxial layer is adhesively bonded to the silicon waveguide circuits by a 50 nm thick divinylsiloxane-bis-benzocyclobutene (DVS-BCB) bonding layer [29]. The following process steps are shown in Fig. 2. After bonding, the InP substrate is removed using HCl wet etching (Fig. 2(a)). Then the integrated lasers are processed on the III-V-on-silicon membrane. Firstly, a 200 nm SiN_x layer is deposited on the sample as a hard mask. Then the III-V waveguide is defined using 320 nm UV contact lithography. After dry etching of the SiN_x hard mask and the p^+ -InGaAs contact layer, the 1.5 μm thick p -InP cladding layer is etched using a 1:1 HCl:H₂O solution (Fig. 2(b)). This anisotropic wet etching creates a “V”-shaped undercut, which ensures the III-V/silicon SSC have a very narrow taper tip, leading to an

efficient coupling between the III-V waveguide and silicon waveguide. Afterwards, a second SiN_x hard mask is deposited on the sample to protect the III-V taper tip in the following wet etching. Then the active region is etched in a 1:1:20:70 H₃PO₄:H₂O₂:Citric Acid:H₂O solution using the n -InP layer as the etch stop layer (Fig. 2(c)). Afterwards, Ni/Ge/Au is deposited on the n -InP layer (Fig. 2(d)). After metallization and lift-off, the n -InP is etched by 1:1 HCl:H₂O to isolate different devices (Fig. 2(e)). Then a ~ 3.5 μm thick DVS-BCB layer is spin-coated on the sample to passivate the devices (Fig. 2(f)). After curing, the DVS-BCB layer is etched back to the p^+ -InGaAs layer to expose this contact layer. Subsequently, Ti/Au is deposited on the sample as p -contact (Fig. 2(g)) and probe pad (Fig. 2(h)). A scanning electron microscope (SEM) image of the fabricated III-V-on-silicon lasers is shown in Fig. 2(i). This fabrication process is the same as that of the III-V-on-silicon photodetectors operating in the 2-2.5 μm wavelength range [30], thereby fully integrated spectroscopic sensors can be realized based a single epitaxial layer stack and process flow.

III. HETEROGENEOUSLY INTEGRATED 2.3 μm III-V-ON-SILICON DFB LASER ARRAY

A. Single III-V-on-silicon DFB laser

In a heterogeneously integrated InP-based type-II DFB laser a first-order DFB grating is implemented underneath the III-V-on-silicon SOA as schematically shown in Fig. 3. In the device, the tail of the optical mode interacts with the DFB grating, which selects the emission wavelength of the laser. In order to have stable single mode lasing, a quarter-wave shifted grating structure is used to break the modal degeneracy. The coupling coefficient κ of this DFB grating is calculated to be 80 cm^{-1} . Since the gain section length of the DFB lasers shown in this paper is 700 μm , the normalized coupling coefficient κL of these DFB lasers is around 5.6.

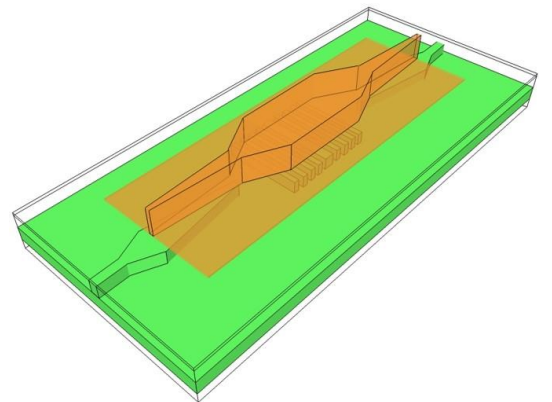


Fig.3. Schematic of the heterogeneously integrated III-V-on-silicon DFB laser.

The integrated lasers are mounted on a temperature-controlled stage during measurements. The light in the silicon waveguide is coupled to a standard single-mode fiber (SMF-28) via integrated chip-to-fiber couplers. To determine the waveguide-couple optical output power of the DFB laser, the

fiber-to-chip coupler loss is measured on reference structures on the same wafer. An optical spectrum analyzer (OSA, Yokogawa AQ6375) is used to study the optical output power and emission spectra of the lasers. Figure 4 shows the continuous wave (CW) on-chip output power-current (L-I) curve of a heterogeneously integrated InP-based type-II DFB laser with a silicon DFB grating pitch of 347 nm. In CW regime, the laser can operate till about 25 °C. The maximum on-chip output is 1.3 mW at 5 °C and reduces to 0.38 mW at 20 °C, while the threshold current increases from 52 mA to 76 mA. The performance of this III-V-on-silicon laser is comparable to state-of-the-art InP-based type-II quantum well lasers on InP substrate [27], [31]. Further improvement can be realized by optimizing the III-V epitaxial layer stack, especially the current injection efficiency. A fiber-coupled lasing spectrum of the device for a bias current 150 mA at 10 °C is shown in Fig. 5. The dominant mode is located at 2318.5 nm. Single mode emission with a side mode suppression ratio (SMSR) of 50 dB is achieved.

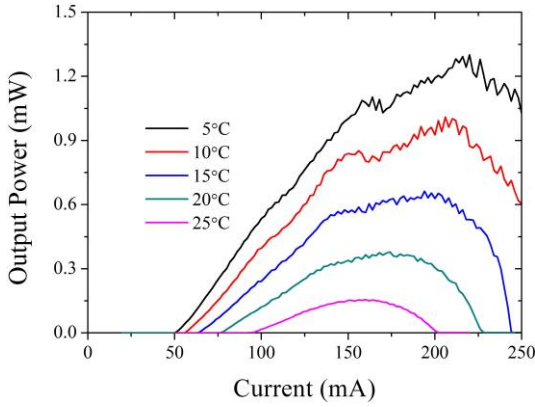


Fig. 4. CW light-current (L-I) curve of the III-V-on-silicon DFB laser with grating pitch of 347 nm.

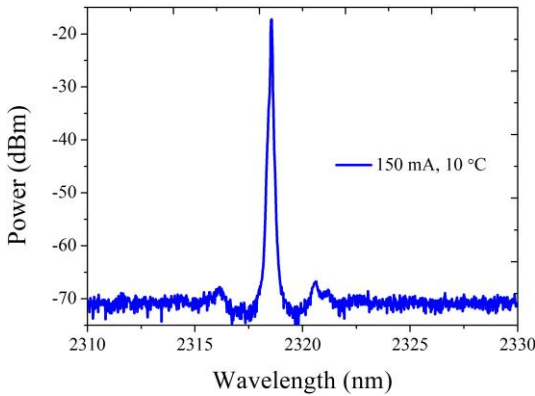


Fig. 5. Fiber-coupled laser spectrum of the III-V-on-silicon laser with DFB grating pitch of 347 nm.

High-performance tunable diode laser absorption spectroscopy (TDLAS) requires laser sources with stable and mode-hop-free tuning. The spectral map of the DFB laser with 347 nm grating pitch as a function of the bias current at 5 °C and 20 °C is shown in Fig. 6. In both maps, the emission spectra

are single mode with a very high SMSR of more than 40 dB throughout the current range. The lasing wavelength linearly changes with the bias current. The device exhibits more than 4 nm and 2.5 nm mode-hop-free tuning at 5 °C and 20 °C, respectively. The current-tuning coefficient is around 0.02 nm/mA at 5 °C and 0.018 nm/mA at 20 °C. A single DFB laser has more than 6 nm current-tuning range when varying the chip temperature between 5 °C to 25 °C. Therefore, a broad wavelength coverage III-V-on-silicon DFB laser array with wavelength spacing around 6 nm can be used to detect any absorption features of molecules in this spectral range. Compared with our previously demonstrated heterogeneously integrated InP-based type-II DFB laser [32]-[33], the device shown here can operate in CW at room temperature and above without mode-hopping.

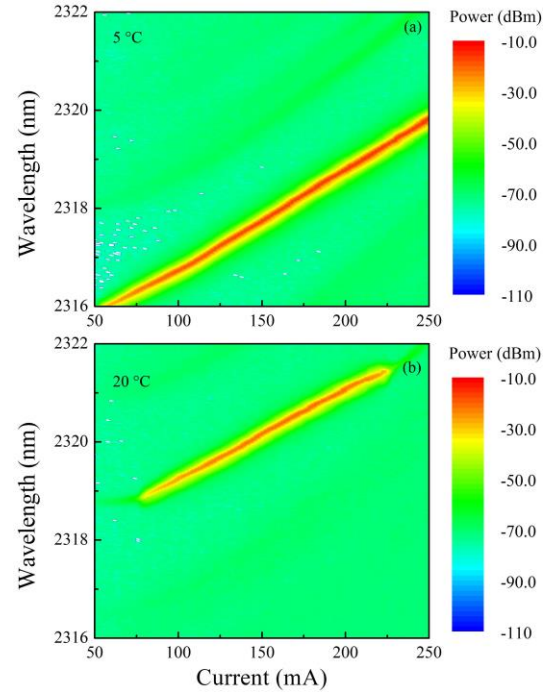


Fig. 6. Spectral map of fiber-coupled emission from the III-V-on-silicon DFB laser with grating pitch of 347 nm at 5 °C and 20 °C.

B. III-V-on-silicon DFB Laser Array

We have demonstrated III-V-on-silicon DFB laser arrays with wavelength spacing of 30 nm at 2.35 μm wavelength range [33]. In order to achieve complete spectral coverage, in this paper we report a heterogeneously integrated InP-based type-II DFB laser array with a wavelength spacing of 6 nm (combined with the wavelength tuning discussed above). Here we take advantage of the state-of-the-art silicon photonics pilot line to fabricate silicon grating arrays with a pitch increment of 1 nm. Figure 7 shows the normalized lasing spectra of a III-V-on-silicon DFB laser array with grating pitch variation of 1 nm. The lasers with grating pitch of 341 nm and 355 nm are measured at 5 °C while other lasers are measured at 10 °C. All lasers are operated CW regime with a bias current of 180 mA. It can be found that a SMSR higher than 30 dB can be achieved for all of lasers. The emission wavelength shifts from 2277 nm

to 2289 nm as the DFB grating pitch increases from 340 nm to 359 nm. 1 nm change in the grating pitch results in 6 nm change in the emission wavelength. The laser with a grating pitch of 344 nm did not lase because of material defects in the III-V waveguide, which could be observed during device processing. The output power of some lasers is substantially lower than others since these lasers have material defects in the III-V taper, which introduce a large loss in the III-V/silicon SSC. The wavelength coverage of this DFB laser array overlaps with absorption bands of many gases, e.g., CO, CH₄, NH₃, HF, C₂H₂. Therefore, it can be used to detect these gases from absorption lines within this spectral range.

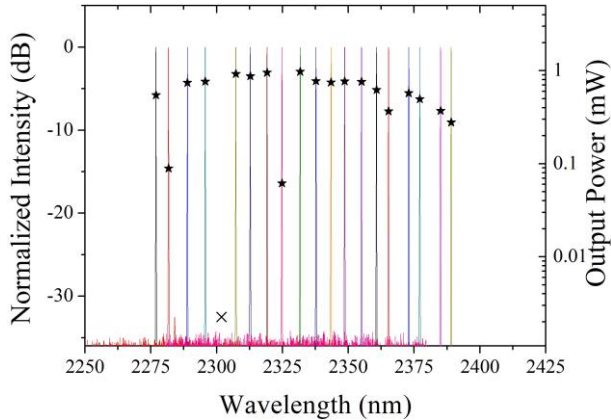


Fig. 7. Normalized emission spectra and output power (indicated by the stars) of III-V-on-silicon DFB lasers with a silicon grating pitch ranging from 340 nm to 359 nm.

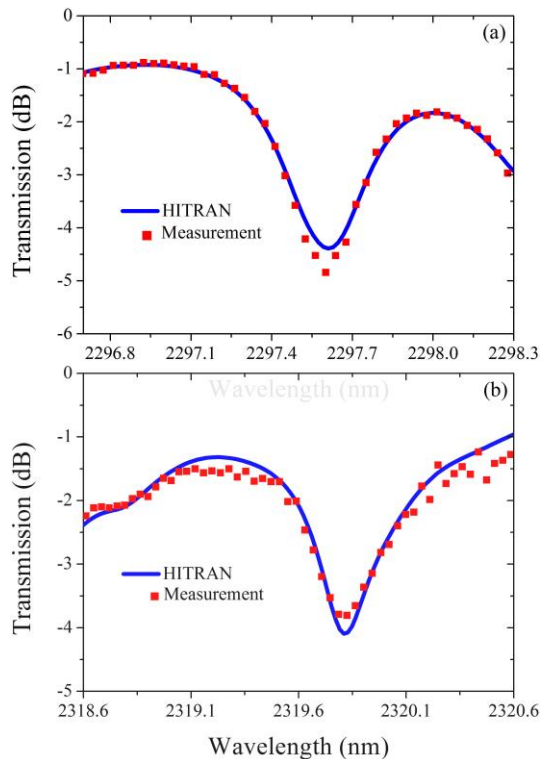


Fig. 8. TDLAS spectra of NH₃ using DFB laser with grating pitch of (a) 343 nm at 20 °C, and (b) 347 nm at 15 °C.

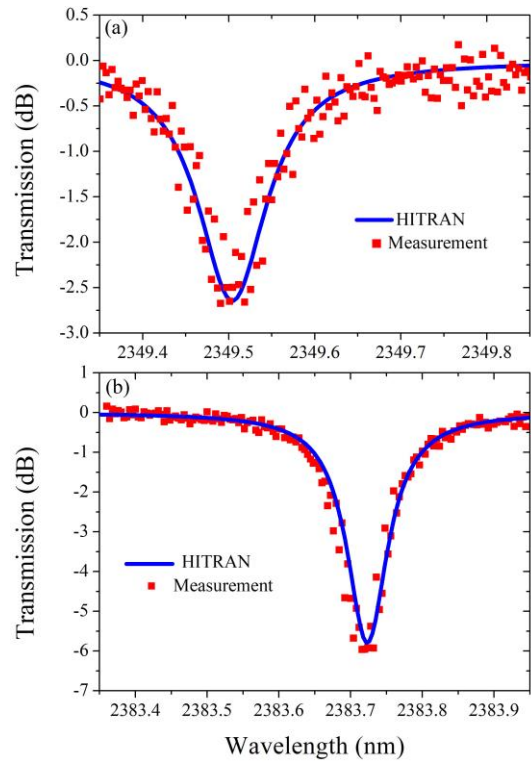


Fig. 9. TDLAS spectra of CO using DFB laser with grating pitch of (a) 352 nm at 10 °C and (b) 358 nm at 5 °C.

The heterogeneously integrated III-V-on-silicon DFB laser array was then used to detect NH₃ and CO based on direct absorption spectroscopy. In the NH₃ sensing setup, the light is coupled from the III-V-on-silicon chip to a single-mode fiber through the integrated on-chip grating coupler, and then coupled to a NH₃ gas cell. The 5.5 cm-long fiber-coupled gas cell contains pure NH₃. DFB lasers with a grating pitch of 343 nm and 347 nm are used to detect NH₃ since their wavelength tuning range overlaps with two strong absorption lines of NH₃. During measurements, the DFB laser with grating pitch of 343 nm is operated at a heat-sink temperature of 20 °C, while the 347 nm device is operated at 15 °C. As the bias current increases, the lasing wavelength is tuned and scanned over the absorption lines of NH₃, showing a dip in the L-I curve. Based on the pre-measured current-wavelength relationship, the absorption spectra can be reconstructed. In this NH₃ sensing measurements, both DFB lasers are tuned in a current step of 2 mA, which corresponds to a wavelength step of around 36 pm. The measured absorption spectra of NH₃ and the corresponding high-resolution transmission molecular absorption (HITRAN) spectra are shown in Fig. 8(a) and 8(b). Good agreement can be observed. In the CO sensing setup, the light from the III-V-on-silicon chip is coupled to a free space gas cell through a collimator. The 10 cm-long CO gas cell contains pure CO and is AR-coated for a wavelength range around 2.35 μm. The DFB laser with grating pitch of 352 nm operated at 10 °C and that with a pitch of 358 nm operated at 5 °C are used. Since CO has much narrower absorption lines than NH₃, the DFB lasers are tuned with a current step of 0.2 mA in the CO sensing measurements, which corresponds to a wavelength step of 4 pm. From the measurement results shown in Fig. 9(a) and 9(b) and

its comparison with the HITRAN data, one can conclude that the III-V-on-silicon DFB laser array is also suitable for gases with very narrow absorption features.

C. Combined III-V-on-silicon DFB Laser Array

For the DFB laser array, the light emitted from different lasers should be combined to a single waveguide for applications in multi-species trace gas spectroscopy [34]. In the telecommunication wavelength range, many types of beam combiners have been developed in integrated optics for wavelength division multiplexing (WDM) optical communications, such as multimode interference (MMI) couplers and funnel combiners [35]. The silicon photonics platform can also provide a low-cost solution to realize high-performance and compact beam combiners for the short-wave infrared wavelength range. In this paper we demonstrate III-V-on-silicon DFB laser arrays integrated with a beam combiner based on cascade 1×2 MMI couplers for applications in broadband spectroscopy and multi-species trace gas sensing. Figure 10(a) shows a microscope image of a four-wavelength DFB array integrated with the beam combiner. The DFB laser array has a separation of $120 \mu\text{m}$ between the different devices, which share a large p -contact pad that is also used as a heat spreader. The beam combiner consists of two stages of 1×2 MMI couplers and S-bend SOI waveguides as shown in Fig. 10(b). The S-bend waveguides from the DFB laser to the MMI coupler have a bending radius of $50 \mu\text{m}$ and those between two MMIs has a bending radius of $100 \mu\text{m}$. The MMI couplers behave as 50/50 splitter/combiners and were chosen because of their small size and high tolerance to fabrication errors. The 1×2 MMI couplers have a length of $28.5 \mu\text{m}$ and a width of $6.5 \mu\text{m}$. A simulated field-intensity distribution of the 1×2 MMI coupler when used as a splitter is shown in Fig. 10(c). The insertion loss of the MMI coupler is lower than 0.3 dB in simulation.

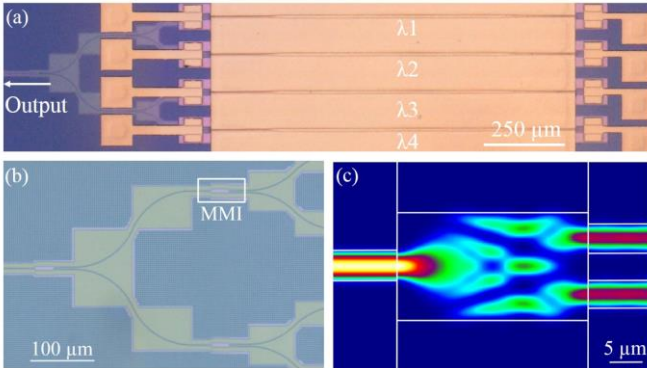


Fig. 10 (a) Microscope image of a four-wavelength III-V-on-silicon DFB laser array integrated with a cascaded MMI beam combiner; (b) zoom-in on the silicon waveguide-based beam combiner; (c) simulated intensity distribution as the light propagates through the 1×2 MMI coupler.

Figure 11(a) shows the normalized emission spectra of a beam combined four-wavelength laser array with different DFB grating pitches. All lasers are biased at 180 mA and operating at 15°C during measurements. The silicon grating pitch varies from 347 nm to 353 nm with a step of 2 nm. The lasing wavelengths of these lasers are located at 2318.9 nm, 2330.9

nm, 2343 nm and 2355 nm. A wavelength spacing of 12 nm is achieved. Besides varying the silicon grating pitch, the lasing wavelength of DFB lasers also can be controlled by adjusting the width of the III-V waveguide, which enables very small wavelength spacing between different channels. Figure 11(b) shows four beam combined lasers (with the same grating pitch) with III-V waveguide widths from $3.8 \mu\text{m}$ to $6 \mu\text{m}$ when driven at the same condition as the array shown in Fig. 11(a). The wavelength spacing in this laser array is around 1.4 nm.

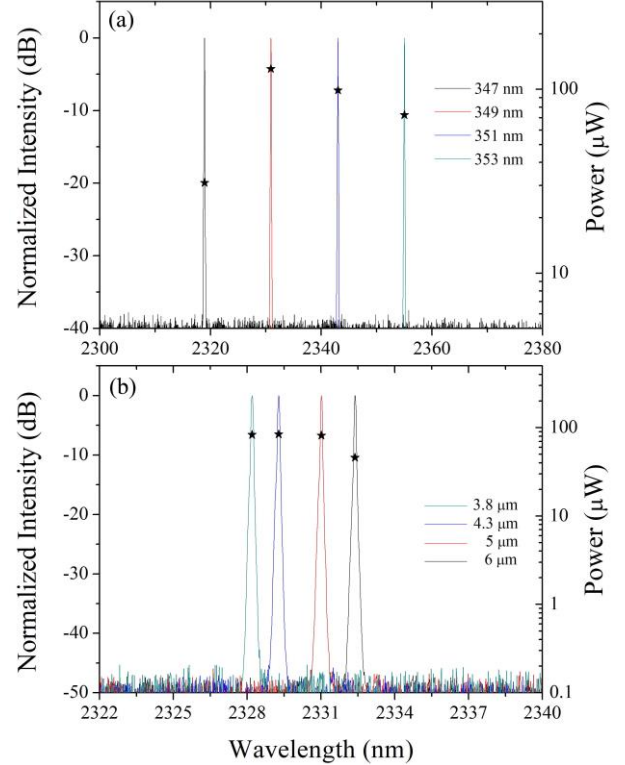


Fig. 11. Normalized emission of the beam combined III-V-on-silicon laser arrays: four DFB lasers with (a) different silicon grating pitches, (b) different III-V waveguide widths. All of lasers in each arrays are measured at the same condition. In both figures, the peak output powers are indicated by stars.

The optical loss in the beam combiners can be extracted by comparing the optical power in the common output waveguide and the waveguide connected with each device on the other side (as the DFB laser structures are symmetrical). In both III-V-on-silicon DFB laser arrays, the loss is around 6.5-7 dB for every channel. The output powers of these lasers are indicated by stars as shown in Fig. 11. This loss mainly comes from the 3dB loss in every 1×2 MMI combiner. By heterogeneously integrating a III-V-on-silicon SOA on the output waveguide, this loss can be compensated. For this, we have demonstrated a heterogeneously integrated InP-based type-II SOA with peak gain of ~ 10 dB and 3 dB bandwidth of 150 nm near $2.35 \mu\text{m}$ wavelength. An alternative solution to reduce the loss in beam combing is replacing the beam combiners with an AWG with low-loss and flat-top passband [36]. Besides, Mach-Zehnder based optical switches also can be used as beam combiners.

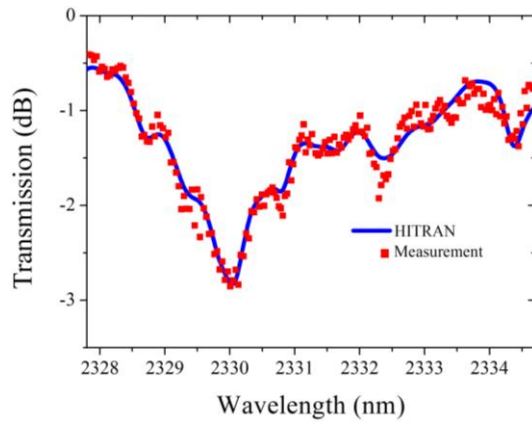


Fig. 12. TDLAS spectrum of NH_3 obtained with the beam combined laser array with different III-V waveguide widths and the corresponding HITRAN spectrum.

The beam combined III-V-on-silicon DFB laser array can be used for a variety of spectroscopic applications. For example, the laser array with large wavelength spacing (e.g., the one shown in Fig. 11(a)) can be used for multi-species trace gas sensing in a broad (>120 nm) spectral range. In this array, each channel can be controlled to lase around a strong absorption line of one gas, that does not overlap with absorption lines of other gases. The laser array with small wavelength spacing can be used for mode-hop free spectroscopy over an extended wavelength range, by only adjusting the bias current of different devices without changing the heat-sink temperature to tune the lasing wavelength. Here we show its application for TDLAS of NH_3 in a >7 nm spectral range as shown in Fig. 12. The beam combined lasers shown in Fig. 10(b) are operated at room temperature during measurements. A good match with the HITRAN data, also shown in Fig. 12, can be observed. Using this approach, we can achieve high-resolution (sub-pm) and fast optical spectroscopy.

IV. WIDELY TUNABLE 2.3 μm III-V-ON-SILICON VERNIER LASER

In the last section, we showed that integrating a series of DFB lasers with silicon photonics beam combiners enables widely tunable single-mode laser sources with mode hop free tuning. In this section, we summarize our recent results on another solution to realize widely tunable laser sources for spectroscopy: heterogeneously integrating short-wave infrared III-V SOAs with widely tunable silicon photonic filters [37]. The schematic of a widely tunable III-V-on-silicon laser using a silicon photonics Vernier filter to select the lasing wavelength is shown in Fig. 13. The Vernier filter and an InP-based type-II quantum well SOA are integrated in a silicon waveguide-based Fabry-Perot laser cavity. The epitaxial layer stack design is the same to the one used in the DFB lasers shown in the last section. The Fabry-Perot laser cavity is formed between a high-reflectivity and relatively low-reflectivity silicon DBR (DBR1 and DBR2 respectively). The light is coupled out from the laser cavity to a single mode silicon waveguide through DBR2. The Vernier filter consists of two silicon micro-ring resonators (MRRs) with

slightly different radii. The radius of MRR1 and MRR2 is $49.1 \mu\text{m}$ and $44.7 \mu\text{m}$, respectively. The different radii lead to different free spectral ranges (FSRs). The FSR of MRR1 and MRR2 is 5 nm and 5.5 nm , respectively. Figure 14 shows the calculated transmission spectra of the two MRRs and the corresponding Vernier filter, assuming an MRR quality factor $Q=2000$ and no waveguide loss. The FSR of the Vernier filter is 55 nm . The transmission of the Vernier filter reaches a maximum when the resonant peaks of the MRRs overlap. Therefore, the lasing wavelength of the III-V-on-silicon Vernier laser is determined by the alignment of the MRR transmission spectra. In order to tune this wavelength position, a microheater is integrated on the MRRs to tune the resonant peak by the thermo-optic effect.

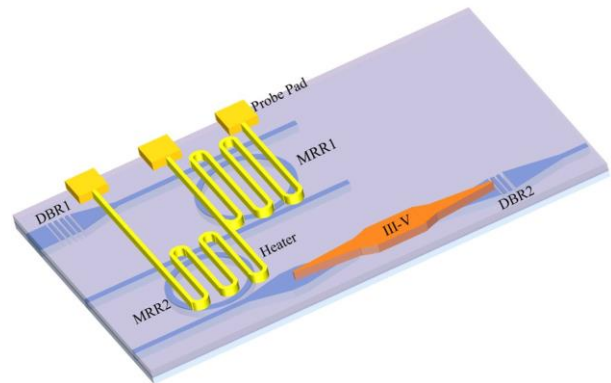


Fig. 13. Schematic of the III-V-on-silicon Vernier laser.

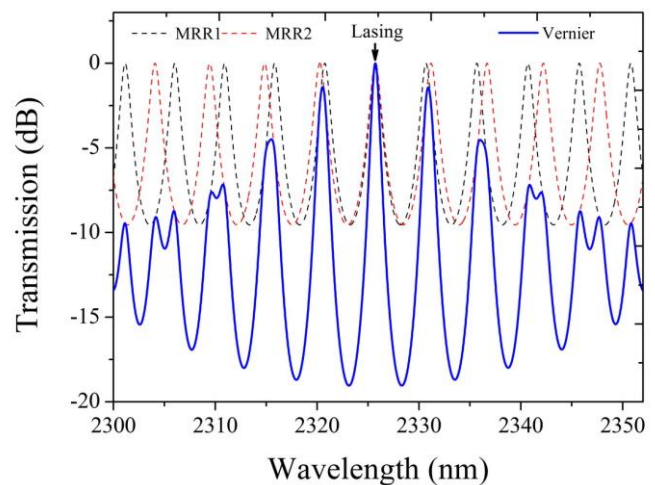


Fig. 14. Simulated transmission spectra of the silicon micro-ring resonators and Vernier filter.

Figure 15 shows CW superimposed lasing spectra and output power (indicated by the stars) of a III-V-on-silicon Vernier laser with a DBR pitch of 435 nm and a MRR Q-factor of 5000 at 0°C . A 30 nm wavelength tuning centered at $2.34 \mu\text{m}$ is achieved by varying the electrical power dissipated in the microheater on top of MRR2. In the tuning, 29 mW change in the heater power dissipation leads to a 5 nm change in the lasing wavelength. In this device, the microheaters are deposited on a $1.8 \mu\text{m}$ thick DVS-BCB passivation layer to avoid optical coupling between the silicon waveguide and heater. Because the DVS-BCB is a low thermal conductivity material, the tuning range of the laser

is limited by the maximum electrical power that can be dissipated in the microheater and the thermal tuning efficiency. Reducing the DVS-BCB gap between the silicon waveguide and microheater can improve the thermal tuning efficiency and maximum affordable power dissipation. Therefore, we also fabricated III-V-on-silicon lasers with a 1 μm DVS-BCB gap. The wavelength tuning range of this laser is improved to 50 nm at 5 $^{\circ}\text{C}$ (when operated in pulsed mode). However, this device did not lase in CW regime at 5 $^{\circ}\text{C}$ because the 1 μm DVS-BCB gap between silicon waveguide and microheaters introduces optical coupling between them, resulting in a higher loss of the laser cavity.

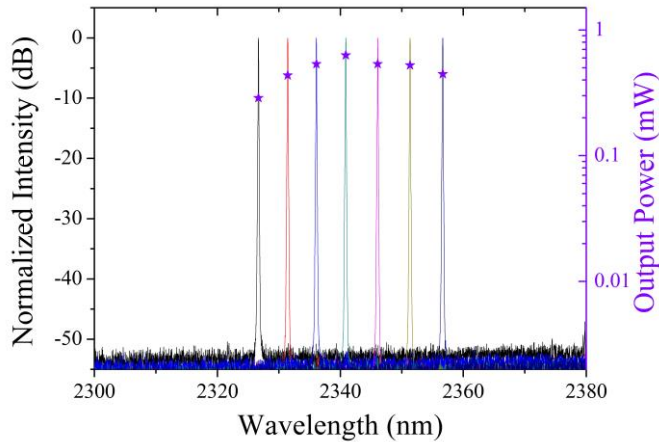


Fig. 15. Superimposed CW lasing spectra and output power of the III-V-on-silicon Vernier laser for different power dissipation in the micro-heater on MRR2.

When the Vernier laser shown in Fig. 13 is tuned by heating one of the MRRs, the tuning resolution is limited by the FSR of the unheated MRR. However, TDLAS of gases with narrow absorption lines requires laser sources that can be continuously tuned near the absorption lines. In order to precisely move the lasing wavelength close to gas absorption lines, both MRRs should be simultaneously heated to achieve a fine wavelength tuning. In this tuning method, the tuning resolution is still limited by the longitudinal mode spacing of the Fabry-Perot cavity. Then we continuously tune the lasing wavelength near the absorption lines by adjusting the bias current of the gain section. The increase of bias current results in a temperature increase in the device, which leads to an increase in the refractive index of III-V waveguide and effective laser cavity length. In this method, a continuous tuning range equal to the longitudinal mode spacing of the Fabry-Perot cavity can be achieved. Figure 16(a) show the spectral map of the fiber-coupled emission spectrum of a III-V-on-silicon Vernier laser as a function of the bias current at 5 $^{\circ}\text{C}$. A continuous tuning range around 0.3 nm is achieved by increasing the bias current by 30 mA. The laser keeps lasing in the 0.3 nm spectral range centered at 2337.4 nm wavelength as seen in Fig. 16 (a) since the FSR of the longitudinal modes is around 0.3 nm. When the lasing mode is tuned too far from the overlapping resonant peak of the two MRRs, the laser will hop to another longitudinal mode closer to the transmission peak of the Vernier filter.

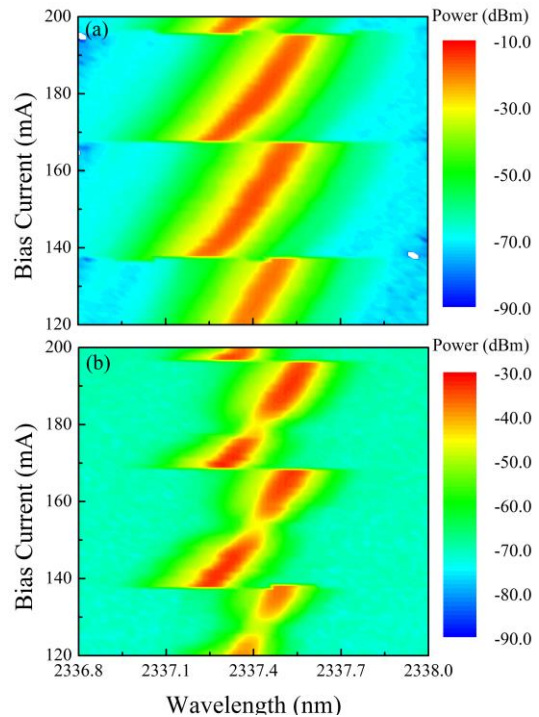


Fig. 16. (a) Contour map of the fiber-coupled emission spectra of a III-V-on-silicon Vernier laser as a function of the bias current; (b) spectral map after the light has passed through the CO gas cell.

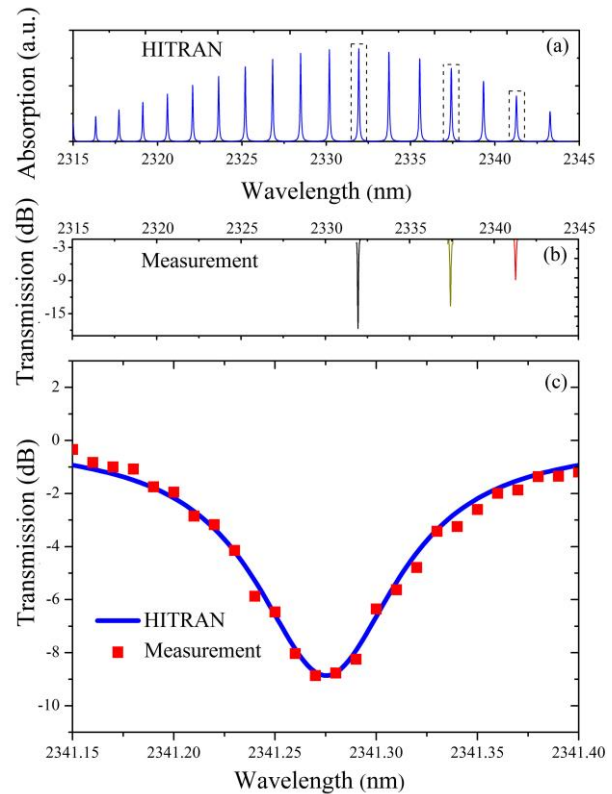


Fig.17. (a) HITRAN absorption spectrum of CO in the 2315-2345 nm range; (b) the measured absorption spectra of three CO absorption lines; (c) zoom-in on the measured absorption line at 2341.2 nm and the corresponding HITRAN spectrum.

We carried out a direct absorption spectroscopy measurement of CO to verify the performance of the III-on-silicon Vernier lasers in TDLAS. Figure 17(a) shows the HITRAN absorption spectrum of CO in the 2315 nm to 2345 nm wavelength range. Many discrete absorption lines with spacing around 2 nm can be seen. The strongest absorption is located around 2332 nm wavelength. In the TDLAS measurements, a CO gas cell identical to the one introduced in the last section was used. A III-V-on-silicon Vernier laser operated at 5 °C in CW regime is used as the laser source. In the measurements, the emission wavelength of the laser is tuned close to one of three absorption lines with different line intensity by heating both MRRs as shown in Fig. 17(b). Then high-resolution spectroscopy is achieved by continuously tuning the laser bias current. Figure 16(b) shows a contour map of the fiber-coupled laser spectra centered at 2337.4 nm wavelength after passing through the CO gas cell. Absorption dips can be seen in the spectral map as the bias current increases from 120 mA to 200 mA. Based on the current-wavelength relationship, the TDLAS spectra and corresponding HITRAN spectra centered at 2341.2 nm are shown in Fig. 17(c). The measured absorption dip and 3 dB bandwidth match very well to the reference HITRAN data in all of three absorption lines. This result indicates the III-V-on-silicon Vernier laser is suitable for high-resolution TDLAS measurements.

V. GASB/SILICON HYBRID EXTERNAL CAVITY LASERS

In the 2-3 μm wavelength range, semiconductor lasers implemented in GaSb-based material systems show better performance than those based on InP-based materials [23]. However, the heterogeneous integration processes of GaSb-based materials are less mature than that of InP-based devices, which results in a lower process yield and laser performance for the former [24]. Here we summarize our recent work on GaSb/silicon external cavity lasers by butt coupling a GaSb-based gain chip with a silicon photonic IC [38]. In this method, a compact widely tunable external cavity laser can be realized by utilizing an ultra-compact silicon photonic IC and high-performance silicon photonic filters, while heterogeneous integration processes are avoided. Figure 18(a) shows the schematic of the GaSb/silicon external cavity laser. A GaSb-based superluminescent diode (SLD) is used as the gain chip. In the 2 mm long gain chip, a HR coating with >95% reflectivity is applied on one facet while an AR coating with <0.1% reflectivity is applied on the facet close to the silicon photonic IC. The AR coated facet has a tilt-angle of 5.2 degrees to avoid self-lasing in the gain chip. The light coupling between the gain chip and silicon photonic IC is realized by a silicon SSC. To match the optical mode of the light from the gain chip, a 6 $\mu\text{m} \times 0.06 \mu\text{m}$ silicon slab waveguide tilted 12 degrees is used as the facet of the silicon SSC. In order to efficiently convert the mode from the slab waveguide to that of the single mode strip waveguide (0.7 $\mu\text{m} \times 0.22 \mu\text{m}$), a 200 μm long silicon waveguide tapered from 180 nm to 700 nm is used in the SSC. Simulations indicate that the coupling loss between the gain chip and silicon slab waveguide is around 1dB, and the mode

conversion loss between the silicon slab waveguide and strip waveguide is also around 1dB. A microscope image of the interface between the gain chip and silicon photonic IC is shown in Fig. 18(b). A Fabry-Perot laser cavity is formed between the HR-coated facet of the gain chip and the silicon DBR. In the silicon photonic IC, similar to the heterogeneously integrated laser shown in Fig. 13, a Vernier filter consisting of two silicon MRRs is used to select the lasing wavelength. In order to continuously tune the lasing wavelength without changing the bias current of the gain chip, a silicon spiral waveguide is integrated in the laser cavity as a phase shifter.

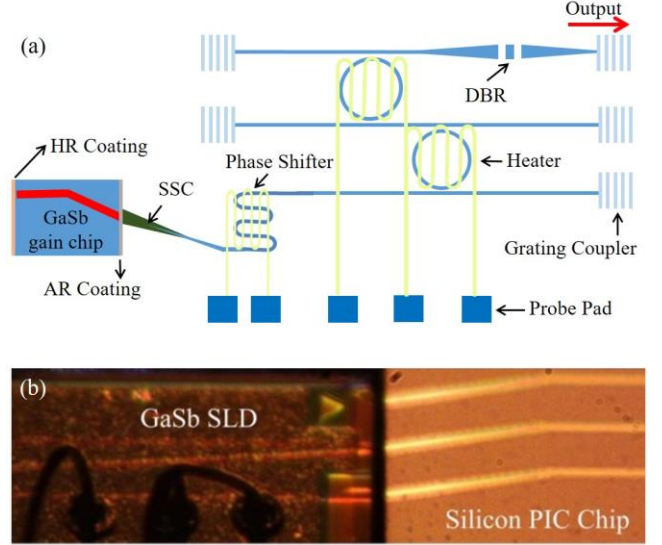


Fig. 18. (a) Schematic of the GaSb/silicon external cavity laser; (b) top-view microscope image of the butt-coupling interface.

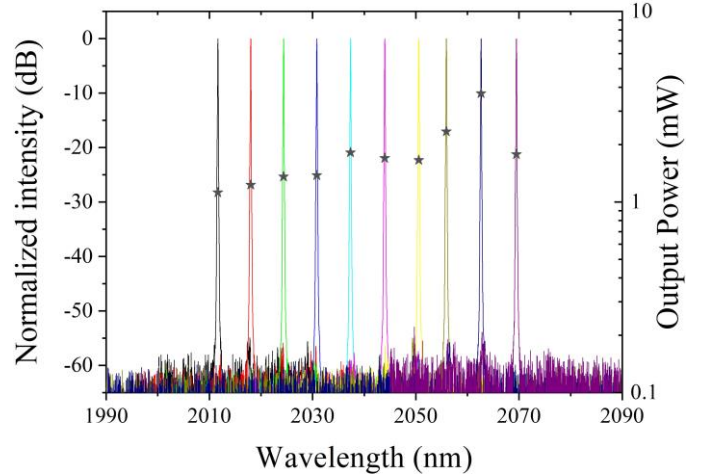


Fig. 19. Superimposed spectra and output power of the GaSb/silicon external cavity laser when the gain chip is operated uncooled.

The wavelength tuning of the GaSb/silicon external cavity laser is also realized by adjusting the electrical power dissipated in the microheaters on the MRRs. Figure 19 shows the superimposed lasing spectra of a GaSb/silicon hybrid laser operating near 2.05 μm wavelength by tuning one MRR. The GaSb-based gain chip is not cooled during measurements. A wavelength tuning range of 58 nm is achieved with a heater

power consumption of 132 mW. Every ~12 mW electrical power change results in 6.5 nm wavelength shift. Over the full tuning range, a SMSR better than 52 dB is achieved. Similar to the heterogeneously integrated Vernier laser, a fine wavelength tuning can be achieved by simultaneously heating both MRRs and a continuous wavelength tuning can be realized by heating the phase section [38]. Under uncooled conditions, the maximum output power of the laser is around 3.8 mW and the threshold current density is 1 kA/cm². The Q-factor the MRRs used in this Vernier laser is 13500. When the Q-factor of the MRRs reduces, the output power will increase and the threshold current can reduce. For example, when the Q-factor of the MRR reduces to 2500, the uncooled laser has a maximum output power of 7.5 mW and a threshold current density of 0.8 kA/cm². However, the SMSR over the full wavelength tuning range reduces to 36 dB and the wavelength stability during tuning also decreases.

VI. CONCLUSION AND PERSPECTIVE

Integrating III-V materials or pre-fabricated gain chips with silicon photonic ICs is very promising approach to realize widely tunable laser sources for advanced spectroscopic applications. The silicon photonics platform can provide plenty high-performance building blocks for III-V/silicon lasers, such as low-loss beam combiners, widely tunable filters and ultra-compact cavities. Based on these silicon photonic components, widely tunable DFB laser arrays, Vernier lasers and external cavity lasers operating in the 2-2.5 μm wavelength range have been demonstrated. These lasers are suitable for TDLAS measurement of gases in a broad spectral range. Moreover, these III-V/silicon lasers can be integrated with silicon waveguide-based probe components and III-V/silicon photodetectors to realize fully integrated on-chip spectroscopic sensors. Further improvements on the III-V/silicon laser performance are still to be made in order to achieve better performance for practical applications. For example, the output power of the heterogeneously integrated lasers at room temperature and above should be improved. This goal can be realized by optimizing the design of the III-V epitaxial layer stack and introducing better heat spreading structures. For the III-V-on-silicon Vernier laser, the DVS-BCB passivation layer can be replaced by material with higher thermal conductivity (e.g., SiN_x) to achieve a wider tuning range in CW mode. For the GaSb/silicon hybrid laser, the Vernier filter (FSR = 65 nm) used in the current device can be replaced by a filter with larger FSR to achieve much wider tuning range. Besides, the GaSb/silicon external cavity laser configuration can be used to realize laser sources in the whole 2-2.5 μm and even at longer wavelengths considering the availability of the GaSb-based gain chips.

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