Hybrid vertical-cavity laser with lateral emission into a silicon waveguide

Park, Gyeong Cheol; Xue, Weiqi; Taghizadeh, Alireza; Semenova, Elizaveta; Yvind, Kresten; Mørk, Jesper; Chung, Il-Sug

Published in:
Laser & Photonics Reviews

Link to article, DOI:
10.1002/lpor.201400418

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Abstract We experimentally demonstrate an optically-pumped III-V/Si vertical-cavity laser with lateral emission into a silicon waveguide. This on-chip hybrid laser comprises a distributed Bragg reflector, a III-V active layer, and a high-contrast grating reflector, which simultaneously funnels light into the waveguide integrated with the laser. This laser has the advantages of long-wavelength vertical-cavity surface-emitting lasers, such as low threshold and high side-mode suppression ratio, while allowing integration with silicon photonic circuits, and is fabricated using CMOS compatible processes. It has the potential for ultrahigh-speed operation beyond 100 Gbit/s and features a novel mechanism for transverse mode control.

Hybrid vertical-cavity laser with lateral emission into a silicon waveguide

Gyeong Cheol Park, Weiqi Xue, Alireza Taghizadeh, Elizaveta Semenova, Kresten Yvind, Jesper Mørk, and Il-Sug Chung

1. Introduction

A laser that can be integrated onto a silicon (Si) wafer and act as an on-chip light source for Si photonics applications, e.g., chip-level optical interconnects, is in much demand and requires innovative breakthroughs in laser diode technology and design. The ideal on-chip laser source needs to meet several criteria [1]: (1) The energy consumption in generating an optical bit (energy/bit) should be no more than $10 \text{ fJ}/\text{bit}$ for on-chip interconnects and around $100 \text{ fJ}/\text{bit}$ for off-chip interconnects. (2) The bit error rate (BER) for the received signal should preferably be less than $10^{-12}$, putting strict requirements on laser output power and noise. At 10 Gb/s, the laser output power thus needs to be well above $10 \mu\text{W}$ [2], with higher bit rates requiring higher output powers.

Several interesting on-chip laser structures have already been reported, including the Si evanescent laser [3, 4], the lambda-scale embedded active region photonic-crystal laser [5, 6], and the Ge laser [7]. While promising, it appears difficult to meet both criteria simultaneously. They have a challenge in either of the two criteria. The vertical-cavity surface-emitting laser (VCSEL) has been the most successful light source for short-reach interconnects (a few meters to less than 1 km). Since this micro laser can provide an energy/bit as low as $69 \text{ fJ}/\text{bit}$ [8] as well as safely satisfying the BER requirement, it can also be an attractive on-chip light source if the emission can be directed efficiently into a Si waveguide, as discussed in [6].

In this letter, we report the demonstration of a promising III-V-on-Si vertical cavity laser that is monolithically integrated onto a Si-on-insulator (SOI) wafer and emits light into an in-plane Si waveguide, hereafter denoted as Si-vertical-cavity in-plane emission laser (Si-VCIEL). Furthermore, as an important technological achievement, the laser was fabricated using direct wafer bonding and CMOS (complementary metal-oxide-semiconductor) compatible processes. The hybrid approach of combining a III-V epitaxial structure with a SOI wafer is proven to be stable in wafer scales [9]. The first idea of in-plane emission was discussed in [10] and the Si-VCIEL structure was proposed in [11], based on numerical simulations. The first experimental demonstration of a double photonic crystal VCSEL with an in-plane waveguide has recently shown that light can be coupled from a vertical laser cavity to an in-plane Si waveguide [12].

2. Device structure

As shown in Fig. 1(a), the Si-VCIEL structure comprises a 7-pair TiO$_2$/SiO$_2$ distributed Bragg reflector (DBR), a III-V active layer, a high-contrast grating (HCG) reflector, and a Si waveguide abutted to the HCG region. The HCG is a

3. Fabrication and Characterization

The sample shown in the Abstract figure, was fabricated by using CMOS-compatible processes: 1) electron-beam lithography for forming a HCG region and a waveguide on a SOI wafer, 2) a direct wafer bonding process for hybridizing the III-V active layer onto the SOI wafer [9], and 3) a lift-off process for forming a DBR. In addition, selective wet etching was conducted to form an air gap between the III-V active layer and the HCG. For characterisation, the fabricated Si-VCIEL sample was cleaved so as to expose the Si waveguide end to the air.

The fabricated Si-VCIEL sample was optically pumped by using a 980-nm diode laser in pulsed operation mode with a 2-% duty cycle \( f_{\text{pump}} \) and a 5-MHz repetition rate. The Si-VCIEL sample was un-cooled. Pumping at 1300 nm would avoid light absorption in the Si layers and subsequent heating, but was not possible in the present samples since the DBR stop band extends to 1300 nm. This is, however, merely a design issue. Due to heat generation, pulsed operation was required. The pumping laser beam was focused onto the top DBR using alignment optics that include a 50× near-infrared objective lens. The white dotted circle in Fig. 2(a) denotes the position of the pumping beam. The measured power transmittance of the alignment optics, \( T_a \) is 21 \%

The sample shown in the Abstract figure, was fabricated by using CMOS-compatible processes: 1) electron-beam lithography for forming a HCG region and a waveguide on a SOI wafer, 2) a direct wafer bonding process for hybridizing the III-V active layer onto the SOI wafer [9], and 3) a lift-off process for forming a DBR. In addition, selective wet etching was conducted to form an air gap between the III-V active layer and the HCG. For characterisation, the fabricated Si-VCIEL sample was cleaved so as to expose the Si waveguide end to the air.

The fabricated Si-VCIEL sample was optically pumped by using a 980-nm diode laser in pulsed operation mode with a 2-% duty cycle \( f_{\text{pump}} \) and a 5-MHz repetition rate. The Si-VCIEL sample was un-cooled. Pumping at 1300 nm would avoid light absorption in the Si layers and subsequent heating, but was not possible in the present samples since the DBR stop band extends to 1300 nm. This is, however, merely a design issue. Due to heat generation, pulsed operation was required. The pumping laser beam was focused onto the top DBR using alignment optics that include a 50× near-infrared objective lens. The white dotted circle in Fig. 2(a) denotes the position of the pumping beam. The measured power transmittance of the alignment optics, \( T_a \) is 21 \%

The pumping power is monitored before the alignment optics. The pumping beam profile on the sample surface and the vertical output profile were imaged by using the alignment optics, an InGaAs camera, and a long-wavelength-pass filter, as shown in Figs. 2(b) and 2(c), respectively. The \( e^{-2} \) diameters for the pumping beam, \( d_{\text{pump}} \), and the vertical output, i.e., transverse mode, \( d_{\text{mode}} \), are 5.84 \( \mu \text{m} \) and 5.99 \( \mu \text{m} \), respectively. The in-plane output was collected.
4. Results and discussion

Figure 2(d) shows the measured light-out, $L_{\text{out}}$ versus light-in, $L_{\text{in}}$ (LL) curve. The light-in represents the power absorbed in the QWs and separate confinement heterostructure (SCH) layers, and is estimated as $L_{\text{in}} = P_m \times T_a \times (d_{\text{mode}}/d_{\text{pump}})^2 \times A$, where $P_m$ is the monitored power incident to the alignment optics and $A$ is the absorption efficiency. The absorption efficiency measures the fraction of the absorbed power in the QWs and SCH layers over the power incident to the Si-VCIEL and is estimated by FDTD simulations to be 30%. The LL curve clearly shows that lasing starts at a threshold input power, $P_{\text{th}}$, of about 29 $\mu$W. The corresponding threshold current, $I_{\text{th}}$, for the continuous wave (CW) case can be estimated as

$$I_{\text{th}} = \frac{29 \mu W}{E_{980} \times q / f_{\text{pump}}} \sim 1.1 \text{ mA},$$

where $E_{980}$ is the photon energy at 980 nm and $q$ is the electron charge. The estimated $I_{\text{th}}$ is similar as that of long-wavelength VCSELs with a similar mode size [17].

The output power in the Si waveguide can be increased to the mW-level. Numerical studies based on FDTD simulations indicate that the output efficiency from the vertical cavity to the Si waveguide is maximized when the tail of the transverse mode overlaps with the starting position of the Si waveguide [11]. The red dotted circle in Fig. 2(a) denotes the pumping position that gives this optimal overlap. However, the laser output power is maximized when the central part of the DBR, indicated by the white circle, is pumped. This is attributed to non-uniformity in the DBR thickness. In Fig. 2(a), the color difference on the DBR surface between the white and red circle positions reflects that the DBR thickness within the red circle is smaller than within the while circle. This implies that the local reflectivity is smaller within the red circle, increasing the laser threshold: thus we could not reach lasing with the available pumping power. Since the optimal position for pumping is displaced by about 10 $\mu$m from the optimal position for lateral waveguide output, the output efficiency from the vertical cavity to the Si waveguide becomes much lower than the designed value: The photon count of $1.15 \times 10^6$ in Fig. 2(d) corresponds to 0.013 $\mu$W for the CW case. The thickness non-uniformity problem caused by the lift-off process can be solved by using etch-back process to define a DBR mesa and/or the Si-VCIEL design can be changed so that the optimal pumping position be located in the center of a DBR. Based on numerical simulations, these changes are expected to increase the output power to a few mW in the Si waveguide [11].

The output light is well confined within the Si waveguide. As shown in Fig. 2(e), the beam profile is clearly centered at the Si waveguide position. The full width at half maximum (FWHM) of the beam profile is $\sim 5 \mu$m which is larger than the waveguide end width of 1.5 $\mu$m. This difference is attributed to the divergence of the output beam from the small-aperture waveguide.

Figure 3(a) shows the in-plane emission spectrum measured from the Si waveguide at a pumping power of 4$P_{\text{th}}$ as well as the vertical emission spectrum measured around $P_{\text{th}}$. Around the threshold, there are three peaks with a spacing of 4.5 nm to 5 nm. At 4$P_{\text{th}}$, the longest wavelength peak becomes dominant with a side-mode suppression ratio (SMSR) of 27.5 dB. It is noteworthy that the spectral linewidth (FWHM) of the lasing peak is 0.66 nm, which is large considering that the pumping power is well above the
threshold. In fact, it appears to comprise about 3 sub peaks. If there are three sub peaks, the sub mode spacing is about 0.2 nm to 0.3 nm.

We find that the appearance of sub peaks can be attributed to anisotropic transverse quantum confinement due to the HCG. The dependence of the vertical cavity resonance frequency, \( \omega \), on the transverse wavevectors, \( k_x \) and \( k_y \), is determined by the transverse dispersions of the propagations within each mirror as well as the spacing between the mirrors, as extensively discussed in [18]. In our vertical cavity, the transverse dispersion contribution from the DBR as well as the spacing between the mirrors are isotropic, while the contribution from the HCG is highly anisotropic. As shown in Fig. 3(b), this results in a highly anisotropic transverse dispersion of the entire vertical cavity resonance: the band curvature in the direction perpendicular to grating bars, \( \frac{\partial^2 \omega^2}{\partial k_z^2} \approx 8.5 \) times smaller than that in the parallel direction, \( \frac{\partial^2 \omega^2}{\partial k_x^2} \approx \frac{1}{m_x} \), where band curvatures are defined following the convention in literature of photonic crystal heterostructures [19]. In our laser sample, the absorption loss in the QWs outside the pumping region determines the transverse mode size, which is confirmed by FDTD simulations. The exponential decay of the transverse mode in the lossy region is equivalent to the decay in the barrier region of a quantum well. Thus, we may model the band-edge frequencies of the pumping and lossy regions as shown in Fig. 3(c).

\[
\omega_{i,j}^2 = \frac{1}{1 + \Delta_0} \left[ \omega_{p,i}^2 + \frac{(\alpha_i \pi)^2}{2m_i L_x^2} + \frac{(\beta_j \pi)^2}{2m_j L_y^2} \right],
\]

where \( i \) and \( j \) are quantum numbers for \( x \) and \( y \) directions, respectively, and \( \alpha_i \) and \( \beta_j \) are rational factors, due to the finite barrier height. Angular frequency \( \omega_n \) and \( \Delta_0 \) determine the cut-off frequency and the barrier height, respectively. Quantum well widths, \( L_x \) and \( L_y \) are assumed to be \( d_{\text{pump}} \). The calculated wavelengths of confined states \( \omega_{i,j} \) listed in Fig. 3(c), reproduce the grouping of modes in Fig. 3(a), which is a good agreement, considering the simplicity of this model. Several transverse mode profiles are listed in Fig. 3(c). The lasing peak should be a mixture of \( \{ \omega_{i,j} \} \). This result shows that the anisotropic dispersion in a HCG-based vertical cavity has huge influence on transverse mode wavelength and profile, which needs to be carefully considered when designing HCG-based vertical cavities.

In the electrically-pumped version of Si-VCIELs, HCG heterostructures will be used for both \( x \)- and \( y \)-directions. Then, not only the band curvature, \( m \), but also the barrier height, \( \Delta_0 \) can be controlled separately for \( x \) and \( y \) directions. This provides rich design flexibilities for transverse mode control. Details based on 3D simulations will be reported elsewhere. The thermal resistance of the electrically-pumped version can be made less than 1K/mW, as discussed in [11].

5. Conclusion

We have experimentally demonstrated a III-V-on-Si vertical-cavity laser with lateral emission into a Si waveguide (Si-VCIEL), using CMOS-compatible processes. This on-chip laser has a threshold comparable to VCSELs, and shows good suppression of higher order modes. The laser has the potential to be modulated at bitrates larger than 100 Gbit/s due to a very high confinement factor, and is capable of novel transverse mode control. These properties make the Si-VCIEL a promising low-cost high-performance light source for chip-level optical systems.

Acknowledgement. The authors gratefully acknowledge support from the Danish Research Council through the FTP project (Grant No. 0602-01885) as well as the Villum Fonden via NATEC Centre of Excellence.

Received: 5 November 2014, Revised: 4 March 2015, Accepted: 30 January 2015

Published online: 13 April 2015

Key words: on-chip laser source, silicon photonics, vertical cavity laser, high-contrast grating.
References