Lateral integration of vertical-cavity surface-emitting laser and slow light Bragg reflector waveguide devices

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We present the modeling and the experiment on the lateral integration of a vertical-cavity surface-emitting laser (VCSEL) and slow light Bragg reflector waveguide devices. The modeling shows an efficient direct-lateral coupling from a VCSEL to an integrated slow light waveguide. The calculated result shows a possibility of 13 dB chip gain and an extinction ratio over 5 dB for a compact slow light semiconductor optical amplifier (SOA) and electroabsorption modulator integrated with a VCSEL, respectively. We demonstrate an SOA-integrated VCSEL, exhibiting the maximum output power over 6 mW. Also, we fabricate a sub-50-μm long electroabsorption modulator laterally integrated with a VCSEL. An extinction ratio of over 15 dB for a voltage swing of 2.0 V is obtained without noticeable change of threshold. In addition, we demonstrate an on-chip electrothermal beam deflector integrated with a VCSEL. © 2014 Optical Society of America

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1. Introduction

High-performance computing and data center markets have grown rapidly as big data increases the demand for systems in recent years. One of the major factors driving the growth of cluster supercomputers has been the rapidly improving performance and efficiency of these systems. Their radically increasing performance comes from the advance of interconnect technologies. Optical interconnects have been extensively developed because optical interconnects offer numerous benefits, such as large bandwidth, low power consumption, high cable density, and immunity to electromagnetic interference [1–5]. A vertical-cavity surface-emitting laser (VCSEL) has been a key component as the light source for use in optical interconnects. A VCSEL proposed by Iga in 1977 has been extensively developed worldwide [6]. It has many advantages over edge-emitting lasers, such as low power consumption, small footprint, a circular light-output mode for high-efficiency coupling to optical fibers, and enabling two-dimensional arrays. High speed and low power consumption VCSELs have been attracting much interest for optical interconnects in data centers and supercomputers [7–14]. However, we still need new challenges in VCSEL photonics for increasing the output power, increasing
the modulation speed, and integrating new functionalities to meet further performance demands for light sources. It has been difficult to increase the single-mode output power of VCSELs because of their small active volume, which limits the output power. The modulation bandwidth is primarily limited by a relaxation oscillation frequency and parasitic capacitance. To solve these issues of VCSELs, there have been reports on vertical integrations of a VCSEL and an amplifier/electroabsorption modulator [15–17]. However, there have been difficulties in their integration because their vertical integration causes the instability of coupled cavities due to strong optical feedback to a VCSEL. Thus, a novel integration scheme of a VCSEL and functional devices will be necessary to make VCSELs to have higher performances. On the other hand, we proposed and demonstrated VCSEL-based slow light devices with Bragg reflector waveguide, including modulators, photodetectors, switches, and beam scanners [18–20]. We are able to integrate with a VCSEL and slow light devices because its vertical structure is the same as that of VCSELs. By slowing light, the modulator length was reduced below 20 μm [18], which potentially offers high-speed modulation beyond 40 Gbps because of its reduced parasitic capacitance.

In this paper, we propose and demonstrate a novel lateral integration scheme of a VCSEL and slow light devices based on a Bragg reflector waveguide toward new functionalities of VCSELs. We carried out the modeling of a slow light semiconductor optical amplifier (SOA) and an electroabsorption modulator integrated with a VCSEL. We demonstrate the lateral integration of a VCSEL and slow light SOA, exhibiting the maximum output power over 6 mW and an external differential quantum efficiency of 43%. Also, we present the experimental result on a sub-50-μm long electroabsorption modulator laterally integrated with a 980 nm VCSEL. An extinction ratio of over 15 dB for a voltage swing of 2.0 V is obtained without noticeable change of threshold. In addition, we demonstrate an on-chip electrothermal beam deflector integrated with a VCSEL.

2. Structure and Modeling of Lateral Integration
The proposed integration structure of a VCSEL and slow light devices is shown in Fig. 1. The slow light devices discussed here include a SOA, an electroabsorption modulator, and a beam deflector having different functions. We propose the lateral optical coupling from a VCSEL to a slow light Bragg reflector waveguide, which is a different approach from the vertical coupling by stacking an optical device on a VCSEL reported so far [15–17]. The vertical emission of a VCSEL is inhibited by a top mirror whose reflectivity is nearly 100%. Lateral optical confinement used in oxide confinement VCSELs is formed using an oxide, which consists of an Al-rich AlGaAs layer [24]. When we reduce the oxide width between a VCSEL and a slow light waveguide, it leads to a leaky traveling wave because the penetration in the lateral direction takes place through the oxide region. It is noted that the group velocity of light traveling along the Bragg reflector waveguide can be reduced [18], thus we are able to integrate compact slow light devices with a VCSEL. The proposed scheme enables us to realize high coupling efficiencies in compact fashion and to avoid instability due to optical feedback. The coupled light is amplified or modulated in a slow light SOA or in a slow light electroabsorption modulator, respectively. The same active region can be used by forward bias or by reverse bias operation, respectively. The output can be taken from a slow light waveguide by decreasing its top-DBR.

First, we calculated the coupling efficiency from a VCSEL to a slow light waveguide with Bragg reflectors. We used a film mode matching method [25] (FIMMWAVE, Photon Design Co.). Figure 2 shows the two-dimensional calculation model. The layer structure in the vertical direction is the same as a conventional 980 nm VCSEL. In this calculation model, a slow light eigenmode of the Bragg reflector waveguide is excited from the left hand and hence a standing wave is formed due to the reflection from the oxide region. Portion of light penetrates through the oxide region and travels in the lateral direction. The lateral optical coupling from a VCSEL to a slow light waveguide can be calculated in this model. We assumed a passive slow light waveguide without gain and absorption loss. The top and bottom mirrors consist of 40-pairs AlGaAs/AlGaAs DBR, respectively, to avoid vertical radiation. The thickness of
oxidized layer \( d \) is 30 nm. The oxide width \( w \) and the vertical position of the oxide are variable to manage the lateral coupling efficiency. We assumed the cutoff wavelength was 980 nm, which is the vertical resonant wavelength. Figure 3 shows the calculated intensity distribution in the lateral direction when the oxide width of 2 \( \mu \)m and one-pair DBR is inserted between an oxidized layer and the one-\( \lambda \) thick core. It shows clearly the lateral optical coupling from a VCSEL to a slow light waveguide.

If the top DBR reflectivity of the VCSEL is high enough, the lateral coupling efficiency \( \eta \) can be expressed by

\[
1/\tau_{\text{out}} = \frac{v_g}{\int|E|^2 \, dy}, \tag{1}
\]
\[
\eta = \frac{1/\tau_{\text{out}}}{1/\tau_{\text{int}} + 1/\tau_{\text{out}}}, \tag{2}
\]

where \( \int|E|^2 \, dydz \) is the integration of the intensity in the VCSEL cavity along the lateral propagation direction \( z \) and the vertical direction \( y \). \( E_0 \) is the electrical field at the boundary between the oxide region and the slow light waveguide and \( v_g \) is the group velocity of the slow light waveguide. \( 1/\tau_{\text{out}} \) denotes the radiation rate in the lateral direction. The internal absorption loss in the VCSEL is assumed as 20 cm\(^{-1} \), which is corresponding to \( 1/\tau_{\text{int}} \). We have confirmed that an excess scattering loss at the boundary is small enough. The coupling efficiency defined in Eq. (2) corresponds to an external differential quantum efficiency of a solitary VCSEL. Figure 4 shows the calculated coupling efficiency as a function of the oxide width \( w \) for different positions of the oxide layer. We are able to obtain a high coupling efficiency of more than 50\%, which is in the same level as high as a conventional top emitting VCSEL.

We fabricated a laterally integrated device with a VCSEL and a slow light waveguide. The schematic structure of a fabricated device is shown in Fig. 5. It consists of 26-pairs Al\(_{0.16}\)Ga\(_{0.84}\)As/Al\(_{0.92}\)Ga\(_{0.08}\)As top DBR, 40-pairs bottom DBR, and \( \lambda \)-cavity containing three In\(_{0.2}\)Ga\(_{0.8}\)As multiple quantum wells (MQWs). The vertical emission of the VCSEL is inhibited by covering with a p-type electrode. A VCSEL and a slow light waveguide are directly coupled without inserting an oxidized layer in between, which are electrically isolated by proton-implantation, as described in Section 4. The width and the length of the gain region of the VCSEL are 4 by 10 \( \mu \)m, respectively. The width of the implanted region is 7 \( \mu \)m. Figures 6(a) and 6(b) show the measured near-field pattern (NFP) and far-field pattern (FFP). The NFP clearly shows the lateral coupling from the VCSEL into the Bragg reflector waveguide. The penetration (propagation) length is 20 \( \mu \)m, which is determined by the radiation through the top DBR and partly by the absorption loss. According to the NFP, we observe the diffraction-limited FFP shown in Fig. 6(b). The radiation (deflection) angle \( \theta_r \) is expressed in the following equation [21]:

\[
\theta_r = k \left( \frac{w}{\lambda} \right) \sin \left( \frac{\pi d}{\lambda} \right)
\]

![Fig. 3. Calculated intensity distribution in the lateral direction when the oxide width is 2 \( \mu \)m and one DBR pair is inserted between the oxide layer and the active region.](image)

![Fig. 4. Calculated coupling efficiency as a function of the oxide width between the VCSEL and the slow light waveguide.](image)

![Fig. 5. Schematic structure of a laterally integrated Bragg reflector waveguide with a 980 nm VCSEL.](image)
where \( n_{wg} \) is the refractive index of the waveguide, \( \lambda_{VCSEL} \) is the lasing wavelength of the VCSEL, and \( \lambda_c \) denotes the cutoff wavelength. The slow down factor can be expressed by the following equation:

\[
f = \frac{c}{v_g} \approx \left( 1 - \frac{\lambda_{VCSEL}}{\lambda_c} \right)^{-1},
\]

where \( c \) is the velocity of light in vacuum and \( v_g \) is the group velocity of the slow light waveguide. Figure 7 shows the calculated radiation angle and the slow down factor as a function of the deviation of a lasing wavelength from a cutoff wavelength. The closed circle shows the experimental observation in Fig. 6(b), exhibiting a slow down factor of over 20. Thus, we are able to make various waveguide devices smaller by a factor of 20 thanks to slowing light.

### 3. Lateral Integration of Semiconductor Optical Amplifier

We carried out the modeling of a slow light SOA laterally integrated with a VCSEL. The slow light SOA based on a Bragg reflector waveguide is also pumped for getting gain. The injection current into the slow light SOA is below the threshold so that the vertical lasing action of the SOA is avoided. We assumed that the oxide width between the VCSEL and slow light SOA is 2 \( \mu \)m, one-pair DBR is inserted between an oxidized layer and the active region having triple 980 nm QWs. Figure 8 shows the calculated intensity distribution in the lateral direction for different injection current densities into the slow light SOA. With increasing the injection current, the intensity in the SOA spread in the lateral direction and hence the penetration length increases. The radiated power from the SOA can be increased by making the SOA longer. The number of the top DBR pairs in the SOA section is optimized to 15 to increase the SOA gain.

The absorption coefficient of the top p-DBR and the bottom n-DBR are assumed as 10 cm\(^{-1}\) and 5 cm\(^{-1}\), respectively. The influence of the gain saturation is not considered in this calculation of the field. We analyzed the gain saturation characteristic of the slow light SOA by using the following traveling rate equations:

\[
\begin{align*}
\frac{dN}{dt} &= \frac{nI}{qV} - (BN^2 + CN^3) - \Gamma g_S S \\
\frac{dS}{dz} &= (\gamma g - (\alpha_r + \alpha_i))S
\end{align*}
\]

Fig. 6. (a) Measured NFP and (b) FFP from the slow light Bragg reflector waveguide with an offset wavelength of 20 nm between the lasing wavelength and the QWs photoluminescent peak of the epitaxial wafer.

Fig. 7. Calculated radiation angle and slow down factor as a function of the lasing wavelength deviation from the cutoff wavelength.

Fig. 8. Calculated intensity distribution in the lateral direction for different injection current densities into the slow light SOA.

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where \( N \) is a carrier density, \( S \) is a photon density, \( I \) is injection current into the SOA, \( V \) is the volume of the active layer of the SOA, \( q \) is elementary electric charge, \( \eta_i \) is internal quantum efficiency, \( B \) and \( C \) are recombination coefficients, \( v_g \) is a group velocity, \( \Gamma \) is an optical confinement factor, \( g \) is a gain coefficient, \( \alpha_r \) is a radiation loss, \( \alpha_i \) is an internal loss, and \( z \) is the direction of propagation, respectively. Then \( f \) is the slow down factor, which is defined in Eq. (4). If we assume that the output can be coupled directly with a multimode fiber, the radiation power can be expressed by

\[
P_{\text{out}} = \int_0^L (Sa_\nu)wdv \frac{h\nu}{\Gamma} dz.
\]

(6)

where \( w \) is the width of the waveguide, \( d \) is the thickness of the active layer, \( h \) is the Plank constant, \( \nu \) is frequency, \( \alpha_r \) is the radiation loss, and \( L \) is the SOA length. If the gain is equal to the loss, the small signal gain can be expressed by

\[
G = 10 \log(\alpha_rL).
\]

(7)

Figure 9 shows the calculated gain saturation characteristic of the slow light SOA when the injection current density is 8.5 kA/cm\(^2\), which is below the threshold for 15-pairs top DBR. The SOA length is assumed as 50 \( \mu \)m, which enables the direct coupling to a multimode fiber. The result shows a possibility of several milliwatts of output power from our SOA-integrated VCSEL whose length is 50 \( \mu \)m or less. We can expect that the output power can be increased with increasing the SOA length and the injection current.

We fabricated a laterally integrated SOA with a 980 nm VCSEL. The schematic structure of a fabricated device is similar to Fig. 5 except the electrical isolation. The top view of the fabricated device is shown in Fig. 10. A VCSEL and a slow light SOA are directly coupled without inserting an oxidized layer in between, which are simply isolated by separating two electrodes. The width and the length of the gain region of the VCSEL are 12 \( \mu \)m \( \times \) 10 \( \mu \)m, respectively. The spacing between p-electrodes of the VCSEL and the slow light SOA is 50 \( \mu \)m. The output is taken from the SOA section. Increasing the injection current in the slow light SOA, the propagation loss including the radiation loss can be compensated. By balancing the gain and the radiation loss, the intensity distribution along the propagation direction can be kept constant. Thus, the output power (radiation power) from the SOA section increases by increasing the injection current. We measured the light output as a function of an injection current in a VCSEL for different injection currents into the slow light SOA. The isolation of p-electrode between a VCSEL and a slow light SOA is not large enough in the present device, which can be avoided by proton implantation, as described in Section 4. This low isolation causes a leakage current between a VCSEL and a slow light SOA. Figure 11 shows the I-L characteristics for different SOA injection currents excluding a leakage current. The slope of the I-L curve and the output power could be increased by increasing the injection current into the slow light SOA. We obtained the maximum output power over 6 mW and an external differential quantum efficiency of 43% at a SOA injection current of 20 mA. This is 7 dB larger than that without the
SOA current. In addition, no noticeable change in the threshold could be seen, which indicates avoiding optical feedback from the SOA.

We also measured the NFP from the top surface of the SOA. The output light distribution captured by a CCD camera at different SOA injection currents of 10, 15, and 20 mA are shown in Figs. 12(a) and 12(b), respectively. The penetration length in the SOA section is clearly increased with increasing the SOA current, indicating that the propagation loss in the SOA section can be compensated. We found that the coupling efficiency from a VCSEL to the SOA is not large enough because the coupled light is absorbed in the large separation of 50 μm between the p-type electrodes. We can expect that the output power can be increased when the separation between the p-type electrodes is decreased and also reducing the reflectivity of the top mirror is useful for increasing the power. In addition, we are able to increase the output power with increasing the SOA length and the injection current.

We also carried out the spatially resolved spectrum measurement of the output light. We measured the spectrum of the output light at the SOA section for different SOA injection currents when the VCSEL current is 10 mA. We can see the lasing wavelength of a VCSEL, as shown in the inset of Fig. 13, which exhibits that the light is coupled from the VCSEL to the slow light SOA. The intensity at this wavelength is shown as a function of the SOA current in Fig. 13.

4. Lateral Integration of Electroabsorption Modulator

When a reverse-bias voltage is applied in the slow light waveguide, it works as an electroabsorption modulator. We carried out the modeling of a slow light electroabsorption modulator. The structure parameters are the same as those of the SOA in the previous section. We assumed the absorption coefficient as 200 cm\(^{-1}\) and 1200 cm\(^{-1}\) in InGaAs/GaAs QWs \([26]\) for nonbiased and reverse-biased operation, respectively, to follow the quantum-confined Stark effect \([27,28]\). Figure 14 shows the calculated intensity distribution for different absorption coefficient of QWs in the modulator section. With increasing the absorption coefficient in the modulator, the lateral penetration of the intensity is decreased and hence the total radiation power decreases. The modulator length can be shorter than 50 μm. The calculation shows a possibility of extinction ratio.
over 5 dB for a compact slow light modulator integrated with a VCSEL.

The layer structure of the integrated modulator we fabricated is the same as that of conventional 980 nm InGaAs/GaAs QWs VCSELs. The schematic structure of the fabricated device is shown in Fig. 15(a). Figure 15(b) shows the top view of the fabricated device, which consists of 21-pairs Al\textsubscript{0.16}Ga\textsubscript{0.84}As/Al\textsubscript{0.02}Ga\textsubscript{0.98}As top DBR, 40-pairs bottom DBR, and λ-cavity containing three In\textsubscript{0.2}Ga\textsubscript{0.8}As MQWs. A VCSEL and a slow light modulator are directly coupled with no oxide layer in between. Proton ion implantation was carried out for electrical isolation between the VCSEL and the modulator. The width and the length of the gain region of the VCSEL are 4 μm x 10 μm, respectively. The spacing between the top p-type electrodes of the VCSEL and the slow light modulator is 7 μm. Light is emitted both from the VCSEL and the modulator section. Intensity modulation in the modulator takes place by applying a reverse-bias voltage in the modulator when the penetration length in the modulator section is reduced due to the electroabsorption in QWs. We carried out the proton implantation with six-step different acceleration voltages from 60 to 350 kV and proton-implant doses of 10\textsuperscript{15} cm\textsuperscript{-2} between the two electrodes. The measured SIMS profile shows that the proton penetrated into the almost entire top DBR whose total thickness is 4 μm. Electrical isolation over 10 MΩ between the two electrodes was obtained thanks to the proton ion implantation, which is large enough for avoiding leakage current under a reverse-bias operation of the modulator.

We carried out the static measurement of the fabricated device with different applied voltages in the slow light modulator. We measured the L/I characteristic with protecting the output from the VCSEL by using a needle, as shown in Fig. 15(b), which enables us to measure the radiation dominantly from the modulator. The threshold current is 1.0 mA. The slope of the L/I curve and the output power are reduced by increasing a reverse-bias voltage in the slow light modulator. No noticeable changes in threshold current and no ripples could be seen, which indicates avoiding optical feedback from the modulator. No antireflection coating is needed in our lateral integrated scheme in contrast to modulator integrated edge-emitting lasers. An extinction ratio is 4 dB at a bias current of 1.5 mA, as shown in Fig. 16(a). The maximum output is 0.1 mW. We are able to increase the output power from the modulator by inhibiting the vertical emission from the VCSEL. We also expect noticeable improvements in output power from the modulator by increasing the top mirror reflectivity of the VCSEL side while keeping the reflectivity of the modulator section.

We found that the measured extinction ratio as shown in Fig. 16(a) is deteriorated by the scattering at the needle detected into a large-area detector for the L/I measurement. In order to measure the spatially resolved intensity, we measured the output from the modulator through a multimode fiber. Figure 16(b) shows the spectra of the coupled power at a bias current of 2 mA through a multimode fiber.
for different bias voltages of 0 V and −2.0 V. The change of the peak intensity shows an extinction ratio of over 15 dB for a voltage swing of 2.0 V, indicating a possibility of a high extinction ratio of over 15 dB through a multimode fiber. Also, the wavelength shift is as low as 0.01 nm, which is also the clear evidence that the optical feedback from the modulator to the VCSEL is negligibly small.

We measured the NFP and FFP from the integrated device with protecting the output from the VCSEL. The output light distribution was captured by a NFP/FFP imaging system at different voltages of 0 and −2.0 V. The measured NFP and FFP are shown in Figs. 17(a) and 17(b), respectively. The intensity in a VCSEL area comes from scattering at the needle, which can be avoided by covering the VCSEL area by a high reflectivity mirror. The lateral optical coupling from the VCSEL to the slow light modulator can be clearly seen and the intensity modulation takes place in the modulator section due to electroabsorption. Also, the effective length of the modulator at the on-state (V = 0 V) is below 30 µm. At a modulator voltage of −2.0 V, the deflection peak in the FFP is clearly suppressed. The result indicates a possibility for the integration of an ultracompact (30 µm long) slow light modulator with a VCSEL.

5. Integration of Beam Scanner

Optical beam scanners have been used for various fields, such as sensing and imaging [29]. There have been a lot of reports on optical beam steering techniques [30]. A mechanical scanner with a rotated polygonal mirror has been widely used because of its high resolution performance [29,30]. However, those devices are bulky and the speed of steering is also slow. We recently proposed and demonstrated a beam steering device based on a slow light Bragg reflector waveguide [21,22]. We found that the deflection angle of output radiated from a slow light waveguide can be widely tuned by changing the wavelength of the wavelength, thanks to the giant waveguide dispersion. Also, a diffraction-limited pattern of a narrow divergence angle of below 0.1° can be obtained at the same time. We realized a number of resolution points over 1000 based on our Bragg reflector waveguide [23].

The schematic structure of an integrated device with 980 nm InGaAs VCSEL and a slow light beam deflector is shown in Fig. 18(a), which is the same as the modulator-integrated device in Section 4. Figure 18(b) shows the measured FFP for different injection currents into the VCSEL. The deflection angle \( \theta_r \) is given by Eq. (3). When we electrothermally change the lasing wavelength by increasing the injection current, the deflection angle can be also changed. We obtained continuous electrothermal beam steering over 5°. The wavelength redshift is estimated to approximately 1.4 nm. The obtained beam-steering angle is in good agreement with the calculation shown in Fig. 7.

6. Conclusion

We proposed the lateral integration scheme of a VCSEL and various slow light waveguide devices...
for new functions of VCSELs. The modeling shows that the lateral optical coupling from a VCSEL to a slow light waveguide takes place and a slow light mode is directly exited from a VCSEL. The coupling efficiency from a VCSEL to a slow light waveguide can be over 50%, which shows the feasibility of a compact slow light SOA and an electroabsorption modulator integrated with a VCSEL. The modeling results also show that 13 dB chip gain, 7 dBm maximum output power, and over 5 dB extinction ratio can be expected for 50-µm-long slow light SOA and modulator, respectively. We demonstrated the lateral integration of a VCSEL and slow light SOA, exhibiting the maximum output power over 6 mW and an external differential quantum efficiency of 43%. Also, we present the experimental result on a 980 nm compact electroabsorption modulator laterally integrated with a VCSEL. An extinction ratio of over 15 dB for a voltage swing of 2.0 V is obtained without noticeable changes of threshold. In addition, we demonstrate an on-chip electrothermal beam deflector integrated with a VCSEL. Our integration scheme offers a new platform of VCSEL-based integrated photonics for various functions.

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