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Compact beam deflector based on slow-light Bragg reflector waveguide monolithically integrated with VCSEL

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Abstract: We demonstrate the monolithic integration of an electro-thermal beam deflector based on a slow-light Bragg reflector waveguide with a VCSEL for the first time. The slow-light mode is laterally exited from a VCSEL and is directly coupled to the slow-light waveguide. The chip size is smaller than 300 μm. The fabrication process is the same as that of conventional VCSELs. Continuous electro-thermal beam steering of over 9° with a diffraction-limited divergence angle of 2.2° is obtained. In addition, a potential in compact and high-resolution on-chip beam deflectors is suggested.

Keywords: VCSEL, slow-light, beam steering, integration

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

References

[1] J. C. Wyant: Appl. Opt. **14** (1975) 1057.
[2] T. Matsuda, F. Abe and H. Takahashi: Appl. Opt. **17** (1978) 878.
[3] Y. Sun, D. A. Francis, S. A. Biellak, A. E. Siegman and C. J. Chang-Hasnain: Electron. Lett. **30** [24] (1994) 2034.
[4] Y. Kurosaka, S. Iwahashi, Y. Liang, K. Sakai, E. Miyai, W. Kunishi, D. Ohnishi and S. Noda: Nat. Photonics **4** (2010) 447.
[5] D. F. Siriani and K. D. Choquette: IEEE Photon. Technol. Lett. **23** [3] (2011) 167.
[6] X. Gu, T. Shimada and F. Koyama: Opt. Express **19** [23] (2011) 22675.
[7] F. Koyama: J. Lightw. Technol. **24** [12] (2006) 4502.
[8] Y. Sakurai and F. Koyama: Jpn. J. Appl. Phys., Part 1 **43** (2004) 5828.
[9] X. Gu, T. Shimada, A. Fuchida, A. Matsutani, A. Imamura and F. Koyama: Appl. Phys. Lett. **99** [21] (2011) 211107–1.
[10] X. Gu, T. Shimada, A. Fuchida, A. Matsutani, A. Imamura and F.

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Koyama: Jpn. J. Appl. Phys., Part 1 **51** (2012) 206.
[11] X. Gu, T. Shimada, A. Fuchida, A. Matsutani, A. Imamura and F. Koyama: Electron. Lett. **48** [6] (2012) 336.
[12] X. Gu, T. Shimada, A. Matsutani and F. Koyama: IEEE Photon. J. **4** [5] (2012) 1712.
[13] T. Shimada and F. Koyama: IEEE Photonics Society 23rd Annual Meeting (2010) 244.
[14] T. Shimada and F. Koyama: OECC 2011 (2011) 271.
[15] T. Shimada, A. Fuchida and F. Koyama: ECOC 2011 (2011) 1.
[16] M. Nakahama, X. Gu, T. Shimada and F. Koyama: Jpn. J. Appl. Phys., Part 1 **51** (2012) 040208.

1 Introduction

Optical beam deflectors/scanners have been key components for various fields such as sensing, imaging, free-space switching and so on [1, 2]. A mechanical scanner with a rotated polygonal mirror has been widely used because of its high resolution performance. However, those devices are bulky and the speed of steering is also slow. There have been various approaches using laser diodes for beam steering including in-plane laser arrays, photonic crystal lasers, phase-locked VCSEL arrays and so on [3, 4, 5]. While non-mechanical beam steering was demonstrated, the number of resolution points N ($= \theta_{rmax}/\theta_{div}$), which can be defined as the maximum beam-steering angle θ_{rmax} divided by a beam divergence angle θ_{div}, has been limited below 100. The number of resolution-points N is needed to be over 1,000 for practical applications. We recently proposed a beam steering device based on a slow-light Bragg reflector waveguide [6] whose structure is the same as that of conventional VCSELs [7]. We found that the deflection angle of output radiated from a slow-light waveguide can be widely tuned by changing the wavelength of an external light source thanks to the giant waveguide dispersion [8] of a Bragg reflector waveguide. Also, a diffraction-limited pattern of a narrow divergence angle of below 0.1° can be obtained at the same time. We demonstrated the ultra-high resolution-points over 1000, which is the highest number ever reported in non-mechanical beam steering devices [9, 10, 11, 12]. However an external light source was needed for our beam steering devices. If we integrate a VCSEL and a beam deflector, an on-chip beam steering device can be realized in a compact fashion. We already proposed and demonstrated the lateral integration of a VCSEL and a slow-light amplifier/modulator [13, 14, 15]. The same structure could be applied for an on-chip beam steering device.

In this paper, we demonstrate a VCSEL based on-chip beam deflector involving a 980 nm VCSEL with a laterally coupled slow-light Bragg reflector waveguide. Continuous beam steering is demonstrated by electro-thermal tuning.

2 Structure

We fabricated a VCSEL based on-chip beam deflector consisting of a 980 nm InGaAs QW VCSEL and a laterally coupled slow-light waveguide.

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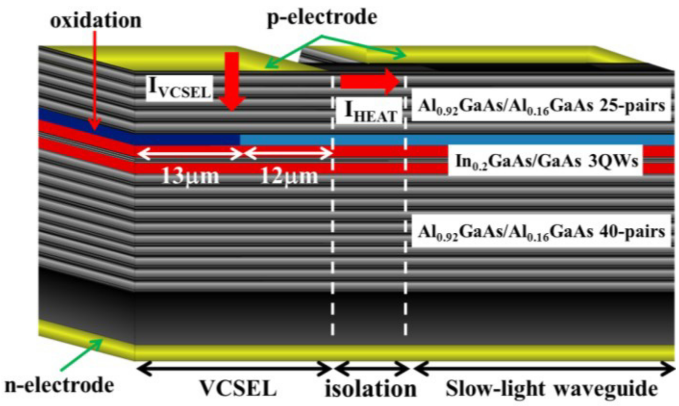
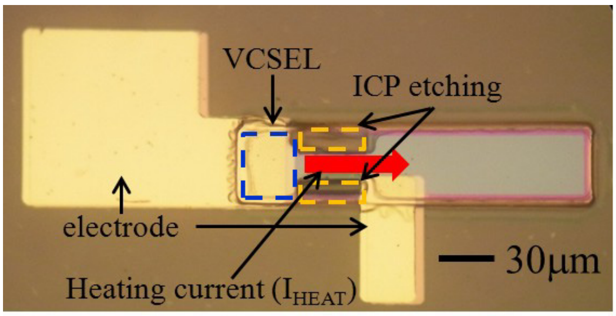
The schematic view and the top view of a fabricated device are shown in Figs. 1 (a) and (b), respectively. The wafer structure is the same as that of conventional 980 nm top-emitting VCSELs. An active region which consists of triple $In_{0.2}Ga_{0.8}As$ MQWs and one $-\lambda$ cavity are sandwiched by top and bottom distributed Bragg reflector mirrors (DBR). The vertical emission of the VCSEL is inhibited by covering with a top electrode, which makes the portion of confined light to be coupled into a slow-light waveguide. The Bragg reflector waveguide can support the lateral guiding of a slow-light mode with giant waveguide dispersion. The output is taken from the surface of a slow-light waveguide functioning as a beam deflector. The top mirror is composed of 25-pairs of $Al_{0.16}Ga_{0.84}As/Al_{0.92}Ga_{0.08}As$ DBR for getting the output from the surface of a slow-light waveguide. On the other hand, the bottom mirror is composed of 40-pairs $Al_{0.16}Ga_{0.84}As/Al_{0.92}Ga_{0.08}As$ DBR, providing almost 100% reflection. The gain region of the VCSEL are $12\,\mu m \times 12\,\mu m$ which was defined by the lateral wet-oxidation process of an AlAs layer. Two top p-type electrodes are formed on the surface of the integrated chip. One is for injecting current into a VCSEL. The other one is used for electro-thermal tuning of the refractive index of the slow-light waveguide. By flowing current between the two electrodes I_{HEAT}, the surface of the slow-light waveguide is heated, resulting the refractive index change of the waveguide. The spacing between the top electrodes of the VCSEL and the slow-light waveguide is $40\,\mu m$. A part of mesa is etched by inductively-coupled plasma etching for efficient electro-thermal tuning. The fabrication process is the same as that of conventional VCSELs.



(a)



(b)

Fig. 1. (a) Schematic structure and (b) top view of an integrated beam steering device.

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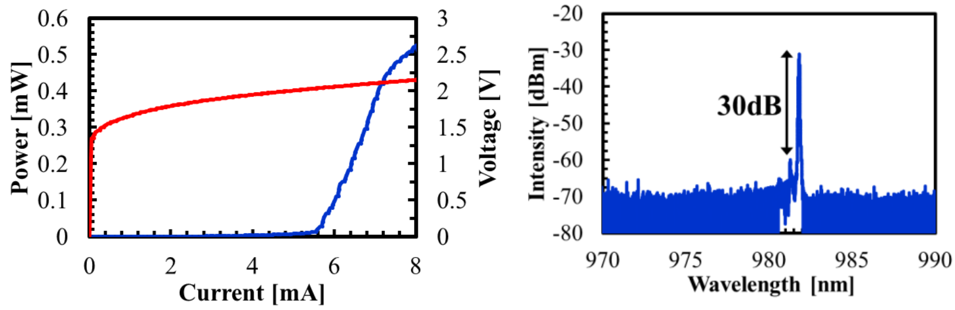
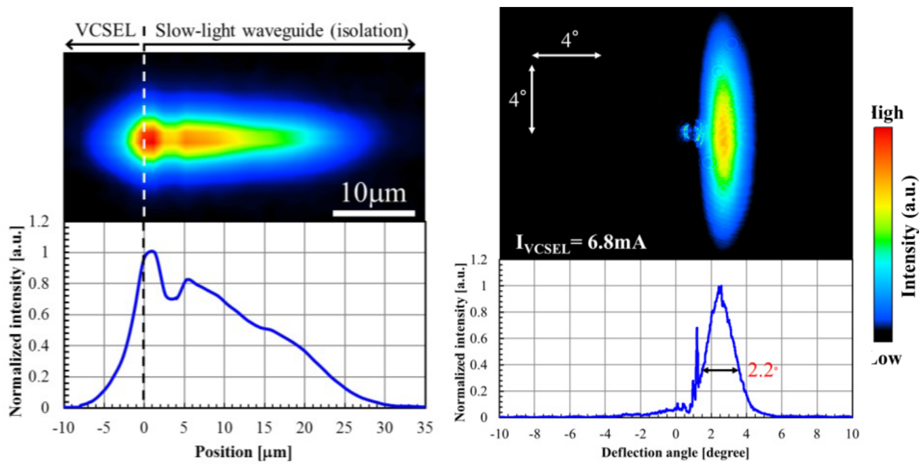
3 On-chip electro-thermal beam steering

The I-L-V characteristic and the lasing spectrum of a VCSEL, exhibiting a single mode operation, are shown in Figs. 2 (a) and (b), respectively. Its relatively high threshold comes from a lateral leakage current into a slow-light waveguide, which can be avoided by introducing an electrical isolation using proton implantation. The measured near-field pattern (NFP) and far-field pattern (FFP) are shown in Fig. 3 when an injection current into a VCSEL is 6.8 mA. The position 0 μm indicates the point of the edge of the top VCSEL electrode. We can clearly see the lateral excitation of a slow-light mode from a VCSEL to a Bragg reflector waveguide. According to the propagation length (20 μm) observed in the measured NFP, we can estimate a diffraction-limited divergence angle of 2.8°, which is in agreement of the measured value. This indicates the radiated field from the Bragg reflector waveguide is diffraction-limited.



(a) (b)

Fig. 2. (a) I- L-V characteristics and (b) lasing spectrum at bias current of 6.8 mA.



(a) (b)

Fig. 3. (a) Measured near-field pattern. (b) Measured far-field pattern. The injection current is 6.8 mA. Position 0 μm indicates the edge of VCSEL top electrode in NFP.

The operating principle of our integrated beam scanner is based on the giant waveguide dispersion of a Bragg reflector waveguide. It is noted that the slow-light mode propagation constant β is highly dispersive in a Bragg

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reflector waveguide [8], which makes a large beam steering angle possible [6]. Following the Snell's law, the deflection angle θ_r is approximately given by [6]

$$sin\theta_r = n_{wg} \times \sqrt{1 - \left(\frac{\lambda_{VCSEL}}{\lambda_c}\right)^2} \quad (1)$$

where n_{wg} is a refractive index of the waveguide, λ_{VCSEL} is a lasing wavelength of the VCSEL and λ_c is a cut-off wavelength of a Bragg reflector waveguide. Equation (1) shows that the deflection angle θ_r can be tuned by changing either the input wavelength λ_{VCSEL} or the cut-off wavelength of the slow-light waveguide λ_c.

When we increase the heater current I_{HEAT}, the waveguide is heated up and λ_c is larger, and hence the deflection angle is increased. On the other hand, if we keep the λ_c constant while thermally changing λ_{VCSEL} by increasing the VCSEL current by (ΔI_{VCSEL}), the deflection angle can be decreased. Therefore, the deflection angle θ_r can be tuned by changing either the injection current into the VCSEL or the heater current of the slow-light waveguide surface.

We carried out beam steering by changing either the VCSEL current (I_{VCSEL}) or changing the heater current (I_{HEAT}). Figures 4 (a) and (b) show the measured FFP with changing ΔI_{VCSEL} and I_{HEAT}, separately. Figure 4 (c) shows the deflection angle as a function of the deviation of the two currents. We can see the change of deflection angles depending on ΔI_{VCSEL} and I_{HEAT}. Here, the multiple-peak ripples in the FFP can be seen. In our fabricated device, the side of the mesa was etched for efficient

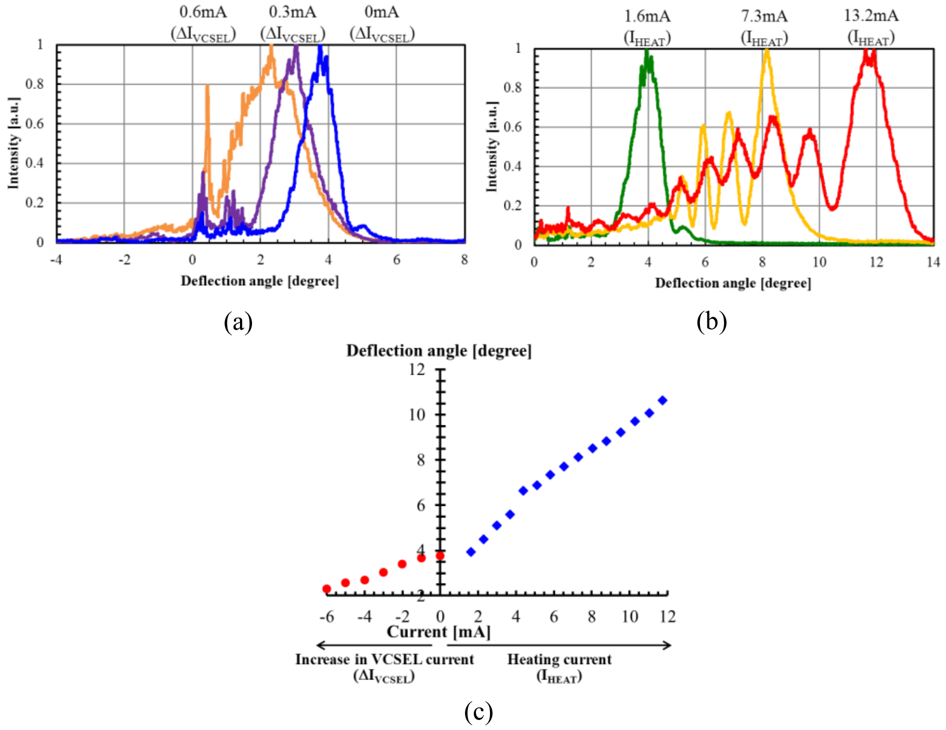

Fig. 4. Far-field patterns controlled by currents in a VCSEL (ΔI_{VCSEL}) (a) and an on-chip heater (I_{HEAT}) (b), and deflection angle as a function of controlling currents (c).

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electro-thermal tuning as shown in Fig. 1 (b). The boundary between the VCSEL and the etched region makes noticeable scattering, which may contribute to lower angles radiation apart from the main lobe of the FFP with increasing the heater current. The interference between the scattering and the radiation from the slow-light waveguide may cause the ripples in Fig. 4. This could be avoided by eliminating the scattering. Careful design of side-etching and/or the use of other electrical isolation technique for efficient electro-thermal tunign such as proton-implantation could be great help.

We obtained continuous beam steering of over 9° for the main lobe. From the experiment, we estimate a local temperature change of approximately 50 K. The number of resolution points N, which is defined by te ratio of the maximum beam steering range $\Delta\theta_{rmax}$ and divergence angle θ_{div} [6], is limited to approximately 4 in the present device. In order to increase N, not only larger $\Delta\theta_{rmax}$ but also smaller θ_{div} is important. The divergence angle θ_{div} depends on the propagation length L. We are able to obtain smaller divergence angles with increasing the propagation length in a lower-loss Bragg reflector waveguide. The divergence angle in the present device is mainly limited by the absorption loss and the radiation loss in the slow light waveguide. These losses can be reduced by injecting current in the slow light waveguide to compensate the propagation loss and increasing the number of pairs of the top DBR. We could obtain a few mm propagation length resulting in a divergence angle of below 0.04° in a solitary beam scanner [12].

Figure 5 shows the calculated number of resolution-points N as a function of temperature changes and propagation length L in a Bragg reflector waveguide. As shown in Fig. 5, we expect a much larger number of resolution-points over 100 by increasing the propagation length over 500 μm in the Bragg reflector waveguide, which could be realized by injecting current in the slow-light waveguide to compensate the propagation loss and/or increasing the top mirror reflectivity [9].

Another possibility for a higher-resolution on-chip beam deflector is to integrate a widely-tunable MEMS VCSEL and a slow-light amplifier [16]. This scheme enables a tunable steering angle of over 30°. A number of

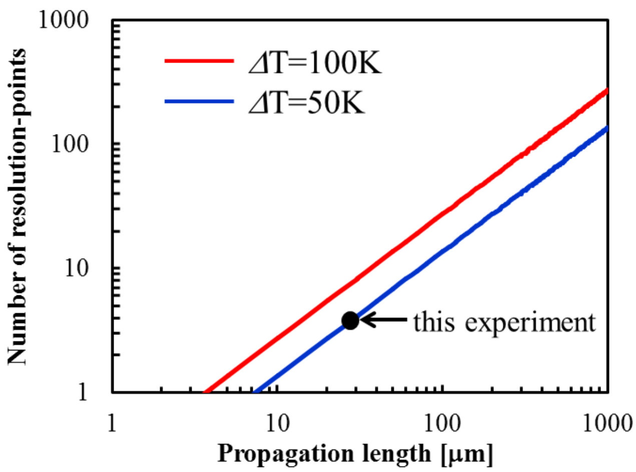

Fig. 5. Number of resolution-points as a function of temperature change and propagation length in Bragg reflector waveguide.

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resolution-points over 300 can be expected by combining this large steering angle with a small divergence angle below 0.1° which can be obtained in case of 1 mm long propagation length. The tuning speed of MEMS VCSELs is typically a few hundred kHz which is 100 times faster than that of polygonal mirror beam scanners. Thus, the lateral integration of a MEMS VCSEL and our slow-light beam scanner could be an alternative for higher-resolutions without sacrificing the steering speed and compactness. An on-chip beam deflector based on VCSEL, which has a number of resolution-points over several hundreds, can be expected by combining these approaches such as reducing the propagation losses for a small divergence angle and the integration of a widely tunable MEMS VCSEL for a larger beam steering angle.

4 Conclusion

We demonstrated the on-chip electro-thermal beam deflector based on a highly-dispersive Bragg reflector waveguide laterally integrated with a VCSEL. A diffraction-limited divergence angle of 2.2° and continuous beam steering of over 9° were obtained by changing the current in a VCSEL and the heater current. A potential in compact ($<500\,\mu$m) and high resolution (>100) on-chip electro-thermal beam deflector is suggested. Our lateral integration scheme may open up new functionalities in VCSELs.

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