Single-mode and High-speed Intracavity Metal Aperture VCSEL with Transverse Coupled Cavity Effect

H. R. Ibrahim (1, 2), Ahmed M. A. Hassan (1, 3), M. Ahmed (2), F. Koyama (1)

(1) Institute of Innovative Research, Tokyo Institute of Technology, ibrahim.h.aa@m.titech.ac.jp
(2) Faculty of Science, Minia University, Egypt
(3) Department of Physics, Faculty of Science, Al-Azhar University, Assuit, Egypt

Abstract *We present a novel design of intracavity metal-aperture VCSELs toward high-speed and single-mode operations. The intracavity metal contact causes the transverse resonance which provides the modulation bandwidth enhancement. The small-signal modulation bandwidth can be double with a large mode-field diameter of 10µm and single-mode operations.*

Introduction

Vertical cavity surface emitting lasers (VCSELs) have exhibited the advantages of low cost, ease of fabrication into arrays, small footprint, wafer-scale testing, and low power consumption [1, 2]. Therefore, VCSELs are attracting much attention for use in data center networks. The network traffic in data centers is increasing rapidly and hence the development of high speed VCSELs is a key issue. The modulation bandwidth of VCSELs is typically less than ~ 20 GHz due to the limited intrinsic carrier-photon resonance (CPR) [3]. Therefore, many efforts have been done to push the modulation bandwidth of VCSELs further into the mm-wave band [4-16] However, there still remain difficulties in increasing the modulation bandwidth of single-mode VCSELs in comparison with multi-mode VCSELs, although single-mode VCSELs offer a longer link length of MM fibers thanks to narrower spectral widths. Also, the poor reliability has been a limiting factor for single-mode, small oxide aperture VCSELs.

In this paper, we propose and demonstrate intracavity metal aperture VCSELs (MA-VCSEL) with a rectangular shaped oxide aperture. The fabrication process is exactly the same as intracavity contact VCSELs. We found that the intracavity metal contact causes the transverse resonance which provides the modulation bandwidth enhancement. We demonstrate the enhancement of the modulation bandwidth and single-mode operation thanks to the optical-transverse coupled cavity effect. The mode-field diameter could be increased to 10 µm with stable-single-mode operations.

Device Structure

Figure 1 (a) illustrates the schematic structure of the fabricated single-mode MA-VCSEL. The device is fabricated on a half-VCSEL wafer grown by MOCVD with 4 pairs of top p-type DBR. The active region includes three 850 nm quantum wells (3QWs). In order to form cavity structures, rectangular shaped mesas were formed by dry-etching process and followed by wet-oxidation process. The size of an active region oxidation aperture is 9 x 10 m, as shown in Fig.1(b) which is large enough for high reliabilities. Polyamide was used for planarization and passivation. AuGe/Ni/Au was deposited to form n-type electrodes. The p-type electrode (Au/Zn/Au) were deposited with a rectangular aperture. Finally, 8 pairs of dielectric Ta_2O_5/SiO_2 were deposited above the surface of the mesas as a top hybrid DBR. We found that two lateral boundaries cause the transverse resonance as shown in Fig. 1(c). A key parameter is the distance d-W between two boundaries, which should be 1.5-2 µm to observe the transverse coupled cavity effect, we found.

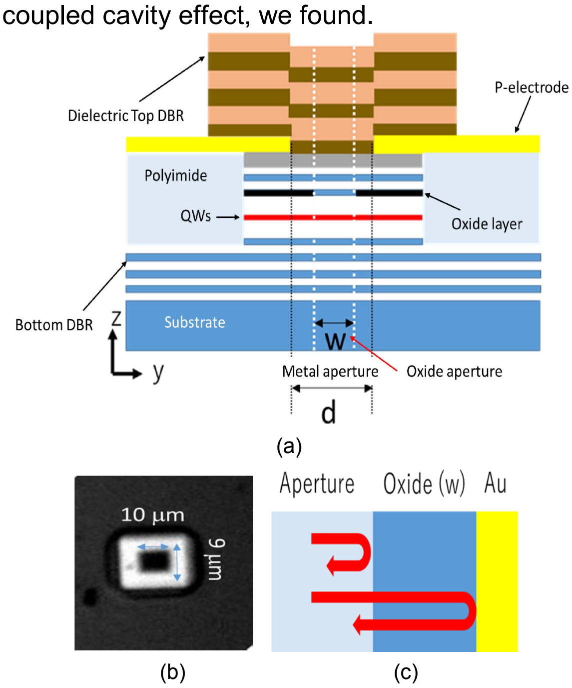


Fig.1. (a) Schematic (b) top-view of infrared image of oxide aperture of 9 x10 µm^2 and (c) the physical picture of the transverse resonance.

Results and discussions

The L-I curves of two fabricated devices were measured; one is for metal-aperture-VCSEL (MA-VCSEL) with a distance of less than 2um between the oxide aperture and metal aperture and the other one is conventional VCSEL (C-VCSEL) with a distance larger than 2um for comparison. Figure 2(a) plots the measured L-I curve of the C-VCSEL with oxide aperture of 9x10 μm^2.when the distance is larger than 2μm. The L-I curve is smooth and no kinks appear.

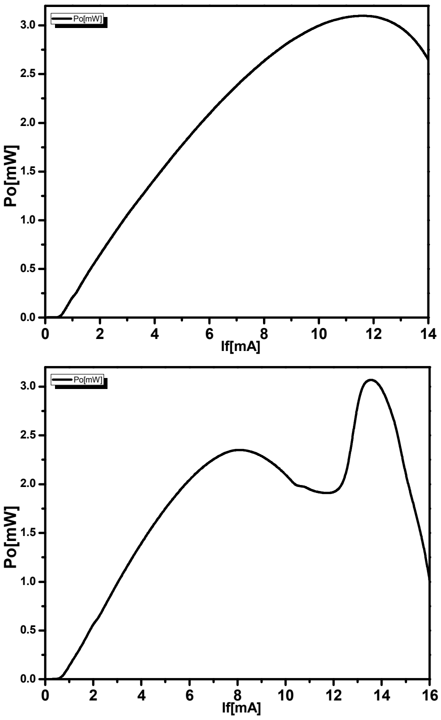


Fig.2. L-I curve for (a) C-VCSEL, and (b) MA-VCSEL.

On the other hand, Fig. 2(b) illustrates the L-I curve of MA-VCSEL with a distance of 1.5 - 2 μm with the same oxide aperture size. A kink appeared in the L-I curve as optical feedback induced from the metal boundary is coupled into the primary VCSEL cavity. The lasing spectra of the MA-VCSEL was measured for different bias currents. A single-mode operation was obtained in the entire current range with SMSR of more than 40 dB as shown in Fig. 3. The intracavity metal aperture works as transverse coupled cavities which cause single mode operation and the enhancement in modulation response. Please note that the operating principle for single-mode operation is totally deferent from metal aperture VCSELs [15] and surface relief VCSELs [16].

Figure 4 shows the measured NFP at 9mA bias current. The mode field diameter is as large as 10 μm which is equal to the oxide aperture size.

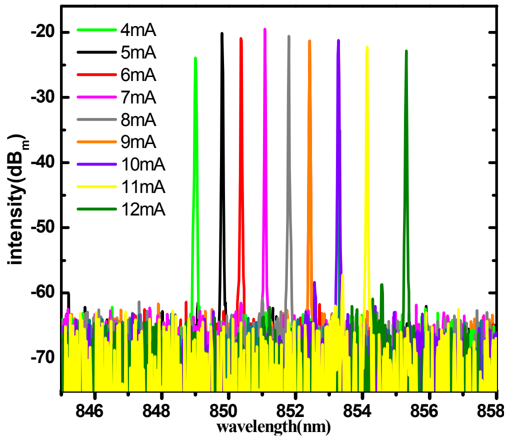
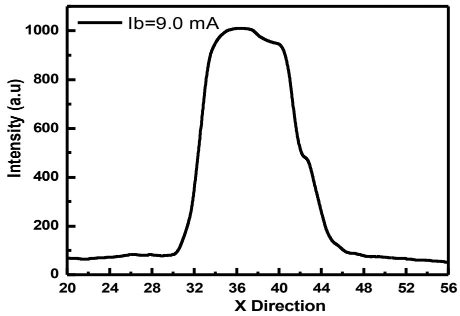
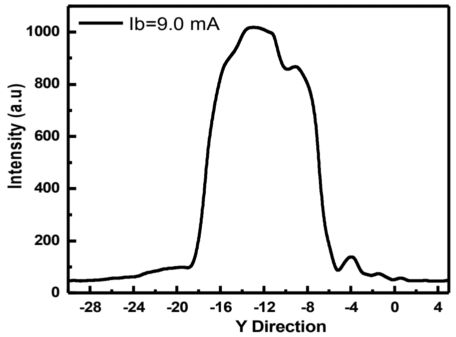


Fig.3. Spectra measured at currents of 4mA to 12mA



(a)

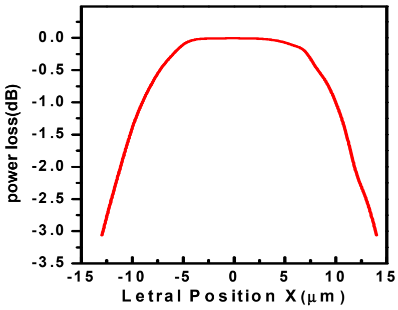


(b)

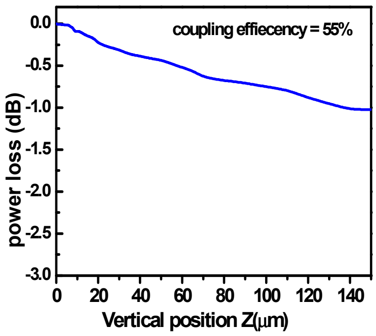
Fig. 4. NFP of MA-VCSEL in the X (a) and Y (b) directions

The direct coupling efficiency with a conventional 1,300 nm single mode fiber was measured which is 55%. The coupling loss partly comes from the mismatch in mode field diameters. The lateral displacement tolerance was observed by change the lateral position of a fiber in both X and Y directions which was plotted in Fig. 5.(a) For the tolerance in the vertical direction, the result was illustrated in Fig.5.(b). The lateral tolerance is as large as 10 μm for 1dB-penalty, which makes a great impact for low cost packaging with a single-mode fiber. We are working on a long wavelength (1,100nm-band) VCSEL directly coupled to a single-mode fiber. We could expect a longer link length in single-mode fibers.

The enhancement of modulation bandwidth is attributed to the coupling between the primary VCSEL cavity and the transverse coupled cavities. The small signal modulation response in MA-VCSEL is shown in Fig. 6. The small signal modulation bandwidth is over 20 GHz while it is 10 GHz for conventional VCSELs fabricated on the same wafer. The small-signal modulation bandwidth can be double thanks to the transverse coupled cavity effect. We also tested a large signal modulation (NRZ) as shown in Fig. 7. We obtained an eye opening at 36 Gbps.



(a)



(b)

Fig. 5.(a) Lateral and (b) vertical displacement tolerance between VCSEL and a single-mode fiber.

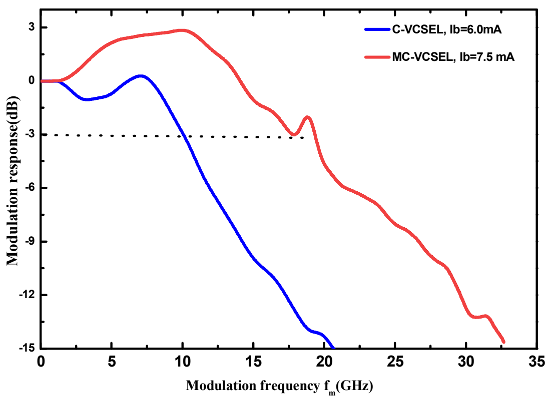
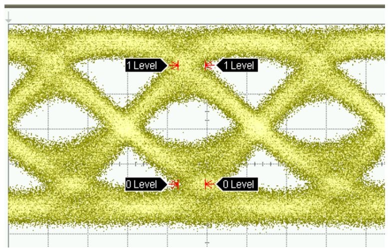
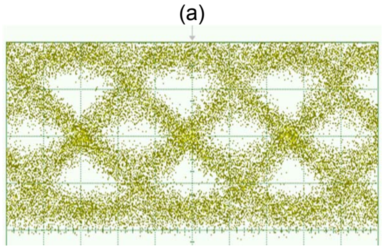


Fig. 6. Small signal modulation response of MA-VCSEL and conventional VCSEL (C-VCSEL) for comparison.



(a)



(b)

Fig. 7. Large signal modulations of MA-VCSEL at the data rate of 32 and 36 Gbps

Conclusions

In conclusion, we proposed and demonstrated the novel concept of high-speed and single-mode VCSELs with a large mode-field diameter. The fabrication process is exactly the same as intracavity contact VCSELs, where no extra process steps are needed. The mode field diameter is as large as 10 μm for single mode operations in the entire current range with SNMR of more than 40 dB. The small- and large-signal characteristics of MA-VCSEL were measured. The bandwidth can be double thanks to the coupled cavity effect. This result shows a possibility of achieving high-speed and single-mode VCSELs with a simple device structure. Further optimizations can be expected for ultrahigh speed operations of 50 Gbps or higher with a narrow spectral width.

Acknowledgements

This work was supported by NICT. The authors thank Dr. Shinada and Mr. Nakajima, NICT, for their support in device fabrication.

References

[1] K. Iga, “Vertical-cavity surface-emitting laser: Its conception and evolution,” Jpn. J. Appl. Phys. 47(1R), 1–10, 2008.

[2] F. Koyama, “Recent advances of VCSEL photonics,” J. Lightw. Technol. 24(12), 4502–4513, 2006.

[3] N. Suzuki, et al., “High speed 1.1-μm-range InGaAs-based VCSELs,” IEICE Trans. Electron. E92-C(7), 942–950 ,2009.

[4] A. Larsson, P. Westbergh, J. S. Gustavsson, E. Haglund and E. P. Haglund, .High speed VCSELs and VCSEL arrays for single and multicore figer Interconnects. , Proc. SPIE, vol.9381, pp.93810D-1, 2015.

[5] A. Larsson, P. Westbergh, J. S. Gustavsson, E. Haglund and E. P. Haglund, .High speed VCSELs and VCSEL arrays for single and multicore figer Interconnects. , Proc. SPIE, vol.9381, pp.93810D-1, 2015.

[6] D. M. Kuchta, A. V. Rylyakov, F. E. Doany, C. L. Schow, J. E. Proesel, C. W. Baks, P. Westbergh, J. S. Gustavsson and A. Larsson, .A 71-Gb/s NRZ modulated 850-nm VCSEL-based optical link. , IEEE Photon. Tech, Lett., Vol. 27, pp. 577-580, 2015.

[7] W. H. S. Wanckel and H. E. Hofmann, Small-signal Analysis of Ultra-High-Speed Multi-Mode VCSELs., IEEE J.Quantum Electron., Vol. 52, No. 7, ASN 2400311,2016.

[8] D. M. Kuchta, C. L. Schow, A. V. Rylyakov, J. E. Proesel, F. E. Doany, C. Baks and B. H. Hamel-Bissell, “A 56.1 Gb/s NRZ modulated 850nm VCSEL-based optical link”, OSA/OFC, Anaheim, California, US, Mar. 2013.

[9] W. Hamad, M. Bou Sanayeh,T. Siepelmeyer, M. Hamad, and W. Hofmann, “Advanced Small-Signal Analysis of High-Speed Multi-Mode VCSELs”, Applied Phys. Lett., Mar. 2018.

[10] P. Westbergh, E. P. Haglund, E. Haglund, R. Safaisini, J. S. Gustavsson, and A. Larsson, “High-speed 850 nm VCSELs operating error free up to 57 Gbit/s,” Electron. Lett., vol. 49, no. 16, pp. 1021–1023, 2013.

[11] H. Dalir, and F. Koyama, "29GHz directly modulated 980nm vertical-cavity surface emitting lasers with bow-tie shape transverse coupled cavity," Appl. Phys. Lett., vol. 103, 091109-1-4, Aug. 2013.

[12] X. Gu, M. Nakahama, A. Matsutani, M. Ahmed, Ahmed Bakry, F. Koyama, "850nm transverse-coupled-cavity vertical-cavity surface-emitting laser with direct modulation bandwidth of over 30GHz", Applied Physics Express, vol. 8, no. 8, pp. 82702-1-4, 2015.

[13] S. Fryslie, M.P.Tan, D.F. Siriani, M.T.Johnson, K.D. Choquette, "37-GHz modulation via resonance tuning in single-mode coherent vertical-cavity laser arrays", IEEE Photonics Technology Letters, 27,415-418, 2015.

[14] H.R. Ibrahim, M. Ahmed, F. Koyama. High speed modulation single mode 850 nm DTCC-VCSEL, High speed modulation single mode 850 nm DTCC-VCSEL, G-2, Nov. 2019.

[15] N. Ueki, A. Sakamoto, T. Nakamura, H. Nakayama, J. Sakurai, H. Otoma, Y. Miyamoto, M. Yoshikawa, and M. Fuse: IEEE Photon.Technol. Lett. 11, 1539,1999.

[16] A Haglund, JS Gustavsson, J Vukusic, P Modh, A Larsson, "Single fundamental-mode output power exceeding 6 mW from VCSELs with a shallow surface relief," IEEE Photonics Technology Letters, 16 (2), 368-370, 2004.