Full 3-inch Wafer Processed 1060 nm Single-mode Transverse Coupled-cavity VCSEL for Data Transmission in Standard 1300nm Single-mode Fiber

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Abstract: We demonstrate full-3inch-wafer processed 1060nm single-mode metal-aperture VCSEL, exhibiting 1300nm-standard single-mode fiber transmission. We obtained a bandwidth・distance product of 2.5Tbps・km. The modal-intensity noise in two-modes fiber link is suppressed with mode-filters.

1. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) [1-4] have been widely used in short distance fiber optics, such as optical interconnects intra- and inter- datacenters. High-speed VCSELs have been developed and 100 Gbps (PAM4) 850nm VCSELs are ready for products [5, 6]. However, the link length is limited below 100m. We demonstrated the metal-aperture coupled cavity VCSEL with bandwidth enhancement and mode control thanks to transverse resonances [7-9]. The next challenge is to develop the stable operation of the coupled cavity VCSELs based on standard VCSEL production platform. Also, we demonstrated 5km standard 1300nm SMF transmission of single mode 1100nm VCSEL [10], but a concern is the modal noise associated two modes coupling in standard 1300nm SMF [11].

In this paper, we demonstrated a 1060nm single-mode metal-aperture VCSEL with surface relief structure by using a full-3inch-wafer process of standard VCSEL fabrication platform. The bandwidth enhancement and single-mode operation are obtained. Thanks to the transverse resonance caused by the surface relief and metal ring, the stable single mode operation was achieved. We carried out 50Gbps (NRZ) data transmission through 5 km-long standard 1300nm SMF (G652). We also tested the effect of two mode coupling in 500m SMF with intentional offset joints. The modal noise caused in such offset joints is suppressed by using a mode filter to avoid the high-order mode.

2. Device Structure

The schematic structure of the metal-aperture VCSEL is shown in the Fig. 1(a). Surface relief process is formed by shallow-wet etching at the surface of the half-cavity VCSEL which includes 6 pairs of top DBR and 30 pairs of bottom DBR. The etching depth is as small as 30nm. The oxidation diameter is 5µm, and a ring-shaped p-contact metal with 7µm of diameter and 3µm of width formed on the surface. The cross-section of the metal-aperture VCSEL is schematically shown in the Fig. 1(b), 5 pairs Ta_2O_5/SiO_2 DBR is formed on the mesa. The top view of the fabricated device is shown in Fig. 1(c) with surface relief structure and ring-shaped p-electrode.

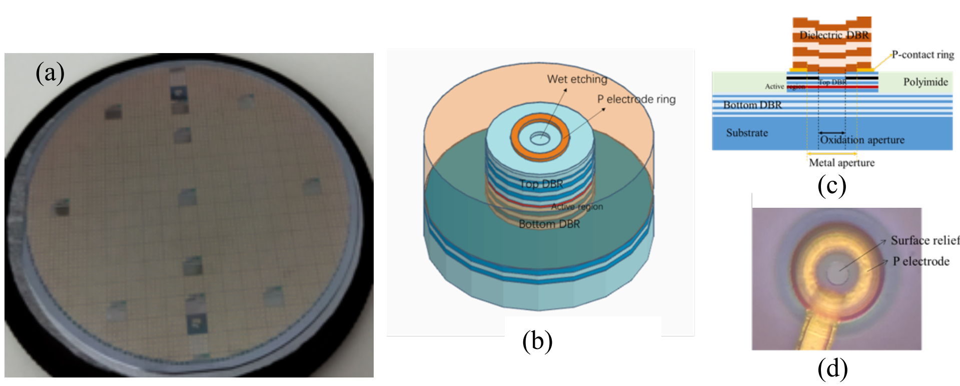
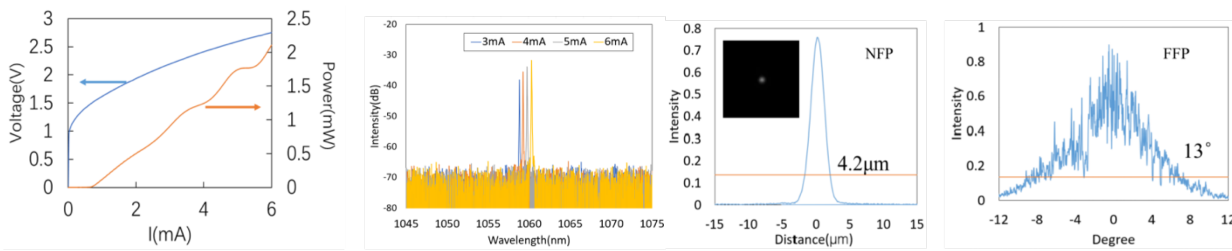


Fig. 1. (a) Photo of 3-inch processed wafer, (b) Schematic structure of the device with metal ring and surface relief, (c) Cross section of the device structure, (d) Microscope image of the mesa.

The lateral resonance takes place due to the reflection at the boundary of the intra-contact metal electrode. The shallow relief of the semiconductor surface enables the lateral coupling in an oxide aperture [9]. The coupling strength is managed by the depth of the surface relief and hence the bandwidth enhancement could be increased.

2. Experimental Results

Measurement results of the metal-aperture coupled cavity VCSEL are shown in Fig. 2. Figure 2(a) shows the V/I and L/I of the metal-aperture VCSEL, and the single-mode power can reach at 2mW at 6mA of bias current. Figure 2(b) shows the lasing spectrum with different bias currents from 3mA to 6mA, and stable single mode can be seen with SMSR of over 30dB in the entire current. The near field pattern (NFP) and far field pattern (FFP) are shown in Fig. 2(c) and Fig. 2(d), respectively. The mode field diameter is 4.2μm and the divergence angle is 13°, exhibiting a diffraction-limited single-lobe profile.



(a) (b) (c) (d)

Fig. 2. (a) Measured V/I & L/I, (b) lasing spectra, (c) NFP and (d) FFP at 4mA of the 1060nm metal-aperture coupled cavity VCSEL.

The small signal modulation of the conventional VCSEL with the same epi-wafer, the metal-aperture VCSEL with back-to-back and 5km transmission are shown in Fig. 3. Compare to the conventional VCSEL which the modulation bandwidth is just around 12GHz, the metal-aperture VCSEL with back-to-back transmission can be increased to 22GHz, and by using 5km single mode fiber (SMF) transmission, the modulation bandwidth can be increased to 25GHz at 6mA thanks to the frequency chirp and negative dispersion of the fiber. Large signal modulations are shown in Fig. 4. We observed eye opening up to 50 Gbps (NRZ) under back-to-back, and 50Gbps (NRZ) through 5km SMF transmission.

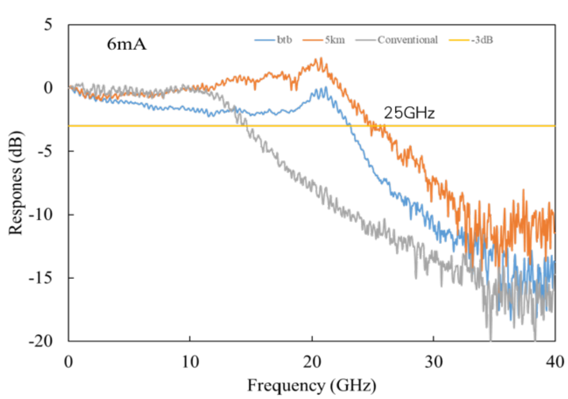


Fig. 3. Small signal response of metal-aperture VCSEL in comparison with a conventional VCSEL.

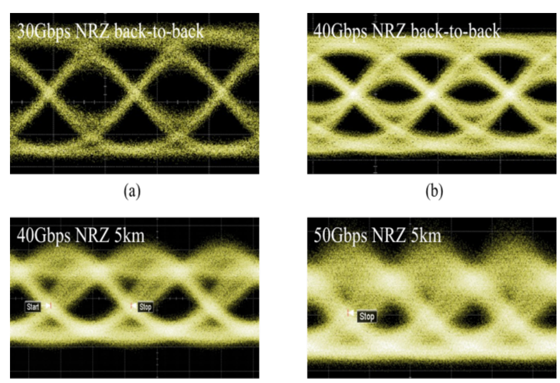


Fig. 4. Eye diagrams with different bit rates through 5km SMF.

There are two modes in standard 1300nm SMF(G652) at 1060nm band. 1060nm single-mode VCSELs with standard SMF would be a promising choice to extend the link length. The concern is the impairment caused by high-order mode (LP11). Modal noise may arise from the random coupling of the fundamental model LP 01 and the higher order mode LP 11. The higher mode LP 11 is generated and the mode coupling takes place in the fiber optic link from imperfect connectors. We performed the fiber link as shown in Fig. 5 for the modal noise generated in a number of splices. Five spans of 100m long SMF are spliced with an intentional offset of 0.6μm, which is corresponding to a connector of 0.1dB. By using the fiber-loop mode filter, the LP11 mode can be eliminated. The mode filter is formed by the optical fiber loop with 5 turns of 10μm diameter.

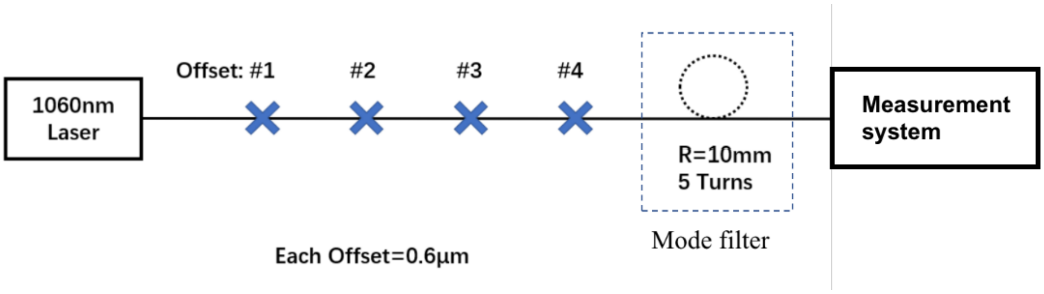
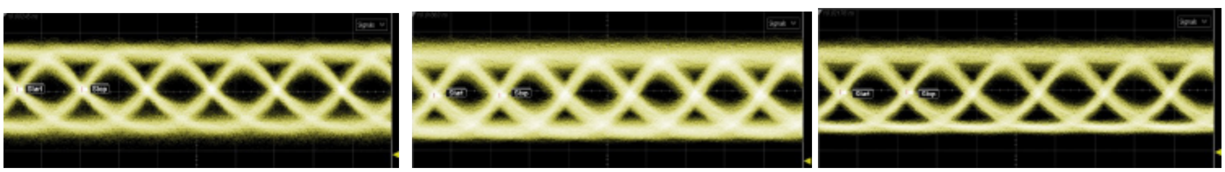


Fig. 5. 500m-long two modes SMF transmission system with ta fiber-loop mode filter.

The 30Gbps NRZ signal is transmitted in the fiber link as shown in Fig. 6. A noticeable increase in the noise can be seen with offset splicing. The eye pattern improved by using a mode filter. The SNR is improved from 23 to 26. No noticeable degradation of eye-patterns can be seen thanks to the mode filter.



(a) (b) (c)

Fig. 6. NRZ 30Gbps eye diagrams of (a) back-to-back, (b) 500m offset-joint SMF w/o mode filter, (c) 500m offset-connected SMF w/o mode filter large signal modulation.

4. Conclusion

We demonstrate 1060nm single-mode metal-aperture coupled cavity VCSEL by using a full-3inch-wafer process of standard VCSEL fabrication platform. The small signal response can reach at 22GHz which is double of a convention VCSEL with the same epi-wafer. 50Gbps (NRZ) could be transmitted through 5km 1300nm standard SMF, which shows a bandwidth･distance product of 2.5Tbps･km. In addition, we performed the fiber link for the modal noise evaluation in a number of offset splicing. While a noticeable increase in the noise can be seen with offset splicing, the noise can be suppressed thanks to mode filters.

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