Uncooled Operations of 100Gbps 1060nm Single-mode Metal-aperture VCSEL for Standard SMF Transmission

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Abstract *We present 1060nm single-mode metal-aperture VCSELs with uncooled operations for standard SMF data transmission. The small-signal modulation bandwidth is as high as 30GHz. We demonstrate 75Gbps(NRZ) and 110Gbps(PAM4) transmissions through 2km SMF. The record bandwidth-distance product of over 450Gbps•km was obtained.*

Introduction

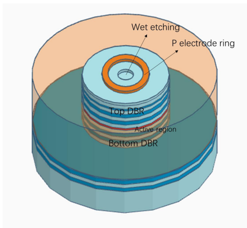
Vertical-cavity surface-emitting lasers (VCSELs) have been widely used for short-reach optical interconnects in data centers [1]. For directly modulated VCSEL, the modulation bandwidth has been limited by the relaxation oscillation frequency, which can be improved by optimizing the active region, series resistance, and other methods [2,3]. Multi-mode 850nm VCSELs with over 30GHz modulation bandwidth have been developed [4, 5], enabling 100Gbps PAM4 VCSELs for 800G ethernet applications [6, 7].

The next challenge is to go beyond the relaxation oscillation frequency toward 200Gbps PAM4 modulations. One potential candidate is a transverse coupled cavity VCSEL for higher modulation frequencies [8-10]. Also, the multi-mode fiber (MMF) link length has been limited below 100m, which should be even shorter at higher baud rates. The use of a longer wavelength band of >1060nm could be an attractive choice with a single-mode VCSEL for extending the link length thanks to lower fiber losses and dispersions [11-14]. In order to meet the requirement of km-long transmission distances in hyper-scale data centers, long wavelength and single-mode VCSELs are desirable. To meet these demands, we demonstrated 1060nm single mode intra-cavity metal-aperture VCSELs with the enhancement of the modulation bandwidth [15-18].

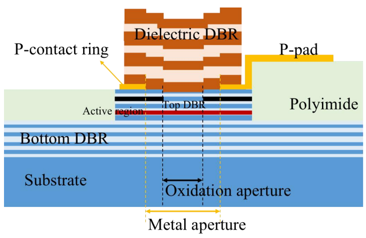
In this paper, we demonstrate the uncooled operation of 1060nm intra-cavity metal-aperture VCSEL. We carried out 75Gbps (NRZ) and 110Gbps (PAM4) data transmission through 2km-long standard 1300nm single-mode fiber (SMF). Also, the SMF link length was extended up to 10km at 45Gbps (NRZ), which shows the record bandwidth-distance product of 450 Gbps·km. Besides, the device shows good temperature stability up to 55°C.

Device Structure

The structure of the intra-cavity metal-aperture VCSEL is shown in Fig.1. Surface relief process is formed by shallow-wet etching with 30nm depth at the surface of a half-cavity VCSEL which includes 6-pair top semiconductor DBR and 30-pair bottom DBR. The oxide aperture diameter is typically 5μm. A ring-shaped p-contact metal with 7μm of diameter and 3μm of width is formed on the surface and a 5-pair top dielectric DBR is finally deposited. The semiconductor surface relief enables the transverse resonance in intra-cavity metal-aperture VCSELs. Since the surface relief region has a shorter resonance wavelength than the un-etched region, the optical field can be laterally spread into the oxidized region and is reflected by the metal-aperture boundary [15-17], resulting in the bandwidth enhancement and transverse mode control at the same time. To further increase the modulation bandwidth, a 3.5μm polyimide layer is inserted below p-contact pads to reduce the parasitic capacitance [18].



(a)



(b)

Fig. 1. (a) Schematic and (b) cross-section of 1060nm intra-cavity metal aperture VCSEL for transverse.

Lasing Characteristics

Figure 2 shows the L/I and V/I characteristics of the fabricated metal aperture VCSEL at 25°C, 55°C, and 85°C. Small ripples in the L/I would be due to the reflection from the backside of a substrate, which could be avoided. The single-mode power at 7mA is 3.2mW at 25°C and 2.8mW at 55°C, respectively. A reduction in output power is as small as -0.6dB thanks to highly strained InGaAs quantum wells for 1060nm wavelengths band [11]. Stable single mode operations can be seen with SMSR over 30dB in the entire current range even for 5-6um oxide apertures thanks to the transverse mode control as shown in Fig. 3.

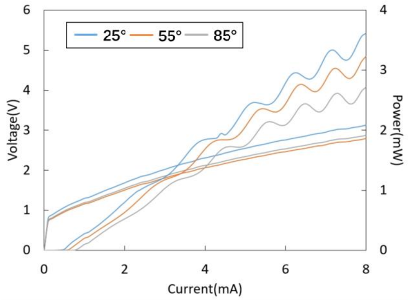


Fig. 2. L/I and V/I characteristics of intra-cavity metal-aperture VCSEL at 25℃, 55℃, and 85℃.

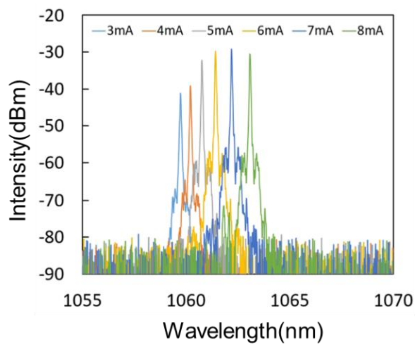


Fig. 3. Lasing spectra of intra-cavity metal-aperture VCSEL at different currents.

Figures 4 (a) and (b) show the small signal modulation characteristics at the bias current from 6mA to 8mA at 25°C and 55°C, respectively. As shown in Fig.4(a), the record modulation bandwidth of over 30GHz was obtained for 1060nm single-mode VCSELs. When the temperature increased to 55°C, the modulation bandwidth could reach at 27GHz as shown in Fig.4(b).

Data Transmission Experiments in Standard Single-mode Fiber

The small signal modulation response for back-to-back, 2km, 5km, and 10km transmission through standard 1300nm-SMF (G652) are shown in Fig. 5. Thanks to the frequency chirp and negative dispersion at 1060nm [19-21], the modulation bandwidth can be increased to 38GHz and 32GHz through 2km and 5km SMF, respectively. The result shows a potential of 50Gbps (NRZ) and 100Gbps (PAM4) transmission up to 5km.

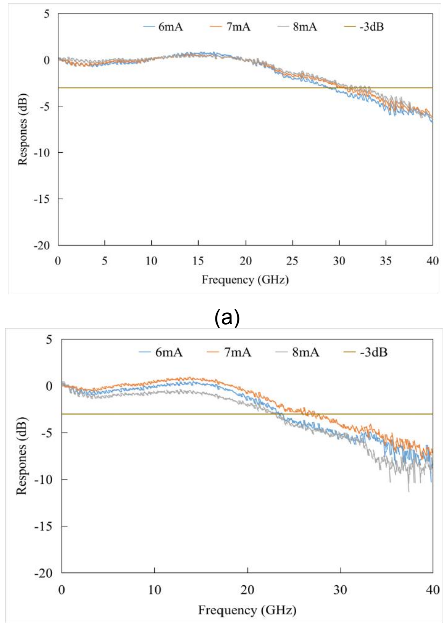


Fig. 4. Small signal modulation bandwidth under different bias current at (a) 25℃ , and (b) 55℃.

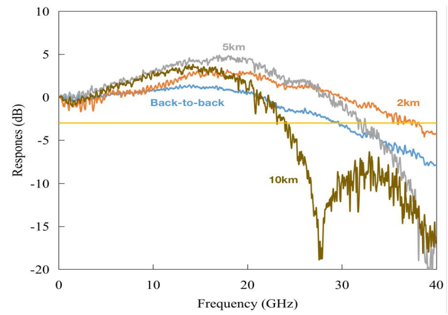


Fig. 5. Small signal modulation response through different lengths of SMF.

We carried out large signal modulations at a 7mA bias current with 5-taps pre-equalization. A 2^9-1 PRBS modulation signal was generated by Keysight M8194A pattern generator. The results of NRZ eye patterns with different bit rates for back-to-back, 2km, 5km, and 10km SMF transmission at room temperature are shown in Fig. 6. We used Keysight N1092X-040A sampling oscilloscope with a bandwidth of 40GHz. We observed eye opening up to 65Gbps for back-to-back, 75Gbps for 2km, 70Gbps for 5km and 45Gbps for 10km SMF transmissions. The BERs are estimated from the waveform analysis software, which are below 7% forward-error-correction (FEC) limit as 1E-6 for back to back, 3E-4 for 2km, 2E-3 for 5km and 2E-4 for 10km SMF transmissions, respectively. The SMF link length was extended up to 10km at

45Gbps, which is 100 times longer than conventional 850nm MMF link. We obtained the record bandwidth-distance product of 450Gbps·km among existing VCSEL technologies.

Figure 7 shows the comparison of 70Gbps NRZ eye patterns through 2km SMF transmission at 25°C and 55°C. When the temperature increased to 55°C, although the eye diagram is degraded, the BER of 9E-4 is obtained. The result shows the good temperature robustness, and hence no needs of precise temperature control for our coupled cavity VCSELs. In addition, the eye diagrams of PAM4 modulation with 5-taps pre-equalization for back-to-back and 2km SMF transmission are shown in Figure. 8. We observe eye-openings of up to 110Gbps with a 4.2dB TDECQ for back to back, and with a 5.1dB TDECQ for 2km SMF transmission. Also, the temperature dependence of the PAM4 eye patterns of 100Gbps is shown in Fig.9. Eye opening with a 3.9dB TDECQ and 5.6dB TDECQ was observed at 25°C and 55°C, respectively. TDECQ could be improved by increasing the modulation speed and linearity of the device. Uncooling operations at 55°C of intra-cavity metal-aperture single mode VCSELs were obtained up to 100Gbps.

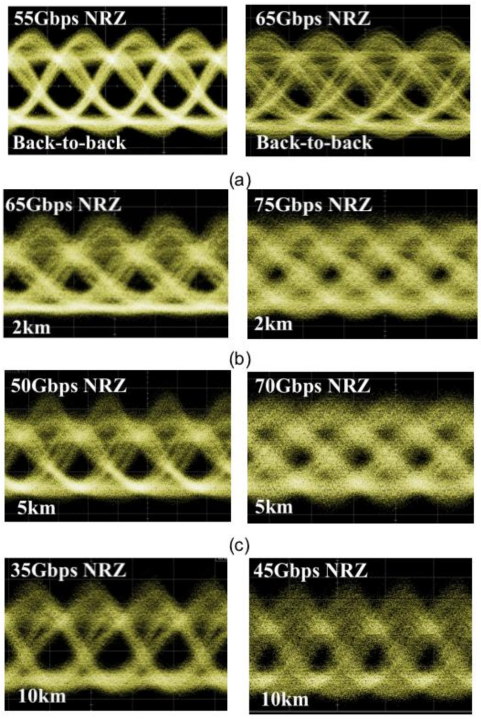
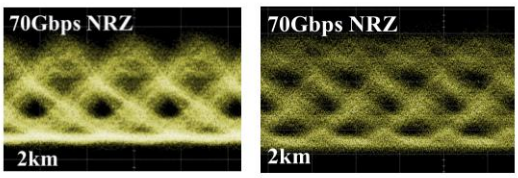
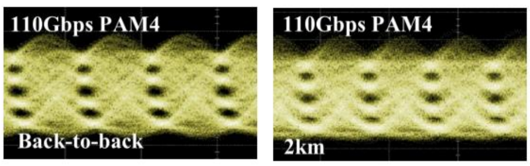


Fig. 6. Eye patterns at 25℃ for different link lengths: (a) back-to-back, (b) 2km, (c) 5km and (d) 10km



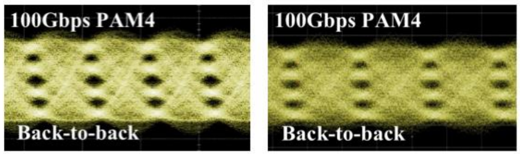
(a) (b)

Fig. 7. NRZ eye patterns at (a) 25℃ and (b) 55℃ for of 2km



(a) (b)

Fig. 8. PAM4 eye patterns at 25℃ for different link lengths: (a) back-to-back and (b) 2km.



(a) (b)

Fig. 9. PAM4 eye patterns at (a) 25℃ and (b) 55℃ for back-to-back

Conclusion

We demonstrate the uncooled operation of 1060nm single-mode intra-cavity metal-aperture VCSELs, exhibiting the temperature robustness. The modulation bandwidth at room temperature is as high as 30GHz, which is the highest for single-mode VCSELs. A small reduction by 0.6dB in output power and 27GHz modulation bandwidth at 55°C shows good temperature stability of our coupled cavity VCSELs. Thanks to the frequency chirp and negative dispersion of the fiber, the 75Gbps (NRZ) and 110Gbps (PAM4) transmissions were successfully demonstrated through 2km standard SMF, which is 20 times longer than that of 850nm MMF links. The link length was extended up to 10km at 45Gbps (NRZ), which shows the record bandwidth and distance product of 450Gbps•km. Also, eye-opening up to 100Gbps with good temperature robustness up to 55°C was obtained. Further extensions on link lengths and higher bit rates could be expected by chirp reduction and bandwidth enhancement in transverse coupled cavity VCSELs. A large-scale 2D array of transverse coupled cavity VCSELs could offer a potential for increasing aggregate bandwidths of over Tbps.

Acknowledgement

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