1060nm Single-mode Transverse Coupled Cavity VCSEL with Surface Relief Engineering for 80Gbps PAM4 Modulation

Shanting Hu[1], Xiaodong Gu[1,2], Hameeda R Ibrahim[1], Masanori Nakahama[1,2], Satoshi Shinada[3] and Fumio Koyama[1]

1 Institute of Innovative Research (IIR), Tokyo Institute of Technology
4259-R2-22 Nagatsuta-cho, Midori-ku, Yokohama, 226-8503 Japan, hu.s.ab@m.titech.ac.jp
2 Ambition Photonics Inc., Tokyo Tech Yokohama Venture Plaza E208, Yokohama 226-8510, Japan
3 National Institute of Information and Communications Technology, Japan
hu.s.ab@m.titech.ac.jp

Abstract: We demonstrate 1060nm VCSELs with surface relief engineering, providing transverse-resonance in transverse-coupled cavity VCSELs, which enables single-mode operation and bandwidth enhancement. We obtained a large signal modulation of 54 Gbps NRZ and 80 Gbps PAM4.

1. Introduction

A vertical-cavity surface-emitting laser (VCSEL) is widely regarded as a key light source in supercomputers, data centers, and access/metro/core networks, in particular for short reach applications [1,2]. However, the modulation speed of VCSELs is limited by their relaxation oscillation frequency to typically less than 20 GHz. We proposed and demonstrated the bandwidth enhancement of a bow-tie-shaped transverse-coupled cavity (TCC) VCSELs [3]. The bandwidth enhancement is due to the transverse-resonance between transverse coupled cavities. The same phenomenon was observed in photonic crystal coupled cavity VCSELs [4]. However, because of unstable coupling strength causing by thermal lensing effect, the performance of the bow-tie-shaped TCC VCSEL has been limited. Recently, we proposed and demonstrated a metal aperture VCSEL, exhibiting more stable transverse resonances for the bandwidth enhancement and transverse mode control [5-8]. In order to increase the modulation bandwidth, a key issue is to increase the coupling strength between coupled cavities.

In this paper, we propose and demonstrate 1060nm VCSELs with surface relief engineering, showing single-mode operation and high modulation speed. Thanks to the optical-transverse resonance brought by the shallow etching of a semiconductor surface, clear eye opening was observed up to 54 Gbps NRZ and 80 Gbps PAM4 modulations. Single mode operations with SMSR of more than 30 dB in the entire current pump range were also realized.

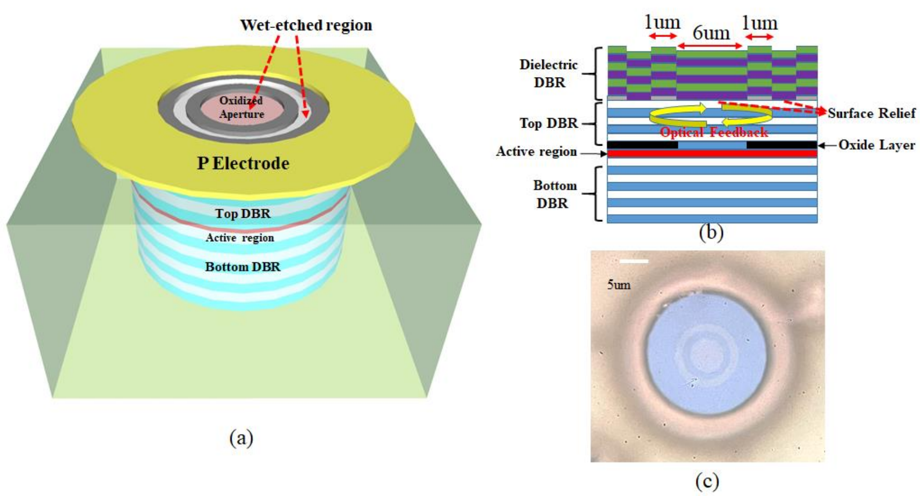

Fig. 1. (a) Schematic structure of the proposed device with surface relief engineering before top dielectric DBR evaporation, (b) Cross-sectional view of the schematic structure after dielectric DBR evaporation, (c) Top view of a surface relief.

2. Device Structure

The 3D schematic structure of our proposed device is illustrated in Fig. 1(a). The device is fabricated based on a half-VCSEL structure including 30-pair bottom DBR, triple 1060nm InGaAs QWs and 4 pairs top p-type semiconductor DBR. The process of surface relief is carried at the first step on the wafer. Round regions with a diameter of 6 μm and a 1μm ring outside was formed by shallow wet-etching process on the surface of a wafer. The etching depth is as small as 20 nm. Then round oxidized apertures were formed by mesa dry-etching and followed by wet-oxidation process with the surface relief pattern at center as shown in Fig. 1(a). The diameter of an oxide aperture is 6μm, which fits in the round etched region exactly. 5 pairs of dielectric Ta_2O_5/SiO_2 were deposited above the surface of the mesas to achieve enough top reflectivity as shown in Fig.1 (b). Because the etched region has a shorter resonant wavelength than the un-etched region, lasing light in the oxidized aperture can travel laterally into the oxidized region and reflects at the boundary of the outside ring, which causes transverse resonance. The distance between boundaries of the round region and outside ring is as small as 1 μm to observe the transverse coupled cavity effect [6]. Fig. 1(c) shows the top view of a surface relief of the mesa.

3. Simulation and Experimental Results

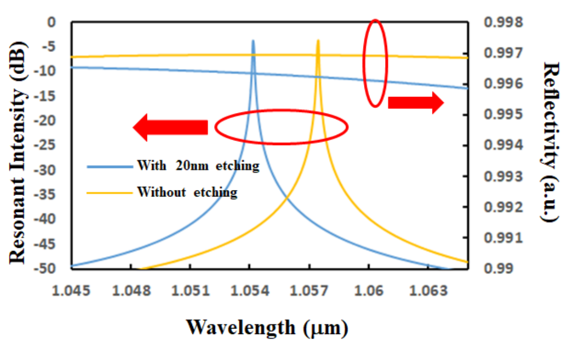

Fig. 2. Calculation of the resonant wavelength and top reflectivity

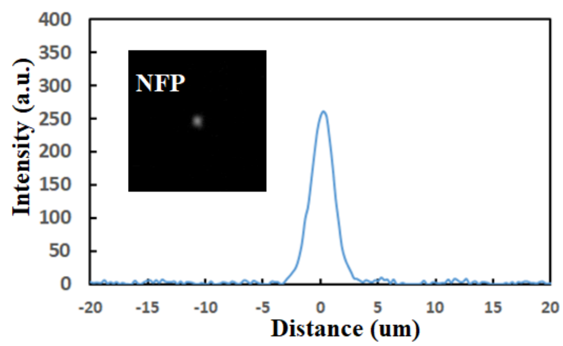

Fig. 3. Measured NFP of the lasing device

The amount of wavelength tuning between the etched and un-etched region is calculated utilizing a standard transfer matrix method. The calculated transmittances and top reflectivity are shown in Fig. 2. A 4 nm detuning of the resonant wavelength between the two region is obtained when the contact layer of the VCSEL is etched by 20 nm. Fig. 3 shows the measured near field pattern (NFP) with pumping the surface relief VCSEL above the threshold, showing a NFP with a mode field diameter of around 5 μm, which is in agreement with the size of the oxidized aperture. Fig. 4(a) shows the measured spectrum of a conventional VCSEL without surface relief fabricated on the same wafer at 5mA of a bias current. Multi-mode operation is observed due to a rather large oxide aperture diameter of 6 μm. Measured spectra of the surface relief VCSEL at different bias currents with the same aperture size are shown in Fig. 4(b). Single mode operation is obtained in the entire current range with SMSR over 30 dB. The transverse mode control due to transverse-resonance is clearly proven by the experimental data and the 4 nm wavelength detuning is in agreement with the simulation. Fig. 4(c) shows the measured L/I of the surface relief VCSEL. As we can see, a single mode power of over 2 mW can be obtained, which could be improved by optimizing the top mirror reflectivity.

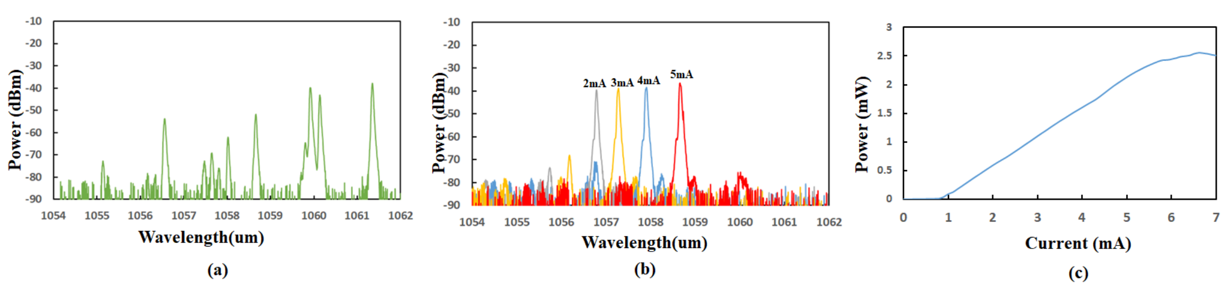

Fig. 4. (a) Measured spectrum of a conventional VCSEL at 5mA, (b) Measure spectra of a surface relief VCSEL at different currents, (c) Measured L/I of the surface relief VCSEL.

We measured the small signal modulation response of the surface relief VCSEL and conventional VCSEL fabricated on the same wafer as shown in Fig. 5. The epi-wafer structure is not optimized for high-speed modulation and thus the bandwidth of conventional VCSEL is limited to only 12 GHz as shown in the figure. The small signal bandwidth for the surface relief VCSEL is almost doubled (around 23 GHz at 5mA current) thanks to the transverse coupled cavity resonance. High speed large signal modulations are also carried out as shown in Fig. 6. We observed clear eye opening up to 54 Gbps (NRZ) with a extinction ratio around 4 dB as shown in Figs. 6 (a) and (b). Eye opening are also achieved for 70 Gbps and 80 Gbps PAM4 modulations as shown in Figs. 6 (c) and (d).

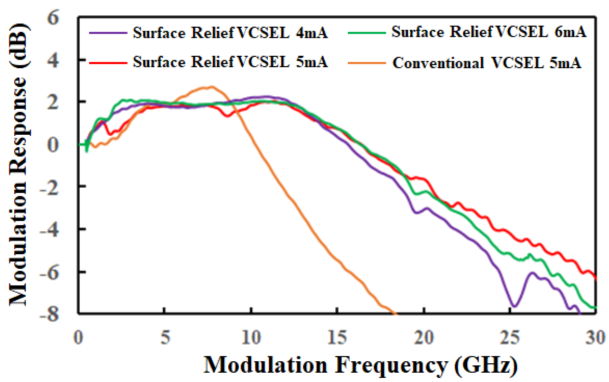

Fig. 5. Small signal response of surface relief VCSEL at different bias currents and conventional VCSEL at 5mA current pump

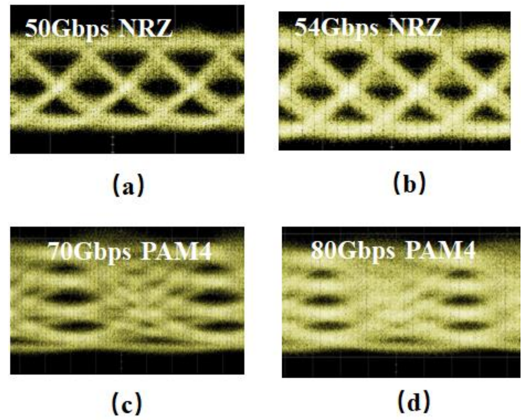

Fig. 6. Eye diagram of large signal modulation

4. Conclusion

We demonstrate the novel concept of high-speed and single-mode 1060nm VCSELs with surface relief engineering. The design shows easiness in fabrication since the process is exactly the same as conventional VCSELs except for the surface relief process at the first stage. The small signal bandwidth can be doubled thanks to the transverse-resonance brought by the surface relief. We demonstrated large signal modulation of 54 Gbps (NRZ) and 80 Gbps (PAM4). Further optimizations in the fabrication could offer high-speed modulations toward 100Gbps modulations with larger single-mode powers. Our device is promising to be used as high-speed transmitters in the next generation data centers and 6G network

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