Developing Single-Mode VCSEL for Extending High-Speed PAM4 Transmitting Distance in SMF-28 Fiber Up to 1 km and 70 °C

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Abstract

A novel Integrated Mode Select Filter (IMSF) is designed and an integrated device process is developed for yield-enhanced single-mode (SM) VCSEL for extending high-speed PAM4 transmitting distance up to 1 km. The SM VCSELs deliver 96 Gbps PAM4 data transmission up to 1 km for SMF-28 fibers with TDECQ < 3.3 dB. The energy per bit is calculated to be 175.1 fJ/bit and 196.9 fJ/bit, respectively. Furthermore, the 70 °C SM-VCSELs test up to 96 Gb/s PAM4 data transmission with TDECQ < 2.7 dB.

Introduction

Since the discovery of the AlGaAs wet oxidation technique in the late 1990s for current and optical confinement in semiconductor lasers by the UIUC team of graduate student John D. Dallesasse and Professor Nick Holonyak, Jr, the oxide-confined vertical-cavity surface-emitting lasers (Oxide-VCSELs) have been widely deployed in the industry. For over twenty years, the oxide-confined VCSELs have provided a cost-effective solution to the short-reach (SR) (< 100 m) optical interconnects in data centers. Due to the differential modal delay and modal and chromatic dispersion, the multi-mode (MM) oxide-VCSEL is limited to transmission distance of < 100 m in OM4 fiber. Thus, MM-VCSEL is not a suitable solution for the transmitter of the DR (~ 500 m) and FR (~ 2 km) optical links in the data center. Recently, the single-mode (SM) VCSELs have been reported based on surface relief techniques, and reduced oxide aperture (< 3-um) can extend the high-speed of 20 Gb/s NRZ data transmission up to 2 km [2]. However, the small aperture oxide VCSEL has thermally limited laser current (power) for high modulation bandwidth required for high-speed NRZ and PAM4 transmission performance over temperature.

At UIUC, we designed SM-VCSELs with a different approach which is based on a novel Integrated Mode Select Filter (IMSF) structure [3] to reduce thermally limited laser operating bandwidth for stable high-speed operation and long-distance data transmission [4], [5]. Our initial work demonstrated state-of-the-art (SOA) and record speed performance of 38 Gb/s non-return-to-zero (NRZ) error-free optical data transmission and 64 Gb/s PAM4 eye-opening over 1 km SMF-28 fiber [6]. With the rapid expansion of cloud services and data centers, the 4-level pulse amplitude modulation (PAM4) has been standardized for 400 Gb/s Ethernet in IEEE Std 802.3 [7]. Thus, the commercial optical transceivers swiftly evolved into 100 Gbps per channel scheme. We recently demonstrated 112 Gb/s two-mode VCSEL for short-reach PAM4 data transmission and 96 Gb/s SM-VCSEL over 1 km PAM4 data transmission in OM4 fiber [8].

In this work, we further improved the SM-VCSEL process yield to over 95 % in a half-inch sample by precise process control of the IMSF structure. We demonstrate 108 Gb/s and 96 Gb/s PAM-4 data transmission over 300 m and 1 km SMF-28 fiber at room temperature, with TDECQ = 2.76 dB and 3.32 dB, respectively. The directly modulated SM-VCSEL with the adoption of the IMSF structure would be a viable, cost-effective solution to the 400 GbE data center reach optical interconnect.

Innovative IMSF structure for SM VCSEL

Compared to conventional multi-mode VCSELs, the IMSF SM-VCSELs demand a unique two-step oxidation process to form top and bottom oxide apertures, as shown in the cross-section view of the SM-VCSEL in Fig. 1. This proposed device structure adopts the design of conventional Oxide-VCSEL, with a typical 1/2-λ cavity VCSEL epitaxial design [8], P-doped distributed Bragg reflector (P-DBR) mesa, electrical current/optical confinement oxide layer, and contact metals, as discussed in our previous works [9].

The use of the innovative IMSF structure for achieving single-mode oxide-VCSEL was first demonstrated by Professor Milton Feng and Dr. Xin Yu at UIUC [3]. The major difference between IMSF SM-VCSEL and conventional Oxide-VCSEL is the incorporation of top oxide aperture as an Integrated Mode Select Filter (IMSF) by the wet-oxidation of the first few P-DBR pairs. In a weakly guided core/cladding waveguide, the fundamental mode peaks in the waveguide center, while the higher-order modes

are concentrated near the periphery. As a result, the small top aperture of IMFS reduces the quality factor "Q" of higher-order modes of MM-VCSEL and alters the modal characteristics of the oxide-VCSEL cavity so that only the fundamental mode operation is favored.

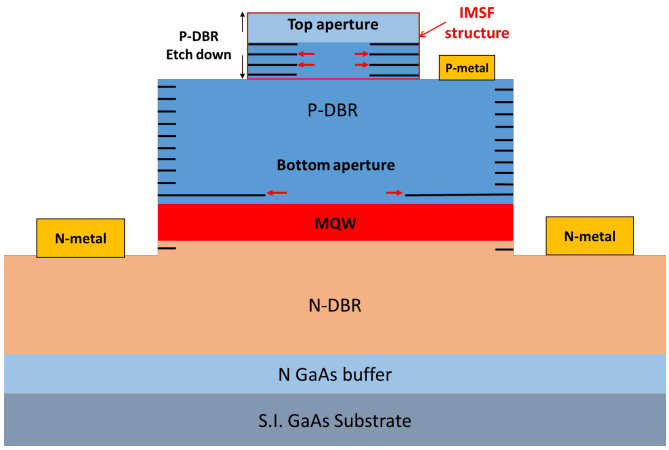

Fig. 1. Cross-section view of the IMSF SM-VCSEL structure designed and fabricated in UIUC.

PROCESS OPTIMIZATION FOR IMSF SM VCSEL

Figure 2 (a) shows an SEM picture of the IMSF structure, a 6-um diameter shallow-etched DBR mesa formed in the first step of the IMSF SM-VCSEL process. The precise process control of the IMSF mesa (~ 6-um) sidewall is smoothly formed by the Cl base RIE/ICP dry etch and is also crucial to the formation of uniform top oxidation layers, as shown in Fig. 2 (b). The 1.9 um diameter top aperture boundary is clearly observed in the microscope. This feature size is very close to the diffraction limit. Furthermore, the cross-section view of the IMSF SM-VCSEL is shown in Fig. 3. The combination of top/bottom apertures inside the IMSF SM-VCSEL cavity exploits the spatial discrimination between the fundamental and higher-order modes to achieve the single transverse mode emission in oxide VCSEL. Appropriate top and bottom aperture ratio, IMSF height, and uniform top oxide aperture are crucial to the Single-mode operation till thermal rollover. In addition, the IMSF sidewall slope, etch foot, and surface roughness are essential process parameters to achieve an enhanced yield in the scaled-up production line.

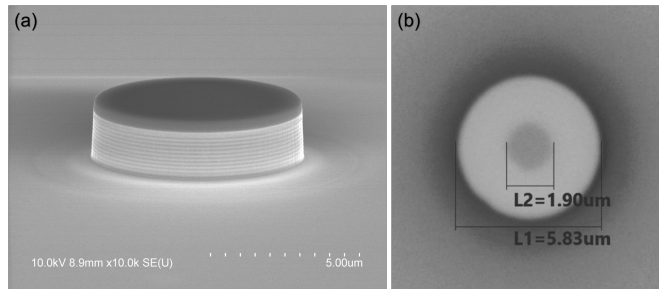

Fig. 2. (a) The SEM image of the IMSF structure dry etching process with SiNx hard mask on top. The IMSF sidewall slope and surface quality are precisely controlled to guarantee uniform top aperture sizes after the AlGaAs oxidation. (b) The uniform top oxidation aperture after the IMSF oxidation.

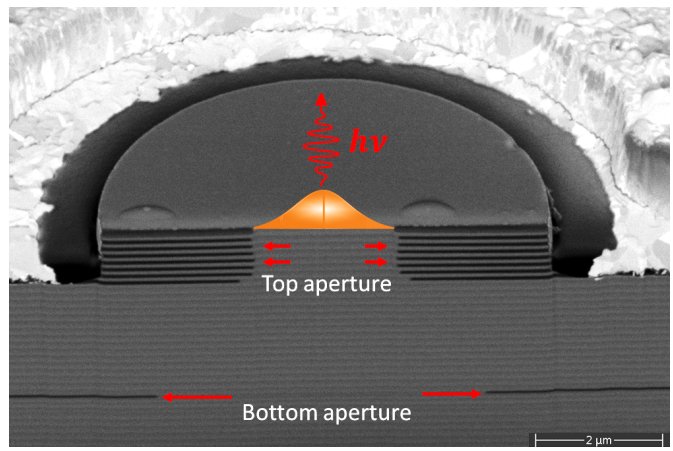

Fig. 3. Cross-section view of the IMSF mesa top aperture for SM-VCSEL. The single transverse mode operation is achieved with optimized top and bottom aperture ratio, IMSF height, aperture alignment, and uniformity.

The DC and small-signal response characterization were performed with ball lens fiber probe optical coupling at room temperature. All Light-Current-Voltage (L-I-V) and spectrum measurements taken are under continuous-wave (CW) operation on wafer probing SM-VCSELs at room temperature. The device I-V characteristics are measured by a HP 4142B DC source, whereas the L-I curves are measured by a NIST-calibrated HP 81531A InGaAs optical module. The measured L-I-V curve and optical spectrum of a typical IMSF SM-VCSEL are shown in Fig. 4 (a) and (b). The optical power ranges from 1.3 mW to 1.6 mW at 8 mA, and the threshold current varies from 0.8 mA to 1.0 mA among all measured devices. Every characterized SM-VCSEL exhibits single-mode operation with fundamental mode wavelength near 852 nm, and the single-mode-suppression-ratio (SMSR) all exceed 34 dB at 8 mA, satisfying the specs of the IEEE 802.3 Std. Having uniformly defined top and bottom oxide apertures, precisely controlled P-DBR dry etching depth, and sidewall profile, we managed to achieve consistent optical power, threshold current, and modal characteristics over the entire sample.

Moreover, Figure 5 (a) shows the map of testing SM-VCSEL optical spectrum at 8 mA of one quadrant on the 1.2 cm x 1.2 cm sample. The green label in the map represents tested SM-VCSELs, and all devices demonstrate single-mode operation till thermal rollover. The measurement data presented in this work is from the red dot labeled IMSF SM-VCSEL on the wafer map. The SEM image of the device under test is also shown in figure 5 (b), in which the IMSF mesa structure, top p-contact, and coplanar waveguide for high-speed VCSEL layout are clearly shown.

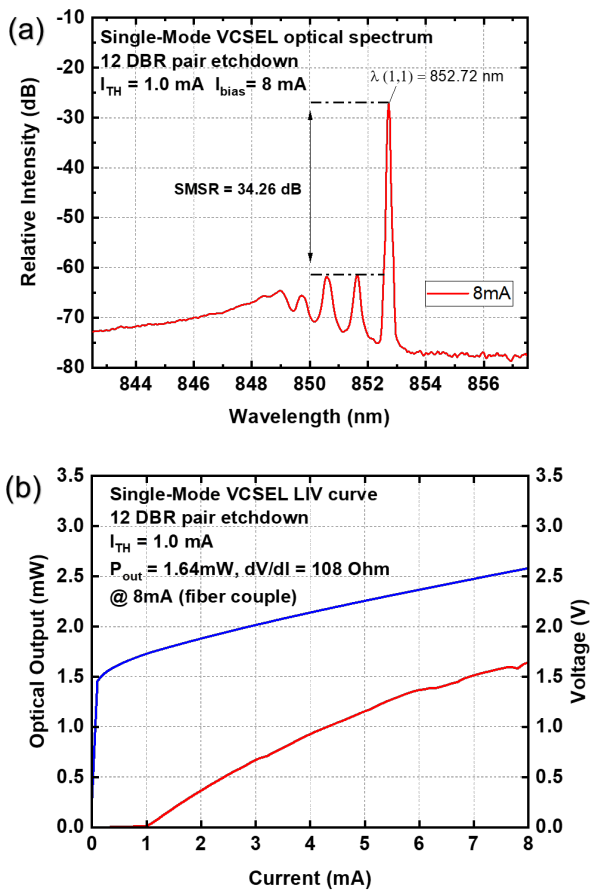

Fig. 4. (a) Measured optical spectrum of the SM-VCSEL. The SMSR exceeds 34 dB, meeting the specification of IEEE 802.3 Std. (b) Typical L-I-V curve of the fabricated SM-VCSEL.

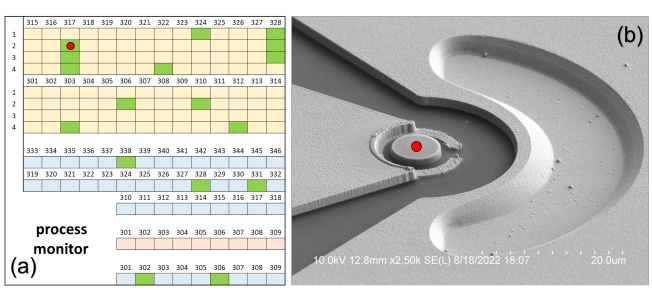

Fig. 5. (a) The SM-VCSEL testing map of one quadrant on a 1.2x1.2 cm² sample. All tested VCSELs are labeled green, showing single-mode operation with SMSR > 34 dB. The red dot labeled SM-VCSEL under test for both DC and PAM4 data transmission. (b) The SEM image of the SM-VCSEL under test. The red dot shows its location on the wafer map.

High-Speed PAM4 Data Transmission over Distances up to 1 km in SMF-28

The PAM4 eye-diagram measurements from room temperature to 70 °C were performed using on-wafer probing and free-space optics. The SM-VCSEL under test was biased with 7 mA DC current via SHF BT65R bias tee and directly modulated by the Gray-coded PRBS13 (PRBS13Q) data pattern, which is generated by the Keysight 120 GSa/s M8194A arbitrary waveform generator (AWG). All eye diagrams are un-averaged, and the TDECQ value is calculated based on the PRBS13Q pattern after a 4-tap feed-forward equalizer (FFE). The transmitter dispersion eye closure quadrature (TDECQ) was calculated based on the target symbol error rate (SER) of 4.8E-4. The measured room temperature PAM4 eye diagrams at 108 Gb/s (300 m SMF-28 fiber data link) and 96 Gbps (1 km SMF-28 fiber data link) are shown in Fig. 6 (a) and (b). The calculated TDECQ values are 2.76 dB and 3.32 dB, respectively. The energy per bit consumption is calculated to be 175.1 fJ per bit and 196.9 fJ per bit for 300 m SMF-28 and 1 km SMF-28 data transmission.

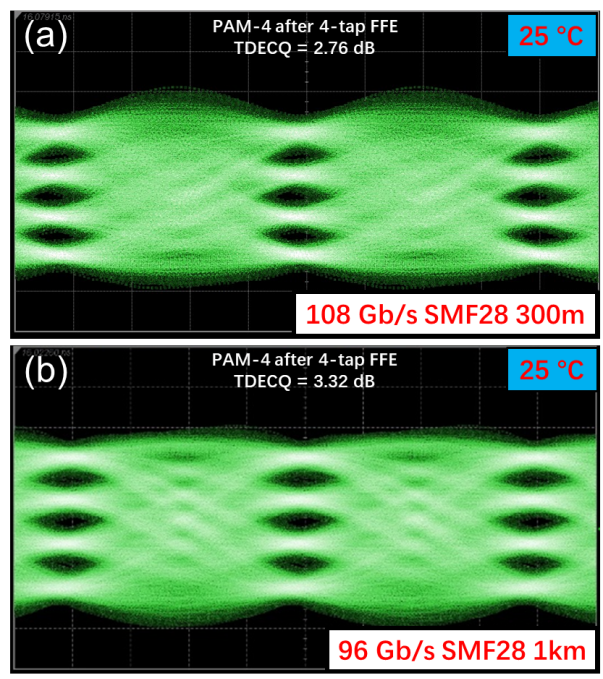

Fig. 6. SM-VCSEL PAM4 eye diagrams at (a) 108 Gb/s (300m SMF-28) and (b) 96 Gbps (1 km SMF-28) with a standard 4-tap feed-forward equalizer (FFE).

High-Speed PAM4 Data Transmission up to 70 °C

Moreover, to investigate the thermal stability of the fabricated IMSF SM-VCSELs, the PAM4 data transmission

up to 70 °C has been characterized. As the temperature increases, the VCSEL cavity resonance wavelength and gain spectrum start to misalign, decreasing direct modulation bandwidth and output optical power. In addition, the increasing ambient temperature will further increase the VCSEL cavity temperature, reducing the average lifespan of the device. Figure 7 (a) & (b) shows a direct comparison between the 70 °C PAM4 eye diagram and the 25 °C PAM4 eye diagram. Although the optical data link is unchanged, the eye diagram signal-to-noise-ratio (SNR) degradation leads to a TDECQ increment from 1.42 dB to 2.66 dB.

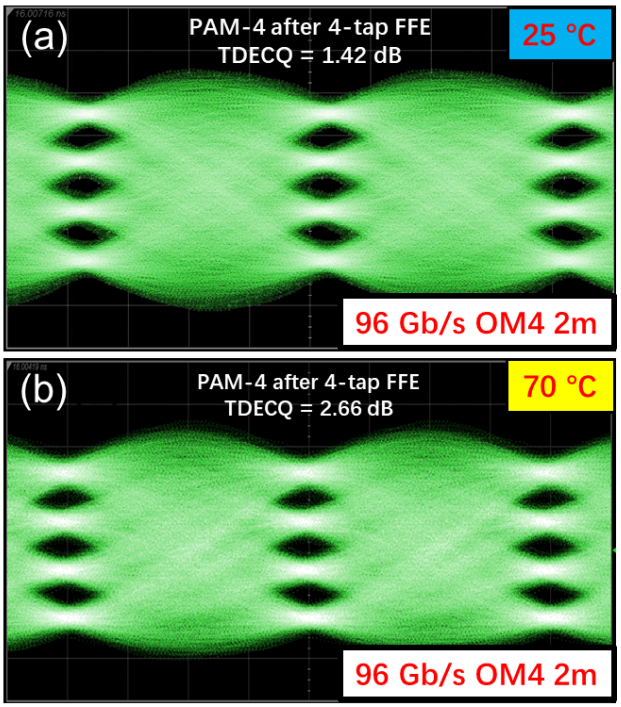

Fig. 7. SM-VCSEL PAM4 eye diagrams at (a) 96 Gb/s (2 m OM4) at 25 °C and (b) 96 Gb/s (2 m OM4) at 70 °C.

Conclusion

We have reported an IMSF-based SM-VCSEL process with significantly improved device yield and performance for high-speed optical interconnects, meeting the specs of DR (500 m) 400 GbE. The directly-modulated SM-VCSEL with IMSF structure would be a cost-effective and viable solution to the transmitter of the 400GBase-DR4 optical link in data centers.

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Acronyms

VCSEL: Vertical Cavity Surface Emission Laser
IMSF: Integrated Mode Select Filter
PAM4: 4-level pulse amplitude modulation
SEM: Scanning Electron Microscopy
SMSR: single-mode-suppression-ratio
AWG: arbitrary waveform generator
PRBS: pseudorandom binary sequence
PRBS13Q: Gray-coded PRBS13 pattern repeated twice
TDECQ: transmitter dispersion eye closure quadrature