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# Single-Mode 940 nm VCSELs with Narrow Divergence Angles and High-Power Performances for Fiber and Free-Space Optical Communications

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**ABSTRACT** Using the Zn-diffusion and oxide-relief techniques with the optimized aperture sizes, we demonstrate a novel single-mode 940 nm vertical-cavity surface-emitting laser (VCSEL) with high brightness performance. The highly single-mode (SM) output optical spectra (SMSR>50 dB) can be sustained under a full range of bias currents and from room temperature (RT) to 85°C operation. Under RT operation, the maximum SM power can be as high as 7.1 mW with a moderate threshold current ($I_{th}$: 1.1mA) and narrow divergence angles in the far-field pattern (FWHM: 5°, $1/e^2$: 7-8°). Furthermore, the maximum 3-dB E-O modulation bandwidth of this high-power SM VCSEL can reach 15 GHz without the low-frequency roll-off induced by spatial hole burning effect. By using this novel device as the transmitter, we can achieve 25 Gbit/sec error-free (bit-error-ratio (BER) < $1\times10^{-12}$) transmission over a 400 meter OM5 fiber without using any signal processing technique. This novel high-speed and high-brightness SM 940 nm VCSEL can serve as a light source in single-mode fiber for medium-reach (>0.3 km) data communications as well as in free-space optical communication.

**INDEX TERMS** Vertical cavity surface emitting lasers, Fiber optics, Data communication

## I. INTRODUCTION

The combination of OM3/OM4 multimode fibers (MMFs) with high-speed MM vertical-cavity surface-emitting lasers (VCSELs) or photoreceivers as the transreceiver (Tx/Rx) module has become the main stream in the very-short reach (VSR<300 meter) optical interconnect (OI) market [1]. The MMF based module provides a much larger alignment tolerance in the active/passive device package compared to that of a single-mode fiber (SMF) module due to the much larger size of the core in the MMF (50 vs. 8 μm). On the other hand, when the linking distance of the OI channel exceeds 0.5 km, the SMF based solution becomes preferable. This is because of the much lower cost for fabrication of SMF and less dispersion during data transmission than for the MMF. In hyper-scale data centers, where the required OI linking distance ranges from VSR to long-reach (2 km) both MMF and SMF coexist making their interface a problem due to incompatibility of the core diameters of these two kinds of fibers. To solve above-mentioned problems, the Corning company developed a new universal fiber [2-4] or a few-mode fiber (FMF) with its fundamental mode being compatible with SM Tx/Rx. It has a core diameter ranging between SMF and MMF which can accommodate both types of transmissions. The development of the FMF simplifies the management of fiber cables and provides flexibility for future transceiver upgrades. However, the output of traditional MM high-speed VCSELs cannot be efficiently coupled into these kind of fibers due to the wide divergence angle ($1/e^2$: ~25°) of the output far-field pattern (FFP). This has driven the development of high-speed and highly SM (high brightness) VCSELs [5-9] to serve as light sources in the next generation of FMF based data centers. In addition, field of free space optical communications (FSO) in aerospace has recently attracted a lot of attention for the purposes of communication between micro or nanosatellites [10]. The key component for effective

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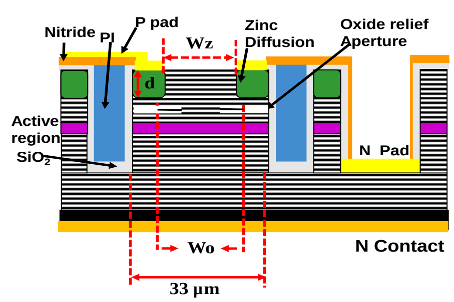
data transmission in FSO based wireless networks are high-brightness and high-speed light sources, which can effectively minimize diffraction loss of its output optical beam and enhance the received optical power in the high-speed receiver with a limited active area. Compared with edge-emitting lasers (EELs), for FSO aerospace applications, VCSELs usually shows better radiation resistance [11]; however, the commercially available high-speed VCSELs usually have a wide divergence angle ($1/e^2$: ~25°) with low brightness performance. In this study, we demonstrate a novel single-mode, high-brightness, and high-speed 940nm VCSEL fabricated using Zn-diffusion and oxide-relief techniques [12,13]. While scanning to the full range of bias current, highly single-mode (SM) output optical spectra (SMSR>50dB) is maintained from RT to 85°C. The fabricated device exhibits maximum SM power up to 7.1 mW with a decent threshold current ($I_{th}$: 1.1mA) maintaining narrow divergence angles in the far-field pattern (full-width half maximum (FWHM): 5°, $1/e^2$: 7~8°). This fabricated novel device has potential to be used for transmitter, as we can achieve 25 Gbit/sec error-free (bit-error-ratio (BER) < $1\times10^{-12}$) transmission over a 400 meter using OM5 fiber without using any signal processing technique. This novel high-speed and high-brightness SM 940 nm VCSEL can serve as a light source with the newly developed universal fiber for medium-reach (2 km) optical communications as well as in FSO. As compared to our previous work about SM 940 nm VCSEL [14], the divergence angle of new device has been significantly narrow down (FWHM: 5° vs. 10°) with a higher maximum SM power (7.1 vs. 6.8 mW) by further optimizing the sizes of Zn-diffusion and oxide apertures. In addition, the high-speed transmission results of this novel device is firstly demonstrated here.

## II. DEVICE STRUCTURE DESIGN AND FABRICATION

Figures 1 (a) and (b), respectively, show conceptual cross-sectional and top views of the demonstrated unit VCSEL. As can be seen in Figure 1(a), there are three key parameters: $W_Z$, $W_O$, and d, which determine the mode characteristics of the single device. Here, $W_Z$ and $W_O$ represent the diameter of the Zn-diffusion aperture and oxide-confined aperture, respectively; d is the Zn-diffusion depth. The addition of Zn-diffusion apertures in the top p-type DBR layers of our VCSEL will induce extra loss in the peripheral region of the optical aperture. Higher order mode lasing can thus be suppressed in the Zn-diffused DBR region due to free-carrier absorption and reflectivity reduction caused by disordering [6]. The disordering of the DBR layers allows us not only to manipulate the number of optical transverse modes inside the VCSEL cavity, as discussed elsewhere, but can also reduce the differential resistance of the VCSEL [12,13]. By properly optimizing the relative sizes of these three parameters to allow significant Zn-diffusion induced internal loss ($\alpha_i$) in the current-confined (gain) region, the device is able to demonstrate high single-mode (SM) performance under the full range of bias currents. Here, the chosen values of $W_Z$, $W_O$, and d are 7.5, 9, and 1.5 μm, respectively.

The epi-layer structure is composed of three compressive strained $In_{0.15}Ga_{0.85}As/Al_{0.37}Ga_{0.63}As$ (4/8 nm thickness) MQWs sandwiched between 36-paired n-type and 23-paired p-type $Al_{0.9}Ga_{0.1}As/Al_{0.05}Ga_{0.95}As$ Distributed-Bragg-Reflector (DBR) layers with a single $Al_{0.98}Ga_{0.02}As$ layer (20 nm thickness) for oxidation. The photoluminescence (PL) measurement results show that the PL peak wavelength of our MQW active region is at around 924 nm at RT. Based on the measured Bragg wavelength (~937 nm) in our VCSEL cavity, the corresponding cavity-to-PL detuning wavelength is around 13 nm. Such a design can improve the high-temperature performance of the VCSEL [15]. The fabrication of the VCSEL starts with the Zn-diffusion process. A high-quality $Si_3N_4$ film is necessary to serve as the mask for the high-temperature diffusion process. The mask defined diameter of the optical aperture (without Zn-diffusion) is around 8 μm. Considering the lateral Zn-diffusion, the final $W_z$ is around 7.5 μm after the finish of the Zn-diffusion process with a ~1.5 μm depth (d). After the diffusion process, the mesa etching process is performed. An oxidation technique is then used to define a circular current-confined area, 9 μm in diameter. The oxide layer for current confinement is removed from the oxide-relief structure by selective wet chemical etching [12,13]. Due to the lower dielectric constant of air compared with that of the $AlO_x$ layers, there is a demonstrated reduction in the parasitic capacitance and improvement in the VCSEL's speed for a single device [12,13]. Furthermore, under high-power and high-current density operation, the reliability of the oxide-confined VCSEL is usually an issue. An improvement in the reliability of our oxide-relief structure has also been verified because of the elimination of oxide layer induced stress on the neighboring active layers. The detail reliability test result will be published somewhere else. After p-type contact metallization (Ti/Au; 50/200 nm), the device is passivated by a $SiO_2$ layer (~150 nm) and an ~3 μm thick polymethylglutarimide (PMGI) layer is then deposited for planarization. Finally, an ~2μm thick Ti/Au pads is evaporated onto the chip for on-wafer probing. The directions of x- and y- axis, which are used for far-field measurements as discussed latter, is specified on Figure 1 (b).

(a)



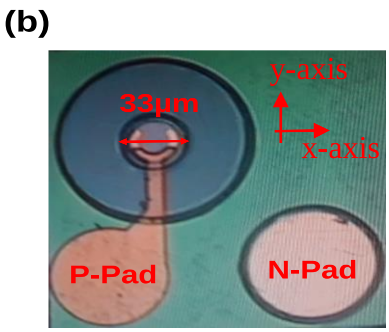



FIGURE 1. (a) Conceptual cross-sectional view of demonstrated VCSEL unit; (b) top view of the demonstrated VCSEL unit with ($W_o$/$W_Z$/d: 9/7.5/1.5 μm).

## III. MEASUREMENT RESULTS

Figure 2 (a) shows the measured L-I-V curves of our VCSEL unit at different operating temperatures varying from room temperature (RT) to 90°C. As can be seen, the VCSEL unit exhibits a threshold current of 1.1 mA and maximum output power, $P_{max}$ of 7.1 mW @ 15 mA. The operation voltage and differential resistance under a 6 mA bias current are found to be 2.0 V and 42 Ω, respectively. Such a low differential resistance has been attributed to Zn-diffusion process and the topmost current spreading layers. Figure 2 (b) and (c) show the optical spectra for a single VCSEL unit measured at RT and 90°C, respectively. Highly single-mode operation (side-mode suppression ratio (SMSR) > 50 dB) can be sustained under the full range of bias currents (from threshold to saturation). The achieved maximum SM power is the highest ever reported for 900-1100 nm VCSELs, comparable with the maximum SM power (~7 mW) reported for 850 nm VCSELs [8] but with a smaller $I_{th}$. This improvement may be attributed to the 940 nm MQWs having a larger compressive strain and a higher optical gain than those of the 850 nm ones.

Figures 3(a) and (b) show the one-dimensional (1-D) (in the x-direction) and 2-D far-field patterns of a single VCSEL unit measured under different bias currents at RT and HT: 90°C, respectively. For 2-D measurement, a charge-coupled device (CCD) camera is installed just above the single VCSEL unit to take pictures of the far-field patterns. In order to avoid saturation of the camera and the influence of the optical feedback effect on the measured patterns, neutral density (ND) filters are inserted between the single VCSEL unit and the CCD. The 1-D patterns are constructed from the measured data points in our 2-D patterns. We can clearly see that Gaussian like far-field patterns (FFP) can be sustained under all bias currents. The measured full width half maximum (FWHM) varies from (5°-5.2°) and the 1/$e^2$ width varies from (7°-8°) under the full range of bias currents at RT and 90°C, respectively. Such narrow FFP divergence angles ensure the good coupling efficiency between our SM VCSEL output and the FMFs.

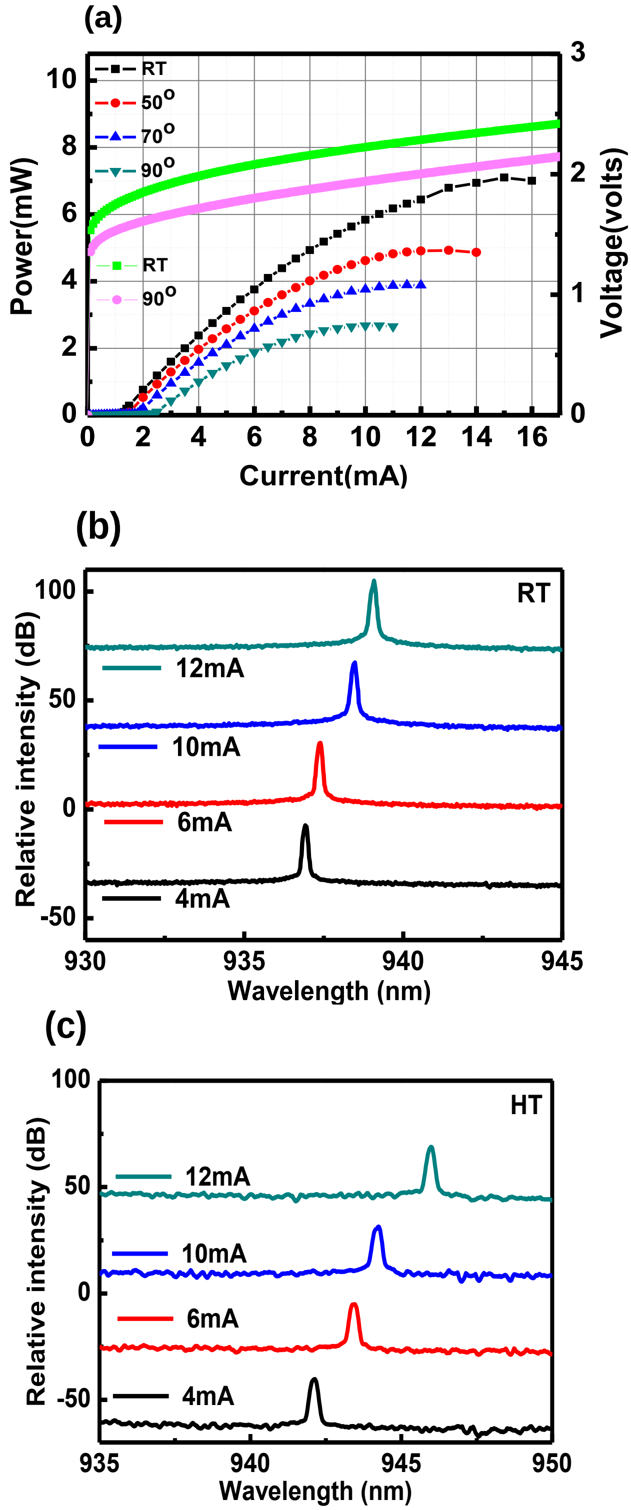



FIGURE 2. (a) Measured L-I-V curves of single VCSEL unit at different operating temperatures. Measured optical spectra of single VCSEL unit under full range of bias currents at (b) RT and (c) HT: 90°C.

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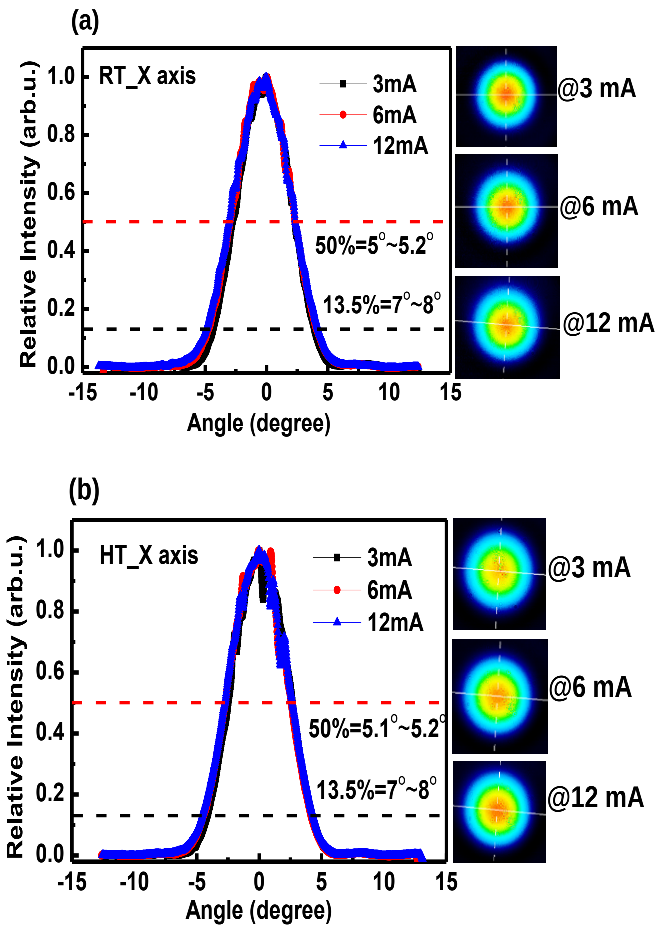


**FIGURE 3.** **Measured one-dimensional (1-D) (in the x-direction) and 2-D far-field patterns of single VCSEL unit under full range of bias currents at (a) RT and (b) HT: 90 ℃. The x-axis is defined at Figure 1 (b).**

The high-speed E-O performance of the fabricated devices was measured by a lightwave component analyzer (LCA), composed of a network analyzer (Anritsu 37397C) and a calibrated photoreceiver module (VI Systems: D50-1300 M), which could cover an optical window from the 850 to 1310 nm wavelengths. The measured O-E -3dB bandwidths for this photoreceiver module are around 27 and 24 GHz at the 850 and 1310 nm wavelengths, respectively. Here, we chose the measured optical-to-electrical (O-E) frequency responses at 850 nm as the calibration files for the de-embedding process for 940 nm VCSEL E-O measurement. Figures 4(a) and (b) clearly show the maximum -3dB E-O bandwidth for a single VCSEL unit to be 15 GHz at room temperature and 11 GHz at 85°C, respectively. For the measured E-O responses reported for the SM 850 nm VCSEL, there is usually a parasitic low-frequency roll-off (> 3 dB) induced by the spatial hole burring effect [6,8,16], which would degrade the quality of the eye-pattern during high-speed data transmission [6,8,16]. The elimination of this phenomenon in our demonstrated SM 940 nm VCSEL may be attributable to the larger compressive strain in the 940 nm active layers than that in the 850 nm ones.  A larger strain in the well layers of the MQWs would lead to a smaller effective mass and larger hole mobility, which would minimize the hole burning effect [16].

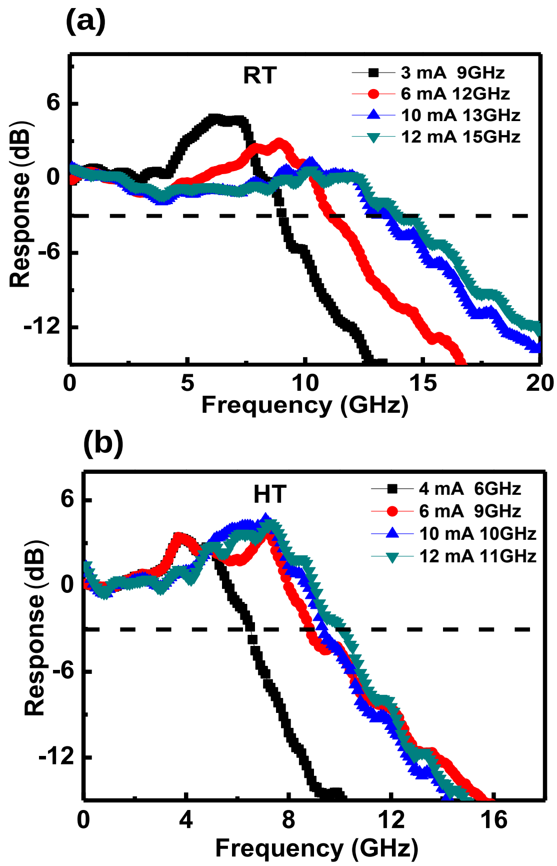


**FIGURE 4.** **Measured bias dependent E-O frequency responses of a single VCSEL unit at (a) RT and (b) 85℃ operations.**

Figure 5. describes the setup used for data transmission measurement. It includes an SHF 12104A bit pattern generator which can generate a non-return-to-zero (NRZ) electrical signal of up to 60 Gbit/sec. The pseudo-random binary sequence (PRBS) data stream used for transmission is $2^9$-1 in length. The OM5 MMFs, which are optimized for 940 nm wavelength transmission, are adopted in our experiment. The optical signal collected at the receiving end is analyzed with a Tektronix sampling oscilloscope with an optical module with a bandwidth of up to 32 GHz.

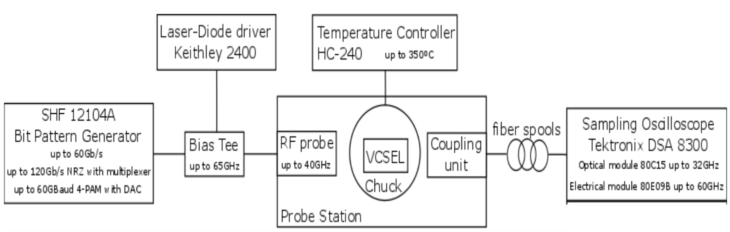


**FIGURE 5.** **Experimental setup used for data transmission measurement**

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Figure 6 shows the 25 Gbit/sec eye patterns obtained with the 940 nm VCSEL unit for different lengths of fiber (back-to-back (B2B), 200, 400, and 600 meter) and under different ambient temperatures (room temperature (RT), 50 and 85°C). Both the bias current (12 mA) and peak-to-peak driving voltage ($V_{pp}$: 0.6 V) applied to the device were optimized to obtain the highest quality of eye-patterns. The measured values of rise time and jitter are specified in each eye-pattern. Clear eye-opening can be observed at all three ambient temperatures for a transmission distance of 400 m. The small eye-opening at 85°C may be attributed to the significant resonance (around 6 dB) and 3-dB E-O bandwidth degradation (from 15 to 11 GHz) in the measured E-O response, as shown in Figure 4 (b). This resonance can be suppressed by further increasing the number of pairs of top-DBR mirrors (mirror reflectivity) and the photon lifetime inside the cavity, but at the expense of lower 3-dB E-O bandwidths [17,18]. In addition, less bandwidth degradation can be expected for 940 nm VCSELs under high-temperature operation by enhancement of the differential gain inside the MQW region with a larger compressive strain and a thinner well width [13].

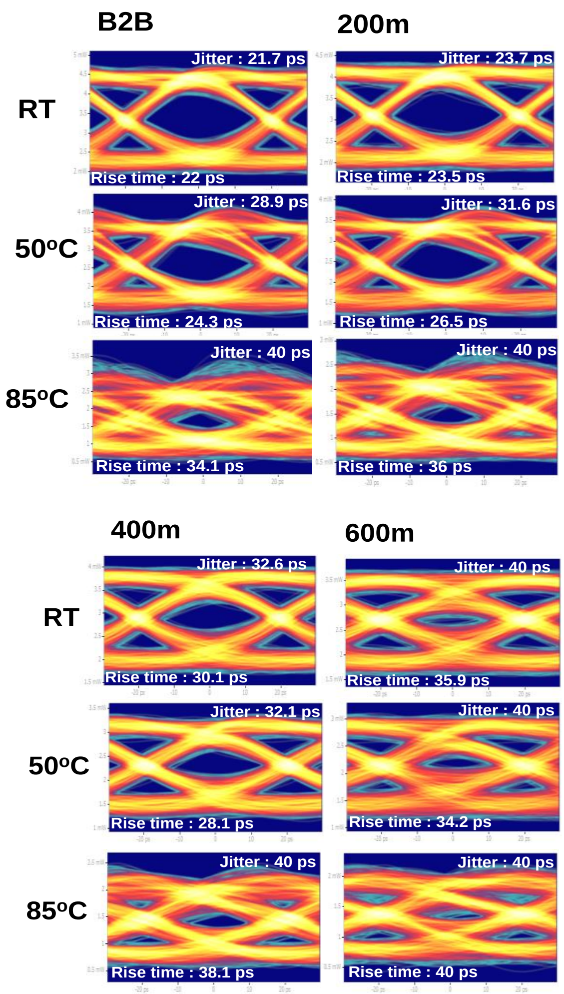
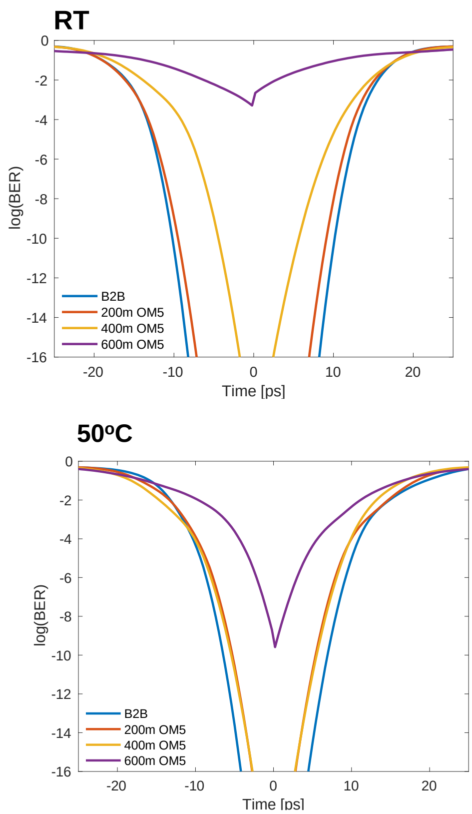



**FIGURE 6.** 25 Gbit/sec transmission eye-patterns over B2B, 200m, 400m, and 600m fibers measured at RT, 50℃, 85℃, respectively.

Figure 7 shows the corresponding bathtub curves. Note that our VCSEL unit can exhibit error-free transmission (BER<$1\times10^{-12}$) for 400 m transmission at temperatures up to 50°C without using any pre-emphasis or equalization techniques. However, when the operation temperature reaches 85°C, the error-free transmission is not feasible for all transmission distances (from B2B to 600 meters). This indicates that the limited E-O bandwidth and significant resonance in the E-O response under 85°C operation, as shown in Figure 4, are the main bottleneck for high-temperature 25 Gbit/sec transmission. On the other hand, we can clearly see that under 50 ℃ operation, the 400 and 600 meter bathtub curves have better performance than those of measured under RT. This can be attributed to that under 50 and 85 ℃ operations, the VCSEL shows larger overshoot (resonance) than at 25 ℃ operation, which is visible in the measured E-O frequency response, as shown in Figure 4 (b). Such overshoot occurs at high frequencies so they can compensate the high-frequency roll-off caused by the dispersion of fiber transmission and thus the 50 ℃ eye-patterns look better than the 25℃ case (faster rise time), as shown in Figure 6. And as the eye-pattern has the better shape-also the bathtub curves calculated out of it show better performance. In our future work, we will measure the BER curves versus the receiving power after OM5 fiber transmission at different ambient temperatures with a well-packaged transmitter optical subassembly (TOSA) module based on our SM VCSEL chip.



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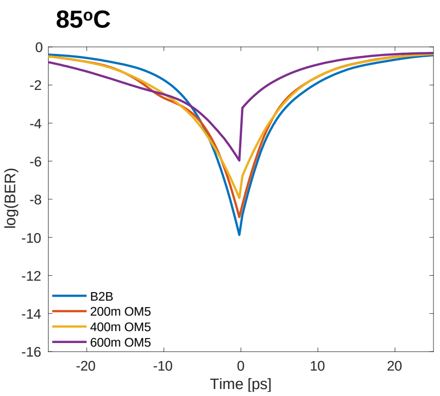


**FIGURE 7. Measured bathtub curves under different operation conditions at RT, 50℃ and 85℃.**

## IV. SUMMARY

We demonstrate a novel high-brightness, high-speed single-mode VCSEL at the 940 nm wavelength. By properly controlling the size of the Zn-diffusion and oxide apertures, we are able to fabricated a device which exhibits highly single-mode (SMSR>50dB), moderate $I_{th}$ (~1.1 mA), stable circular far-field patterns with a narrow $1/e^2$ divergence angle (~8°) under the full-range of bias currents and from RT to 85°C. The maximum SM output power and 3-dB E-O bandwidth at RT are 7.1mW and ~15 GHz, respectively. By the use of such a VCSEL, we can achieve 25 Gbit/sec error-free (BER < $1\times10^{-12}$) transmission over a 400 meter OM5 fiber without requiring the use of any signal processing techniques.

## REFERENCES


[1] X. Chen, S. R. Bickham, J. S. Abbott, J. D. Coleman and M.-J Li, "Multimode Fibers for Data Centers", in Handbook of Optical Fibers, G.-D. Peng, (eds) Springer Singapore, 2018, pp. 1-57

[2] A. A. Juarez, X. Chen, J. E. Hurley, M. Thiermann, J. Stone and M. Li, "Graded-Index Standard Single-Mode Fiber for VCSEL Transmission Around 850 nm," 2019 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 2019, pp. 1-3.

[3] X. Chen et al., "Universal fiber for both short-reach VCSEL transmission at 850 nm and single-mode transmission at 1310 nm," 2016 Optical Fiber Communications Conference and Exhibition (OFC), Anaheim, CA, 2016, pp. 1-3.

[4] X. Chen, J. E. Hurley, J. S. Stone, A. R. Zakharian, D. Coleman and M.-J Li, "Design of universal fiber with demonstration of full system reaches over 100G SR4, 40G SWDM, and 100G CWDM4 transceivers", *Optics Express*, vol. 24, No.16, pp. 18492-18500, 2016.

[5] A. Haglund, J. S. Gustavsson, J. Vukusic, P. Modh and A. Larsson, "Single fundamental mode output power exceeding 6 mW from VCSELs with a shallow surface relief," *IEEE Photon. Technol. Lett.*, vol. 16, No. 2, pp.368-370, Feb., 2004.

[6] J.-W. Shi, C.-C. Chen, Y.-S. Wu, S.-H. Guol, and Y.-J. Yang, "High-Power and High-Speed Zn-Diffusion Single Fundamental-Mode Vertical-Cavity Surface-Emitting Lasers at 850nm Wavelength," *IEEE Photon. Technol. Lett.*, vol. 20, No.13, pp.1121-1123, July, 2008.

[7] R. Safaisini, K. Szczerba, E. Haglund, P. Westbergh, J. S. Gustavsson, A. Larsson, and P. A. Andrekson, "20 Gbit/sec error-free operation of 850 nm oxide-confined VCSELs beyond 1 km of multimode fibre," *Electron. Lett.*, vol. 48, No. 29, pp. 1225-1227, Oct., 2012.

[8] J.-W. Shi, Z.-R. Wei, K.-L. Chi, J.-W. Jiang, J.-M. Wun, I.-C. Lu, J. (Jyehong) Chen, and Y.-J. Yang, "Single-Mode, High-Speed, and High-Power Vertical-Cavity Surface-Emitting Lasers at 850 nm for Short to Medium Reach (2 km) Optical Interconnects," *IEEE/OSA Journal of Lightwave Technol.*, vol. 31, No .24, pp. 4037-4044, Dec., 2013.

[9] N. N. Ledentsov, V. A. Shchukin, V. P. Kalosha, N. N. Ledentsov Jr., J.-R. Kropp, M. Augustin, Ł. Chorchos, J. P. Turkiewicz, and J.-W. Shi, "Anti–waveguiding vertical–cavity surface–emitting laser at 850 nm: From concept to advances in high–speed data transmission," *Optics Express*, vol. 26, No.1, pp. 445-453, Jan., 2018.

[10] E. Kehayas, "Space Photonics: A platform technology for satellite systems", autumn 2017, Accessed: Jan.2020. [online]. Available: https://www.photonics.com/Articles/Space_Photonics_A_Platform_Technology_for/a62298

[11] R.F. Carson, E.W. Taylor, A.H. Paxton, H. Schone, K.D. Choquette, H.Q. Hou, M.E. Warren and K.L. Lear "Surface-emitting laser technology and its application to the space radiation environment" Proc. SPIE OPTO, San Diego, CA, July 29, 1997, pp. 10288.

[12] J.-W. Shi, J.-C. Yan, J.-M. Wun, J. (Jyehong) Chen and Y.-J. Yang, "Oxide-Relief and Zn-Diffusion 850 nm Vertical-Cavity Surface-Emitting Lasers with Extremely Low Energy-to-Data-Rate Ratios for 40 Gbit/sec Operations" *IEEE Jounal of Sel. Top. in Quantum Electronics*, vol. 19, No. 2, pp. 7900208, March, 2013.

[13] C.-L. Cheng, N. Ledentsov Jr., Z. Khan, J.-L. Yen, N. N. Ledentsov, and J.-W. Shi, "Ultrafast Zn-Diffusion and Oxide-Relief 940 nm Vertical-Cavity Surface-Emitting Lasers under High-Temperature Operation," *IEEE Journal of Sel. Topics in Quantum Electronics*, vol. 25, No. 6, pp. 1700507, Dec., 2019.

[14] Z. Khan, J. Shih, C. Cheng and J. Shi, "High-Power and Highly Single-Mode Zn-Diffusion VCSELs at 940 nm Wavelength," *2019 IEEE Photonics Conference (IPC)*, San Antonio, TX, USA, 2019, pp. 1-2.

[15] K.-L. Chi, J.-L. Yen, J.-M. Wun, J.-W. Jiang, I.-C. Lu, J. (Jyehong) Chen, Y.-J. Yang, and J.-W. Shi, "Strong Wavelength Detuning of 850 nm Vertical-Cavity Surface-Emitting Lasers for High-Speed (>40 Gbit/sec) and Low-Energy Consumption Operation," *IEEE Journal of Sel. Topics in Quantum Electronics*, vol. 21, No.6, pp. 1701510, Dec., 2015.

[16] A. Haglund, J. S. Gustavsson, P. Modh, and A. Larsson, "Dynamic mode stability analysis of surface relief VCSELs under strong RF modulation," *IEEE Photon. Technol. Lett.*, vol. 17, No. 8, pp. 1602-1604, July, 2005.

[17] G. Larisch, P. Moser, J. A. Lott, and D. Bimberg, "Impact of Photon Lifetime on the Temperature Stability of 50 Gb/s 980 nm VCSELs," *IEEE Photon. Technol. Lett.*, vol.28, No. 21, pp. 2327, Oct., 2016.

[18] P. Westbergh, J. S. Gustavsson, B. Kögel, Å . Haglund, and A. Larsson, "Impact of Photon Lifetime on High-Speed VCSEL Performance," *IEEE Journal of Sel. Topics in Quantum Electronics*, vol. 17, No. 6, pp.1603, Dec., 2011.


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