Single-Mode VCSEL with Zn-Diffusion Apertures and Strong Immunity Against Optical Feedback for Improved Data Transmission

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Abstract: We demonstrate state-of-the-art performances of single-mode VCSELs, including wide-bandwidth (27GHz), high-power (6.7mW), low-RIN (-137dB/Hz), and invariant 56Gbps eye patterns under strong optical feedback (-6dB). It achieves error-free 46Gbit/sec transmission through 0.5km MMF without using equalizers.

OCIS codes: (140.5960) Semiconductor lasers, (140.7260) Vertical cavity surface emitting lasers

I. Introduction

The use of high-speed VCSELs with single-mode (SM) characteristics as transmitters in a multi-mode fiber (MMF) based optical interconnect system has proven an effective solution to further enhance the bit-rate distance product [1-3]. The most straightforward way to obtain a (quasi-) SM output in high-speed VCSELs is to downscale the size of the oxide apertures to less than ~4 μm [3,4] in order to suppress the higher-order optical transverse modes. By combining these SM VCESLs, which have miniaturized oxide-apertures, with the advanced equalizers in transmission channels, data rates of 54 Gbit/sec over a linking distance of 2 km MMF have been successfully demonstrated [3]. However, ensuring the reliability of this kind of SM VCSEL remains a challenge because of the high current density during high-speed operation. Moreover, the limited maximum output power (usually around 2 mW) from this kind of small aperture VCSEL in turn limits the maximum linking distance due to significant transmission loss of MMF. On the other hand, in order to increase the current-confined aperture size and maximum SM output power, the approaches by using an additional aperture, such as Zn-diffusion [1] and surface relief [2], have been demonstrated. However, the high photon density in the highly SM output usually leads to a serious spatial hole burning (SHB) effect, which is accompanied by an unwanted low-frequency roll-off and more noticeable resonance in the relative intensity noise (RIN) spectrum [5]. These characteristics lead to serious degradation of the large-signal transmission results. In addition, the other important challenge for the practical application of SM VCSELs is that their performance is more sensitive to parasitic reflection induced by device packaging than that of their MM counterparts [1]. In this study, we demonstrate that by further optimizing the structure of the Zn-diffusion aperture, we can produce single-mode VCSELs with state-of-the-art static and dynamic performance, e.g., wide 3-dB electrical-to-optical (E-O) bandwidth (27 GHz), high power (6.7 mW), low RIN (-137dB/Hz), and invariant 56 Gbps eye patterns under strong optical feedback (-6 dB) as well as achieving error-free 46 Gbit/sec transmissions through 0.5km MMF without the need for using equalizers.

II. Device Structure and Measurement Results

Figures 1 (a) and (b) show the top view and conceptual cross-sectional view of the demonstrated VCSEL, respectively. Here, both the oxide-relief and Zn-diffusion processes were applied to manipulate the optical transverse modes and relax the RC-limited bandwidth of our VCSEL device [5]. The epi-layer structure which was grown in a molecular beam epitaxy (MBE) chamber (Intelligent Epitaxy Technology Inc.) is composed of four compressively strained $In_{0.07}Ga_{0.93}As/Al_{0.3}Ga_{0.7}As$ MQWs sandwiched between 39-pair n-type and 24-pair p-type $Al_{0.93}Ga_{0.07}As/Al_{0.15}Ga_{0.85}As$ DBR layers with a single $Al_{0.98}Ga_{0.02}As$ layer (25 nm thickness) for oxidation. In comparison to the traditional Zn-diffusion VCSELs, both the structure and geometric size (W_z and d) of the diffusion aperture have been further optimized to minimize the spatial hole burning effect [1] for high-power and SM operation. The size of W_o for all the devices studied here is fixed at around 6 to 7 μm. The measured L-I curves of the demonstrated novel Zn-diffusion (device A) and traditional VCSEL (device B) are shown in Figs. 2 (a) and (b), respectively. The corresponding bias dependent optical spectra are shown in Figs. 3 (a) and (b). As can be seen, device A exhibits superior static performance, which includes a higher (quasi-) SM power, to that of device B. In device A, under a 9 mA bias current for maximum output power (~6.7 mW), highly SM performance can be sustained. Figure 4 shows the measured bias dependent O-E frequency responses of both devices (A and B). It can be clearly seen that for device A, under a bias current of 6 mA, we can attain a 3-dB E-O bandwidth as wide as 27 GHz, which is much faster (27 vs. 16 GHz) than that of its counterpart, device B. Furthermore, all the measured E-O frequency responses are flat and heavily damp, which implies a low RIN performance under high-speed operation [5]. The influence of the optical feedback on the transmission performance, as shown in Figure 5, was also studied with the application of the reflected optical power onto our SM VCSEL during eye pattern measurement. Here, the reflected optical power from port 4 terminated with a retroreflector can be well controlled and monitored by the tunable optical attenuator (port 4) and optical power meter (port 2), respectively, installed in different ports of 2×2 optical 3-dB coupler. Figures 6 and 7 show the measured back-to-back (BTB) eye patterns at different reflectance values of devices A and B. Here, the reflectance is defined by the ratio of the reflected optical power illumination on the VCSEL to its total output power. The RIN optical modulation amplitude (OMA) values of these eye patterns were directly measured by the built-in firmware of the sampling scope (BERTWave MP2110A). We can clearly see that device A, with its novel Zn-diffusion aperture design, not only exhibits a faster data rate (56 vs. 48 Gbit/sec) but also a lower RIN noise (-133 vs. -130 dB/Hz) under strong optical feedback (-6 dB). Figure 8 shows the transmission results for both devices (A and B) after transmission through a 0.5 km OM4 MMF, without the use of equalizers at the transmitter or the receiver sides. Similar to the trend shown by the BTB results, device A exhibits a larger bit-rate distance product and better quality of eye patterns (jitter: 1.7 vs. 3.7 ps) at a higher data rate (46 vs. 25 Gbit/sec) than those of device B. This result is mainly due to the faster speed performance and less optical modes of device A under a higher bias current (output power), as illustrated in Figures 3 and 4. Table 1 shows the benchmark transmission results reported for high-speed VCSELs over MMF. Thanks to our high SM output power (6.7 mW under 9 mA) and high-speed performance, our device can attain the highest bit-rate distance among all reported high-speed 850nm VCSELs for the same cases, without using equalizers during measurement [3, 6-8].

III. Summary:

In this paper, we discuss a novel Zn-diffusion SM VCSEL further optimized through the design of its Zn-diffusion aperture. Thus, state-of-the-art performance, e.g., heavy damping E-O frequency response with a wide-bandwidth (27 GHz), high SM power (6.7 mW), low RIN (-146 dB/Hz), and invariant 56 Gbps eye patterns under strong optical feedback (-6 dB) with error-free 46 Gbit/sec transmissions over 0.5km MMF without using equalizers is achieved.

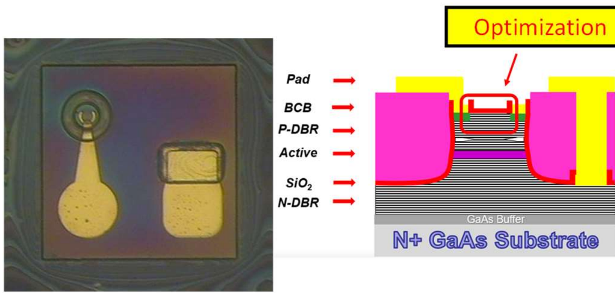

Figure 1. (a) Top-view and (b) conceptual cross-sectional view of the demonstrated VCSEL chip.

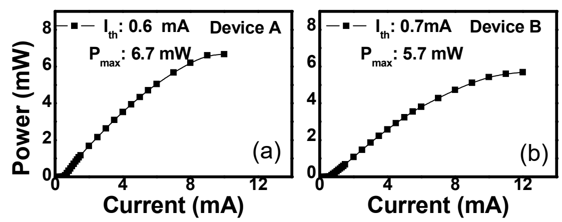

Figure 2. Measured L-I curves of (a) Device A and (b) Device B

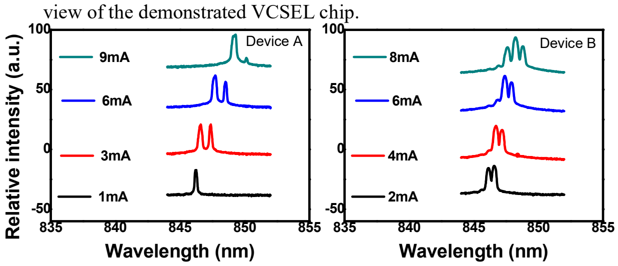

Figure 3. Measured bias dependent output optical spectra of (a) device A and (b) device B

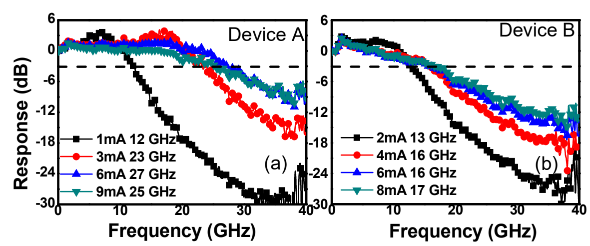

Figure 4. Measured bias dependent E-O frequency responses of (a) device A and (b) device B

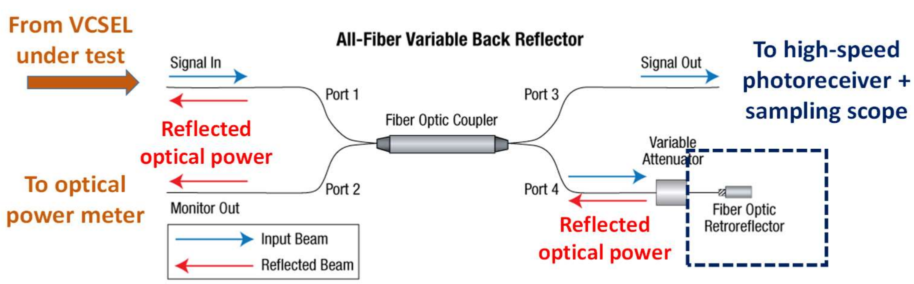

Figure 5. Eye-pattern measurement setups with stress of optical feedback

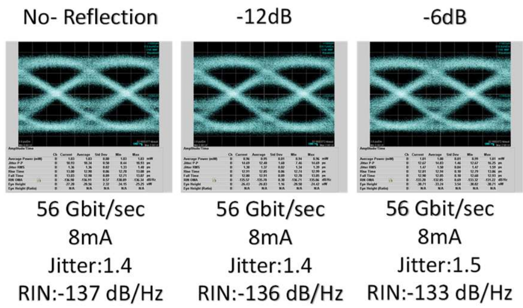

Figure 6. Eye patterns of device A measured under different optical feedback stress

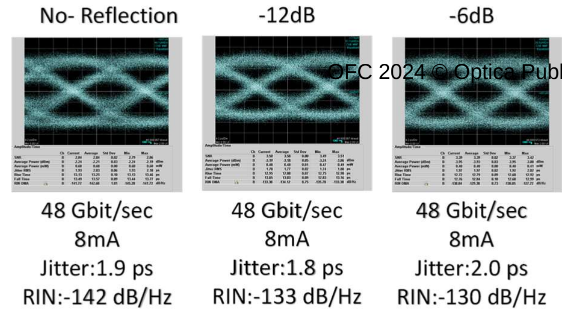

Figure 7. Eye patterns of device B measured under different optical feedback stress

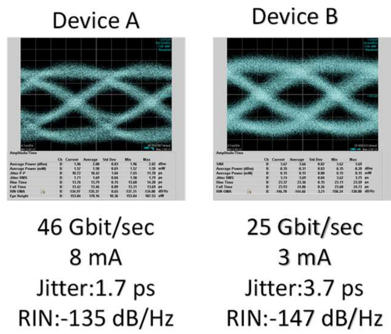

Figure 8. Measured eye patterns of device A and B after 500 meter OM4 MMF transmission under optimized bias currents

TABLE 1. BIT-RATE AND BIT-RATE DISTANCE PRODUCTS REPORTED FOR HIGH-SPEED VCSELS

	This work	**[6]**	**[7]**	**[8]**	**[3]**
Oxide aperture	**6 μm**	4 µm	3.5 µm	8 µm	
Bias current	**8mA**	6.5mA	2.5 mA	13 mA	3 mA
BTB Max data rate	**56 Gbit/s**	57 Gbit/s	50 Gbit/s	57 Gbit/s	25 Gbit/s
MMF Transmission (DSP free)	**500 m (46 Gbit/s)**	100 m (50 Gbit/s)		50 m (50 Gbit/s) 100 m(43 Gbit/s)	600 m (25 Gbit/s)
Bit-rate×distance	**23000 (m×Gbit/s)**	5000 (m×Gbit/s)		2500 (m×Gbit/s) 4300 (m×Gbit/s)	15000 (m×Gbit/s)

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