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Relative intensity noise of temperature-stable, energy-efficient 980 nm VCSELs

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The relative intensity noise (RIN) of temperature-stable, energy-efficient oxide confined vertical-cavity surface-emitting lasers (VCSELs) have been investigated. Low energy consumption data transmission is achieved by using small oxide-aperture diameter VCSELs biased at small currents. We demonstrate that energy efficiency is not in conflict with our VCSELs' RIN characteristics. The experimental results indicate that small oxide-aperture diameter VCSELs, which are most suitable for energy-efficient, temperature-stable operation, exhibit lower laser RIN due to less mode competition inside the smaller optical cavity volume. Our energy-efficient VCSELs fulfill the RIN requirements of the 32G Fibre Channel standard. [http://dx.doi.org/10.1063/1.4974258]

Vertical-cavity surface-emitting lasers (VCSELs) are the typical light sources used for high-speed optical interconnects (OIs) based on multi-mode optical fibers (MMF). The attributes of VCSEL-based OIs include low energy consumption, low cost, efficient optical coupling, and direct current modulation.[1–3] High speed and energy efficiency of OIs is achieved by directly modulating small oxide-aperture diameter VCSELs biased at moderate currents with simple non-return-to-zero (NRZ) on-off keying data coding.[4–6] This modulation format is limited by the analog –3-dB bandwidths of the VCSELs. The VCSEL's relative intensity noise (RIN), which is a major source of OI system noise, degrades the signal quality and increases the bit error ratio (BER) under certain conditions.[7] A low RIN floor across the operating range is needed to achieve a large signal-to-noise ratio (SNR). RIN characteristics often get less attention in device research, where the focus is on the modulation characteristics. System limitations due to poor RIN are often compensated by over-driving the VCSELs, getting larger modulation bandwidth than needed as compared to a system with better RIN characteristics.[8] This strategy increases strongly the required operating power and is in contrast to efficiency optimized approaches.

We previously performed systematic investigations of 980 nm VCSELs in data transmission experiments focusing on energy efficiency.[9,10] The results show that energy efficiency strongly depends on the oxide-aperture diameter.[10] The smallest possible heat-to-bit-rate ratio, defined as $HBR = (P_{el} - P_{opt})/BR$, where $P_{el} = I \cdot V$ is the input continuous wave (CW) electrical power due to a bias current I and a corresponding bias voltage V, P_{opt} is the optical output power, and BR is the bit rate,[11] is usually achieved by using small oxide-aperture diameter VCSELs biased at low currents. Since RIN is also strongly dependent on the oxide-aperture diameter and bias current, the RIN characteristics for energy-efficient VCSELs are important for overall OI system performance. In this paper, we perform a detailed RIN analysis of our energy-efficient, temperature-stable 980 nm VCSELs.

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The device structure of our VCSELs is described in detail in Ref. 10 and summarized as follows. The active region contains five 4.2 nm-thick compressively strained $In_{0.21}Ga_{0.79}As$ quantum wells (QWs) with 6 nm-thick $GaAs_{0.12}P_{0.88}$ tensile strained barrier layers that partially compensate the compressive QW strain. A −15 nm room temperature QW gain peak wavelength to etalon wavelength offset is employed to improve our VCSEL's high temperature static and dynamic performance.[10] Dry-etched bisbenzo-cyclobutene (BCB) is used to produce a flat and thick (>8 µm) dielectric layer to reduce the parasitic pad capacitance as well as to enable coplanar ground-signal-ground (GSG) contact pads to avoid parasitic coupling at the probe tip and thus to improve the accuracy of our high-frequency probing. Details of the static and high bit rate small-signal modulation results are given in Ref. 10. Oxide-aperture diameters of 3 to 4 µm were observed to be most suitable for energy-efficient data transmission. Table I summarizes the results for the VCSELs having oxide-aperture diameters of 3, 3.5, and 4 µm. To study the noise performance of energy-efficient devices, these 3 to 4 µm Oxide-aperture diameters VCSELs are used for the present RIN investigations.

Semiconductor laser RIN is a measure of the relative amplitudes of the optical power fluctuations around the average optical power level, and is quantified by normalizing the noise power by the average power level. Optical power is detected using a large bandwidth photodetector. Thus, the optical power fluctuations are transformed to electrical power fluctuations, which are measured with an electrical spectrum analyzer (ESA). The RIN can be expressed through the electrical values:

$$RIN = \frac{N_{total}}{P_{avg,elec}} = \frac{N_{laser} + N_{th} + N_{PD,shot}}{P_{avg,elec}} \quad (\mathrm{dB/Hz}) \tag{1}$$

where N_{total} (dBm/Hz) is the overall noise and $P_{avg,elec}$ is the average electrical power. The overall noise N_{total} has three noise components: the VCSEL noise N_{laser}, the thermal noise N_{th}, and the shot noise of the detector $N_{PD,shot}$. The overall noise (i.e. the total amplified system noise power spectrum) N_{total} is measured by the ESA with the VCSEL laser diode on. By turning off the laser diode and keeping the operation of the photodetector and amplifiers unchanged, the electrical spectrum analyzer measures only the thermal noise power spectrum $N_{th}(f)$. The frequency-dependent total amplifier power gain $G(f)$ of two cascaded amplifiers is measured using a 40-GHz Network Analyzer, and is subtracted from the measured amplified system noise power spectrum to compensate for the gain and the frequency response of the amplifiers. $N_{PD,shot} = 2qI_{ph}R_L$ is the shot noise power of the photodetector under the average VCSEL input power P_0, while I_{ph} is the photocurrent out of the photodetector, and R_L is the load resistance of amplifier 1's input port (see Fig. 1). The shot noise $N_{PD,shot}$ appears at the photodetector and rises proportionally with the detected optical power. The average electrical power is given by $P_{avg,elec}=I_{ph}2R_L$. After subtracting the system thermal noise and the photodetector shot noise, the intrinsic laser diode RIN can be extracted as:

$$RIN\,|_{laser}\,(f) = \frac{[N_{total}(f) - N_{th}(f)]\,/G(f) - N_{PD,shot}}{P_{avg,elec}} \tag{2}$$

The RIN is characterized with the measurement setup shown in Fig. 1. The VCSEL under test is biased at a constant current, and the optical output is directly coupled into a 5 m-length lensed multimode fiber. The OM2 optical fiber is connected to a fast photodetector (a New Focus 1434-50 having a bandwidth of 25 GHz), and the electrical signal is amplified by two cascaded RF broadband amplifiers (an SHF 100AP and an SHF 804EA) with 19 and 20 dB gain, respectively, to produce enough amplification to raise the signal above the noise floor of our Hewlett-Packard 8562A electrical

TABLE I. Comparison of room temperature energy efficiency for 3, 3.5, and 4 µm oxide-aperture diameter 980 nm VCSELs.

Parameter	3 µm	3.5 µm	4 µm
Temperature (°C)	25	25	25
HBR (fJ/bit)[a] @35Gbit/s	145[5]	161[5]	175[5]
HBR (fJ/bit)[a] @38Gbit/s	147[10]	181[10]	197[10]
I (mA) @35Gbit/s	2.7	3.0	3.3
I (mA) @38Gbit/s	2.9	3.5	3.78

[a]HBR: heat-to-bit rate ratio.

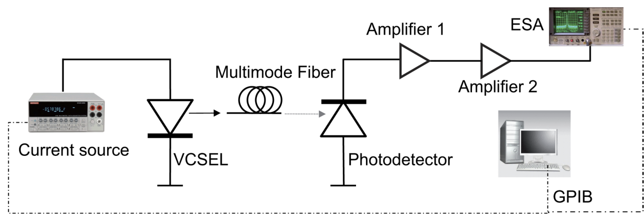

FIG. 1. Experimental setup for the RIN measurements.

spectrum analyzer. The New Focus photodetector has a built-in bias monitor to measure the average photocurrent during the measurements. The resolution bandwidth of the ESA is set to 30 kHz for the highest possible combination of measurement precision and sensitivity.

Figure 2 shows the VCSEL RIN versus frequency of a 3 µm oxide-aperture diameter 980 nm VCSEL at different bias currents. Note that the RIN peak is suppressed from −116 to −129 dB/Hz by increasing the bias current from 1 to 2 mA. It is well known that the decrease of RIN upon an increase in bias reflects the fact that the predominant source of RIN is spontaneous emission. Above threshold, the noise power does not increase very much, while the optical power rapidly increases. The RIN reaches a minimum level of −152 dB/Hz at a bias of 4 mA. When the bias current is increased above 4 mA the RIN peak gradually decreases to the shot noise limit. From the measured photocurrent of 0.55 mA, the shot noise level is calculated to be −152.3 dB/Hz. Fig. 2(b) shows the maximum RIN value at different currents. To indicate the achievable speed, the –3-dB bandwidths obtained from frequency response measurements at corresponding bias currents are also shown. For the bias current of 3 mA, the bandwidth reaches a maximum value of 19.9 GHz where the RIN is as low as –141 dB/Hz. The shot noise limit can be reached by further increasing the forward bias. These RIN data show that our 980 nm VCSELs can be operated at high bit rates with low noise. To realize energy-efficient data

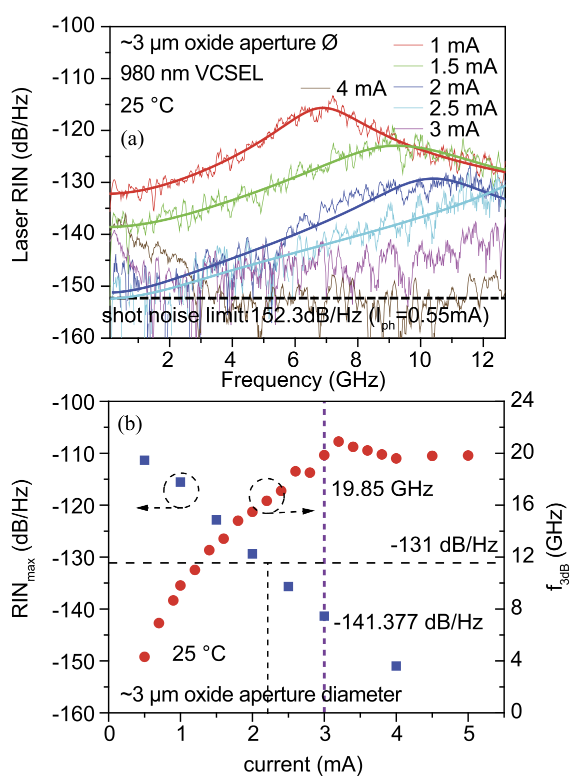

FIG. 2. Measured RIN spectra (a) for different bias conditions at room temperature for a 3 µm oxide-aperture diameter 980-nm VCSEL and (b) the maximum value of RIN spectra and the –3-dB bandwidth versus bias current.

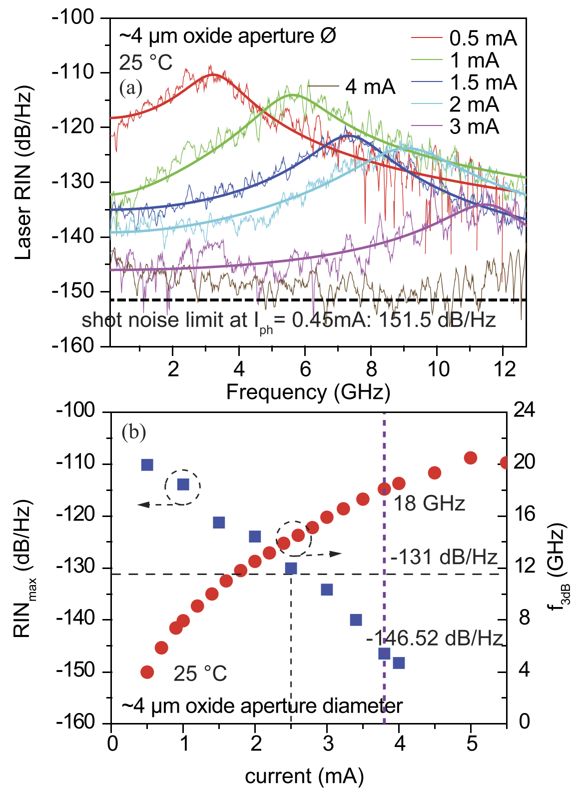

FIG. 3. Measured RIN spectra (a) for different bias conditions at room temperature for a 4 μm oxide-aperture diameter 980-nm VCSEL and (b) the maximum value of RIN and the –3-dB bandwidth versus bias current.

transmission, VCSELs are operated at the lowest currents, where still error-free data transmission is observed. Fig. 2(a) shows that a low bias current usually corresponds to a large RIN value, so it is necessary to know whether the RIN is low enough at a given low current energy-efficient operating point. Table I shows that error-free data transmission at 35 and 38 Gb/s with low energy dissipation of 145 and 147 fJ/bit is achieved at bias currents of 2.7 and 2.9 mA, respectively. According to the 32G Fibre Channel (32 GFC) standard,[12] the laser RIN is required to be below −131 dB/Hz. Fig. 1(b) shows that this RIN requirement can already be meet for currents larger than 2.2 mA. For all error-free data transmissions larger bias points were used and the RIN requirements of the 32 GFC standard are fulfilled. Thus, this implies our 980 nm VCSELs can be operated at high bit rates with low energy dissipation and with low noise.

For a 4 μm oxide-aperture diameter VCSEL the results are shown in Fig. 3. In contrast to the 3 μm oxide-aperture diameter VCSEL, whose noise saturates at the shot noise floor when the bias current is larger than 4 mA, the RIN of the 4 μm oxide-aperture diameter VCSEL is larger due to increased mode competition. The results indicate that the smaller VCSEL exhibits lower RIN, which is consistent with the trend of improved energy efficient operation of smaller VCSELs. The photon density in the active region is larger for 3 μm oxide-aperture diameter VCSELs due to the smaller optical mode volume. The relaxation resonance frequency and the damping both increase with an increase in photon density, which in-turn results in lower RIN values for the smaller oxide-aperture diameter VCSELs. For energy-efficient data transmission at 38 Gb/s, the bias current is 2.9 mA and 3.78 mA as shown in Table I for 3 and 4 μm oxide-aperture diameter VCSELs, respectively. The corresponding RIN values are as low as –141 and –146 dB/Hz, respectively.

In conclusion, we studied the RIN spectra of energy-efficient, temperature-stable 980-nm VCSELs at different bias currents at room temperature for different oxide-aperture diameters. Low RIN operation is achieved even at low bias currents as required specifically for energy-efficient, error-free data transmission operation. We have found that smaller oxide-aperture diameter VCSELs exhibit lower laser diode RIN due to less mode competition at a given –3-dB bandwidth. The trend is consistent with energy-efficient operation. The VCSELs satisfy the bandwidth and RIN requirements for the 32 GFC Fibre Channel standard. Our small oxide-aperture diameter (3 to 4 μm) VCSELs not only benefit from a larger –3-dB bandwidth and lower energy dissipation per transmitted bit, but they also show extremely low noise. being advantageous for short reach optical interconnects in high performance computers and in board-to-board and chip-to-chip integrated photonics systems.

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