Highly Reliable 106 Gb/s PAM-4 850 nm Multi-Mode VCSEL for 800G Ethernet Applications

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Abstract: This paper reviews II-VI's 106 Gb/s PAM-4 multi-mode VCSELs for commercial 800G transceiver applications. The VCSEL provides 27 GHz bandwidth, RIN of -150 dB/Hz, 0.25 nm spectral width and shows an excellent reliability. © 2022 The Author(s)

1. Introduction

Over the last two decades, 850nm oxide-confined multi-mode vertical-cavity surface-emitting lasers (VCSEL) have shown their advantages for short-reach multi-mode fiber Datacom applications in terms of low costs, small footprint, power efficiency, and high dynamic performance over a wide temperature range [1]. They have proven their high reliability and ability to follow the continuously increasing data rate demand [2]. The main drivers for higher data rate demand are data and storage centers as well as supercomputing. Currently, the market is still dominated by 100G SR4 transceivers, using 4 channels with 25Gb/s each, while 200G/400G modules are ramping up since 2021. The bandwidth density continuously grows strongly and scales with switch capacity. This leads to fast Datacom product development cycles of two to three years and therefore a high introduction rate of new technologies. VCSEL based modules provides low-cost optical connectivity and extend long-term application support for legacy multi-mode fiber (MMF) cabling. The upcoming 800G demand is expected to begin in 2022 with ramping up from 2023 onwards [3]. In general, high speed application devices must provide a large bandwidth, low relative intensity noise (RIN), and a narrow spectral width over a temperature range from 0°C to 85°C. With the recent transition from two level pulse amplitude modulation (PAM-2) non-return-to-zero (NRZ) signals towards PAM-4 for 50Gb/s VCSELs these requirements became even more compelling and were extended by others like flat frequency response and high linearity. Several groups made remarkable progress with their work on the next 100 Gb/s PAM-4 VCSEL generation [4,5] Within the last years, VCSELs with even higher data transmission rates and larger transmission distance have been reported [6,7].
In contrast, this paper focusses on a 106Gb/s PAM-4 VCSEL design, fulfilling commercial requirements and specifications in terms of performance, reliability, and volume manufacturability.

2. 106 Gb/s PAM-4 VCSEL

The vertical and lateral design of the 106 Gb/s PAM-4 VCSEL is based on the 56 Gb/s PAM-4 VCSELs design that is in volume production at II-VI, where the epitaxial growth and fabrication are done in II-VI production line. The VCSEL structure is grown with MOVPE and comprises InGaAs multi quantum wells (MQWs) embedded in a lambda half cavity between the top and bottom AlGaAs distributed Bragg reflectors (DBRs). The strained InGaAs gain material was already introduced in prior 28 Gb/s and 56 Gb/s designs and provides an increased differential gain compared to GaAs. Both top and bottom DBRs have been optimized in terms of optical reflection, electric and thermal conductivity as well as reduced free-carrier absorption. Charge carrier and optical mode confinement is given by an oxidation aperture in the p-doped top DBR, defined by an AlGaAs layer containing high Al concentration close to the active region. After mesa definition by dry etching a carefully controlled high-temperature water damp process results in an oxide aperture with a reproducible 6 µm diameter. The 106 Gb/s VCSELs are sealed by an identical humidity blocking layer as the II-VI's 28Gb/s and 56Gb/s VCSELs to ensure the same excellent humidity robustness. The low RIN design results in a suppressed mode competition and reduced impact of spontaneous emission to the lasing modes. The DBR reflectivity was carefully adapted as it directly impacts the photon lifetime and therefore the damping [8]. Almost identical VCSEL designs, but with a strongly reduced damping, showed bandwidths that significantly exceed 30 GHz. However, a higher bandwidth does not necessarily support an increased large-signal performance if it coincides with a strongly increased resonance overshoot resulting in degraded eye diagrams. PAM-4 signals especially suffer from over- and under-shoot as it closes the eyes within the ternary eye stack.

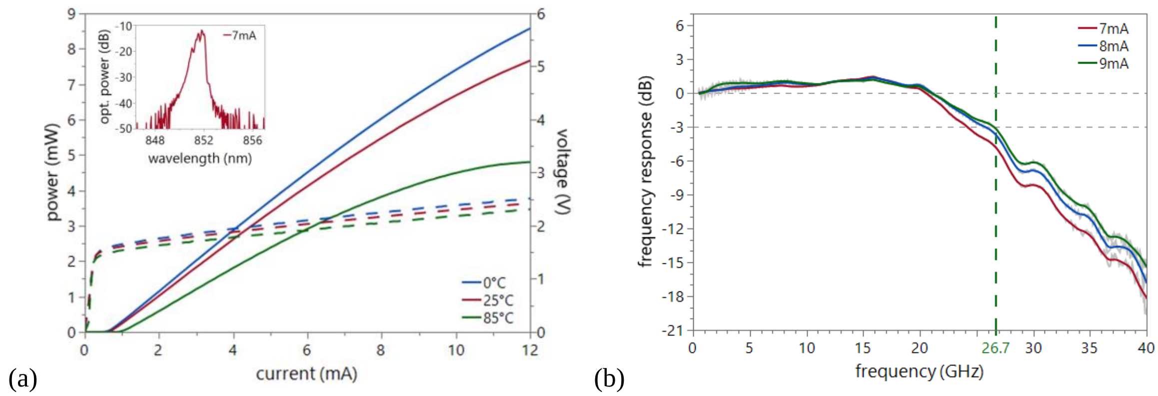

Fig. 1. (a) 106Gb/s VCSEL LIV characteristics at 0°C, 25°, and 85°C and optical spectrum at 7mA with a rms spectral width of 0.25 nm; (b) Small-signal frequency response for 7mA, 8mA, and 9mA at 25°C with a maximum -3dB bandwidth of 26.7 GHz.

Typical LIV characteristics for temperatures from 0°C up to 85°C are shown in Figure 2(a) with threshold currents between 0.65 mA at low temperatures and 0.98 mA at 85°C. The slope efficiency at 25°C is 0.8 W/A and therefore the optical power 4.8 mW at 7 mA. At 85°C, the thermal roll-over of the output power is visible, but the maximum power is still beyond 12mA. The differential resistance at 7 mA is 69 Ohm with a voltage of 2.10 V. The optical spectrum at 7 mA shows a peak wavelength of 851.7 nm. The rms spectral width is 0.25 nm, far below IEEE 802.3 standard specifications and beneficial for larger transmission distances.
Small-signal measurements have been performed with a 43 GHz Keysight PNA network analyzer on wafer level. The frequency response is plotted in Fig 2(b) and shows a very flat characteristic. The -3dB bandwidth is 26.7 GHz at 9 mA. The corresponding resonance frequency was derived to be at 22 GHz.

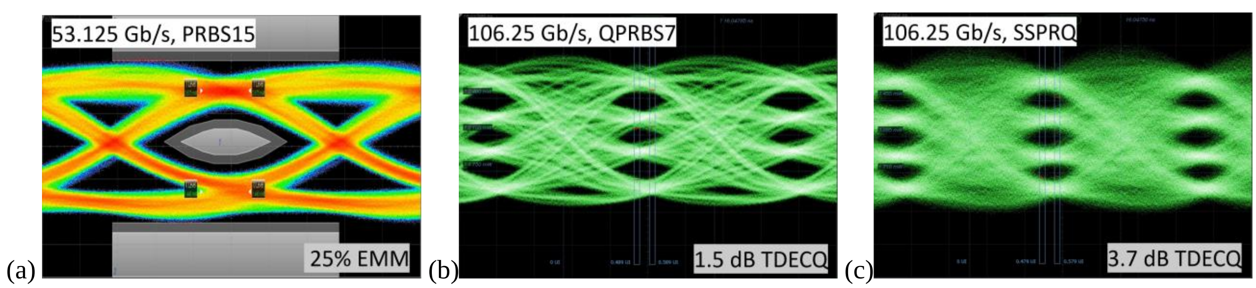

Fig. 2. Eye diagrams at 53.125GBd at 9mA and 25°C (a) 53.125 Gb/s PAM-2; (b) 106.25 Gb/s PAM-4 with QPRBS-7 pattern and (c) with SSPRQ pattern, both with 3 tap pre-emphasis, and TDECQ post-equalization.

The large-signal dynamic under direct modulation is investigated using a 58 GBd Anritsu pulse pattern generator and a Keysight N1092 sampling oscilloscope with optical multi-mode input. The electrical RF signal is directly applied to the VCSEL with a 40 GHz RF probe without any impedance matching or amplification, limiting the possible extinction ratio (ER). The 9 mA DC operation bias is superimposed with the non-return-to-zero RF signal with a 40 GHz bias-tee. The swing amplitude is about 0.5 Vpp and the measurements were performed at 25°C in a back-to-back configuration. A pseudo-random binary sequence (PRBS) pattern with a length of 2^{15}–1 bits is used for the PAM-2 measurements. The resulting 53.125 Gb/s eye diagram is depicted in Fig. 2(a) with a clearly open eye and a mask margin of 25%. The RIN and RIN(OMA) are -150dB/Hz and -140dB/Hz, respectively. Both RIN values are dominated by the internal noise of the oscilloscope. A 3-tap pre-emphasis and a de-embedding of the used RF cable was applied for the 53.125 GBd PAM-4 signal generation. For the detection of the optical signal, a reference receiver with a 26.6 GHz 4th order Bessel-Thomson filter was used. The electrically converted signal was subsequently equalized for the TDECQ measurements according to IEEE 802.3cd standard. Fig. 2(b) and (c) show the resulting 106.25 Gb/s PAM-4 eye diagrams with a QPRBS-7 and a SSPRQ pattern. The corresponding TDECQ values are 1.5 dB and 3.7 dB, respectively. In both cases the outer ER is about 2.5 dB, limited by the maximum Vpp of the used setup.

VCSELs for commercial Datacom applications not only have to be compliant with electro-optic performance requirements, but also with reliability requirements. Extensive reliability tests have been started, comprising accelerated lifetime tests, biased and unbiased damp-heat tests, wear-out-matrix tests, and random failure tests just to name a few. In Fig.3, preliminary results of an accelerated aging test under 9 mA constant bias and 125°C for more than 2750 hours is shown. The devices have experienced a prior 24h burn-in and the optical power at 6 mA and 25°C is read out weekly. The power gradually decreases under the given stress with time. No fail, i.e. no power drop of -1 dB, has been observed within the testing time so far. This behavior is in accordance with II-VI's 28Gb/s and 56 Gb/s InGaAs VCSELs. It is reasonable to assume an identical wear out mechanism and the same conservative aging model is applied. Accordingly, a time to 1% failures (TT1%F) of 10 years at constant operation at 9 mA and 70°C requires about 1000 hours testing time without fails under the applied conditions. The presented 106 Gb/s VCSEL design exceeds this requirement already by a factor of 2.5, ensuring a TT1%F of >25 years.

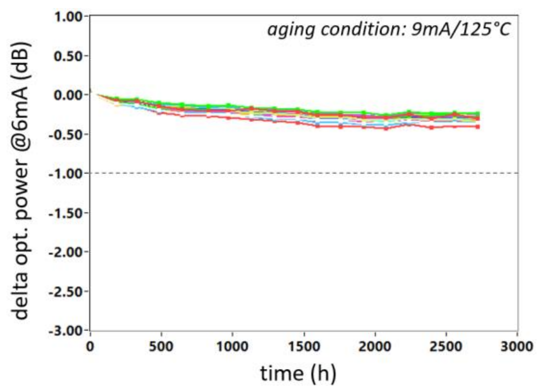

Fig. 3. Change of optical power at 6mA read-out current in accelerated lifetime tests at 9mA and 125°C within 2750 hours. No fails are observed so far, leading to a TT1%F of more than 25 years.

3. Summary

A 106 Gb/s PAM-4 850 nm VCSEL is demonstrated that is suited for volume manufacturing. The large -3dB bandwidth of 27 GHz with a flat frequency response, the low RIN of -150 dB/Hz, as well as the narrow spectral width of 0.25 nm, result in clearly open eye diagrams for 53.125 Gb/s PAM-2 and 106.25 Gb/s PAM-4 measurements. All achieved characteristics are compliant with the requirements of the recent IEEE 802.3db standard draft. Extensive reliability investigations have been started and preliminary accelerated aging test results show an expected wear out time beyond 25 years.

4. References

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