High-Speed Transmission of 850 nm VCSEL Optical Interconnects Across Wide Temperatures

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***Abstract*—Optical interconnects (OIs) using VCSEL-based transceivers provide compact, energy-efficient, and cost-effective solutions for high-speed data transmission. As the demand for higher bandwidth grows, transceivers are positioned closer to integrated circuits (ICs), requiring OIs capable of reliable operation under harsh temperature variations. In this study, we compare the performance of two distinct 850 nm multi-mode multiple quantum well (MQW) VCSEL designs as transmitters. One design incorporates chirped QWs with varying compositions to broaden the optical gain, while the other follows a traditional approach with equal QWs in the active region. The comparison is conducted over an extended temperature range, from room temperature up to 140°C. We demonstrate record error-free transmission (BER $<$ (10^{-12}), at data rates of 40 Gbps at 115°C, 34 Gbps at 125°C, and 25 Gbps at 140°C without any equalization or forward error correction (FEC). The modified design outperforms the standard VCSELs at high temperatures. This work highlight the advancement in VCSEL technology, positioning it as a key enabler for next-generation OIs capable of reliable, high-speed transmission across a wide temperature range.**

***Index Terms*—Vertical-cavity surface emitting lasers, Optical interconnects, High speed data transmission, 850 nm, IM/DD, Pseudo-random bit sequence (PRBS), Fiber-optical communication.**

I. Introduction

THE consolidation of 5G and the imminent introduction of 6G, coupled with advancements in the Internet of Things (IoT), autonomous driving, and cloud computing, have led to an exponential increase in data traffic. This trend is expected to continue in the coming years. The growing use of artificial intelligence, virtual and augmented reality (VR/AR) and machine learning based applications further amplifies the need for high-performance computing. Optical interconnects (OIs) are critical for enabling efficient, high-speed operations in advanced signal processing systems and modern data centers [1], [2].

For short-reach data transmission, data centers typically use high-speed optical transceivers with directly-modulated vertical cavity surface emitting lasers (VCSELs) as the primary light source. VCSELs are favored due to their small footprint, high modulation bandwidth, cost efficiency, low threshold current, excellent beam profiles, and resilience to operating temperature variations [3].

With the recent development of 400 GbE and the upcoming 800 GbE and 1.6 TbE Ethernet standards, the demand for larger interconnect bandwidth is pushing optical transceivers closer to integrated circuits (ICs). This shift exposes the transceivers to excessive heat generated by the ICs, creating a challenging environment with wide temperature variations. For on-board assemblies, typical operating temperatures for optical waveguide-based communication links are expected to reach 100°C or higher [4]. In defense, military, and automotive applications—where multiple sensors are integrated for autonomous driving, advanced driver assistance systems, and LIDAR technologies—optical networks are being adopted to interface sensors with high-performance signal processing units. These environments present even harsher conditions, with temperatures ranging from -40°C to 125°C [5], [6].

Numerous studies have been conducted during the last 20 years to enhance VCSEL-based optical links operating at higher temperatures [7]–[10]. A prominent contribution was made in 2001 when Peters et al. demonstrated InGaAs VCSELs achieving 10 Gbps operation at temperatures up to 150°C and 12.5 Gbps between -50°C and 100°C [11]. Then in 2012, Li et al. fabricated VCSELs with InGaAs quantum wells achieving a 3 dB bandwidth of 15 GHz at 85°C and demonstrated 25 Gbps non-return-to-zero (NRZ) modulation up to 85°C [12]. In 2013, Westbergh et al. presented 850 nm InGaAs/AlGaAs oxide-confined VCSELs with a modulation bandwidth of ≈27 GHz at room temperature (RT) and ≈21 GHz at 85°C. Their updated distributed Bragg reflector (DBR) design improved thermal conductivity, reducing self-heating and enabling higher photon density, which allowed for higher output power and modulation bandwidth. This led to error-free data transmission at 40 Gbps at 85°C [13]. In 2019, state-of-the-art error-free NRZ transmissions of 36 Gbps at 100°C and 30 Gbps at 115°C were demonstrated using 850 nm InGaAs oxide-confined VCSELs, marking the highest reported temperature for 30 Gbps transmission [14].

To achieve sufficient performance over a wide range of temperatures, we designed and fabricated an 850 nm VCSEL with chirped QWs in the active region. In contrast to conventional MQW VCSEL designs, where the active layer of the device has identical equal QWs, our design implements five unequal $In_xGa_{1-x}As/Al_{0.37}Ga_{0.63}As$ quantum wells in the active region with different In-compositions to broaden the optical gain spectrum. The composition of the QWs was designed with the intention of minimizing the temperature dependence of the threshold current across wide temperature range. As reference, we also fabricated an otherwise identical design, but with five equal $InGaAs/Al_{0.37}Ga_{0.63}As$ QWs in the active region. Both designs are a modification of the design desbribed in [13] and are characterized and compared in detail in this study.

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We successfully demonstrate error-free transmission (BER < (10^{-12})) at data rates of up to 40 Gbit/s at 115°C. Furthermore, we achieve error-free transmission at 25 Gbit/s at 140°C using the unequal QW design. This marks the highest reported bit rates for error-free transmission of the QW VCSELs at 115°C, 125°C, and 140°C without the use of equalizers. We also report improvements in receiver sensitivity compared to previous work as referenced in [14].

II. Experimental Setup

The experimental setup, as illustrated in Fig. 1, consisted of an SHF 12103A bit pattern generator (BPG) driven by an HP 83712B clock. For higher data rate clocks, the frequency multiplier MX2M200400 was used (for data rates above 20 GHz). The BPG generated the Pseudo-random bit sequence (PRBS) data signal to drive the VCSEL, utilizing a $2^7 - 1$ pattern length. The generated sequence was amplified using an SHF 804TL amplifier (22 dB gain) and passed through an Anritsu V255 bias tee (50 kHz – 65 GHz), which was connected to a signal-ground probe for direct probing of a VCSEL, biased accordingly at various temperatures. The optimum VCSEL aperture size selected was 6 microns for the equal QW VCSEL and 7 microns for the unequal QW VCSEL. At room temperature, the equal QW VCSEL had a 3 dB small-signal modulation bandwidth of 32 GHz with a bias current of 8 mA, while the unequal QW VCSEL had a bandwidth of 20.3 GHz at the same bias current. The VCSELs were housed in a closed capsule probe station capable of varying the temperature from -60°C to +300°C. The VCSEL output was coupled into a 1 m multi-mode OM4 Thorlabs graded-index fiber (50 micron core) and passed through an FVA-3150 Variable Optical Attenuator (VOA) and directed to a 32 GHz bandwidth MACOM optical receiver. The corresponding electrical signal was either sent to an SHF 11100B Error Analyzer (EA) or an Agilent Infiniium DCA-J 86100C equivalent time oscilloscope with a 70 GHz bandwidth.

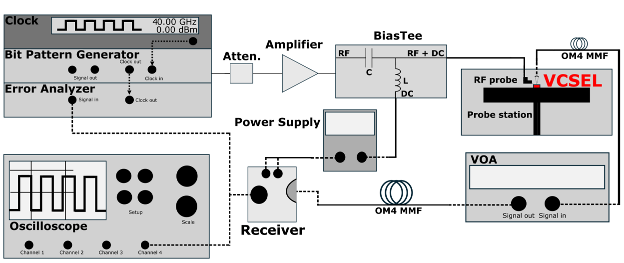

Fig. 1: Experimental setup used for transmissions.

III. Measurement results and discussion

A. Static and Small Signal Measurements

To perform the inital characterization of the devices, light-current-voltage (LIV) and small signal modulation response (S_{21}) measurements were carried out. We extracted various key performance parameters from these measurements.

Fig. 2 compares the LIV characteristics of the equal (Fig. 2(a)) and unequal (Fig. 2(b)) QW VCSELs at various temperatures. The VCSELs were biased using a DC power source, and the output optical power was measured with a large-area photodetector. The equal QW VCSEL demonstrates a maximum output power of 7.2 mW at a rollover current of 14.3 mA at room temperature (RT). Both the maximum output power and rollover current decrease linearly with increasing temperature, reaching an optical output power of 0.8 mW at 6 mA at $140\,°\mathrm{C}$. In contrast, the unequal QW VCSEL achieves a maximum output power of 13.2 mW at a rollover current of 18.5 mA at RT. As the temperature increases, both the output power and rollover current decrease linearly, reaching an optical output power of 2.7 mW at 8 mA at $140\,°\mathrm{C}$. However, it is important to note that the rate of decline in output power with increasing temperature is lower for the unequal QW design.

The IV measurements provide information on the differential resistance of the two VCSEL designs by extracting the respective slopes. At RT, the differential resistance for the equal QW design is 0.1 Ω, while it is higher for the unequal QW design at 0.12 Ω. As the temperature increases to 85°C, the gap narrows, with the equal QW design showing a resistance of 0.088 Ω and the unequal QW design showing 0.1 Ω. This trend continues up to 125°C, where the differential resistance for the equal QW design remains slightly lower at 0.087 Ω compared to 0.088 Ω for the unequal QW design. However, at 140°C, the differential resistance of the equal QW design increases to 0.09 Ω, surpassing that of the unequal QW design, which decreases to 0.08 Ω. This concludes that, at extreme temperatures, the equal QW design have higher differential resistance than the unequal QW design. The higher voltage drop at 140°C in the equal QW VCSEL also results in greater heat generation, leading to increased self-heating and reduced output power, as shown in Fig. 2.

The increased differential resistance also affects the modulation bandwidth of the device by increasing the RC time constant, which degrades the VCSEL's ability to respond to high-speed signals [15]. To study the dynamic response, small-signal modulation response (S_{21}) measurements were performed using a 67 GHz vector network analyzer (VNA). Fig. 3 presents the small-signal modulation responses of the two VCSEL designs at various temperatures. At RT, the 3 dB bandwidth of the equal QW design Fig. 3(a) is 32 GHz, while that of the unequal QW design Fig. 3(b) is 20.3 GHz. As the temperature increases, the modulation bandwidth decreases for both designs. At 100°C, the equal and unequal QW designs operate at bandwidths of 22.9 GHz and 19.3 GHz, respectively. Notably, the equal QW design shows a higher rate of bandwidth reduction as temperature increases. At 140°C, the modulation bandwidth of the equal QW design falls below that of the unequal QW design, with values of 11.5 GHz and 14.1 GHz, respectively. The S_{21}-response thus illustrates the temperature dependence of the -3 dB bandwidth for the VCSELs at various temperatures. The unequal QW design maintains sufficient bandwidth at extreme temperatures to support error-free transmission, which is demonstrated in the following section.

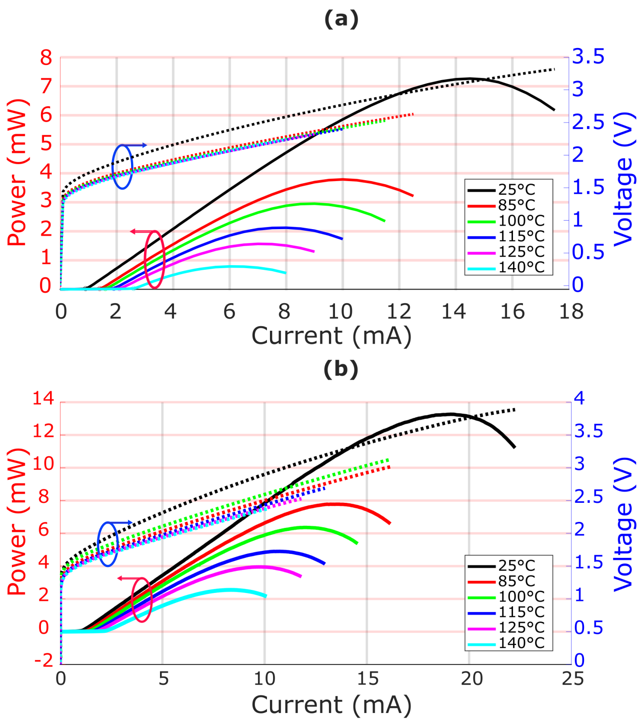

Fig. 2: LIV-characterisitcs of the (a) Equal and (b) Unequal QW VCSELs.

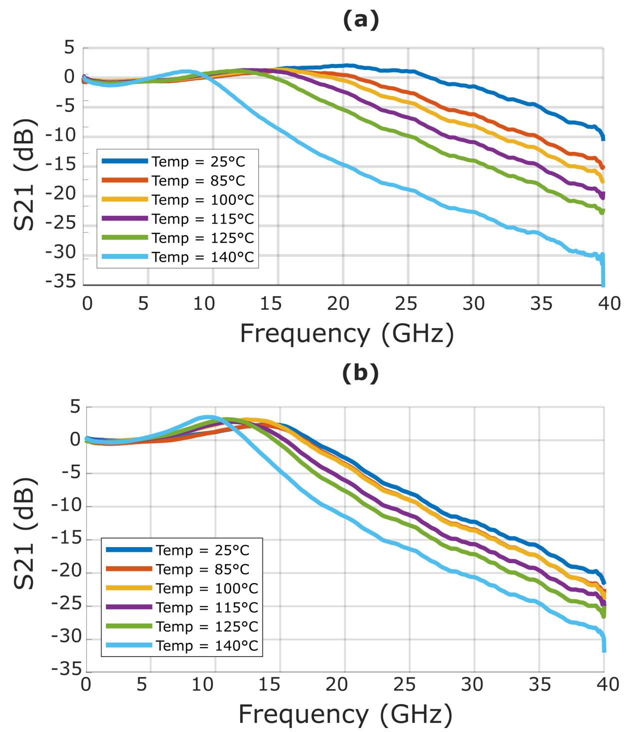

Fig. 3: Small-signal modulation response of (a) Equal and (b) Unequal QW VCSEL.

B. Dynamic and Large signal measurement

A comparison of the large signal modulation of the two VCSEL designs at RT is conducted using NRZ On–off keying modulation. The BER results at RT for both VCSEL types are presented in Fig. 4, with the equal QW VCSEL shown in black and the unequal QW VCSEL in red. In all cases, a minimum BER below (10^{-12}) is achieved. The equal QW VCSEL records a receiver sensitivity of -5.2 dBm at 40 Gbps (BER $= 10^{-12}$) . In contrast, the unequal QW VCSEL shows a sensitivity of -4 dBm at the same bit rate and BER. At 50 Gbps, the equal QW VCSEL requires -2.9 dBm, while the unequal QW VCSEL requires 0.6 dBm for error-free operation. This indicates that the sensitivity penalty in unequal QW VCSELs increases more rapidly with the bit rate compared to equal QW VCSELs.

The high-temperature comparison of the two VCSEL designs is made with the results reported in [14] as a benchmark which used an equal QW VCSEL design. The BER curves in Fig. 5 show the results from [14] in blue, while the equal and unequal QW VCSEL results are shown in black and red, respectively. At 115°C and 30 Gbps, both designs outperform the benchmark, with the unequal QW VCSEL showing a 5.5 dB sensitivity improvement and the equal QW VCSEL demonstrating an even greater improvement of 6.5 dB.

The system is further tested under extreme conditions by increasing the temperature and analyzing the performance of both VCSEL designs. The BTB performance is illustrated in Fig. 6. At 85°C, the equal QW VCSEL shows an advantage of $\approx$ 1.85 dB over the unequal QW VCSEL. However, while the equal QW design continues to perform better up to 125°C,

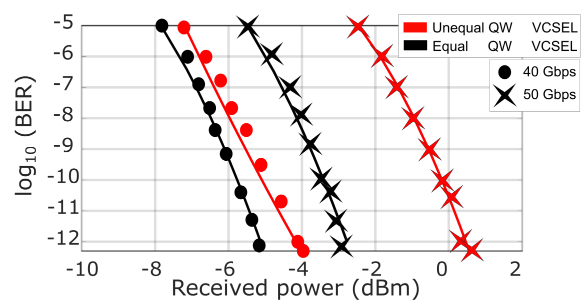

Fig. 4: Measured BER curves at room temperature for the equal and unequal QW VCSELs at 40 Gbps and 50 Gbps.

it exhibits significant degradation as the temperature rises to 130°C, where it fails to achieve error-free transmission, showing a (10^{-3}) error floor at 23 Gbps and a (10^{-5}) error floor at 21 Gbps. In contrast, the unequal QW VCSEL maintains its performance, achieving error-free transmission at 23 Gbps and 21 Gbps with sensitivities of -5.9 dBm and -7.2 dBm, respectively. At 140°C, the unequal QW VCSEL further demonstrates its robustness by achieving error-free transmission at 25 Gbps. For extremely low temperatures, such as -40°C, the experimental setup encountered vibration issues, making it challenging to perform the prolonged measurements required for BER analysis. However, based on eye diagram analysis at this temperature, we observe a similar trend: the equal QW VCSEL performs better at moderately low temperatures, while at extreme low temperatures like -40°C, the unequal QW VCSEL exhibits a better eye opening. These results suggest that the unequal QW VCSEL design may be crucial for applications requiring reliable transmission over extremely wide temperature ranges.

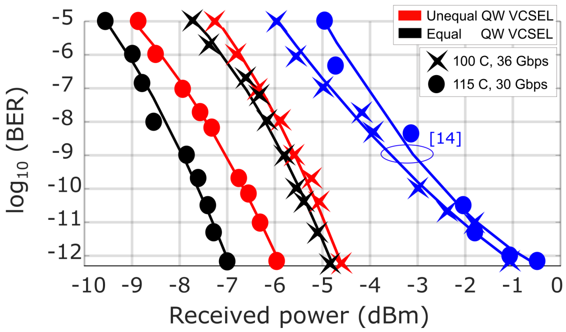

Fig. 5: Comparison of BER performance between previous state-of-the-art results (blue) [14] and our two VCSEL designs at two bit rates: 36 Gbps at 100°C and 30 Gbps at 115°C.

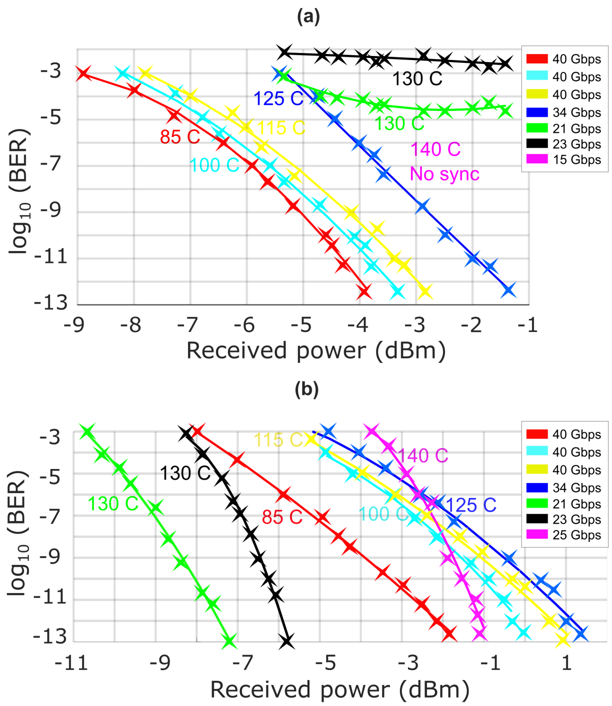

Fig. 6: BER comparison between (a) equal QW design VCSEL and (b) unequal QW design VCSEL across 85°C to 140°C.

IV. Conclusion

In this study, we successfully demonstrated two VCSEL designs: one with equal QWs and another with unequal QWs. The unequal QW design aims to achieve a broader gain spectrum, allowing stable transmission across extreme temperatures. We achieved record-breaking performances, including state-of-the-art results with the equal QW design, and extended these results using the unequal QW design without the need for equalization or pre-emphasis. The performance of OIs can be further enhanced by employing advanced modulation formats, coding, and equalization techniques. Such OIs, capable of operating efficiently across a wide temperature range, are critical for various applications, including military defense systems, signal processing units, automotive networking systems, and advanced chip technologies. This work contributes to the development of robust and efficient optical interconnect systems, offering a pathway toward next-generation technologies that require reliable high-speed communication under harsh environmental conditions.

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