



Performance of 1550 nm VCSEL at 10 Gb/s in G.655 and G.652 SSMF

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Abstract: Vertical cavity surface emitting lasers (VCSELs) are now major optical sources in optical communication and technology. The VCSEL-based transmission systems satisfy the next generation optical fibre access networks requirements such as low output power, low threshold currents, no optical amplification and use of single fibre for signal transmission. High speed and long wavelength 1550 nm VCSEL are attractive candidates for use in short distance transmission system due to its cost effectiveness and low drive currents. The performance of VCSEL, especially with respect to the low output power characteristics, has made significant progress. However, dispersion and attenuation is a major hurdle to VCSELs transmission at bit rate of 10 Gb/s and above. In this study, we experimentally and theoretically evaluate the capability of 1550 nm VCSEL to operate upto 10 Gb/s on G.655 and G.652 fibres. We present VCSEL characterization and BER performance as a function of received power. A 1550 nm VCSEL was directly modulated with 10 Gb/s NRZ PRBS 2^7-1 and transmitted over 25 km ITU. T G.652 and ITU. T G.655 fibres. Error free transmission (with bit error rate, BER, of 10^{-9}) over 25 km G.655 single mode fibre (SMF) has been demonstrated. The Q factor was used theoretically to quantify the performance of the VCSEL. The Q factor increased with the increase in the output power at the receiver. High Q factor values of 6 and above were achieved when 1550 nm VCSEL was transmitted over G.655 fibre. These results show the feasibility of long-wavelength VCSELs in the deployment of enhanced optical access networks.

Keywords: BER, Dispersion, Fibre, VCSEL Introduction

1. Introduction

VCSEL- operating at a wavelength of 1550 nm are potentially important light sources for optical access applications, such as central-office interconnects, parallel-optical data links or metro-feeders where they could allow for the low-cost deployment of short links [1]. It is found that pulses generated in semiconductor lasers are usually highly chirped and have a large time-bandwidth product [2]. However, VCSELs have a number of drawbacks based on large frequency chirp and polarization insensitivity

which limit their performance in optical fibre systems as well as causing limitations in transmission and data rates. The frequency chirp was proved to interact with fibre dispersion in such a way to degrade performance of fibre communication systems [3].

VCSEL is a type of semiconductor laser diode with laser beam emission perpendicular from the top surface. They are promising candidates for light sources at the customer premise because of their cost-effective production and capability for chirp integration with low threshold and driving currents [4]. However, VCSEL is a low optical power source which restricts

the coverage power for application in passive optical networks (PON) links in long distance signal transmission. Single-mode VCSELs at 1550 nm are widely anticipated as low-cost light sources in telecommunication networks. 10 Gb/s Ethernet standards are expected to focus on low-cost high performance laser diodes such as long-wavelength VCSELs. An efficient and affective way of utilizing an optical fibre link is to transmit multiple wavelengths signals [5]. Tunable lasers are recognized as highly desirable component for present point-to-point dense wavelength division multiplexing (DWDM) systems [6]. It is vital for enabling the future intelligent optical networks with applications in all-optical switching and dynamically re-configurable optical add/drop multiplexers. For all these applications it is important to resolve the output of the VCSEL to identify the optimal driving conditions and to predict and mitigate degradation from optimal fibre transmission impairments. In this paper we demonstrate the application of a 10 Gb/s VCSEL operating at 1550 nm for use in a 25 km WDM-PON with no dispersion compensation. The device was first characterized in terms of output power and wavelength tuneability. Transmission over 25 km standard single mode fibre (SSMF) has been demonstrated in terms of bit-error-rate (BER) and Q factor measurements.

2. Theory

Modern cost-effective and broadband fibre networks, such as the fibre-to-the-home (FTTH) and radio over fibre (RoF), require directly modulated laser diodes with bandwidth exceeding 25 GHz for operating the fibre links with transmission speeds exceeding 40 Gbps [7]. In short-haul applications such as fibre channel and gigabit Ethernet, the efficiency and high speed 850-980 nm VCSEL at low power have made them the light source of choice. However, for longer reach applications, long wavelength (1300-1600 nm) laser diodes are required in order to operate with low loss and dispersions [8]. Fibre optics transmission is a major building block in the telecommunication infrastructure. Its high bandwidth capabilities and low attenuation characteristics make it ideal for gigabit transmission and beyond. SMF's are suitable for long haul data transmission when used in 1310 nm and 1550 nm transmission windows. I-TUT G.652 and G.655 fibres are the conventional single mode (SMF) that has been in used in most telecommunication networks. It operates on the second window of optical communication.

Frequency chirp and CD are the main limiting factors for VCSELs. Light chirping is the instantaneous change of the central wavelength in response to variation in optical power. A 5mW power is sufficient if the temperature stability within the locking range is high enough [9]. The frequency chirp $\Delta\nu$ associated with direct modulation of a VCSEL can be described as [10].

$$\Delta\nu(t) = -\frac{\alpha}{4\pi} \left(\frac{d}{dt} \ln P(t) + kP(t) \right) \quad (1)$$

where α is the linewidth enhancement factor, $P(t)$ is the instantaneous optical power, k is the structure dependent constant which is proportional to the modal confinement factor and inversely proportional to the volume of the active region. The term $\frac{d}{dt} \ln P(t)$ describes the transient chirp relating to the time derivative of the changing instantaneous optical power with rising and falling pulse edges. The term $kP(t)$ describes the adiabatic chirp related to the instantaneous optical power itself.

The light-current curve of a VCSEL has a constant slope above the threshold is common for laser diodes but shows a characteristic roll-over for higher currents due to internal heating. For VCSEL to produce an ideal signal, the drive current should be in the region just above the threshold where the VCSEL starts lasing and just below the saturation of the output power [11]. Unlike for edge emitting lasers (EELs), it is uncritical to operate VCSELs up to their maximum output powers since power densities remain in the lower kW/cm² range and cannot induce optical damage to the semiconductor material or laser facet. Depending on the wavelength and material composition, VCSELs can be designed for top emission through a ring contact or bottom emission through a transparent substrate [12]. The main difference of VCSELs light sources in respect to conventional edge emitting lasers (EEL) is the emission being normal to the surface of the device. This unique characteristic makes VCSEL convenient for 2-D array integration on wafer testing with potential low-cost manufacture and circular emission with high fibre-coupling efficiency. Besides, the small cavity volume enables for low thresholds and high-speed modulation at low currents. This combination of features has led to a high interest and rapid development of VCSELs for short reach high-capacity optical interconnects. VCSELs are promising candidates for light sources at customer premises because of their cost-effective production and capability for chirp integration [13]. The power dissipated in the laser induces to VCSEL self heating. The internal temperature within the VCSEL can be described as;

$$T = T_o + P_d \cdot R_{th} - \tau_{th} \cdot \frac{dT}{dt} \quad (2)$$

Where T_o is the ambient temperature, P_d is the power dissipated, R_{th} is the device thermal impedance (relates the change in device temperature to the power dissipated as heat), τ_{th} is thermal time constant.

The current-voltage relationship can be modeled in great detail based on the diode-like character of the VCSEL [14]. The voltage across the device is an arbitrary empirical function of current and temperature using

$$V = f(I, T) \quad (3)$$

The quality of a received signal is directly related to the BER, which is a major indicator of the quality of the overall system. BER is affected by attenuation, noise, dispersion,

crosstalk between adjacent channels or jitter. Its performance may be improved by launching a strong signal into a transmission system.

$$BER = \frac{1}{2} \operatorname{erfc} \left(\frac{Q}{\sqrt{2}} \right) \approx \frac{\exp \left(-\frac{Q^2}{2} \right)}{Q\sqrt{2\pi}} \quad (4)$$

Generally, the BER decreases as the Q-factor increases. For a Q-factor ranging from 6 to 7, the BER is obtained as of 10^{-9} up to 10^{-12} [15]. BER can be increased by either increasing the difference between the high and low levels in the numerator of the Q-factor or by decreasing the noise terms in the denominator of the Q-factor.

3. Experimental Set-Up

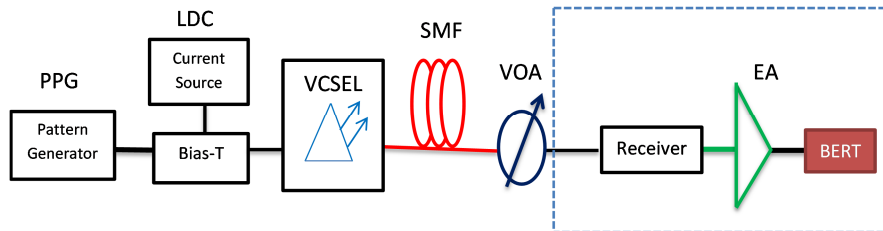


Figure 1. Experimental set up of the directly-modulated VCSEL.

4. Results and Discussions

4.1. Biasing the VCSEL Source

The VCSEL used in this experiment was operated without any temperature stabilization. The variation of the output power of a VCSEL as input bias current was increased as shown in figure 2.

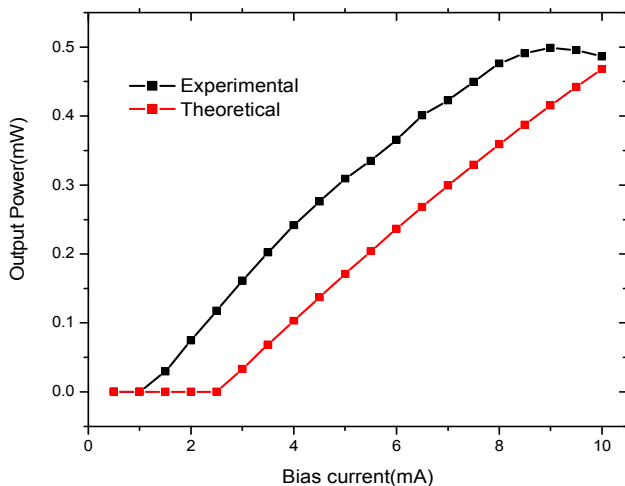


Figure 2. Biasing of VCSEL in the 1550 nm transmission window.

High output powers was achieved at low bias currents. From the experimental results, the threshold current of the device was found to be 1 mA. However, from the simulation results, the VCSEL threshold current was found to be 2.3 mA.

A 10 Gb/s 1550 nm VCSEL was directly modulated with a non-return to zero (NRZ) pseudo-random binary sequence (PRBS) of pattern length of 2^7-1 and propagated over an ITU-T G.652 SSMF. Laser diode controller (LDC) was used to adjust VCSEL bias current. The 10 Gb/s signal was then propagated over a span of 25 km standard G.652 and G.655 fibres as the BER and Q factor was measured. The bias current and voltage was adjusted to achieve a better VCSEL modulation index. In order to measure and monitor the optical power going into the receiver, a variable optical attenuator (VOA) and optical power meter were placed after the transmission fibre. The signal was detected by positive-intrinsic-negative (PIN) with a receiver sensitivity of -19.3 dBm. An electrical amplifier was (EA) was used to amplify the electrical signal to meet the operational requirements of the bit error rate tester (BERT).

Above the threshold, the output power from a VCSEL varied linearly with current. Experimentally, the saturation current of the device was found to be 8 mA. Above the saturation level, the output power of the VCSEL reduced as the current was further increased. As a result, the best operational bias points for the VCSEL are between the threshold and the saturation current point's i.e the linear region. Under theoretical simulation, it was assumed that constant temperature was maintained hence the VCSEL device didn't heat up hence there was no saturation.

4.2. VCSEL Wavelength Tuneability

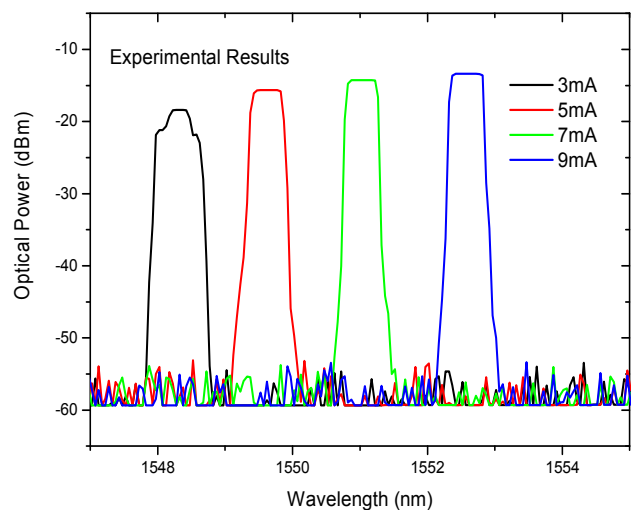


Figure 3. Experimental characterization of the VCSEL wavelength tuneability for 1550 nm.

VCSEL wavelength tuning with varying bias currents is plotted in figure 3. The shifting of the emission spectra with increasing current indicates internal heating of the VCSEL. The broadening decreases with increase in current and its peak location shifts to longer wavelengths. This implies that VCSEL can be tuned to different wavelengths using bias currents. The output power increases with increase in the bias current of the VCSEL. By operating the VCSEL up to the 9 mA saturation current point, the maximum optical output power recorded was below -10 dBm. This show the energy efficiency of the device.

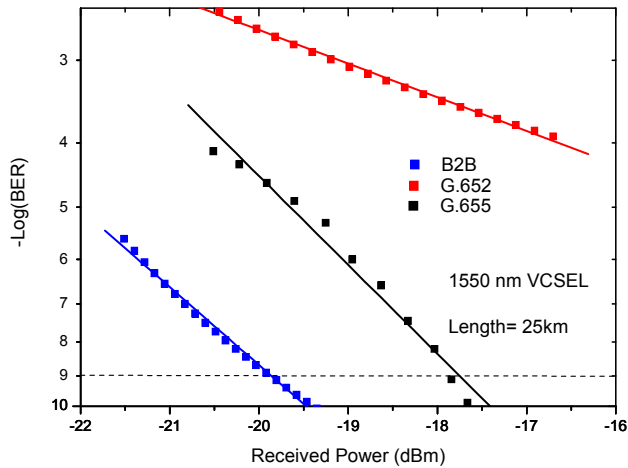


Figure 4. BER measurements of back to back, G.652 and G.655 fibres at 1550nm VCSEL.

Figure 4 shows experimental BER measurements of G.652 and G.655 fibres of lengths 25 km with 1550 nm VCSEL transmitting at 10 Gb/s. A receiver sensitivity of -17.8 dBm was obtained when G.655 fibre was transmitted. The dispersion effects are lower for G.655 fibre on this transmission window. From the figure 4, it was observed that G.652 fibre operated at the error floor region when transmitted on this window. Error floor refers to a point at which the BER flattens without crossing the telecommunication threshold ($BER=10^{-9}$). The error floor was due to the high dispersion that affected the signal resulting in the increased number of errors hence limiting the transmission distance.

The system performance was also quantified theoretically using the Q factor and is related directly to the BER. It was not possible to analyze the systems quality factor experimentally because of equipment limitation. However, it was found that the higher the values of Q factor the better the OSNR and therefore a lower BER values.

From figure 5, it should be noted that the Q factor increased with the increase in output power at the receiver. It can also be seen that low Q value corresponded to lower output power and this is because at lower power, the system error increases due to attenuation in the fibre which decreases the Q factor of the system. At a bit rate of 10 Gb/s, the 1550 nm VCSEL transmission over G.655 fibre recorded high quality factor values. A minimum power of -17.4 dBm was required at the output on G.655 fibre to achieve the Q factor of 6. However,

when the wavelength was transmitted over G.652 fibre, low Q values below 6 was recorded. This is because dispersion introduced uncertainty at the receiver due to accumulated C. D over distance of transmission.

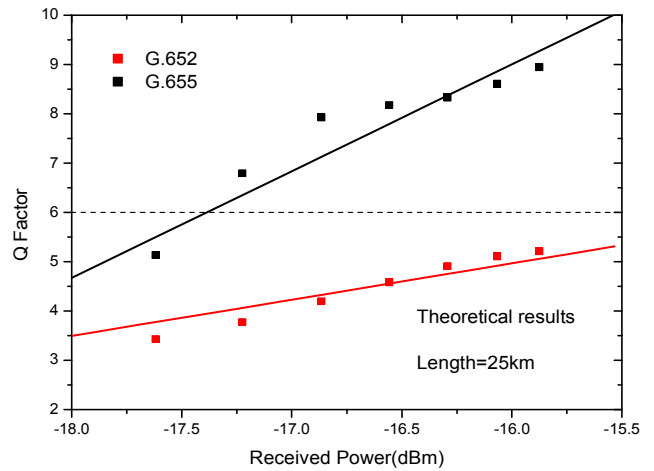


Figure 5. Variation of the VCSEL's received power with the Q Factor.

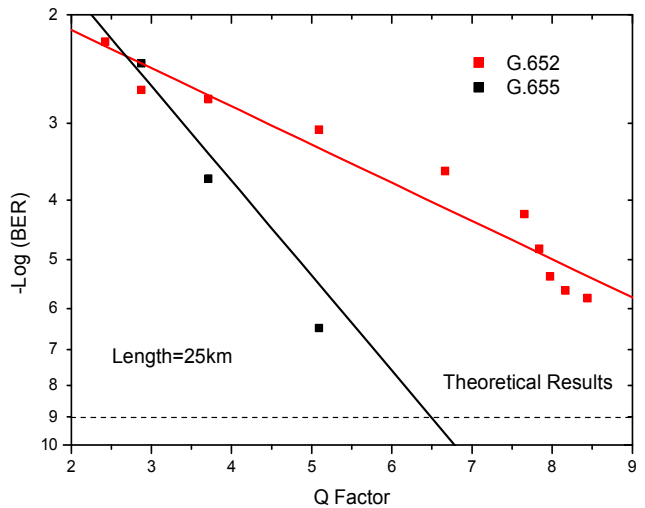


Figure 6. BER as a function of Q factor.

From figure 6, it can be seen that the BER is inversely proportional to the Q factor. The higher the value of Q factor means the better the OSNR and therefore a lower BER values. If the system error decreases, the BER will thus decrease. The simulation results show that G.655 fibre recorded Q factor value of 6.0 when the BER measurements were performed at 10^{-9} threshold level. The minimum value of Q Factor that will enable a system to operate in region below BER of 10^{-9} is 6 and this is the most used value in telecommunication systems. However, the G.652 fibre exhibited the worst performance with high BER values when transmitted over 1550 nm window. Therefore, to reduce the BER we must increase the Q factor. Higher values of Q factor mean better performance.

5. Conclusion

The characterization of 1550 nm VCSEL has been studied.

Both experimental and simulation results showed similar characteristics in terms of power output. The VCSEL operated in the mA range showing the energy efficiency of the device. We have presented the results of BER and Q factor of an optical network using a directly modulated 10 Gb/s 1550 nm VCSEL on a G.652 and G.655 SSMF. It was found that BER reduced with increase in the received power. The receiver sensitivity was measured to be -17.8 dBm after 25 km in G.655 fibre. However, when 1550 nm VCSEL was used in G.652 fibre, the system operated at error floor region. It was noted that Q factor increased with the increase in the output power at the receiver. High Q values were obtained when a 1550 nm VCSEL was transmitted over G.655 fibres. It has also been shown that BER was inversely proportional to Q-factor so it can be concluded that the signals with smaller bit rate travel more than the one with higher bit rate. This research work recommends the use of 1550 nm window on G.655 fibre in high bit rate and long haul optical transmission systems.

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