Chromatic Dispersion Compensation for VCSEL Transmission for Applications such as Square Kilometre Array South Africa

E K Rotich Kipnoo, H Y S Kourouma, R R G Gamatham, A W R Leitch and T B Gibbon
Physics Department, Nelson Mandela Metropolitan University, P. O. Box 77000, Summerstrand South, Port Elizabeth-6031, South Africa
Email: Enoch.Rotich@live.nmmu.ac.za

Abstract-In addition to attenuation, optical fibre transmission suffers significant penalty from dispersion related effects. We theoretically and experimentally investigate the compensation of chromatic dispersion of 4.25 Gbps 1550 nm vertical cavity surface emitting laser (VCSEL) transmission using inverse dispersion fibre. Simulated results show that inverse dispersion fibre can compensate up to 3.7 dB on a 35 km ITU-T G.652 fibre. The residual dispersion penalties are small, thus effective compensation is achieved. In an experimental demonstration, a 25.4 km low water peak (LWP) fibre with a low negative dispersion value was found to improve the signal clarity when combined with a G.652 fibre. Inverse dispersion fibres cancel the cumulated dispersion in transmitting fibres, hence improving the VCSEL transmission significantly. This is a cost effective and simple chromatic dispersion mitigation technique, suitable for square kilometre array application as the transmission distances increase at different construction phases.

1. Introduction

Attenuation and dispersion in fibres are two factors that determine the distance information can be sent in an optical network. The two main types of dispersion in fibres are chromatic dispersion (CD) and polarization mode dispersion (PMD) [1]. With the modern fibres of low PMD values and the development in coherent transmission technologies [2], PMD which is a secondary effect has not been of a major concern. Vertical cavity surface emitting lasers (VCSELs) have shown a great potential in applications such as passive optical networks (PONs) [3,4]. This includes fibre to the home/curb/building/premise/node (FTTx) as well as wavelength division multiplexing (WDM) demanding applications. VCSELs are suitable for these applications because of low power consumption, wavelength tuneability, suitability for relatively short distance transmission, relatively low cost, high bandwidth, single mode operation within C-L bands and the convenience of direct modulation [5,6]. These VCSELs are however limited by the CD and chirp [4]. SKA South Africa is a big telescope project that is under construction. The construction is in different phases; KAT-7, MeerKAT, SKA 1 and SKA 2. KAT 7 consists of 7 dishes that are currently functional. The

MeerKAT phase will consist of 64 dishes and is currently under construction and will be completed in 2016. The number of dishes is expected to increase to about 3,000 extending out to about 3,000 km upon completion in 2025 [7]. This will constitute to 120 TB/s data for aggregation and processing. SKA distances between the individual dishes and the processing station for the various construction phases is expected to increase, for example, in the MeerKAT, the farthest dish is 12 km while in SKA 1, it will extend out to about 100 km from the central core. As the transmission distance increase, the effects of CD should be mitigated so as to boost the efficiency of the VCSEL and reduce the dispersion penalties. In this paper, we show the effect of chromatic dispersion compensation on the transmission performance of the 1550 nm VCSEL.

2. Theory

The inherent property of the fibre is responsible for the dispersion. Speed of light is dependent on the refractive index of the fibre. The refractive index therefore varies with wavelength. The different wavelengths in a light pulse will propagate with different group velocities, v_g in the fibre due to finite spectral widths of the signal thus resulting to group delay being dependent on the optical frequency, ω. This leads to spreading of pulse.

The group velocity is given by

$$v_g = \left(\frac{\partial \beta}{\partial \omega} \right)^{-1} \quad (1)$$

where v_g is the group velocity and β is the propagation constant. Different group velocities lead to group delay, T_G is given by

$$T_G = \frac{\partial \varphi}{\partial \omega} \quad (2)$$

where φ is the optical phase and ω is the optical frequency.

Differentiating T_G with respect to optical frequency, ω

$$\mathrm{D} = \frac{\partial^2 \varphi}{\partial \omega^2} \quad (3)$$

where D is the fibre dispersion.

Mathematically, D is the second order derivative of the optical phase with respect to the optical frequency as shown in equation (3). Second order dispersion parameter, β_2 describes the group-velocity dispersion (GVD), and is related to the dispersion parameter at the reference wavelength, λ as

$$\beta_2 = -\frac{\lambda^2}{2\pi c} D \quad (4)$$

Therefore dispersion, D in equation (3) can be rewritten as

$$D = \frac{\partial}{\partial \lambda} \left(\frac{1}{v_g} \right) = -\frac{2\pi c}{\lambda^2} \beta_2 \quad (5)$$

where v_g is group velocity, c is speed of light, β_2 is the group-velocity dispersion and λ is reference wavelength. Differentiating equation (5) with respect to wavelength, it yields the dispersion slope, S given by

$$S = \frac{\partial D}{\partial \lambda} = \frac{2\pi c}{\lambda^3}\beta_2 + \left(\frac{2\pi c}{\lambda^2}\right)^2 \beta_3 \qquad (6)$$

where S is the dispersion slope, β_2 is the group-velocity dispersion and β_3 is the third order dispersion parameter. At zero dispersion wavelength, β_2=0. So the dispersion slope is proportional to β_3 [3].

The broadening of the pulse limits the available bandwidth and transmission distance especially as the bit rates increase. Therefore to increase the transmission distance at increased bit rates some compensation is needed. Compensation approaches have been suggested [8, 9, 10,11,12], these are precompensation scheme that involve electronic chirp implementation on laser diode and modulator chirp, in-line compensation that make use of dispersion compensating fibre (DCF), fibre Bragg grating (FBG) and phase conjugation and lastly postcompensation scheme involving electronic equalization at the receiver.

Dispersion compensating fibre (DCF) is a fibre with large negative dispersion coefficient at 1550nm. It is used in optimizing 1550 nm transmission in a G.652 single mode fibre (SMF) [13]. The DCF is added to an existing SMF to cancel the dispersion. The length of the DCF required for compensation can be reduced by using fibres with very large negative dispersion coefficients [13]. Therefore, the higher the dispersion coefficient of the compensating fibre, the smaller the length. The relationship is given as

$$L_{DCF} \times D_{DCF} = -L_{SMF} \times D_{SMF} \qquad (7)$$

where L_{DCF} is the length of the DCF, L_{SMF} is the length of the SMF, D_{DCF} is the dispersion value of the DCF and D_{SMF} is dispersion value of the SMF.

The negative dispersion and dispersion slopes are achieved by doping the core of the compensating fibre. This makes it possible for the accumulated dispersion in transmission fibre over a wide range of wavelength [14]. The dispersion and dispersion slope of the DCF and transmitting fibre should be matched in order to compensate the accumulated dispersion effectively over all the wavelengths [15,16]. New design of DCF called inverse dispersion fibre (IDF) has been introduced [17]. It has high negative dispersion values depending on SMF to DCF length ratios and negative dispersion slope enabling dispersion and dispersion slope compensation [17,18]. This work presents the CD compensation using the IDF.

3. Research design

The experimental setup is as shown in figure 1. In this work, a 4.25 Gbps 1550 nm VCSEL was directly modulated and the signal transmitted over a SMF fibre. A large negative dispersion IDF of -54 ps/nm.km was used to cancel the cumulative dispersion introduced by G. 652 fibre at 1550 nm transmission. The dispersion for the standard SMF, G.652 was 17 ps/nm.km [19] and that of nonzero dispersion shifted fibre (NZDSF-), ITU-T G.655 was -2.8 ps/nm.km. A VOA was used to vary the input power on the photo detector as the BER measurements were performed. Different fibre lengths for G.652 fibre were also separately simulated and the BER obtained. The experimental validation with compensation was performed on a 36.9km (11.5 km G.652 fibre combined with 25.4 km Truewave submarine reduced slope (SRS)) fibre. This is compared to 11.5 km G.652 fibre transmission without compensation.

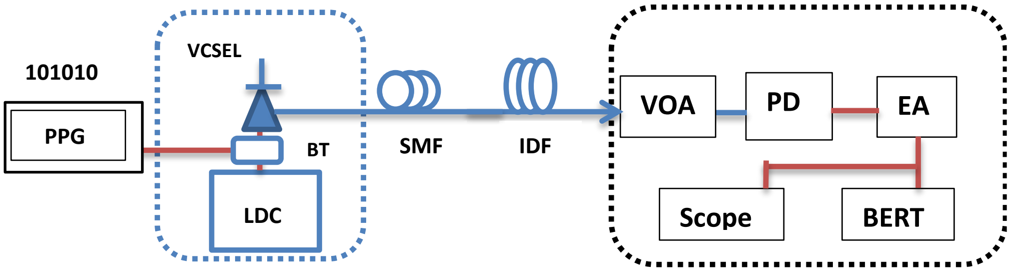

Figure 1: Setup for VCSEL transmission with CD compensation; PPG is pulse pattern generator, LDC is laser diode control, BT is a bias tee, SMF is single mode fibre, IDF is inverse dispersion fibre, VOA is variable optical attenuator, PD is photo detector, EA is electrical amplifier and BERT is bit error rate tester.

4. Results and Discussions

VCSEL are relatively low power devices. Figure 2 (a) shows the current power curve of the 4.25 Gbps 1550 nm VCSEL. The operating range is in mA with optimum performance at approximately 6 mA giving an output power of about 0.8 mW. The inset graph shows the wavelength tunability as the modulation current is varied from 2 mA to 9.9 mA. The signal wavelength is found to vary from 1545 nm to 1549.8 nm on tuning the modulation current. This is an advantage for applications such as wavelength division multiplexing (WDM) systems. Figure 2 (b) on the other hand shows the BER measurements for 1550 nm transmission on an ITU-T G.652 fibre. The error floor at acceptable BER threshold of 10^{-9} without CD compensation on an ITU-T G.652 fibre is about 35 km.

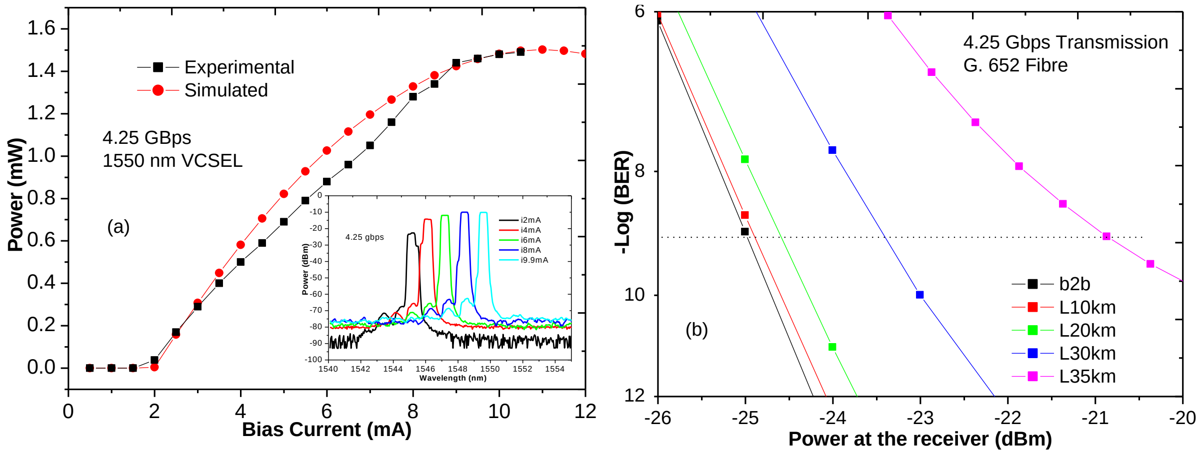

Figure 2: (a) 4.25 Gbps 1550 nm VCSEL characterization. Inset: wavelength tuneability on different bias currents (b) Simulated BER measurements on an ITU-T G.652 fibre without compensation.

Figure 3(a) presents the compensated case on a 35 km ITU-T G.652 SMF. In this transmission, 3.72 dB of power is compensated. A 10.4 km IDF fibre with dispersion value of -54 ps/nm.km was used. The dispersion slopes of SMF and IDF were 0.08 ps/nm^2.km and -0.18 ps/nm^2.km respectively. The IDF length is derived from equation (7), this relation is shown on the inset graph in figure 3(b). The power compensated is seen to increase with increase in the fibre length as shown in figure 3(b). This is due to cumulative dispersion effects in the fibre. With IDF, we are able to enhance the reach on a G.652 SMF using the 4.25 Gbps 1550 nm VCSEL with receiver sensitivity of about -24.5 dBm as shown experimentally in figure 4. In this regard, the transmission limitation is the attenuation which is about 0.3 dB/km on this G.652 fibre. This implies that with compensation, SKA phase 1 inner baselines (up to 50 km) clock transmission can be achieved using VCSELs. Figure 3 (a) shows that the residual dispersion is very small and amount to a penalty of about 0.4 dB over 35 km G.652 fibre, hence the compensation is efficiently attained.

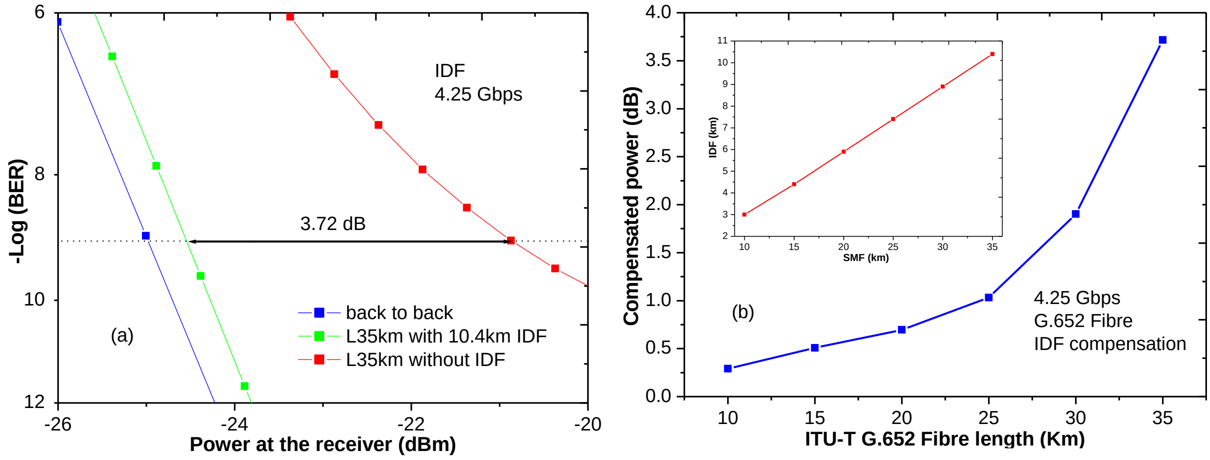

Figure 3: (a)Simulated BER curves showing compensated power in a 35 km G.652 with and without IDF compensation (b) Simulated compensated power with increasing fibre length in a 4.25 Gbps VCSEL. Inset: DCF and SMF relation.

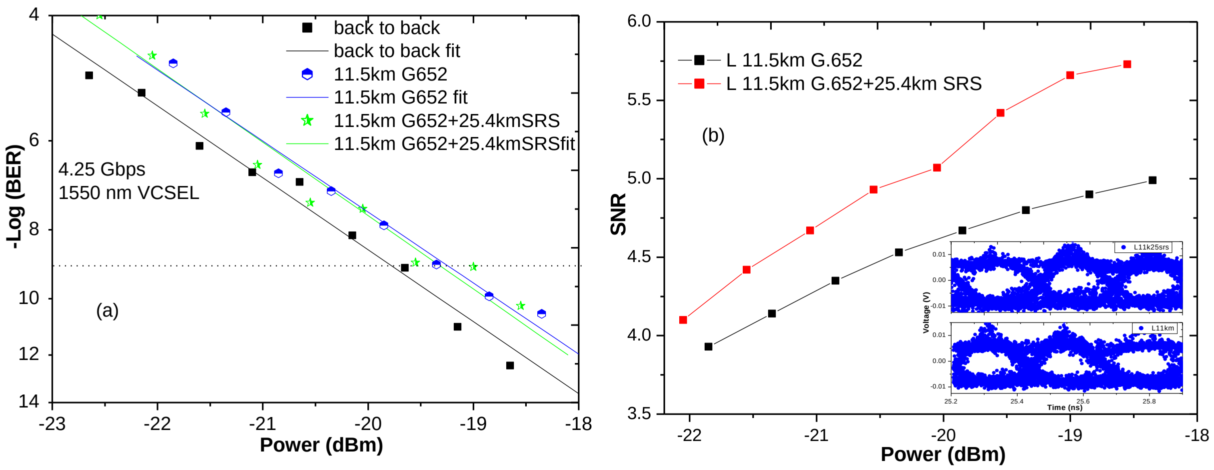

Figure 4: (a) Experimental BER estimation for 4.25 Gbps VCSEL transmission at 36.9 km (11.5 km G.652 combined with 25.4 km SRS fibre) and11.5 km G.652 fibre lengths. (b) Corresponding signal to noise ratios (SNR) Inset: Eye diagrams for 36.9 km and 11.5 km respectively.

In experimental investigation, non-return zero (NRZ) pseudorandom bit sequence (PRBS 2^7-1) was transmitted over 11.5 km G.652 and 36.9 km (a combination of 11.5 km G. 652 and 25.4 km SRS) fibres. An Avalanche photodiode (APD) receiver was used. The performance of the two fibres is shown in figure 4 (a) and (b).The penalties in both cases are less than 1dB. This is a relatively low penalty at this transmission rates. The quality factor (Q-factor) was used to estimate the BER. Details of using Q factor technique to estimate BER are given in [20]. Signal to noise ratio (SNR) of the signal is compared in figure 4 (b). We notice that in both cases, the eye is open. Considering transmission distance, the combined G.652 and SRS fibre (36.9 km) should have had reduced eye opening as compared to11.5 km G.652 fibre. The SRS fibre has low negative dispersion which cancels the dispersion thus improving the signal. This is observed on the signal strength as inferred from the SNR. However, the compensation in this case is not achieved fully because of low negative dispersion SRS fibre. IDFs have high negative dispersion values, therefore to cancel the dispersion of the transmitting fibres, short lengths are required. By combining the negative dispersion fibre with a positive dispersion one, we cancel the dispersive effects and eventually improving the signal clarity. This increases the VCSEL transmission distance without errors.

5. Conclusion

An inverse dispersion fibre is a promising dispersion management tool for VCSEL transmission. The use of IDF should solve the chromatic dispersion limitation in VCSELs by reducing the dispersion penalties and improving the quality of signal. A 3.72 dB compensated power has been achieved on a 35 km G.652 fibre. This has significantly improved the transmission distance of a 4.25 Gbps 1550 nm VCSEL attained without compensation. This should help in improving the VCSEL performance as well as the reach in applications such as access networks and SKA clock reference distribution.

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