VCSEL Technology for Square Kilometre Array (SKA) Optical Fibre Network

E. K. Rotich Kipnoo, D. Waswa, A. W. R. Leitch and T. B Gibbon

Physics Department, Nelson Mandela Metropolitan University, P. O. Box 77000, Port Elizabeth 6031, South Africa. Tel: +27 41-504-2141; Fax: +27 41-504-2573.

Email: Enoch.Rotich@live.nmmu.ac.za

Abstract. For the first time, we propose the use of Vertical Cavity Surface Emitting Lasers (VCSELs) within the optical fibre network supporting data collection and transmission for Square Kilometre Array (SKA) in South Africa. We have theoretically demonstrated VCSEL transmission over typical SKA required distances. We show that VCSELs are ideal for per-channel transmission rates of 2.5 Gb/s, 5 Gb/s and 10 Gb/s within SKA project. It is found that Bit Error Rate (BER) decreases with increase in power. This work is valuable in providing SKA with a VCSEL technology, option for extremely high network performance at reasonable cost.

1. Introduction

Square Kilometre Array (SKA) Radio Telescope in South Africa will be the most powerful radio astronomy project that will allow us to understand the physics and the evolution of the universe and its structures as well as new aspects of astrophysics, like the origin of extremely high-energy particles, cosmic jets, black holes, and the structure and evolution of magnetic fields in cosmic structures, which will probably be addressed for the very first time [1]. Its design, construction and operation at Karoo region of the Northern Cape is to be completed in 2025. A major component of the SKA telescope array will be an extensive array of approximately 3,000 antennas. Half of these will be concentrated in a 5 km diameter central region, and the rest will be distributed out to 3,000 km from this central concentration. The Karoo project specification demands high sensitivity with fast survey speeds on a very well calibrated instrument to achieve the necessary observational performance. The proposed implementation is summarized in table 1[2]. This proposed scheme constitutes 4.192 Pb/s (10^{15} bits per second) of data collected for transmission and eventual processing at Cape Town ~300 km away (Fig. 1). Square Kilometre Array (SKA) South Africa demands high transmission rates at reasonable cost because of enormous data rates. This calls for the most efficient means of data transmission. For the first time, we propose the use of Vertical Cavity Surface Emitting Lasers (VCSELs) within the optical fibre network supporting data collection and transmission.

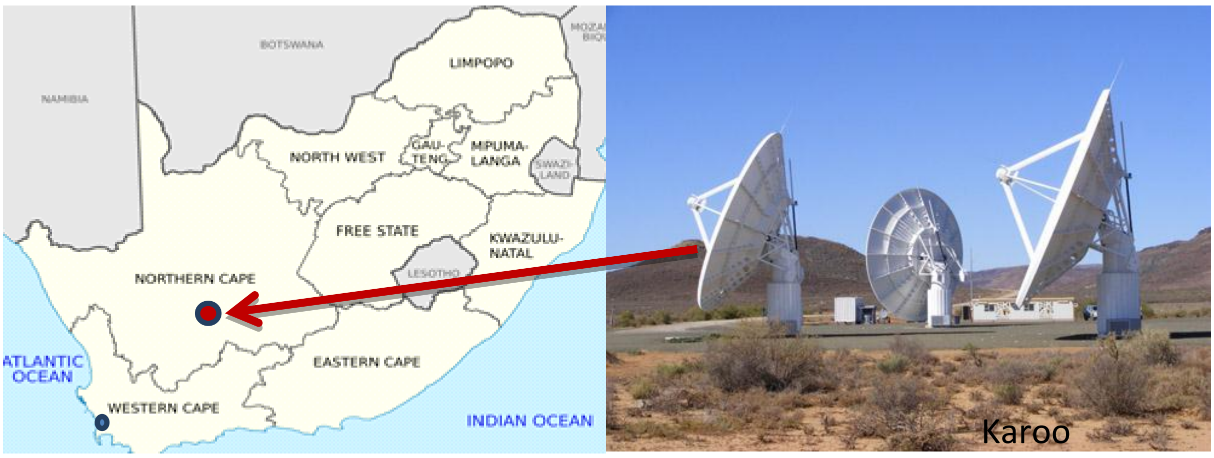

Figure 1: Map of South Africa indicating the proposed Karoo SKA site.

VCSELs are high performing, energy efficient optical sources ideal for relatively short distance high speed optical communication networks. VCSELs offer high bandwidth, single mode operation within C-L bands, wavelength tunabilities, the convenience of direct modulation and energy efficiency at low drive currents. VCSEL operation is however limited by wavelength chirp and chromatic dispersion [3]. In this study, we demonstrate VCSEL transmission over typical SKA required distances over ideal per-channel transmission rates of 2.5 Gb/s, 5 Gb/s and 10 Gb/s within SKA project.

Table 1: Proposed SKA implementation showing antennae characteristics and distribution [2]

Freq. Range	Collector	Sensitivity	Number/size	Distribution
0.07-0.45 GHz	Aperture array (AA-lo)	4,000 m^2/K at 100 MHz	250 arrays, Diameter 180 m	66 % within core 5km diameter, rest spread out to 180 km radius
0.4-1.4 GHz	Aperture array (AA-hi)	10,000 m^2/K at 800 MHz	250 arrays, Diameter 56 m	
1.2-10 GHz	Dishes with wideband single pixel feed (SD-WBSPF)	5,000 m^2/K at 1.4 GHz	1,200 dishes, Diameter 15 m	50 % within core 5 km diameter, 25 % between core and 180 km, 25 % between 180 km and 500 km radius.

2. Theory

VCSELs are semiconductor lasers with a monolithic laser resonator, where the emitted light leaves the device in a direction perpendicular to the chip surface as shown in Fig. 2. The cavity is realized with two semi-conductor Bragg mirrors between which there is an active region with (typically) several quantum wells and a total thickness of only a few micrometers. The active region is electrically pumped with a few tens of milliwatts and generates an output power in the range from 0.5 to 5 mW (-3.01 to 6.99 dBm), or higher powers for multimode devices. The current is often applied through a ring electrode, through which the output beam can be extracted, and the current is confined to the region of the resonator mode using electrically conductive (doped) mirror layers with isolating material around them [4].

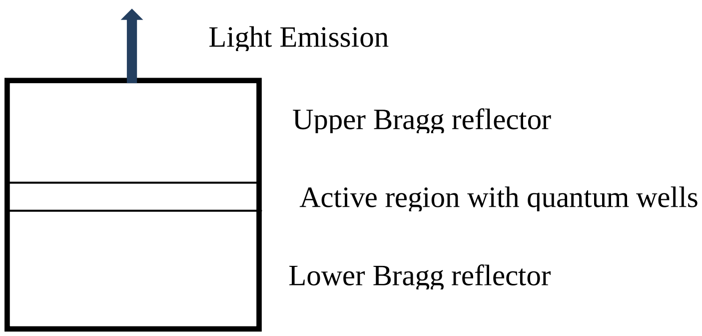

Figure 2: Schematic structure of a VCSEL

VCSELs have been studied for use in fibre-optic networks and as optical interconnects [5] [6]. The major advantages of the VCSEL are; compatibility with low-cost wafer scale fabrication and testing methods, high-volume, lower-cost manufacturing and compatibility with most active optical devices. The VCSEL has other attractive characteristics that make it well suited for use in fibre-optic systems. These include a circularly shaped output beam for high coupling efficiency, high modulation bandwidths at low current levels, single mode operation, low power consumption and the potential for producing integrated modules and arrays on wafer [5]. However, chirp and chromatic dispersion is a limitation. Frequency chirping is defined as the instantaneous change of the central wavelength or optical frequency υ in response to variations in optical power i.e. residual frequency modulation of an amplitude modulated optical wave. The instantaneous frequency chirp can be expressed as [7] [8]

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

where P(t) is the instantaneous optical power, and α is the linewidth enhancement factor and the κ parameter are constants. The κ parameter is related to the non-linear gain and depends on the geometry of the device. The first term describes transient chirp relating to the time derivative of the changing instantaneous optical power with rising and falling pulse edges. The second term describes adiabatic chirp relating to the instantaneous optical power itself. Chirp has generally been avoided in Non-Return-to- Zero (NRZ) systems because it increases the optical bandwidth and hence the effects of Group Velocity Dispersion (GVD). Mitigation techniques include; introduction of an offset between the VCSEL wavelength and Array Waveguide Grating (AWG) channel as a way of reducing chirp-related dispersion penalty [3] and phase modulation prior to launch as a countermeasure against the deleterious effects of the fibre nonlinearity [9].

3. Research design

The schematic diagram for the simulation using VPI transmission Maker & VPI component Maker is as shown in fig. 3. The VCSEL is modulated at various bit rates (2.5, 5 and 10 Gb/s) by a Non-Return-to- Zero (NRZ) Pseudo-Random Binary Sequence (PRBS) signal and propagated over a single mode fibre. On –Off Keying (OOK) receiver was used. During Bit Error Rate (BER) measurements, attenuator (Att.) was used to vary the receiver input power and to fix input power to the detector.

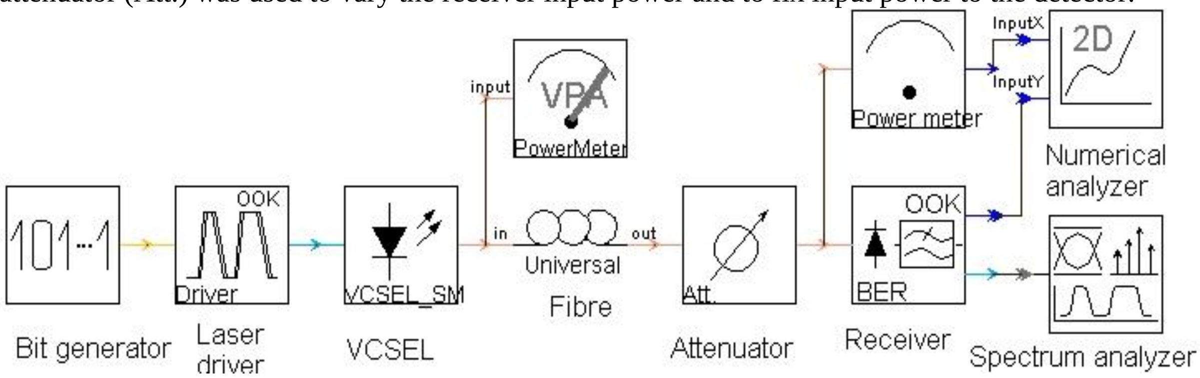

Figure 3: Simulation set up showing BER measurement.

The length of the fibre is varied from 1.4 km, 5 km, 7.5 km and 10 km and the dispersion penalties established.

4. Results and discussion

Efficient VCSELs have high output power (above 0 dBm), high extinction ratio and low chirp. Fig.4 presents the VCSEL characterization i.e. output power verses bias current. The unmodulated bias current was set to 9 mA giving an output power of 1.09 mW (0.37 dBm). The threshold lasing bias is 3 mA.

Modulation currents, I_{pp} (off '0' - on '1') in VCSELs defines its optimum performance. I_{pp} (off-on) was adjusted to 5 mA (7-12 mA), 7 mA (7-14 mA), 9 mA (6-15 mA) and 11 mA (5-16 mA) and the corresponding eye diagrams obtained were as shown in fig. 5. The Extinction Ratio (ER) values are 14.8 dB, 7.6 dB, 5.3 dB and 4.2 dB for I_{pp}; 11 mA, 9 mA, 7 mA and 5 mA respectively. An increase in modulation current increases the chirp and ER and vice versa.

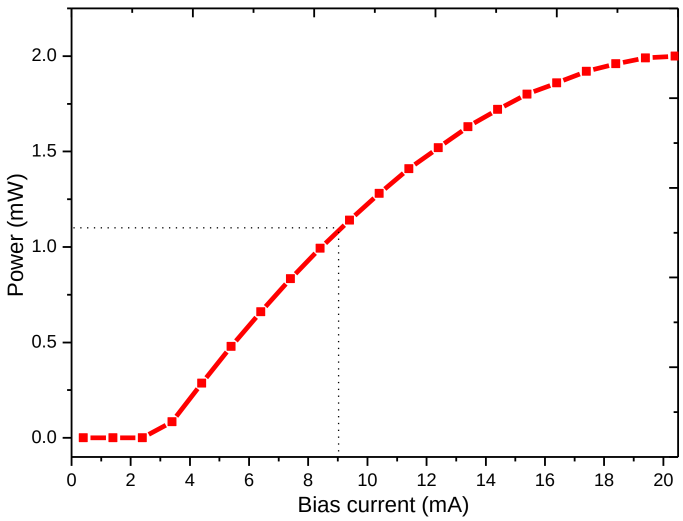

Figure 4: Unmodulated VCSEL output power as a function of bias current

Modulation current of 9 mA (off '0' - on '1'; 6mA and 15 mA) was set and the BER measurements for 2.5 Gb/s, 5 Gb/s and 10 Gb/s taken. At 10 Gb/s transmission, an acceptable bit error rate threshold of BER<10^{-9} is achieved at an optical sensitivity of -23.05 dBm, -22.66 dBm, -21.59 dBm, and -17.88 dBm for back to back, 1.4 km, 5 km, 7.5 km and 10 km respectively as shown in fig. 6(a). Hence the fibre dispersion introduces a power budget penalty of 0.37 dB, 1.47 dB, 2.52 dB and 5.17 dB respectively.

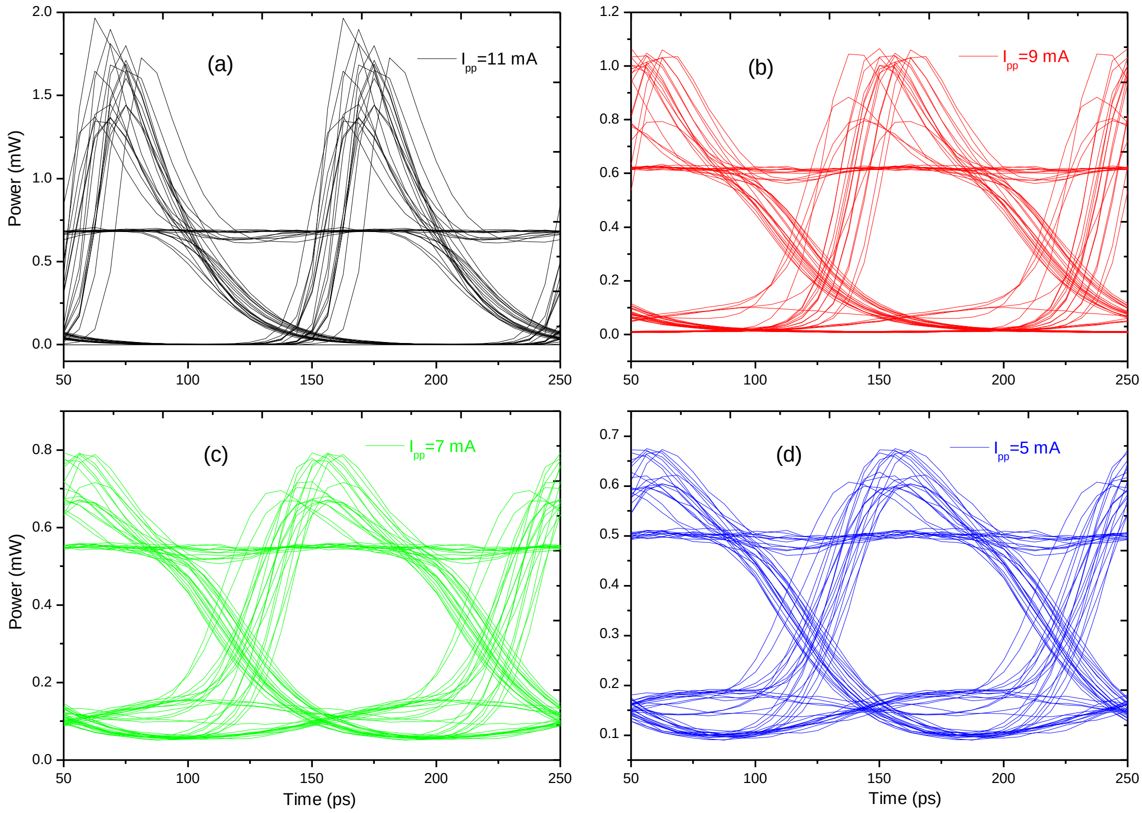

Figure 5: Eye diagrams for various modulation currents; (a) 11 mA (b) 9 mA (c) 7 mA (d) 5 mA.

Transmission penalty increases with increase in fibre length. Fig. 6 (b) gives the transmission penalty for the various bit rates, then penalty increases with increase in bit rate. Therefore, the findings of this study agree with acceptable penalty budget of 3-5 dB for a typical network design.

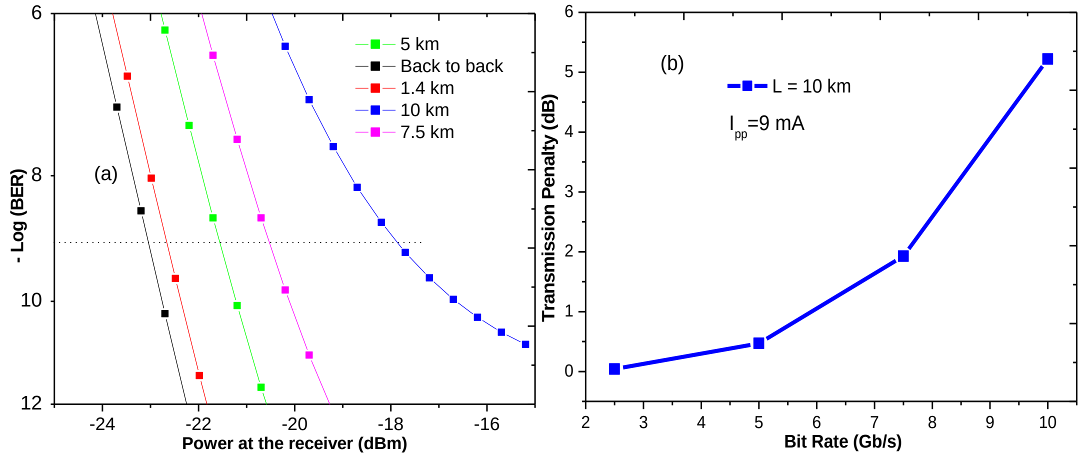

Figure 6: (a) VCSEL BER at various fibre lengths (Reference BER =10^{-9}) (b) Transmission penalties at different bit rates.

5. Conclusion

We have shown that VCSELs are ideal for up to 10 Gb/s transmission over 10 Km fibre length. Dispersion penalties of 0.038 dB, 1.47 dB and 5.17 dB for 2.5 Gb/s, 5 Gb/s and 10 Gb/s respectively over 10 km fibre length were realized. This work is valuable in providing SKA with an option for extremely high network performance for the enormous data.

6. Acknowledgement

We are grateful for Research Funding from: Telkom, Dartcom, Ingoma, NRF, CSIR, THRIP, and Scholarship Funding from SKA/NRF.

References

[1]. http://www.ska.ac.za//index.php

[2]. The SKADS Teams, *Aperture Arrays for the SKA: the SKADS White Paper***,** Design Study 8 Task 1 Deliverable 0.5 Rev.:0.91, 17 March 2010.

[3]. T.B. Gibbon, K. Prince, T.T. Pham, A. Tatarczak, C. Neumeyr, E. Rönneberg, M. Ortsiefer, "VCSEL transmission at 10 Gb/s for 20 km single mode fibre WDM-PON without dispersion compensation or injection locking"*Elsevier. Opt. Fib. tech*. 17, pg 41-45 (2011).

[4]. R. Paschotta, *Encyclopaedia of Laser Physics and Technology*, Straus, Morlenbach, 2008.

[5]. A. Karim, S. Bjorlin, J. Piprek and J. E. Bowers., "Long-wavelength vertical-cavity lasers and amplifiers", *IEEE J. Sel. Top. Quant. Electron.* **6**, 1244 (2000).

[6]. T.B. Gibbon, K. Prince, C. Neumeyr, E. Rönneberg, M. Ortsiefer and I. T. Monroy, "10 Gb/s 1550 nm VCSEL transmission over 23.6 km single mode fibre with no dispersion compensation and no injection locking for WDM PONs", *Proceedings Optical Fibre Communication Conference & Exposition and the National Fibre Optic Engineers Conference*, San Diego, CA, USA, (2010).

[7]. T. L. Koch, R. A. Linke, "Effect of nonlinear gain reduction on semiconductor laser wavelength chirping*", Appl. Phys. Lett.*, vol.48, no.10, pp.613-615, Mar 1986.

[8]. L. Bjerkan, A. Rgyset, L. Hafskjaer, and D. Myhre, "Measurement of Laser Parameters for Simulation of High-speed Fibre optic Systems," *J. of Lightwave Tech.*, Vol. 14, No. 5, pg 839-850 (1996).

[9]. S. T. Cundiff, B. C. Collings, L. Boivin, M. C. Nuss, K. Bergman, W. H. Knox,and S. G. Evangelides, Jr "Propagation of Highly Chirped Pulses in Fibre-Optic Communications Systems" , *J. of Lightwave Tech.*, Vol.17, No. 5, pg 811-816 (1999).