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Modulated Raman pump for integrated VCSEL-based reach enhancement and clock tone dissemination in optical communication

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ABSTRACT

The fast growth of data traffic in access networks calls for high speed and low-cost optical links. To extend reach for users in metro areas requires optical amplification of the signal carrying data. In this paper we experimentally demonstrate a cost effective technique of extending reach by exploiting Raman pump to both amplify data signal and transmit clock signals. A 1550 nm VCSEL is modulated with a 10 Gbps data and coupled into a 50.7 km fibre to co-propagate with a 4 GHz modulated Raman pump. Error free and enhanced data transmission was achieved with minimum receiver sensitivity of −14.8 dBm and distributed stable clock signal over 50.7 km SMF-Reach. A maximum phase noise of −100.6 dBc/Hz at 10 kHz offset frequency is experimentally measured for 50.7 km fibre transmission with backward Raman amplification. This work presents a real-time technique of transmitting accurate data and stable clock signal for long-reach optical networks.

1. Introduction

The increase in demand for higher data transmission capacity has been accelerated in the last few years by rise in internet traffic. New technologies trend such as Hyper-scale data centres not only require increased data transmission speed, but also reach extension [1]. Advanced technologies have enabled more data to be transmitted through a single optical fibre over long distances [2,3]. Long-Reach optical network enables broadband access for many customers in the access and metro areas while decreasing operational expenses.

High demand for bandwidth has resulted to invention of new access network architectures to bring high capacity optical fibre closer to end users. Among many competing technologies, passive optical networks (PON) are the best candidate for next generation access network. PONs can accommodate broadband voice, data and video traffic simultaneously.

Development in PON offers potential for unprecedented access bandwidth to consumers. PON include Ethernet PON, asynchronous transfer mode (ATM)-PON, Broadband PON, Gigabit-PON and wavelength division multiplexing (WDM) PON [4,5]. The architecture requirement for PON is highly cost effective since the network infrastructure is shared by many users and does not require active components, like routers in the path between the telecommunication provider's central office and the customer. While these PONs offer significant bandwidth improvement, they may not provide the best ultimate solution for service providers seeking to significantly reduce the cost of delivering future broadband services to customers. This has led to more far reaching network solutions based on optically amplified long reach PONs (LR-PONs) [6]. LR-PONs extend the distance between the central office and end users from the traditional range of 20 km to 100 km and beyond, leading to consolidation of metropolitan and access networks [7]. Optical amplification using EDFA in LR-PON is key, but the amplification introduces amplified spontaneous emission (ASE), which has detrimental effect on system performance for instance low signal power [8], that leads to slow speed in adjusting its gain. The transmitters in traditional PON are designed for transmission range which is less than 20 km. The challenge arises when applying them in a LR-PON where the signal needs to recover a range of 100 km and beyond. There is therefore need for an improved technology that modifies LR-PON to transmit amplified data signal and clock signal simultaneously.

Distribution of stable clock signals to remote ends is necessary for applications, such as deep-space exploration [9], astronomy and coherent aperture radar [10]. To overcome free space link limitation, fibre transmission of standard frequency over optical fibre has been investigated for years [11]. The technique takes advantage of low attenuation, high reliability and availability of fibres. RF frequency can be transferred over 86 km fibre using optical compensator [12]. Direct optical frequency transfer with better stability and over long distances has been done [13]. Ultra stable RF transport in NASA antennas has been successfully distributed [14]. Long distance phase

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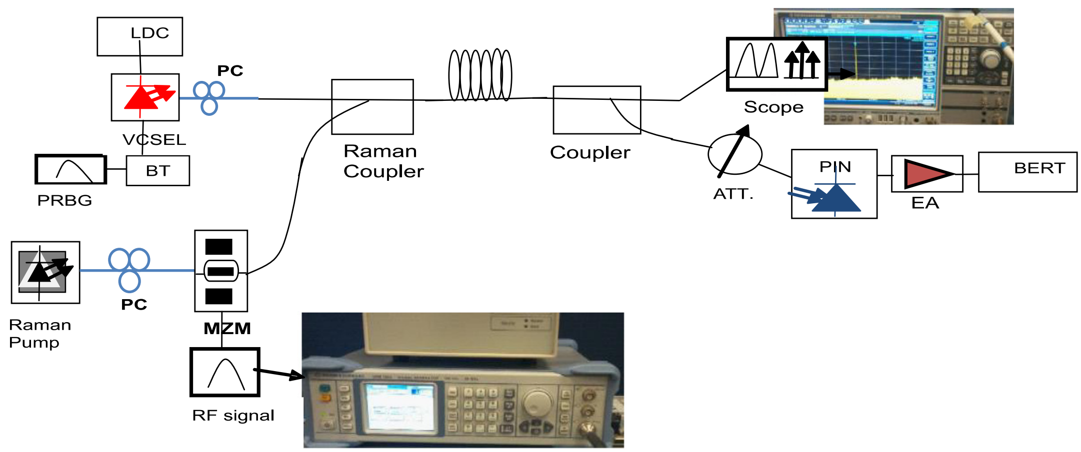

Fig. 1. Experimental setup for simultaneous transmission of data and clock signals. LDC: laser diode controller, VCSEL: Vertical cavity surface emitting laser, BT: bias tee, PRBG : Pseudorandom bit sequence generator, PC: Polarization controller, MZM: Mach–Zehnder modulator, ATT: Attenuator, PIN: Positive intrinsic negative-Photo diode, EA: Electrical amplifier, BERT: Bit error rate tester.

stabilized 100.02 GHz millimetre (mm) wave distribution over 160 km optical fibre has been demonstrated [15]. Combined optical/RF dissemination system that offer higher stability is being explored. Since optical frequencies have higher order magnitude than RF, they offer corresponding higher stability. Backward Raman pump has been used to simultaneously amplify the signal and distribute clock signal [16]. Raman can be used to extend reach by adopting VCSEL four level pulse amplitude modulation and dense wavelength division multiplexing (DWDM) [1]. We report a technique that disseminates clock signal and data signal simultaneously for 50.7 km fibre by combined use of modulated forward Raman pumping and VCSEL technology. In our technique there is no need of using an amplifier to enhance attenuated signal, the factor that makes the technique simple and less costly. The main motivation for using Raman amplification to boost the VCSEL is broad bandwidth, high saturation input power and low noise figures. Raman process occurs in any fibre type and gain depends on pump and signal wavelength [17]. The results show that VCSEL performance with modulated Raman gives higher receiver sensitivity.

2. Experimental setup

Fig. 1 shows experimental setup used to demonstrate simultaneous 10 Gbps data transmission and 4 GHz reference clock signal dissemination over 50.7 km standard single mode fibre (SMF).

A 1550 nm VCSEL laser with an output power of −10.14 dBm at 7.04 mA bias current and a 1450 nm Raman pump laser diode were used in our experiment. PC controllers were adopted to orient the states of polarization of the signal and pump wavelengths. VCSEL laser was modulated with a 10 Gbps pseudorandom bit sequence generator (PRBG) electrical signal of pattern length ($2^7 - 1$). A 1450 nm Raman pump with output power of 22.01 dBm was modulated by a 4 GHz RF clock signal from signal generator via MZM. The signal wavelength was coupled with Raman pump wavelengths by a 1450 nm/1550 nm optical coupler and co-propagated into a 50.7 km fibre. At the receiver end, the output optical signal was directed to a 1450 nm/1550 nm optical coupler to separate the signal wavelength from the pump wavelength for simultaneous analysis. A weak signal at the output of VCSEL co-propagated with Raman pump in the transmission fibre resulting to Raman amplification. A photo diode (PD) is used to recover transmitted data for BER measurement and eye diagram analysis. Also the transmitted clock tone is recovered by a PD and the phase noise was measured directly using an electrical spectrum analyser.

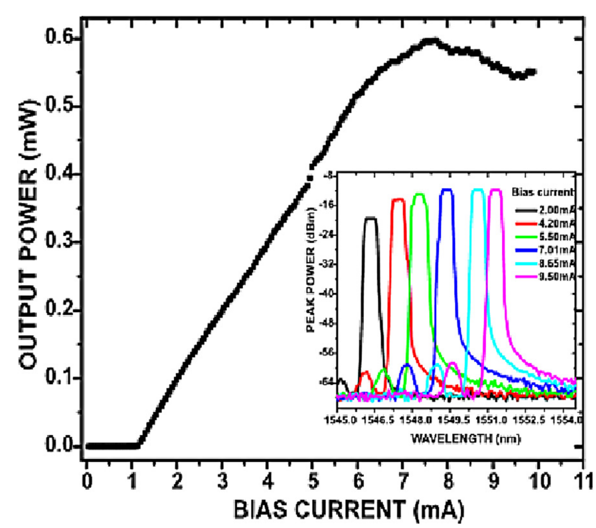

Fig. 2. VCSEL output optical power variation with bias current. Inset: VCSEL wavelength tuneability.

3. Results and discussions

VCSELs emitting at 1550 nm have gained much interest in optical communication networks because they offer high energy efficiency, high bandwidth density, and tunable capability to higher wavelength [18,19].

Fig. 2 shows VCSEL bias characteristics at different bias currents. The VCSEL used showed a threshold current of 1.3 mA and saturation level at 7.5 mA. Output power from VCSEL varied linearly with current above the threshold. Beyond saturation point output power of VCSEL reduced with further increase in current. Increasing current shifts the spectrum to longer wavelength as shown in the insert of Fig. 2. We obtained a wavelength tuning range of 8 nm by varying current from 2.0 mA to 9.5 mA.

VCSEL was adopted as data transmitter because it consumes low power and its wavelength can be tuned by varying bias current as shown in the insert of Fig. 2. For optimal performance we biased the laser at 7.04 mA (providing an output power of 0.57 dBm) for subsequent experiments.

Data transmission performance was analysed by varying power getting into the Photodiode receiver to measure Bit error rate (BER) at different bias currents. BER measurement in data transmission is used to compare quality of different systems for data transmission.

Fig. 3(a) shows that increasing bias current increases receiver sensitivity. Receiver sensitivity for 4.85 mA, 7.04 mA and 9.09 mA are −18.4 dBm, −17.3 dBm and −16.9 dBm respectively. The eye pattern measurements show overall signal integrity of a data path. Fig. 3(b), (c) and (d) indicates clearly open eye diagrams. Clear eye openings are observed for all bias currents, showing quality data transmission. During transmission the signal carrying data is attenuated hence need for enhancement.

Optical access networks require reliable, cheap and energy efficient broadband optical sources. VCSELs are suited for short distance data transmission and for 10 Gb/s and above data transmission however, they suffer from fibre dispersion and attenuation thus affecting their transmission performance over extended reach networks. Therefore VCSEL lasers require amplification in order to transmit over 50 km fibre while maintaining the integrity of data transmitted.

To obtain on–off gain we varied the input pump power and measured the gain on the signal. We used two pumping schemes namely; forward and backward pumping. In forward pumping the pump and signal propagate in the same direction while backward pumping they propagate in opposite direction.

A 25.25 km of single mode fibre SMF-Reach fibre was used to demonstrate Raman amplification. Fig. 4 shows that gain increases with increase in input pump power for the two pumping schemes. Maximum gain of 6.3 dB and 4.5 dB was obtained for forward and backward pumping respectively on a −10.14 dBm signal by using a 22.01 dBm pump power. It is evident from the graph that forward pumping has higher gain than backward propagation. This is due to the fact that both the pump power and the signal power propagate in the same direction and the forward pumping ratio remains almost the same for forward pumping leading to more power transfer to the signal. Much pump power is therefore transferred to the signal resulting to higher gain. Insert of Fig. 4 shows frequency evolution for pump and the signal when coupled through a fibre. Raman gain increases with wavelength offset between signal and pump peaking at 100 nm and drops rapidly with increased offset. Since forward Raman pumping scheme gives higher gain than backward pumping we adopted it for high signal quality transmission.

Fig. 5 shows measured BER curves of the transmission performance for VCSEL without Raman, with forward modulated and unmodulated Raman. VCSEL transmission is analysed with modulated and un-modulated Raman pump. The transmission performance is presented in Fig. 5. The receiver sensitivity of −14.12 dBm, −13.7 dBm and −14.8 dBm was obtained experimentally for VCSEL without Raman, VCSEL with un-modulated forward Raman and VCSEL with modulated forward Raman respectively. VCSEL with forward modulated Raman assisted gave lowest receiver sensitivity.

The eye diagrams for the three scenarios are shown in Fig. 6. Eye diagram for modulated forward Raman is clearly open than for other schemes indicating better performance.

Raman pump was also utilized to transmit clock signal. Clock signals are important in timing applications. Accurate and precise synchronized time and frequency distribution is key to optical communication networks like massive data centres. High speed data transport requires use of optical fibres for timing frequency signals as well for data transfer [20]. A 50.7 km optical fibre was used to distribute optical signal and the effect it has on the phase stability of the clock was studied.

Phase noise is the most common method of expressing frequency instability. Carrier frequency instability is expressed by averaging carrier frequency and then measuring the power at various offsets from

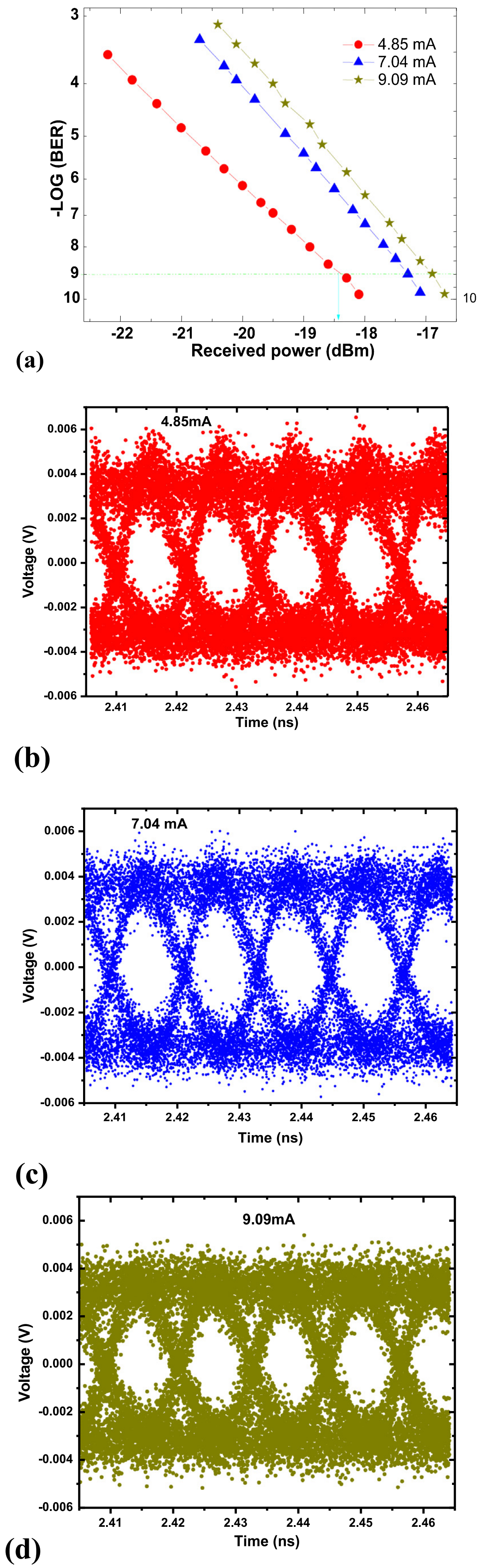

Fig. 3. (a) VCSEL transmission performance (b) Eye diagram at 4.95 mA (c) Eye diagram at 7.04 mA (d) Eye diagram at 9.09 mA.

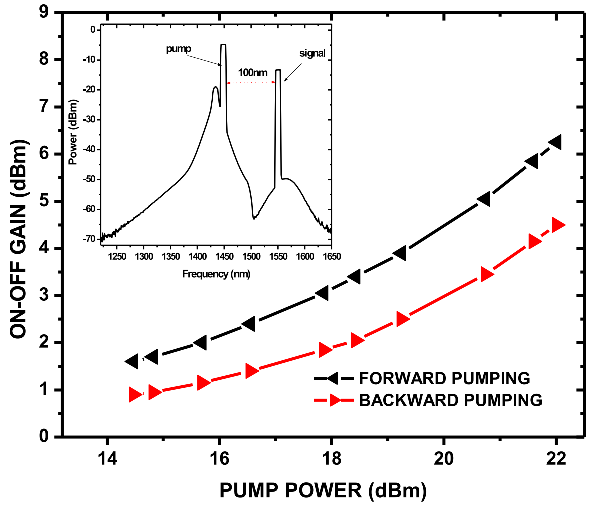

Fig. 4. Variation of on-off gain with input pump power for 25.25 km fibre. Insert: Raman gain profile.

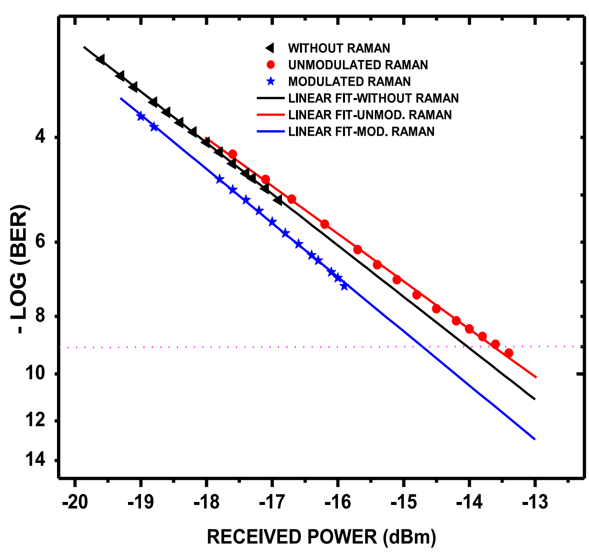

Fig. 5. Transmission performance for VCSEL Raman assisted technique.

the carrier frequency in a defined bandwidth. By measuring the total carrier power and then measuring the noise signal at a specified offset from the carrier, a phase noise measurement can be derived.

Fig. 7 shows a graph of SSB phase noise against frequency offset as measured from Electrical spectrum analyser (ESA). Phase noise performance profile changes with increasing offset frequency. At 10 kHz frequency offset the phase noise obtained was −115.2 dBc/Hz, −100.6 dBc/Hz and −102.2 dBc/Hz for electrical signal, backward and forward signals respectively. Introducing data in a system carrying clock signal causes interference that degrades the measured noise.

Fig. 8 shows power spectrums for different schemes. The peak powers are −9.8 dBm, −35.4 dBm and −37.9 dBm for electrical signal, backward enhanced signal and forward enhanced signal respectively.

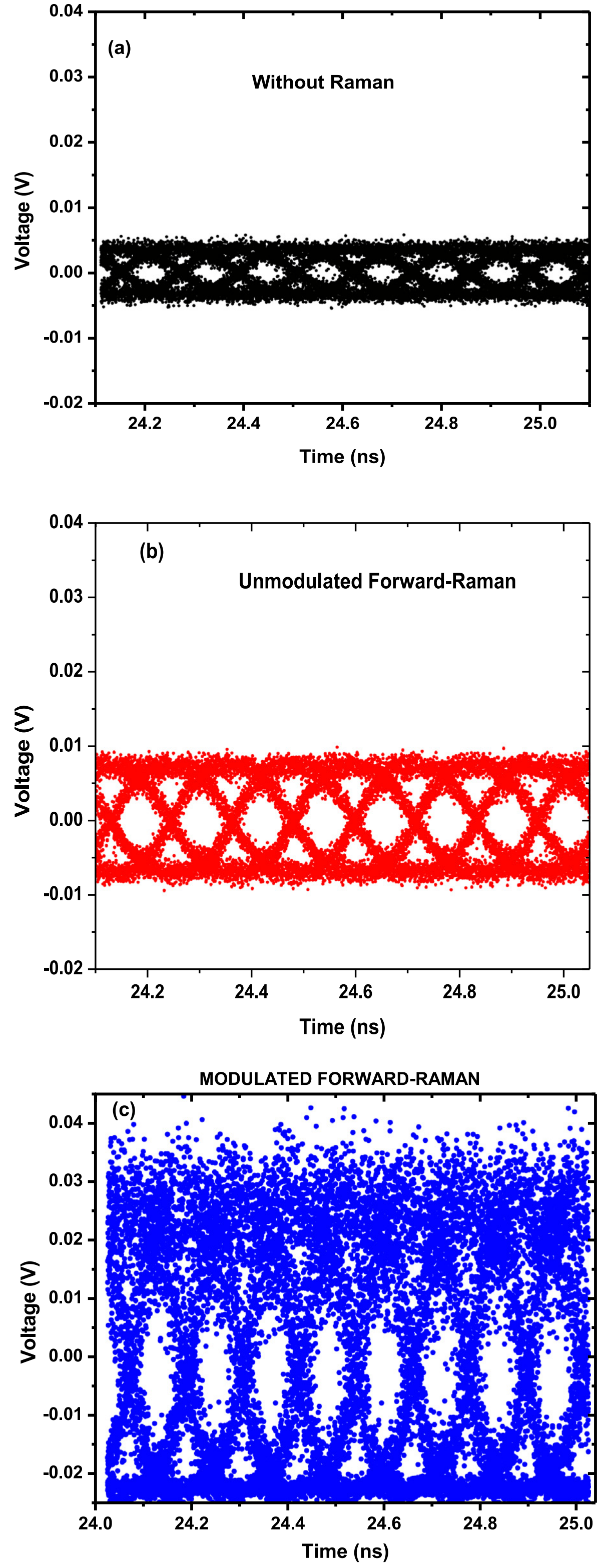

Fig. 6. Eye diagrams for VCSEL Raman assisted technique (a) VCSEL without Raman, (b) VCSEL with un-modulated Raman and (c) VCSEL with modulated Raman.

The spectrums have same characteristic appearance peaking at 4 GHz. Forward pumping has the lowest peak power hence lower noise floor.

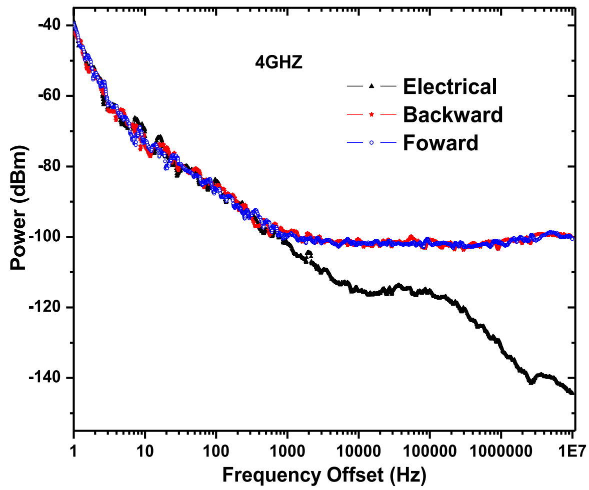

Fig. 7. SSB phase noise evolution with offset frequency.

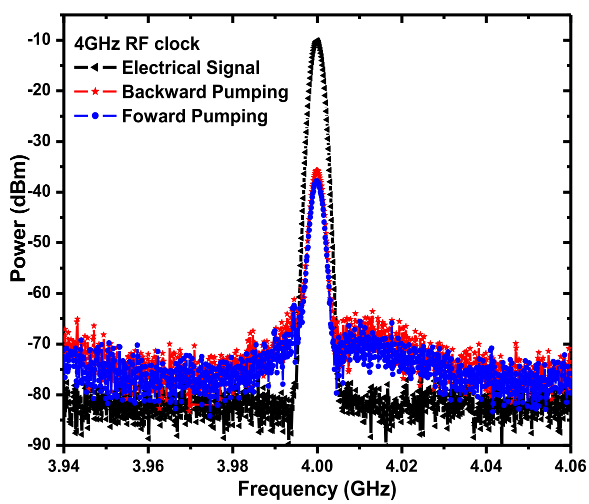

Fig. 8. Spectra for electrical signal, forward pump and backward pump optical signals.

4. Conclusion

We have demonstrated experimentally real time data transmission enhancement and clock distribution by utilizing VCSEL with Modulated forward Raman. Using Raman coupler data from a modulated VCSEL laser was launched in a fibre to co-propagate with modulated Raman pump. We report amplified error-free data transmission and clock signal over long optical fibre with little degradation of frequency stability. Combining VCSEL and modulated Raman is an attractive technique to be adopted in future data centres because forward Raman pump is fully utilized. Since there is no need for an amplifier, our technique is simple and less costly. With Raman assisted VCSEL transmission distance is extended since the signal is amplified. This technique will be of much benefit in LR-PON and data centres.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

D.M. Osiemo: Data curation, Conceptualization, Formal analysis, Validation, Writing original draft, editing. **D.W. Waswa:** Funding acquisition, Conceptualization, Project administration, Supervision, Validation. **K.M. Muguro:** Supervision, Validation. **G.M. Isoe:** Conceptualization, Project administration, Data curation, Supervision, Review, Validation. **T.B. Gibbon:** Funding acquisition, Resources, Conceptualization, Project administration, Supervision, Validation. **A.W. R. Leitch:** Funding acquisition, Resources, Project administration, Supervision.

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