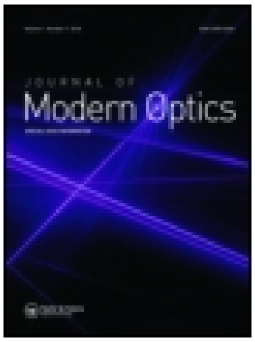

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ABSTRACT
We experimentally present the first reported integrated cross-modulated forward Raman pump, with low-cost, power-efficient VCSELs. A single-mode VCSEL is directly modulated with 8.5 Gbps data and transmitted over a 50.7 km SMF-Reach fibre. Exploiting the 6.9 dB flat-gain of a forward Raman pump, an error-free transmission is experimentally achieved. Network efficiency is maximized by modulating the forward Raman pump with 8.5 Gbps data and transferred over the fibre link. To the best of our knowledge, it is the first time a forward Raman pump is utilized for simultaneous data amplification and transmission. Inherent VCSEL frequency chirping leads to an error-flow over a 50.7 km fibre link. With unmodulated forward Raman pump, a transmission penalty of 0.83 dB is incurred. However, modulated forward Raman pump results in a crosstalk penalty of 0.47 dB over the transmission link. This work offers a novel enabling technique for simultaneous network capacity, efficiency and reach optimization for next-generation optical interconnects.

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VCSEL; Raman amplification; optical interconnect; optical fibre; modulation; network efficiency

Introduction

In the recent past, there has been an incredible increase in data rates of optical transponders due to the explosive development in smart handheld devices and the proliferation of new bandwidth demanding the application with much more strict quality of signal requirements (*1*). Moreover, data traffic transmission/detection has seen the transformation from traditional one-dimensional modulation formats to multi-level phase modulated formats and coherent digital signal procession (*2*–*5*).

Despite diverse transformations in the transmission layer of optical-based communication systems, current optical fibre networks are still dominated by C-band erbium-doped fibre amplifiers (EDFAs). EDFAs are the main building blocks of the transport systems that define the performance characteristics of extended reach optical network independent of transponders. EDFAs have advantageous features such as the ability to achieve high gain and can support several modulation formats. However, the main limiting factor EDFA is that the output optical power of the EDFA is a combination of amplified spontaneous emission noise (ASE), which increases the noise figure, therefore limiting the optical signal-to-noise ratio (OSNR) (*6*). Reducing ASE noise in optical networks may require additional techniques such as minimizing the optical bandwidth or adoption of optical filtering techniques, which are complex and power consuming (*7*). Moreover, some signal improvement techniques such as the adoption of powerful forward error correction (FEC) codes have allowed data rates to increase without necessarily improving the transport network. Combined advances in FEC (G-FEC, soft-decision FEC, enhanced FEC) and modulation formats (on–off keying, differential phase shift keying, polarization multiplexed differential quadrature phase shift keying, polarization multiplexed non differential 8 and 16 quadrature amplitude modulation) have made 100 Gbps transmission beyond a possibility (*5*). However, FEC techniques are complex, power and consuming as they require extra circuits to effectively execute. It should be noted that the complexity of electronic modulator, demodulator and transmitter laser driver circuits is also a practical consideration in the design stage of any communication system. Higher complexity means higher power consumption,

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which is undesired in densely packed optical networks (8–10).

Raman amplification is a key developmental technology to improve the optical fibre network performance with improved OSNR. Other than high distributed gain, Raman systems are compatible with a wideband transmission window (up to 100 nm) and can support different advanced modulation formats. In this work, we experimentally present the first reported integrated cross modulated forward pumped distributed Raman amplifier (DRA) with low-cost, power-efficient vertical cavity surface emitting lasers (VCSELs). In our previous work (9), we demonstrated a low-cost energy efficient technique for maximizing carrier spectral efficiency and extending transmission reach through combined adoption of VCSELs, four-level pulse amplitude modulation (4-PAM), dense wavelength division multiplexing and Raman amplification. Here, we experimentally demonstrate a technique to maximize the network efficiency by adopting an 8.5 Gbps modulated forward Raman pump to simultaneously offer distributed Raman amplification over a VCSEL channel as well as the transfer of data signals.

Distributed Raman amplification propagation equation

DRAs is a vital signal boosting technology in long-haul optical communication networks. DRAs are well known to minimize noise generation and boost signal levels along fibre transmission links reducing system vulnerability to nonlinear effects. DRAs are based on the stimulated Raman scattering phenomenon, which is well known to offer benefits of a broad flat gain in silica fibres, at any wavelength for which the pump frequencies are higher than that of the signal by stokes shift (11). Fundamental modelling and rate equations governing Raman amplification are explicitly shown in Ref. (12). The model described in Ref. (12) only describes optical power propagation in the one-dimensional waveguide and does not factor the effect of dispersion and fibre nonlinearities such as parametric and Kerr effect, which is mainly responsible for self-phase modulation.

The pump p_p and signalp_s power evolution over a longitudinal fibre axis $z$are governed by the following coupled equations (13):

$$\frac{\mathrm{d}p_s}{\mathrm{d}z} = g_R p_p p_s - \alpha_s p_s, \tag{1}$$

and

$$\mp \frac{\mathrm{d}p_p}{\mathrm{d}z} = -\frac{\omega_p}{\omega_s} g_R p_p p_s - \alpha_p p_p. \tag{2}$$

where g_R is the Raman gain coefficient and ω_s and ω_p are the signal and pump angular frequencies, respectively, while α_s and α_p are the signal and the pump attenuations, respectively. The $\mp$ sign represents a backward and forward propagation of the pump wavelengths, respectively.

Equations (1) and (2) imply that the signal is amplified by the pump at a certain proportion, with the constant of proportionality being determined by the Raman gain coefficient (g_R), and losses as a result of attenuations within the optical fibre.

Solving Equation (2), the total pump power $P_P(z)$ at a distance z is obtained as follows:

$$P_P(z) = P_O e^{-\alpha_p z}. \tag{3}$$

Sibstituting Equation (3) to Equation (1), we obtain

$$\frac{dP_s}{dz} = C_R P_O e^{-\alpha_p z} P_s - \alpha_s P_s. \tag{4}$$

Due to pump absorption, the effective amplification length is reduced as follows:

$$L_{eff} = \frac{1 - e^{-\alpha_p L}}{\alpha_p}. \tag{5}$$

Experimental setup

Figure 1 shows the experimental setup used to demonstrate our technique. The single-mode VCSEL used in this work was biased at 5.72 mA giving an output power of −1.25 dB, with a central emission wavelength of 1550.25 nm. This was then modulated directly with an 8.5 Gbps none-return-to-zero (NRZ) electrical signal from a pseudo-random binary sequence (PRBS) of length 2^7-1. The NRZ electrical signal used in this work was generated from the single-ended output of an 8-bit, bit error rate tester (X-BERT) from Luceo Technologies. This X-BERT had an NRZ bitrate operation range of 8.5–11.3 Gbps and a selectable PRBS pattern ability and a maximum input V_{PP} of 1.0 V. The X-BERT used had a reference clock frequency range between 531 and 707 MHz, with a pattern invert ability available for all patterns and an 8B10B encoding for precisely accurate clock recovery and BER computation. The electrical voltage swing was set to 500 $\mathrm{mV_{pp}}$ and fed to a 10 GHz 3-dB bandwidth VCSEL, leading to the generation of an optical signal with approximately −1.89 dBm optical output power.

To realize VCSEL transmission over extended reach network, Raman amplification was adopted. A high-powered Raman laser from JDSU company model number 34-GVT-074 mounted on an LM14S2 universal 14-pin laser diode controller with integrated thermoelectric cooler circuit was used as the Raman pump. The Raman

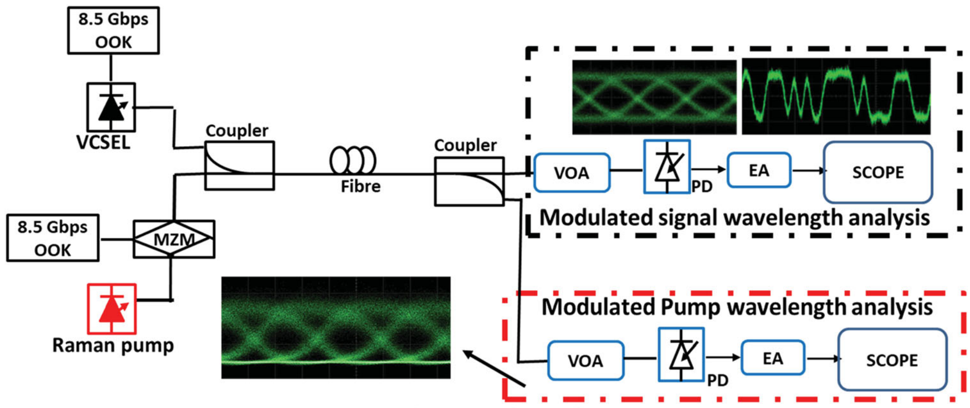

Figure 1. Experimental setup.

pump power was set at 24.72 dBm to induce stimulated Raman scatting within the transmission fibre, therefore resulting in energy transfer from the shorter pump wavelength to longer signal wavelength, thus achieving distributed signal amplification within the transmission fibre link. A high flat gain of over 6.8 dB was achieved experimentally in this work. Two pumping configurations namely forward Raman and backward Raman were investigated in this work. Here, forward pumping is used to imply when the Raman pump is coupled with the transmitted signal from the transmitter end; therefore, the two are allowed to propagate in the same direction, while the backward pumping implies a case where the Raman pump is placed on the receiver end to amplify the signal before its recovery, therefore the signal propagates in a direction opposite to that of the transmitted signal. A WDM 1450/1550 nm optical coupler was used together with a set of polarization controllers to ensure pump to signal interaction by vary the orientation of signal and pump polarization states to ensure best coupling into the fibre. A 50.7 km of TrueWave Reach fibre from OFS Furukawa company was used in this work (*11*, *14*). TrueWave Reach optical fibre provides maximum performance for optically amplified systems over longer distances with higher capacity. This fibre meets both the ITU-T G. 655 C and E and G. 656 standards. Optimized for Raman amplification, the fibre minimizes the need for complex dispersion management and additional amplification (*15*). A WDM 1450 /1550 nm optical coupler was used to de-multiplex the pump wavelength from the signal wavelength for simultaneous analysis. A variable optical attenuator was used at the photodiode input to facilitate performance measurements as a function of received signal power. A positive intrinsic negative photodiode with a typical receiver sensitivity of −18 dBm at 8.5 Gbps data rate was used as a photo receiver. The photocurrent was captured in real time by a digital oscilloscope with 20 GHz analogue bandwidth Agilent sampling oscilloscope model number 86100D, with a transition time of 28.2 ps. To verify our concept, the Raman pump was also modulated externally with an 8.5 Gbps data using a Mach Zehnder modulator. It is important to mention that in this study, no forward equalization (FFE) or any correction mechanisms were employed. Correction mechanisms such as the use of FFE at the input electrical signals and equalization mechanism could scale the system to higher data rates and improved performance but was not within the scope of this work.

Results and discussion

For large-scale commercial installation of cost-effective high bandwidth optical fibre networks, low-cost, power and spectral efficient VCSEL technology is a viable approach. This is due to their vast unique features such as low-power consumption, high-speed modulation with low drive currents and wavelength tuneability (*16*–*22*).

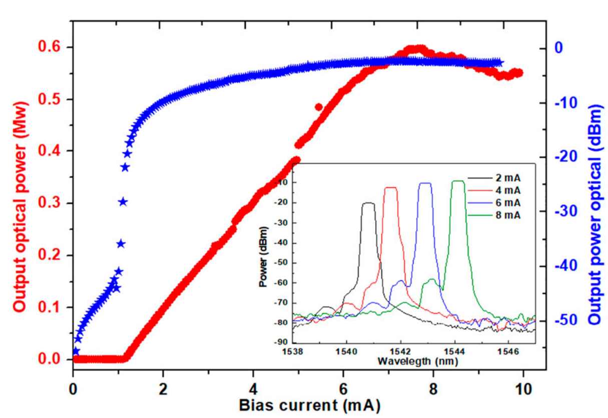

Figure 2. VCSEL static performance. Insert: VCSEL wavelength tuneability.

Figure 2 shows experimentally measured optimization results of the considered VCSEL for direct modulation with the data. These measurements were taken by varying the bias current of the VCSEL carrier from 0.65 to 9.64 mA. As shown in Figure 2, a threshold current of 1.48 mA with a current rollover point of 9.64 mA was attained. The drive current also remained below 10 mA, therefore showing a good energy efficiency of the devise. Energy efficiency is an attractive feature for large-scale deployments of VCSELs, particularly in densely packed optical interconnects. The insert of Figure 2 shows central emission wavelengths of the considered VCSEL channel at different bias currents.

Distributed Raman gain optimization in optical fibre networks is highly dependent on wavelength separation between the pump wavelength and the signal wavelength. The frequency difference between the pump and the signal is referred to as the Stokes shift or the pump signal detuning (*12*). Figure 3 shows experimentally measured pump signal wavelength separation. For the demonstration purpose, a forward Raman pump and a 25 km SMF-Reach fibre were used in these measurements. From Figure 3, a maximum gain is achieved when the pump is detuned 100 nm below the signal wavelength as depicted in Figure 3.

It is important to note that Raman gain spectrum in standard single-mode optical fibres is extremely broad and extends over a wide range of wavelengths (*9*, *23*, *24*). The broad gain is an indicator of the continuum nature of the vibrational states of silica corresponding to different transition states as reported in refs. (*25*, *26*). The Raman on–off gain performance on a VCSEL laser source at different pump powers is shown in Figure 4. On–off gain here refers to the difference between the signal power at the receiver end when the Raman pump laser

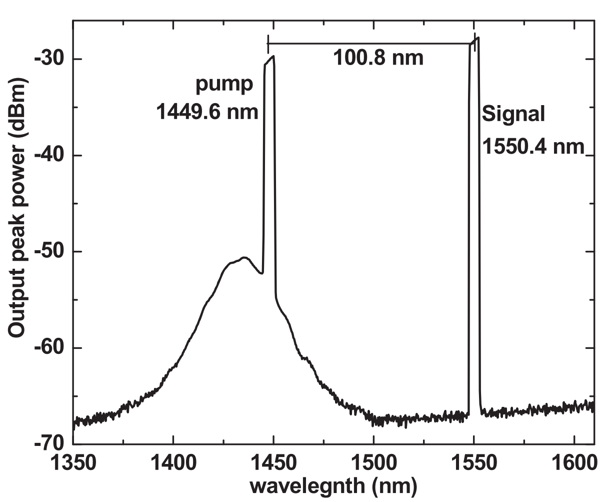

Figure 3. Raman pump signal wavelength detuning.

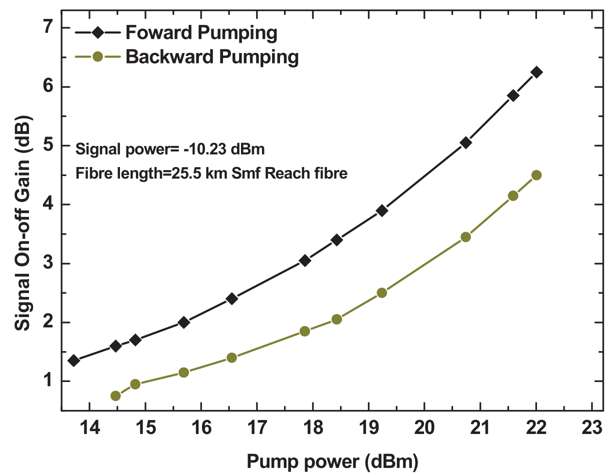

Figure 4. Experimentally measured Raman on–off gain performance with different pump power for forward pump and backward pump configurations.

diode is on and when off. The experimentally measured VCSEL-based Raman on–off gain for forward pumping and backward pumping schemes was attained by exploiting VCSEL tuneability with a change in bias current to attain the 100 nm wavelength detuning from the pump central emission wavelength.

The VCSEL was biased at 3.6 mA, attaining a central emission wavelength of 1549.7 nm. Figure 4 shows experimentally measured Raman gain performance at different pump powers for forward and backward pumping schemes. A signal power of −10 dBm and an SMF-Reach fibre of length 25.5 km were used throughout this measurement. As depicted in Figure 4, Raman gain was noted to increase with an increase in pump power for both pumping schemes. This is because as the pump power is increased, the relative power difference between the pump and the signal also increases, thus the pump transfers more energy to the signal resulting in more Raman gain (*12*, *27*, *28*). From results in Figure 4, forward pumping was noted to have a superior Raman gain performance as opposed to backward pumping. It is true that when a pump wavelength is co-propagated with a signal wavelength, more pump energy is transferred to the weak signal, and thus, higher amplification levels can be achieved due to proper utilization of the pump power (*12*, *29*).

Figure 5 shows Raman on–off gain for 26 and 51 km fibres at forward and backward pumping schemes. From these measurements, it was observed that the Raman on–off gain increased with an increase in fibre length. A maximum gain of 5.4 dB was experimentally realized for a 50.7 km fibre length at 22.1 dBm pump power. An increase in the fibre length means more pump to signal interaction time, which leads to more pump to signal

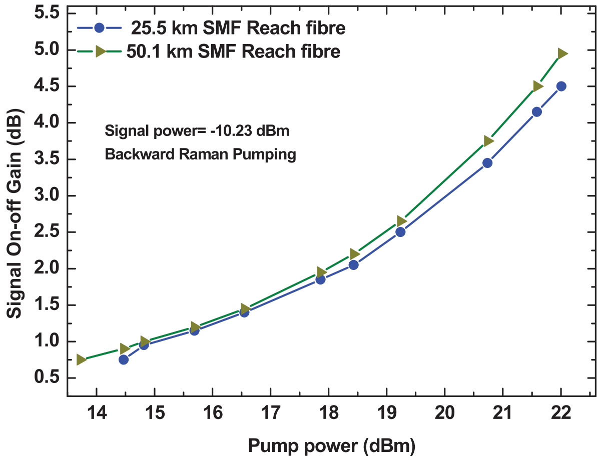

Figure 5. Raman on–off gain for 26 and 51 km fibres at forward and backward pumping schemes.

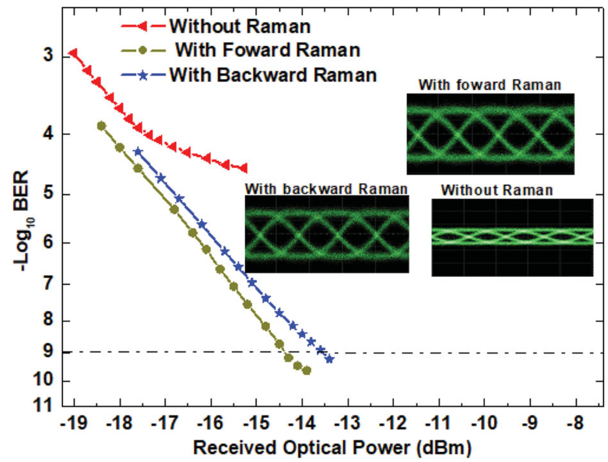

Figure 7. Bit error rate (BER) curve for 8.5 Gbps VCSEL performance at back-to-back (B2B) and 50.7 km Raman-assisted fibre transmission.

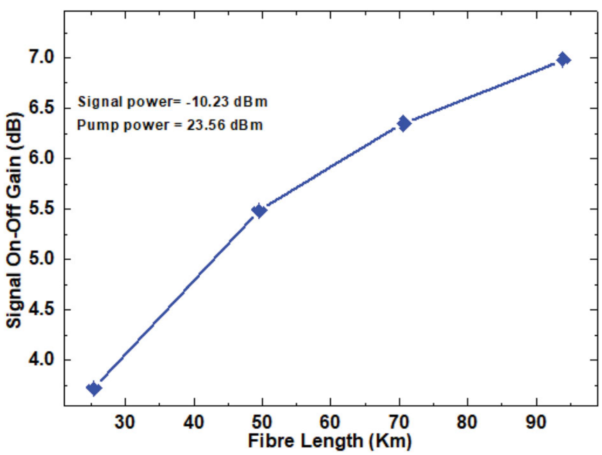

Figure 6. Raman on–off gain for forward pumping at varying fibre lengths.

energy transfer, therefore improving the obtained Raman gain (*25*, *30*). This is clearly shown in Figure 6.

After optimizing for Raman amplification, the transmission performance of the designed network was carried out and analysed for quality of signal through BER measurements and eye diagram analysis. This can be regarded as a network upgrade scenario where the generated high capacity data needed to be transmitted over extended lengths of SMF fibre without necessarily replacing the VCSEL transmitters. Experimentally measured BER curves of the transmission link are shown in Figure 7. The transmission perfomance of the VCSEL channel is accurately measured in real time without Raman pumping and with forward and backward Raman pumping over a 50.7 km fibre link. As shown in Figure 7, an error flow is incurred over a 50.7-km fibre link without Raman amplification, due to low optical power from the VCSEL as well as chirping property of this carrier. However, with the introduction of Raman amplification, a receiver sensitivities of −14.30 and −13.55 dBm were eperimentally measured for forward Raman and backward Raman, respectively. Forward Raman was noted to have a better BER perfomance than backward pumping due to its high Raman on–off gain as discussed in the previous section and shown in Figure 4. It should be noted that all BER measurements in Figure 7 were taken without any FEC, equalization and pre-emphasis mechanisms. Respective eye diagrams are shown in the insert of Figure 7.

After attaining a successful error-free VCSEL-based Raman-assisted transmission over the 50.7-km fibre link, maximizing the network efficiency was experimentally demonstrated. This was attained by modulating the forward Raman pump externally with an 8.5 Gbps data signal. Therefore, the Raman pump was used to simultaneously amplify the VCSEL channel as well as to transfer the modulated data over the transmission link, therefore maximizing the network efficiency. Receiver sensitivities of −14.38, −13.91 and −13.07 dBm were attained for a transmission configuration with unmodulated forward Raman pump, modulated forward Raman pump and modulated backward Raman pump, respectively, as shown in Figure 8. A VCSEL-based Raman-assisted transmission link with a modulated forward Raman pump configuration was noted to have a superior performance opposed to a modulated backward Raman pump configuration. The respective eye diagram as collected by a sampling Agilent oscilloscope is shown in Figure 8. The collected eye diagram results showed that a clearly open eye diagram was achieved in both scenarios, implying a successful error-free operation.

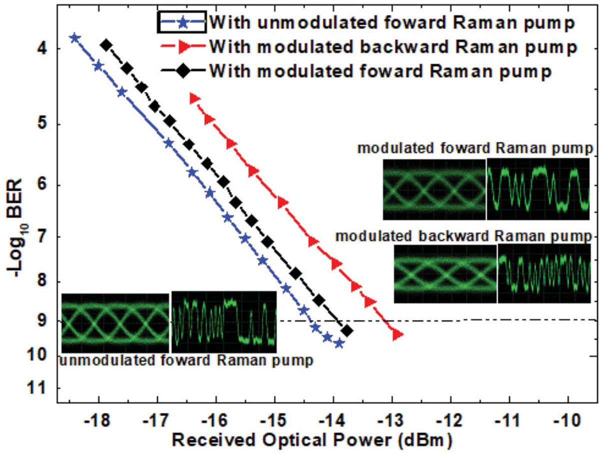

Figure 8. Experimentally measured BER curves for the VCSEL channel with and without modulated forward and backward Raman pumps.

Conclusion

This work has experimentally demonstrated the first reported integrated cross modulated forward pumped DRA with low-cost, power-efficient VCSELs. An 8.5 Gbps directly modulated VCSEL has been shown to achieve successfully error-free Raman-assisted transmission over 50.7 km class G 655 SMF-Reach fibre. VCSEL frequency chirping has been showed to result in error floor over a 50.7 km fibre link. The introduction of an unmodulated forward Raman pump with a gain of 6.9 dB has been shown to attain successfully transmission over a 50.7 km fibre link with penalty of 0.83 dB. Moreover, an 8.5 Gbps modulated forward Raman pump has been reported to suffer course a crosstalk penalty of 0.47 dB on the transmitted data signal. This work proves that a key concept for adoption in high capacity wavelength flexible extended reach optical interconnects.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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