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Regular Articles

A VCSEL-based backbone extended-reach optical fibre network: Supporting up to 10 Gbps flexible access networks for Africa

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ABSTRACT

In this paper, using vertical cavity surface-emitting lasers (VCSELs) and Raman amplification, a low power consuming, energy-efficient and cheap technique to transmit high speed data signals over optical fibre is experimentally demonstrated. Several channels are joined through dense wavelength division multiplexing (DWDM) technique and transmitted over a single fibre link. With a 24.7 dBm forward Raman pump, a 8 dB flat gain is distributed over a spectral width of 5.2 nm (650 GHz). Moreover, different wavelength paths are realized by tuning the emission of the VCSEL from 1546.8 nm to 1552 nm while adjusting its bias currents. In realizing extended-reach, two DWDM/flexible channels spaced at 50 GHz and with each transmitting at 10 Gbps have been transmitted for 76.8 km while incurring a 3.2 dB power penalty as measured at a bit-error-rate (BER) threshold of 10^{-9}. In a typical network, the wavelength adjustment of the VCSEL avoids incidences of denial of service whenever there is either fibre-cuts, increased network traffic or channel collisions. Finally, by combining Raman amplification and chromatic dispersion mitigation using negative dispersion shifted fibres, this work presents robust VCSEL-based technique that is tailored to provide 10 Gbps per channel for backbone optical fibre supporting long-haul access networks in Africa.

1. Introduction

Optical transport network and hardware capabilities have been stretched by the tremendous demand for bandwidth by end-user devices such as bring-your-own-devices (BYODs) and fixed terminal-electronics such as CCTVs, HDTVs, telepresence (TP) units and cell-towers. Several technologies that increase capacity and reach for most backbone optical fibre transport networks have been reported and implemented. These technologies include wavelength/time/polarization division multiplexing (xDM), amplification, advanced modulation formats and coherent detection [1]. Apart from improved capacity and reach, most technological advances have and will focus on cost and energy efficiency so as to minimize the CapEx and OpEx [2]. In terms of infrastructural, geographical, economic and social challenges, optical fibre deployment in Africa becomes a disadvantage as compared to most developed countries across Europe, Asia and America. From the sparse distribution of population to the energy-power shortages in Africa, cost and energy efficient technologies that support the realization of high speed internet and 5G access are needed.

Fibre-to-the-home connections have been rolled out in some African cities such as Harare (Zimbabwe), Cape Town and Johannesburg (South Africa), Kigali (Rwanda), Nairobi and Mombasa (Kenya), Lagos (Nigeria) and other major cities around the continent. In terms of cost, internet access costs 30–40 time more than in most developed countries [3]. An example illustrating the typical geographical and distribution of buildings in the city of Barcelona and the sparse distribution of house/huts in an African village is shown in Fig. 1. In the densely populated and well-planned cities, multiple users can easily be connected using fibre-to-the-home (FTTH). For the African homesteads that spread over 50 km away from the metropolitan region, an integration of both fibre and free-space networks prove to be an ideal topology. With the availability of network access, platforms have revolutionized and enabled e-health, e-governance, e-agriculture, e-education and e-commerce [4,5]. A major example is the Mpesa service and mobile banking in Kenya which despite the huge terrestrial and demographic disadvantages, many people are able to access socio and economic empowerment [6].

Vertical cavity surface-emitting lasers (VCSELs) have proven to be attractive signal carriers due to their low power consumption, low current threshold (in mA range), single longitudinal-mode operation

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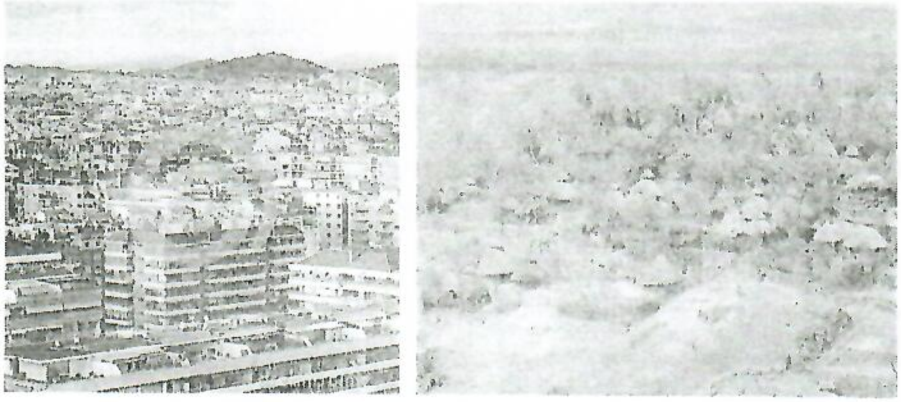

Fig. 1. An illustration of a well-planned modern city in Barcelona and a remote African village.

and low cost [7]. VCSELs for up to 10 Gbps per channel for 850 nm, 1310 nm and 1550 nm transmissions are available. Additionally, VCSELs with the capability of transmitting 40 Gbps and 71 Gbps have also been reported [8,9]. An interesting characteristic of the VCSEL is the ability to tune its emission wavelengths by adjusting the bias currents. The advantage of VCSEL wavelength tuneability makes it ideal for DWDM and wavelength conversion [10].

A backbone fibre deployment to serve long distance multi-users is shown in Fig. 2. In a typical fibre transmission, data or analogue signals are modulated into signal carriers (lasers) and transmitted to either point to point (P2P) or point to multi-point (P2MP) users. In distributing the optical signal, a wavelength selective switch (WSS), hub or an optical splitter can be used to supply the signal to the last mile users.

Signal continuity and having a reliable end to end communication is a real challenge to most transport networks. Flexible spectrum techniques eliminate the rigidity of most fixed network parameters by allowing dynamic adjustments during fibre-cuts, traffic overload, spectrum demands, routing and channel assignment [11]. Subsequently, the fixed channel spacing associated with WDM systems can be replaced by flexible channel spacing which allows sub-and super-channels to be assigned to transmissions [12]. Thus, in a typical network, a self-healing, demand-aware and end-to-end multi bitrate fibre transmissions can be implemented.

In this study, the advantages of wavelength tuneability of a VCSEL and Raman amplification have been implemented to transmit 10 Gbps per DWDM/flexible channel over the standard G.655 fibre-links for 76.8 km. Cascaded G.655 fibres with both positive and negative dispersion coefficients are used to increase transmission distance and reduce the cumulative dispersion effects that lower the quality of the transmitted signal. In this paper, single and multiple DWDM channels at a 50 GHz channel spacing have been experimentally transmitted within the 1550 nm transmission window. The VCSEL emission wavelengths were adjusted from 1547 nm to 1552 nm which also fall within the DWDM and flexible nominal central wavelengths [13]. Above their threshold bias levels, the VCSELs demonstrated a 5 nm (725 GHz) spectrum range which represents approximately 14 DWDM or flexible channels spaced at 50 GHz spacing. The low 3.2 dB transmission penalty for a 76.8 km, makes the low cost and energy effective VCSELs ideal candidates for providing 10 Gbps backbone optical fibre data transport to the end users in Africa and developing continents.

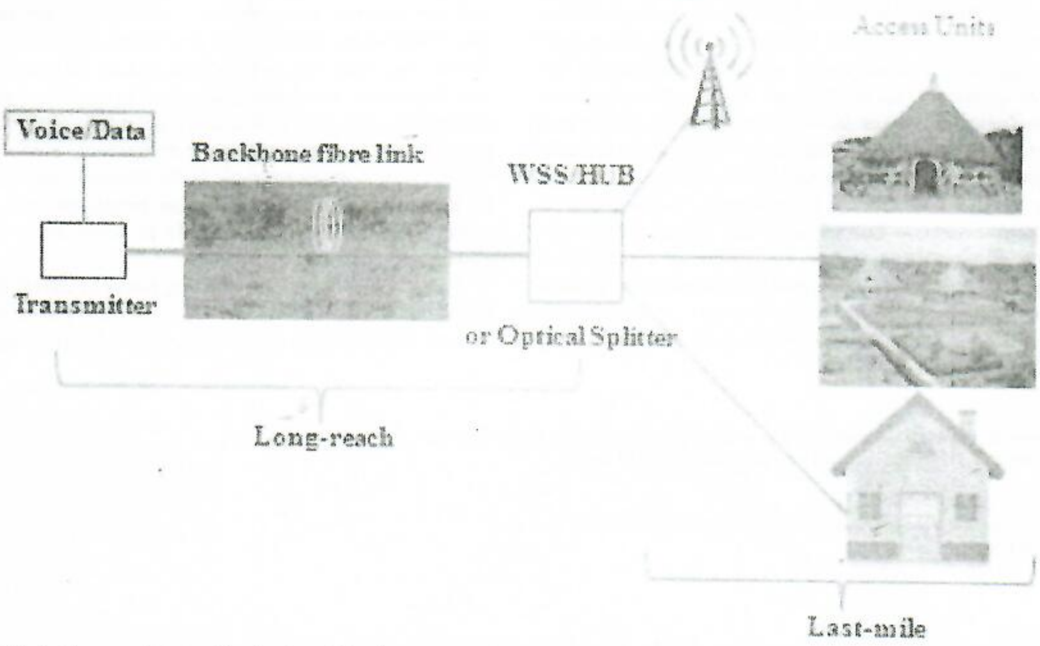

Fig. 2. A schematic illustrating a point to multipoint signal distribution from a data/voice modulated signal transmitter to the last mile access users via a backbone fibre link.

2. Signal impairments

In the transmission medium, the quality of the signal is mainly affected by the linear and nonlinear effects that are cumulative over the length of transmission. These effects are either spontaneous or are stimulated by the high intensity optical signals traversing over the fibre. The most common effects include self-phase modulation (SPM), chromatic dispersion, polarization effects, cross-phase modulation (XPM), four-wave mixing (FWM) and scattering effects such as Raman and Brillouin scattering [14]. The eventual effects on the signal are intersymbol interference (ISI), crosstalk and pulse broadening effects. They are mainly aggravated by operating at high optical powers, uneven channel spacing, high speeds and long distances [15].

To mitigate and compensate chromatic dispersion, different types of fibre with varying dispersion properties at the 1310 nm and 1550 nm transmission windows are used. For 1310 nm signal transmission, the standard G.652 fibre is used while the non-zero dispersion shifted fibre (NZDSF) G.655 fibre is used for 1550 nm transmission. Moreover, negative dispersion fibres are used to reduce the accumulated dispersion properties within the fibre link [16].

3. Experimental setup

An experimental demonstration of a VCSEL-based Raman aided signal transmission over fibre is shown in Fig. 3. This set-up represents a backbone supporting a 10 Gbps per channel transmission for long-reach networks that distribute signals to the last mile users. In demonstrating the flexibility of the signal carrier, the bias currents driving the VCSEL were varied to change the emission wavelengths of the VCSELs to match the nominal central wavelengths of a DWDM/flexible spectrum grid. To fit the DWDM/EDFA/Flexible spectrum channels, 1550 nm VCSELs from Raycan company were used as signal carriers [17].

In the experimental set-up, a pseudorandom binary sequence (PRBS 2^7-1) from a programable pattern generator (PPG) was used to generate digital bits of data and used to modulate VCSEL 1 and VCSEL 2 at 10 Gbps. To ensure that the VCSELs were modulated with different data, VCSEL 1 was modulated with data $\overline{D}$ and VCSEL 2 with D. Decorrelation of the data from the PPG was done by using different lengths of the RF cables which resulted in varying delay times for the electrical signal prior to modulation. The two data carriers were then combined using a 50 GHz wavelength-selective multiplexer while an optical isolator was connected to prevent the backscattered light. The combined channels were then amplified using a forward 1450 nm Raman pump via 1450 nm/1550 nm optical coupler.

To achieve Raman amplification, the 1450 nm Raman pump power was increased to 24.7 dBm to provide the necessary non-linear effect that stimulates Raman scattering (SRS) to facilitate energy transfer from the lower wavelength to the longer wavelengths satisfying the 100 nm (13.2 THz) wavelength shift that is necessary for Raman amplification [18]. The two channels were then transmitted over a total distance of 76.8 km. The 76.8 km length represents the transmission fibre (FUT) while the distribution fibre is considered to be 0 km or of shorter lengths compared to FUT that was added after the HUB/WSS. In signal transmission, three types of G.655 fibre spools from OFS company were used; (i) a 24.7 km TrueWave REACH fibre which is ideal for Raman amplification, (ii) A 26.6 km TrueWave reduced slope (RS) with a 2.8 ps/nm.km dispersion coefficient and (iii) a 25.5 km TrueWave submarine reduced slope (SRS) with a −2.8 ps/nm.km [19–21]. Combining TrueWave RS and SRS fibres not only extends the reach but also mitigates chromatic dispersion effects that cause received error-bits. To separate the main 1550 nm channels from the 1450 nm Raman pump, a 1450/1550 nm filter-based optical coupler was used. Subsequently, a 50 GHz demultiplexer was used to separate the two DWDM/flexible channels.

To investigate the quality of the received signal at the access site, a variable optical attenuator (VOA) was used to vary the optical power received by the positive intrinsic photodiode (PIN) for optical-to-electrical conversion. The sensitivity of the PIN photodiode that was used was −18 ± 1 dBm. The variation of the optical power was done to represent the typical link losses that result due to connectors, insertion losses or fibre losses. After optical to electrical conversion of the signal, an electrical amplifier (EA) was used to amplify the electrical signal carrying data to the operational power requirements of the bit error-rate tester (BERT). The quality of the signal (QoS) and quality of transmission (QoT) was evaluated using bit error rates (BER) measurement at the acceptable 10^{-9} threshold. The received bits were compared with the original bits from the PRBS that were modulated into the VCSELs.

4. Results and discussion

The ability to change the emission wavelengths of a VCSEL by adjusting the bias current using a laser diode controller (LDC) is shown in Fig. 4. Adjusting the bias current from 0 to 10 mA not only changes the emission wavelengths but also varies the optical output power of the VCSEL. It was found that the threshold current of the VCSEL was found to be 1 mA. Above this threshold bias level, the VCSEL operated at the linear region which is optimum for modulation with data since the best extinction ratio can be achieved. Increasing the bias current from 3 mA to 9.8 mA enabled the VCSEL emission wavelengths to be varied from 1547 to 1552 nm thus providing a 5.4 nm (675 GHz) spectrum width. The maximum optical output power of the VCSEL was measured to be 0.75 mW (−1.3 dBm) obtained at 8.3 mA bias current. The maximum bias current was restricted to 9.8 mA to prevent damaging the laser.

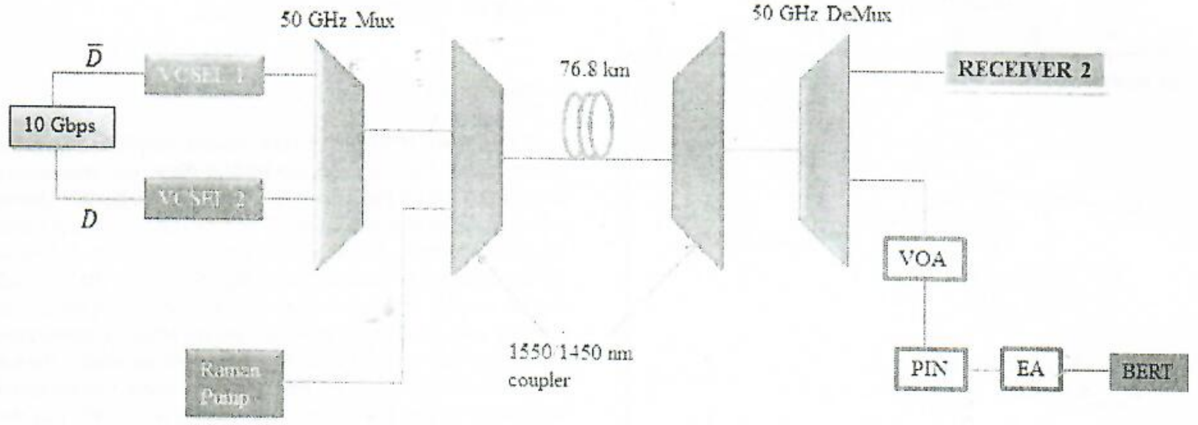

Fig. 3. An experimental demonstration of backbone 10 Gbps per channel VCSEL-based 76.8 km long-reach.

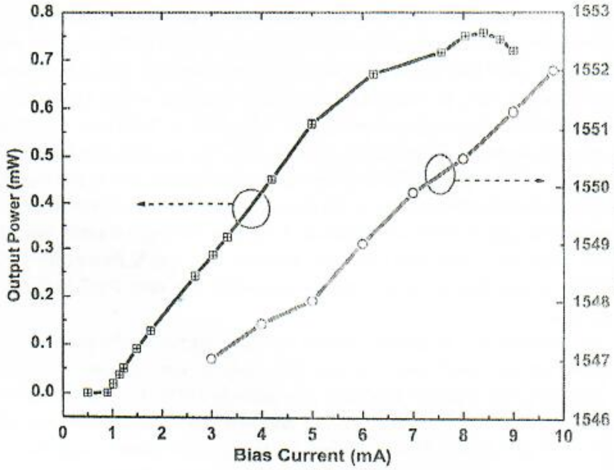

Fig. 4. Wavelength tuneability and output power as a result of change in bias currents.

To match the nominal central wavelengths of the DWDM and flexible spectrum with 50 GHz channel spacing and operating the VCSEL above threshold level, a 1546.82 nm to 1552.02 nm wavelength range which represented 5.2 nm (650 GHz) spectral width was obtained. Moreover, for a 50 GHz spacing, 13 channels can all be multiplexed into a single optical fibre therefore increasing its capacity.

To increase the output power of the VCSEL and to maintain the quality of the signal, forward Raman amplification was done as described in Section 3. Through stimulated Raman scattering because of the 24.7 dBm Raman pump, a flat gain of 8.0 dB was obtained for over 5 nm spectral width within the 1550 nm transmission window as shown in Fig. 5. In this setup, the REACH fibre provided a medium for optimum Raman gain. Therefore, with a single Raman pump, a distributed flat gain of 8 dB can be used to amplify multiple channels which reduces the need to use individual amplifiers for each channel. Thus, the cost to implement VCSEL transmissions for long-reach access networks is relatively reduced.

With each channel carrying data signals at 10 Gbps, the two VCSELs were biased to emit at 1550.02 and 1550.41 nm respectively and then multiplexed into the 76.8 km fibre. The two wavelengths were randomly selected to fit the nominal central wavelengths of the DWDM/flexible grid system and with channel outputs of the available multiplexers with a 0.4 nm or 50 GHz spacing. A demultiplexer was used to selectively route the desired wavelength for evaluation. It was necessary to evaluate the QoT and QoS before distribution to the end-users at the last mile access terminal. Therefore, the BER analysis for 1550.41 nm was done as shown in Fig. 6(a). Since a 1450 nm Raman pump was used, the VCSEL was therefore biased at 7 mA producing a 1550.41 nm signal. As a result, the 100 nm wavelength difference between the data signal and pump as required for SRS and Raman amplification was satisfied [18].

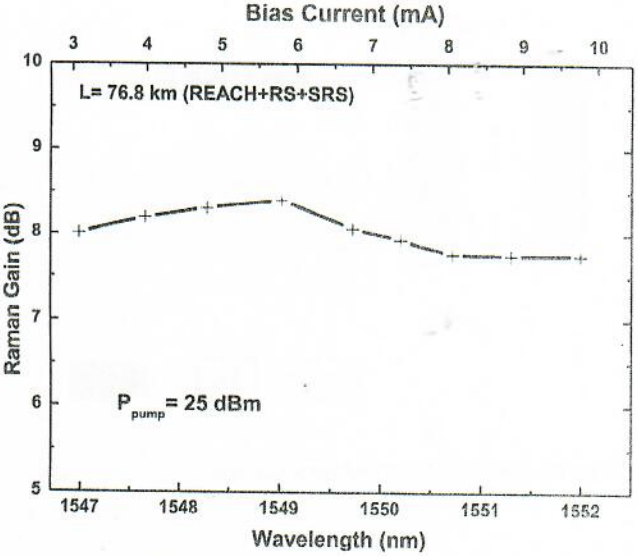

Fig. 5. A distributed flat gain of 8 dB over a 5 nm spectral width as a result of a single forward Raman pump.

The error-free receiver sensitivity at the 10^{-9} BER threshold of the PIN of the original data without transmission (B2B) as shown in Fig. 6(a) was measured to be -18.2 dBm. After transmitting the two 10 Gbps signals for 76.8 km, the receiver attained an error-floor implying that for the unamplified transmission, the receiver was unable to distinguish between the received "1" and "0" bits. As a result, many error-bits were received instead of the original transmitted data bits. The main cause of the errors was chromatic dispersion that resulted in bits overlapping at low optical powers which led to ISI. By biasing the data signal at different bias levels of 3 mA, 7 mA and 9 mA, the BER performance is as shown in Fig. 6(b). Biasing the 3 mA resulted in high received error-bits due to low modulation index (MI) and lower lasing levels. The low MI resulted to higher dispersion effects for longer signal transmission. A 5.7 dB penalty was therefore incurred. Laser chirping of the VCSEL at a higher bias level of 9 mA resulted in reduced receiver sensitivity than a 7 mA bias.

By amplifying the two channels with forward Raman amplification and obtaining a 8 dB flat gain, the receiver sensitivity was increased to -15.0 dBm. The high optical gain increased the power of the two channels thus enabling them to be transmitted for long distances and minimising the effects of crosstalk and ISI. Additionally, the inclusion of the SRS fibre after a combination of REACH and RS fibres, mitigated the effects of chromatic dispersion. The negative dispersion properties in the SRS fibre reduced the cumulative dispersion effects over the entire fibre link thereby reducing the errors due to chromatic dispersion. From the -18.2 dBm B2B receiver sensitivity to the -15.0 dBm error-free sensitivity after 76.8 km transmission and using the 10^{-9} BER threshold, a 3.2 dB penalty was incurred for the Raman-aided and dispersion-mitigated transmission link. The 3.2 dB receiver power penalty was due to the high-speed data signals interfering because of the dispersion and crosstalk effects in the fibre. This power penalty can be reduced by using a more sensitive photodiode such as the Avalanche photodiode (APD) whose sensitivity is ~ -28 dBm and which is most suitable for long distance transmissions.

5. Conclusion

By utilising 1550 nm VCSELs, Raman amplification and mitigation of chromatic dispersion in the optical fibre, we have successfully demonstrated a 8 dB flat gain amplifying DWDM/flexible channels within a 5.2 nm spectral width from 1546.8 to 1552 nm being transmitted for 76.8 km. Multiple channels have successfully been multiplexed with a 50 GHz spacing to increase fibre capacity. From the successful experimental outputs of using Raman-aided VCSELs to transmit 10 Gbps signals for over 76.8 km, a cost and power effective transmitter-receiver can be implemented for long distance access networks. The flexibility of path assignment has been demonstrated using wavelength/frequency tuneability of the VCSEL emission wavelengths. While at the distribution hub, a wavelength selective demultiplexer was used to route the incoming signal to the designated terminal. In implementing this system, this paper recommends more sensitive APD receivers to enable reception of low power signals due to high splitting ratios at the hub. Finally, the low power penalty scheme provides an effective VCSEL-based backbone optical fibre deployment that is suitable for distributing signals to the last mile in the African homes and digital villages.

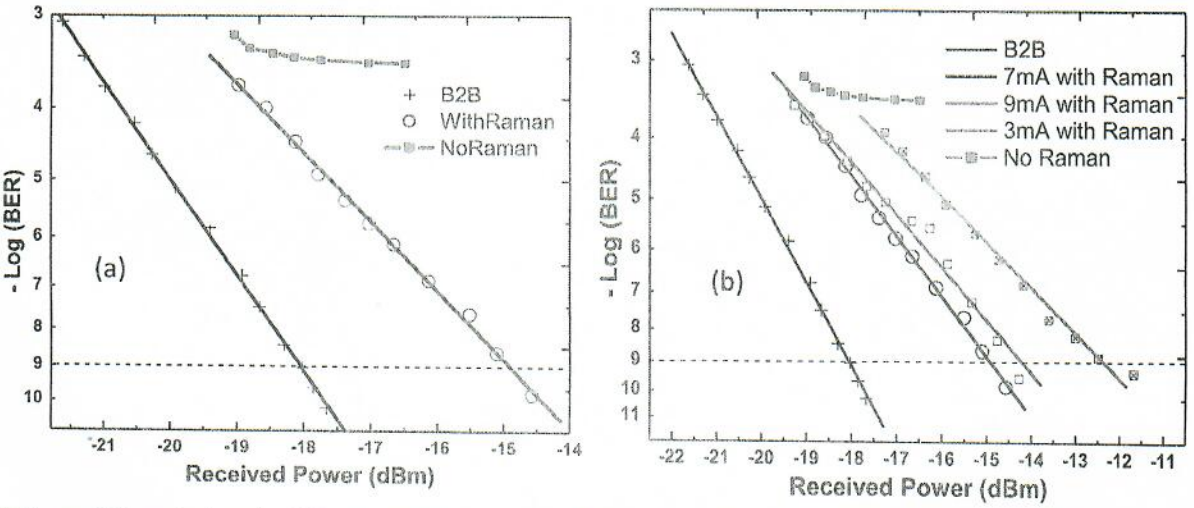

Fig. 6. Receiver sensitivity evaluation using BER measurements of a backbone 10 Gbps per channel DWDM/flexible transmission over 76.8 km with and without Raman amplification for (a) data signal biased at 7 mA, (b) data signal biased at 3 mA, 7 mA and 9 mA.

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