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WDM transmission with in-line amplification at 1.3μm using a Bi-doped fibre amplifier

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***Abstract*—Extension in the reach of 1.3μm optical communication systems has traditionally been restricted by the availability of suitable low-noise fibre amplifiers. Addressing this challenge, we present the first repeatered wavelength division multiplexing (WDM) experiments using a bismuth-doped fibre amplifier (BDFA) that exhibits 8.4THz (50nm) of gain bandwidth in the O-band. WDM signals arranged either with coarse or dense wavelength spacings are transmitted over lengths of SMF-28e ranging between 100km and 140km.**

***Index Terms*—bismuth-doped fibre amplifier, O-band, optical fibre transmission, wavelength division multiplexing.**

I. Introduction

Wavelength division multiplexing (WDM) has enabled massive utilisation of the fibre bandwidth in optical fibre transmission systems. Today, it is routinely deployed in the C-band (1530-1565nm) and has facilitated the rapid growth of global data traffic. However, as the growth in demand for communication traffic shows no signs of reaching saturation, current transmission systems are gradually being driven towards their capacity limits. The different routes towards increasing transmission capacity have been heavily debated in recent years. A well-documented but somewhat radical approach, relies on adopting spatial division multiplexing and upgrading the whole transmission fibre infrastructure with the corresponding multi-core/multi-mode technology [1]. A related, but more modest implementation of the same relies on exploiting dense fibre bundles and parallelising communication routes in this manner. These approaches however, are quite costly since they rely on installing a wholly new fibre infrastructure. Perhaps a more sustainable solution is to extend the scope of WDM and to enable its use in other wavelength regions before deploying new physical routes. This option relies upon the availability of low noise optical amplifiers operating outside of the conventional C and L bands. The wide transmission bandwidth offered by modern optical fibres, i.e. the SMF-28 family, is capable of transmitting data at wavelengths between 1200nm and 1650nm, where the average signal attenuation is less than about 0.3dB/km [2]. However, within this whole spectral region, only certain wavelength bands have their own effective optical amplifiers, suitable for low noise, low nonlinearity, and high gain amplification, as required for WDM transmission.

A spectral region with a notable lack of low noise fibre amplifiers is the O-band (1260-1360nm), which lies about the zero dispersion wavelength of standard silica single-mode fibres. Amplification in this band is desirable due to its popularity in short-haul networks. The availability of a suitable fibre amplifier would not only enable the extension of reach of such systems, but also facilitate the deployment of dense wavelength division multiplexing (DWDM). Most commercial amplifiers available in the O-band region are semiconductor optical amplifiers (SOAs) [3]. However, SOAs are not generally suitable for use in transmission because of their high noise figure (NF), fast dynamics, polarisation sensitivity, and nonlinearity [3,4]. Also, cross gain modulation and four-wave mixing (FWM) frequently occur when using SOAs in multi-channel systems [4,5].

Early development of 1.3μm fibre amplifiers relied on doping fluoride glass hosts with either praseodymium or neodymium [6,7]. However, fluoride glasses are costly, fragile, and offer limited chemical stability [8,9]. More recently, bismuth (Bi) has emerged as a promising dopant for fibre amplifiers. Depending on the core composition (silica, aluminosilicate, phosphosilicate, germanosilicate, and others), construction, and pumping wavelength(s), BDFAs can be used to offer gain across a wide range of spectral regions from 1150nm to 1800nm [10-15]. Recently, Melkumov et al. demonstrated E-band transmission using a Bi-doped germanosilicate fibre amplifier to amplify a 10.6Gbit/s on-off keying (OOK) signal at 1440nm after transmission over an 80-km length of non-zero dispersion shifted fibre [16].

In this paper, we present the first demonstration of WDM O-band transmission using the BDFA presented in [17] as an in-line amplifier. This amplifier uses a Bi-doped phosphosilicate fibre to provide flat gain around 1346nm with a 5-dB bandwidth of 50nm (~8.4THz). Extending on the work we presented in [18], we demonstrate coarse-WDM (CDWM) transmission of six and four 9.953Gbit/s OOK channels over 100km and 120km of SMF-28e, respectively, as well as transmission with a dense

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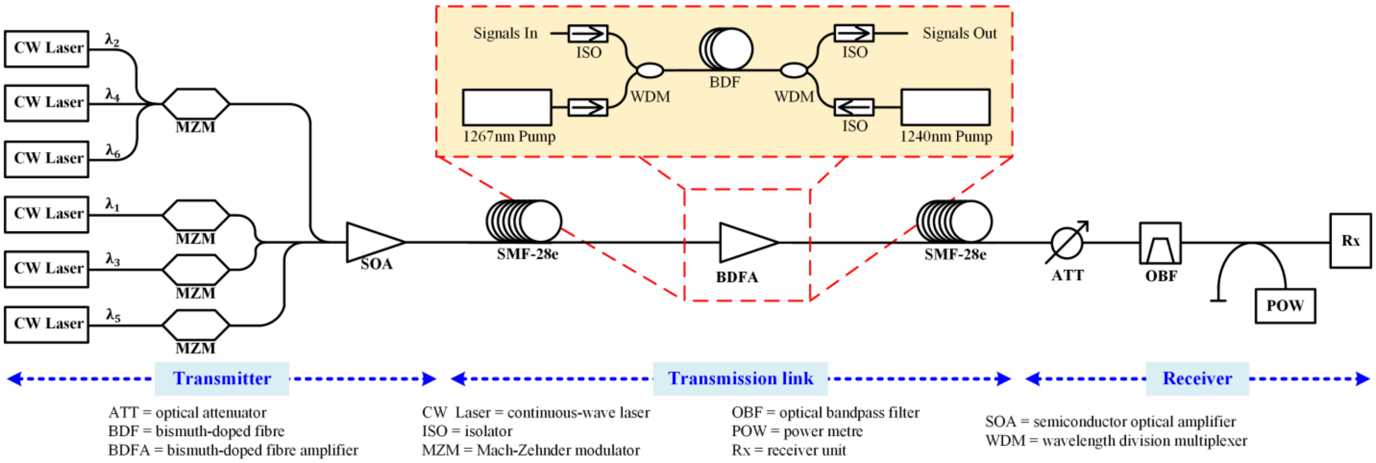

Fig. 1. Experimental set-up of the transmission link and a schematic diagram of the BDFA (inset).

spacing (which we denote DWDM hereafter) of three channels (spaced by 100 GHz) and two channels (spaced by 200 GHz), each carrying 9.953Gbit/s OOK signals over 120km and 140km of SMF-28e, respectively. Negligible power penalties are demonstrated for all signals in both cases, showing the potential of this amplifier to enable long-reach transmission throughout the zero dispersion region of silica glass fibres.

II. Experimental Set-up

In order to experiment on O-band WDM transmission with in-line amplification, we built a six-channel transmission testbed, as shown in Fig. 1. The testbed used six wavelength sources, four of which (λ_2, λ_3, λ_4, λ_6) were distributed feedback (DFB) lasers, and two (λ_1, λ_5) were tunable external cavity lasers. This allowed us to experiment with either a CWDM configuration of up to six wavelengths λ_1 = 1321nm, λ_2 = 1331nm, λ_3 = 1341nm, λ_4 = 1351nm, λ_5 = 1361nm, and λ_6 = 1371nm, or a DWDM configuration of up to three wavelengths spaced by 100GHz (λ_1 = 1342.4nm, λ_3 = 1343nm and λ_6 = 1343.6nm). Note that the 50-nm span of the widest CWDM case we experimented with corresponds to a bandwidth of 8.4THz, i.e. 87% broader than the bandwidth of the C-band.

A. Transmitter

In both the CWDM case and the DWDM case, λ_1, λ_3, and λ_5 were modulated in separate modulators before being combined, whilst λ_2, λ_4 and λ_6 were first combined before being modulated, as shown in Fig. 1. As a result, after multiplexing the various wavelengths, no two neighbouring signals carried the same data. In all cases, the lasers were modulated to carry 9.953Gbit/s OOK 2^{31}-1 pseudorandom bit sequences. After multiplexing, the signals were amplified using an SOA to provide sufficient transmission power.

The O-band SOA was a commercial device (Thorlabs BOA1036S) consisting of an InP/InGaAsP Quantum Well layer structure. Its gain spectrum is shown in Fig. 2. Its maximum total output power after adjusting the powers and states of polarisation of all laser sources (to ensure the powers of all channels were identical at the output of the SOA), was approximately 10dBm (in both the CWDM and DWDM cases).

It is noted that the SOA exhibited a strong polarisation dependent gain – its polarisation extinction ratio (PER) was about 16dB – thus preventing us from using it at any other point than just after the transmitter, where we could ensure that the states of polarisation of the different wavelength channels were aligned relative to one another.

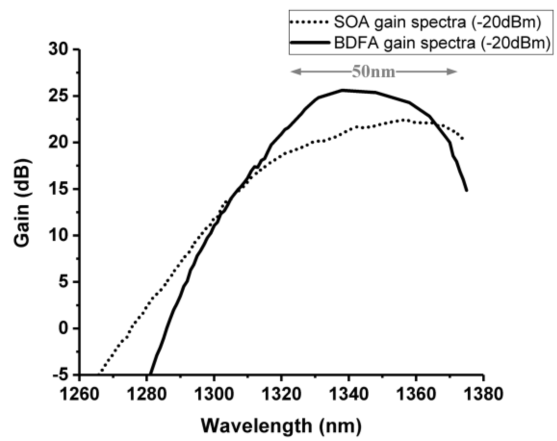

Fig. 2. Gain spectra of the BDFA and SOA for an input power of -20dBm.

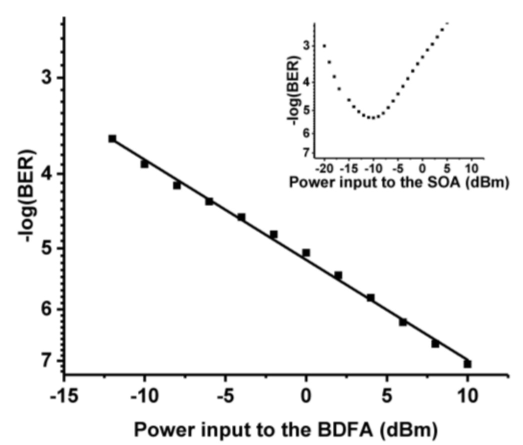

Fig. 3. Nonlinearity measurement of the BDFA and SOA (inset).

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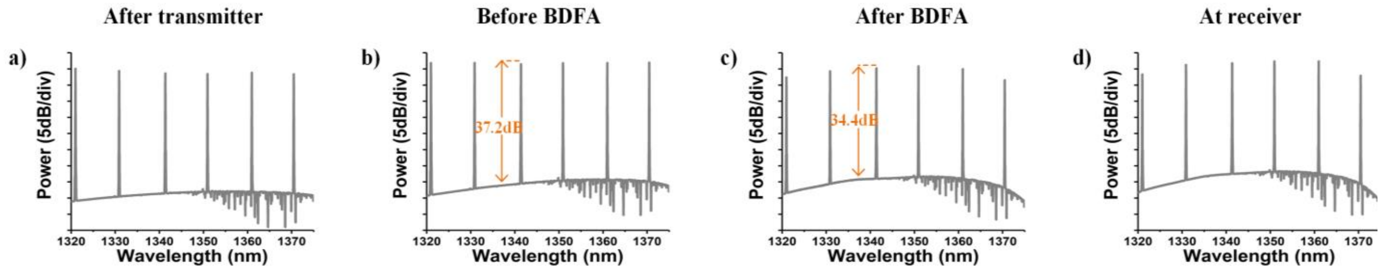

Fig. 4. Optical spectra measured at various positions of a 100-km transmission system for an experiment considering six channels at coarse spacing.

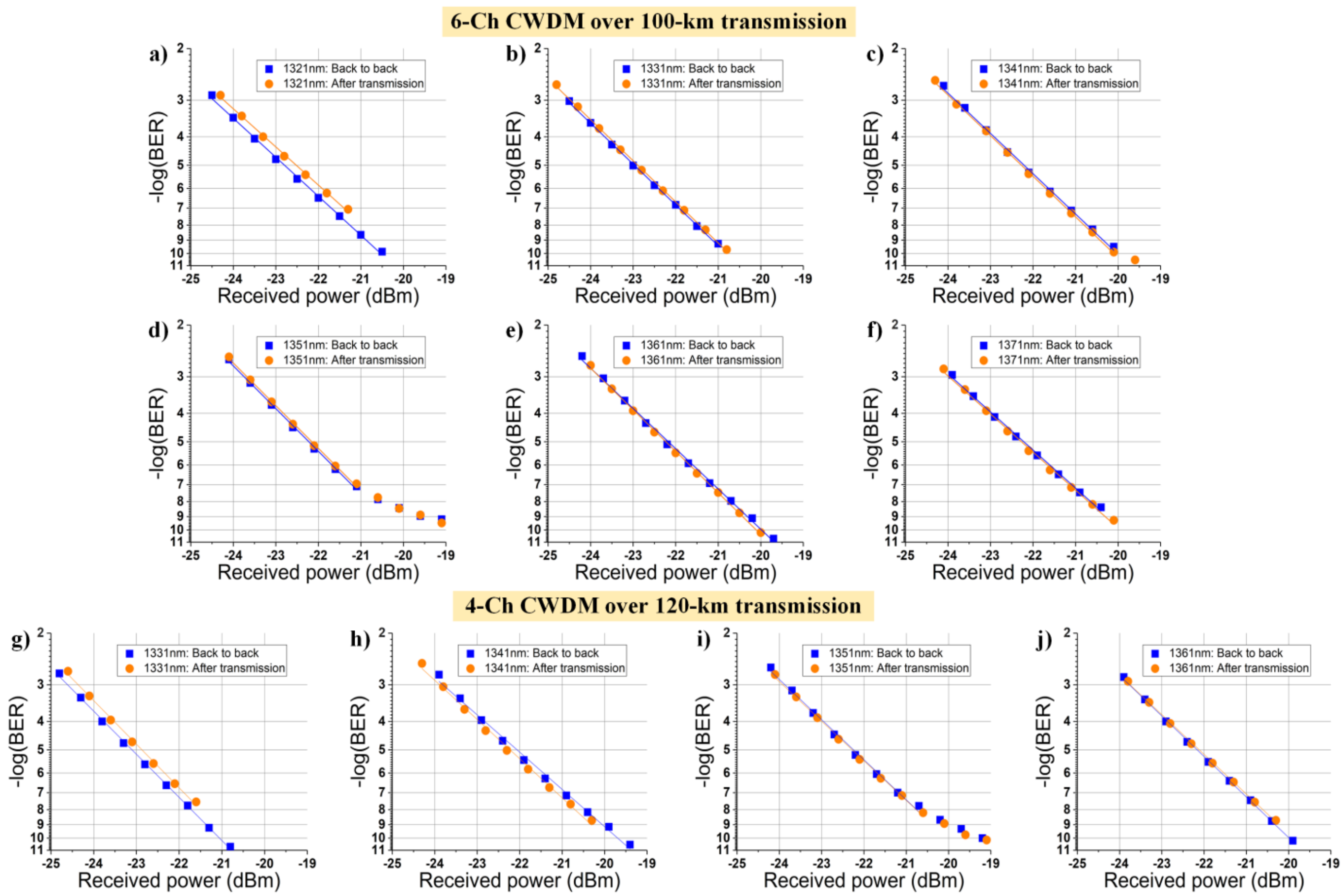

Fig. 5. BER curves of a)-f) 6-channel CWDM case and g)-j) 4-channel CWDM case.

B. O-band in-line amplification

After boosting the signal power in the SOA, the signals were launched into the transmission fibre. We experimented with various lengths of SMF-28e, with an average loss of 0.34dB/km at our wavelengths of interest. All our experiments involved two spans of fibre, with the BDFA employed in the middle to compensate for the link loss. A schematic diagram of the BDFA is shown as an inset within Fig. 1. It consisted of 150m of a phosphosilicate Bi-doped fibre pumped bidirectionally at two different wavelengths, 1267nm and 1240nm, with a total pump power of 720mW. The pumps were multiplexed and demultiplexed with the signal using WDM multiplexers to reduce coupling losses. Use of the two pump wavelengths ensured that the gain bandwidth was broadened to cover the full 50-nm region between 1321nm and 1371nm. Fig. 2 shows the gain profile of the BDFA in comparison to that of the booster SOA. The saturated output power of the BDFA was ~16dBm and its noise figure was approximately 4.5dB across the bandwidth we utilised [17]. A discussion of the gain characteristics of the BDFA can be found in [17]. Here, we additionally characterized the performance of the BDFA as a function of the input signal power. We deactivated all signals other than the one lying at 1341nm, launched it into the BDFA and measured the BER of the signal at the output of the BDFA after filtering with the optical bandpass filter. BERs were taken for a range of launch powers into the BDFA, from -15dBm to 10dBm.The result is presented in Fig. 3 and confirms that the BER improves monotonically as the input power and hence the power into the photodetector increases. This is to be contrasted to the performance of SOAs (see inset to Fig. 3), which strongly distort the signal at high input powers due to patterning effects [19,20]. (It is noted that due to the polarization sensitivity of the SOA used in our measurements, the plots of the BDFA and

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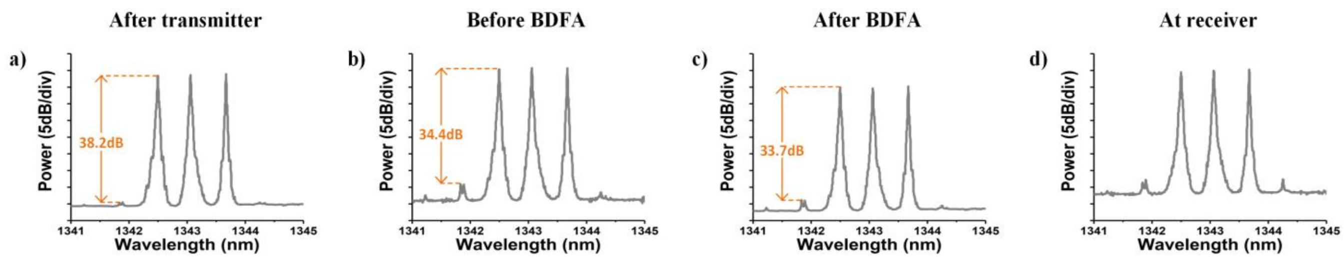

Fig. 6. Optical spectra measured at various positions of a 120-km transmission system for an experiment considering three channels at dense spacing.

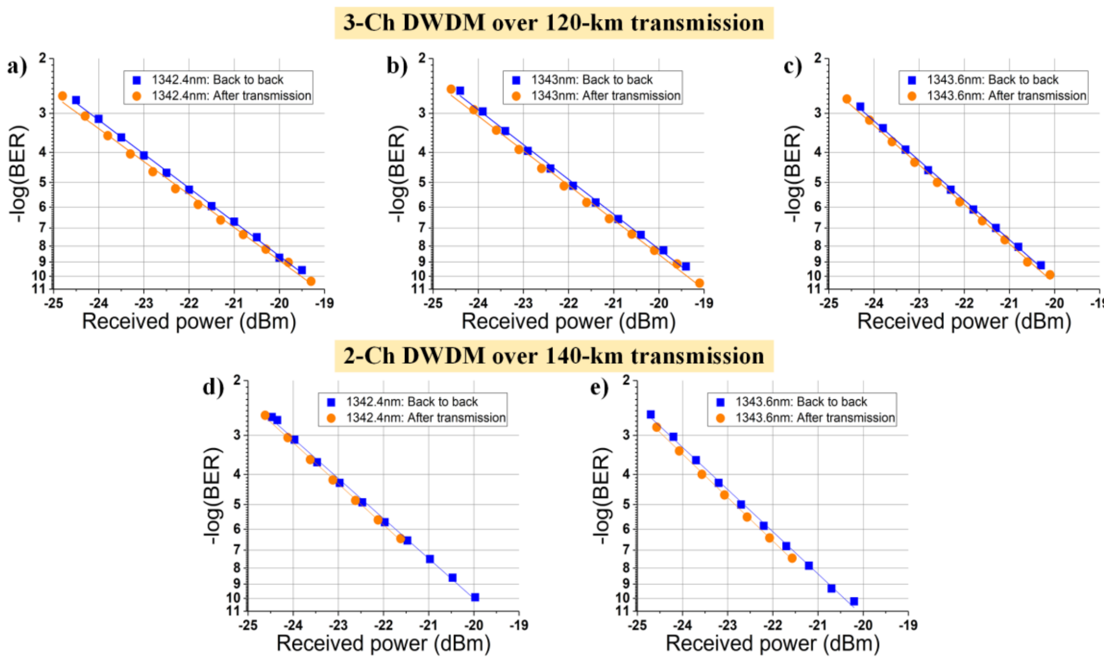

Fig. 7. BER curves of a)-c) 3-channel DWDM case and d)-e) 2-channel DWDM case.

SOA shown in Fig. 3 are not directly comparable to one another.)

C. Receiver

After the second span of transmission fibre, one of the WDM signals was selected using an optical bandpass filter (OBF) with a 20dB bandwidth of 1.25nm, before being detected using a clock and data recovery receiver, and passed to the bit-error ratio (BER) tester. Therefore, our BER measurements are provided relative to received optical power, which was controlled through attenuation of the signal before the photodetector.

III. Results

In all cases we studied, the BDFA provided a gain of ~25dB. The received power limited the useable span length. In addition, the transmitted power was constrained by the SOA performance, which effectively determined the number of channels we could use. In this section, we will divide the discussion into two scenarios – CWDM (large spacing) and DWDM (small spacing). Starting from the six-channel CWDM case, which had the lowest power per channel, we experimented with gradually reduced channel counts, and correspondingly increased transmission lengths.

A. Coarse Wavelength Division Multiplexing (CWDM)

For the 6-channel CWDM case (Fig. 4), the span length was limited to 50km (~17dB span loss), i.e. a transmission distance of 100km in total. By comparing Fig. 4.b) and Fig. 4.c), it can be seen that the OSNR degradation of each signal after in-line amplification was approximately 2.8dB. Fig. 5.a) to .f) provide BER plots of the six channels. The plots obtained after transmission (orange circles) are compared to those taken immediately after the transmitter (blue squares). All signals show negligible change in receiver sensitivity after amplification. Note that the results for λ_4=1351nm (Fig. 5.d), contain a noise floor in both the back-to-back and post-transmission cases due to excessive noise on this carrier at the transmitter.

By deactivating the signals at λ_1 and λ_6, the number of channels was reduced to four in total. Consequently, due to the increased power per channel in the link, we were able to extend the span length to 60km (~20.4dB span loss), 120km in total. BER curves for this case are presented in Fig. 5.g) to j). Similar performance as in the six-channel case was observed. (Note again the error floor observed at 1351nm that was due to the transmitter itself).

B. Dense Wavelength Division Multiplexing (DWDM)

We next used the two tunable sources (λ_1 and λ_5) combined with λ_3 to experiment on a dense wavelength grid (100-GHz spacing). The signals were transmitted over 120km. Figure 6.a) shows a spectral trace of the three DWDM signals at the transmitter output; it is interesting to note some weak FWM components that were generated after amplification in the SOA. A comparison between the spectra presented in Fig. 6.a) and Fig. 6.b) reveals that transmission along the fibre enhanced the FWM due to the Kerr effect. A small (but negligible) further enhancement of the four-wave mixing (FWM) products (of ~0.7dB) was observed after in-line amplification in the BDFA (Fig. 6.c)). BER measurements for the three channels in this transmission experiment are presented in Fig. 7.a) to c) and confirm there was no power penalty due to the transmission and that the FWM did not affect the transmission performance. It is noted that no FWM was observed in the CDWM case, owing to the broad spacing between the optical carriers.

Finally, by further removing one channel (λ_3), we were able to extend the reach to 70km per span, resulting in 140km transmission in total. BER measurements for this case are summarised in Fig. 7.d) and e). Note that due to the extra loss induced by the additional fibre length, the maximum optical power at the receiver was -21.5dBm. This prevented us from carrying out a full power scan in our BER measurements, however as in the previous cases, the trend indicates no performance degradation in the transmitted signal.

IV. CONCLUSION

We carried out a series of WDM transmission experiments in the O-band, enabled through the use of a bismuth-doped fibre amplifier delivering ~25dB of gain. The amplifier offered gain across a 50-nm spectral region (8.4THz), which is approximately 87% broader than the bandwidth of the whole C-band. The experimental results also show that the amplifier performs linearly over input powers of at least up to 10dBm. We demonstrated transmission of six and four 9.953Gbit/s OOK CWDM channels over 100km and 120km of SMF-28e, respectively. Furthermore, we also demonstrated the transmission of three and two 9.953Gbit/s OOK DWDM channels over 120km and 140km, respectively. All results confirmed negligible sensitivity penalty, whereas the main limitation in transmission reach was imposed by the available power at the receiver. We anticipate that the use of an additional BDFA as either an in-line amplifier and/or a pre-amplified receiver will facilitate an extended transmission reach.

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