Experimental comparison of E-band Raman amplifier and BDFA performance over 50 km SSMF using 30-Gbaud DP-16-QAM

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Abstract *We report a direct comparison of three different E-band amplifiers: a distributed Raman amplifier, a discrete Raman amplifier, and a bismuth-doped fibre amplifier. Comparison is made in terms of gain, NF, and BER performance over 50 km of G.652.D fibre.*

Introduction

To tackle the ever-increasing demand for data capacity, ultra-wideband transmission techniques have been identified as an important, alternative, short-to-medium term approach to the long-term solution of space division multiplexing (SDM)[1]–[3]. A key technology requirement to open up the spectrum of the optical fibre, and so make full use of the low loss window, is the optical amplifier for unconventional (non C+L-band) signal band amplification.

There have been several recent demonstrations of optically amplified, E-band coherent data transmission using various amplifiers, including a distributed Raman amplifier (RA)[4], a discrete RA[5], and a bismuth-doped fibre amplifier (BDFA)[6]. However, the transmission conditions (fibre length, channel count) of these experiments were quite different, and so direct comparison of E-band amplifier performance was not possible.

In this paper, therefore, we further explore the performance of these three different optical amplifiers (distributed RA, discrete RA and BDFA) in the E-band, a spectral domain well-removed from the traditionally used C and L bands, and incorporating wavelength regions historically associated with strong transmission impairments, due to the presence of high loss water peaks[1]. Experimental performance of the amplifiers is compared at 1430 nm, 1445 nm, and 1460 nm in terms of gain, noise figure (NF), effective NF, and achieved BER after the transmission of 30-GBaud dual polarisation (DP)-16-QAM through 50 km of G.652.D with no water peak.

Experimental Setup

The setup of the E-band data transmission experiment is presented in Fig. 1. The data carrier signal is generated by a transmitter (Tx) comprised of a tuneable laser (TL) operating from 1430-1460 nm and a DP-IQ modulator driven by a digital-to-analog converter (DAC) to generate a 30-GBaud DP-16-QAM signal. After the modulator, the signal is amplified by an in-house BDFA designed for E- and S-band operation[7], followed by a variable optical attenuator (VOA) to control the input power to the transmission line. In the case of back-to-back (B2B) transmission, the signal is directed to an optical bandpass filter (OBPF), where the data carrier is filtered from the amplified spontaneous emission (ASE). When transmission is performed, the signal is directed into a 50 km-long G652.D fibre and then amplified by one of the three in-line amplifiers under test.

In all B2B and transmission experiments, after filtering by the OBPF, the signal is attenuated to a fixed input power of -20 dBm, and then amplified by a receive BDFA. The receive BDFA is based on doped fibre reported previously[8], and has a similar design to the booster amplifier. The input power to the coherent receiver is controlled by another VOA to 8 dBm. A second TL operating from 1430-1460 nm is used as the local oscillator (LO) for the coherent detection. Channel reception is completed by a standard set of balanced receivers and 80 GSa/s analog-to-digital converters (ADCs), and a digital signal processing (DSP) chain described previously[9].

Tab. 1: Pumping wavelength and power of Discrete and Distributed RAs

Wavelength	Distributed	Discrete
1325 nm	213 mW	261 mW
1345 nm	276 mW	111 mW
1365 nm	148 mW	267 mW

In the distributed RA case, the 50 km-long G.652.D fibre is used simultaneously as a transmission and amplification medium. In total, three pumps are used for amplification with the wavelengths and powers as indicated in Table 1. All

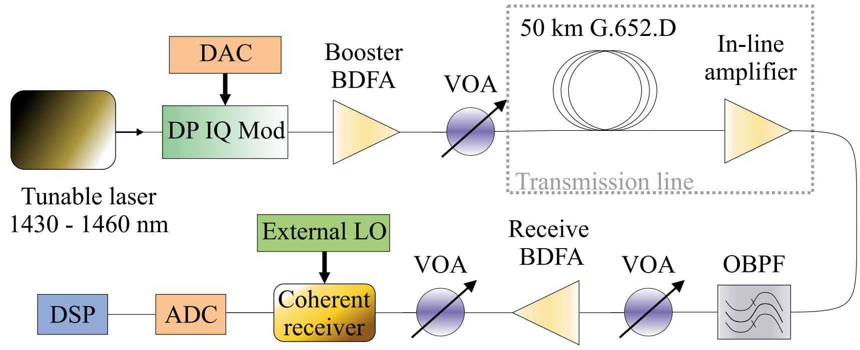

Fig. 1: Experimental setup of the transmission over 50 km-long G.652.D

the pumps are counter-propagated to the signal to minimise the effective NF and nonlinear impairments due to the amplifier. The amplifier pump powers are optimised to achieve flat-top gain. The gain of amplifiers under test is presented in Fig 2,a. The NF and effective NF for 2 dBm launch power are illustrated in Fig. 2,b. The minimum effective NF is -1.9dB and maximum gain is 15 dB at 1430 nm.

The discrete RA comprises of a 7.5 km long, nonlinear, inverse dispersion fibre (IDF) as a gain medium[10], backward-pumped using the same set of diode pump laser wavelengths, with pump powers as indicated in Table 1. The NF of the discrete RA for 2 dBm launch signal power (approximately -12 dBm input power to the discrete RA) is shown in Fig. 2,a. A minimum NF of 6.5dB and maximum gain of 14 dB are achieved at 1430 nm.

The BDFA consists of two signal isolators and two thin-film-filter wavelength-division-multiplexers (TFF-WDMs). The 173-m long active bismuth-doped fibre has a 6 µm core diameter and 125 μm cladding diameter. The refractive index difference (Δn) is around 0.004. The fibre core consists of 95 mol% SiO_2, 5 mol% GeO_2 and $<$0.01 mol% of bismuth. The cutoff wavelength (λ_c) of the fibre is measured to be around 1000 nm. This amplifier design has been described previously[8], but here, we use a single pump laser diode with 460 mW at 1320 nm for backward pumping to maximise the amplifier performance. The NF of the BDFA for 2 dBm launch power (approximately -12 dBm input power) is shown in Fig. 2,a. The amplifier features minimal NF of 6 dB at 1460 nm and maximum gain of 30 dB at 1430 nm. It should be noted that the BDFA used here was designed for compensation of longer fibre spans, thus, its gain is significantly higher than those of the RAs. However, as the input to the receive amplifier is fixed to -20 dBm throughout the experiment, higher gain of the BDFA under test should not impact the comparison.

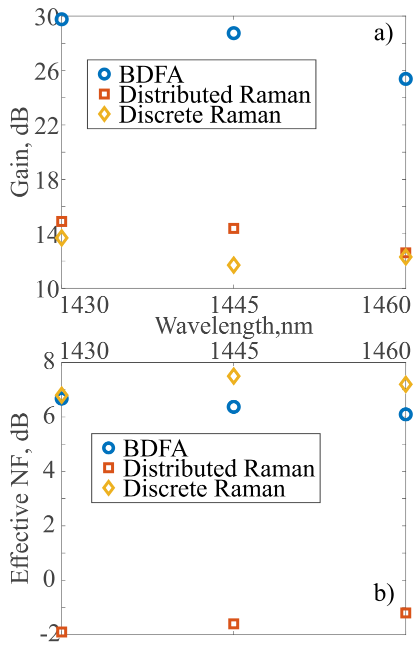

Fig. 2: Gain for amplifiers under test (a); NF for for BDFA, discrete RA and effective NF for distributed RA (b)

Results

The recorded results of the coherent data transmission of 30-GBaud DP-16-QAM are shown in Fig. 3. The wavelength dependence of the bit-to-error rate (BER) of the signal is recorded by tuning the wavelength of the TLs (signal and local oscillator) from 1430 to 1460 nm. The measurement of BER is conducted with each amplifier and at each wavelength for launch powers in the range from -10 dBm to 8 dBm. The input power to the receive amplifier and the receiver remained constant throughout the experiment.

As shown in Fig. 3,a, at 1430 nm, the distributed RA features a minimum BER of around $1.5 \cdot 10^{-4}$ at -4 dBm launch power. The BDFA performance is similar at a launch power of 4 dBm with a BER equal to $1.2 \cdot 10^{-4}$. The BER in linear regime of the distributed RA is lower at shorter wavelength than that of the BDFA. How-

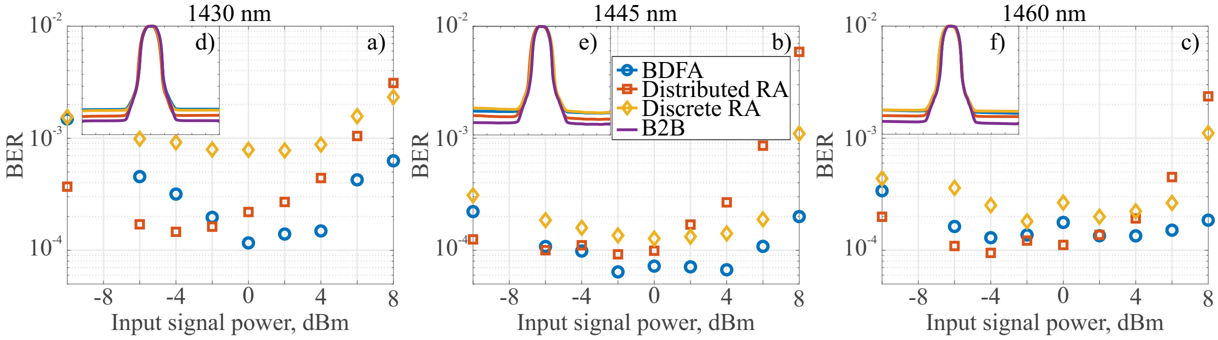

Fig. 3: Comparison of BER for different launch powers for amplifiers under test for (a) 1430 nm, (b) 1445 nm, (c) 1460 nm; The comparison of the signal output spectra for amplifiers under test with input signal spectra for (d) 1430 nm, (e) 1445 nm, (f) 1460 nm.

ever, the rise of BER in nonlinear regimes for distributed RA occurs quicker than in the BDFA case. This is because in distributed RA the signal power remains relatively high in the G.652.D due to parallel amplification inducing higher nonlinearity. The discrete RA operates at higher BER than the aforementioned amplifiers and has the lowest BER of $7.7 \cdot 10^{-4}$ at 2 dBm launch power due to the additional nonlinear impairments in the IDF.

The performance of all three amplifiers is best at 1445 nm. The relative performance of the amplifiers is similar to that at 1430 nm, however, the performance in the linear regime is much flatter. At 1445 nm, the BDFA reaches a BER minimum of $6.7 \cdot 10^{-5}$ at 4 dBm launch power (-10 dBm input signal power), and the distributed RA reaches $9.9 \cdot 10^{-5}$ BER at 0 dBm launch power. As at 1430nm, the discrete Raman amplifier shows the highest BER among the three amplifiers, however, BER in its nonlinear regime does not rise as quickly as BER of the distributed RA. This is because in distributed RA at high input launch power the additional amplification in SMF raises the signal power level inducing high nonlinear impairments. The discrete RA reaches a minimum of $1.3 \cdot 10^{-4}$ at 0 dBm launch power (-14 dBm input signal power).

Finally, at 1460 nm all three amplifiers show similar behaviour to that observed at 1445 nm. However, at 1460 nm, the best BER performance of $9.5 \cdot 10^{-5}$ is achieved at -4 dBm with the distributed RA. The BDFA performance is slightly worse in this case with $1.2 \cdot 10^{-4}$ at -4 dBm launch power (-18 dBm input signal power). Lastly, the discrete RA performs similarly to the BDFA with a minimum BER of $1.8 \cdot 10^{-4}$ at -2 dBm launch power (-16 dBm input signal power).

If we look at the NF (Fig. 2,b) we would expect the distributed RA to outperform both the discrete RA and BDFA in terms of achieved BER. If we, then directly compare the achieved optimal BER with measured NF and effective NF, it would be clear, that the dominant factor that leads to the poorer performance of distributed RA to BDFA at 1430 and 1445 nm is the induced nonlinearity in the SMF. This effect is because nonlinear interference is proportional to nonlinear coefficient (growing with a wavelength decrease) and is inversely proportional to dispersion (decreasing with a wavelength decrease). Thus, the impact of nonlinearity is higher at shorter wavelength. The similar logic can be applied to discrete RA which is based on 7.5 km long IDF with nonlinear coefficient 2.7 times higher than standard single mode fibre[10]. Thus, NF and effective NF do not provide the full picture of the potential signal performance degradation and should be compared with care. In summary, out of the three E-band amplifiers, the distributed RA and the BDFA show comparable performance at their optimal power levels, somewhat better than the discrete RA. The worse BER performance of the discrete RA may be attributable to higher nonlinearity.

Conclusion

We performed a direct comparison of three E-band amplifiers (distributed RA, discrete RA, and BDFA) in terms of gain, effective NF, and BER achieved after the transmission of 30-GBaud DP-16-QAM over 50km of SSMF. The best performance was achieved with the BDFA (minimum of $6.7 \cdot 10^{-5}$ BER at 1430 nm) and distributed RA (minimum of $9.9 \cdot 10^{-5}$ BER at 1430 nm).

Acknowledgements

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