E-band transmission of 30-Gbaud PM-16-QAM supported by Neodymium-Doped Fiber Amplifier

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Abstract: We experimentally demonstrate the first E-band transmission through 50 km of G.652.D fiber using 30 Gbaud 16-QAM signals enabled by a neodymium doped fiber amplifier with 14 dB gain and 5 dB noise figure.

1. Introduction

Over recent years, escalating traffic growth and a congested C-band has stimulated interest in novel solutions to upgrade optical telecommunication networks. Extensive ongoing research on novel techniques to increase the capacity of WDM networks, such as space division multiplexing (SDM) and multi-band transmission (MBT), has shown that MBT systems have the potential to be practical, feasible and sustainable solutions in the short-to-mid term. However, extending beyond the C+L band requires a significant leap in technology and one of the key challenges is the development of optical amplifiers that can provide sufficiently high gain and low noise figure over such wide bandwidths [1]. Options of amplification technologies include Raman amplifiers, doped fiber amplifiers, semiconductor optical amplifiers, as well as combinations of different amplifiers, with each amplification technology having its own set of performance and practical trade-offs [2,3].

The E-band may be a good candidate for MBT, especially due to the availability of low water peak fibers [1,4]. Moreover, a diverse selection of amplification techniques in available in the E-band, such as well-developed Raman amplifiers [5,6], emerging bismuth-doped fiber amplifiers (BDFAs) [7], semiconductor optical amplifiers, and neodymium-doped fiber amplifiers (NDFAs) [8,9]. Despite the challenges with competitive electronic transitions, recent research showed that use of photonic-crystal fibers enables efficient E-band amplification based on fibers doped with neodymium [8]. Moreover, these amplifiers featured low NF ($\sim$ 5 dB). However, to date there has been no demonstration utilizing this technology for optical communication. Thus, here, for the first time, we successfully demonstrate 50 km E-band transmission using dual-polarisation (DP) 30 Gbaud 16-QAM signals enabled by a NDFA with a 14 dB gain and 5 dB noise figure. In this work, we perform the transmission in the 1405-1430 nm spectral band, utlizing the NDFA as an in-line amplifier.

2. Experimental Setup

The schematic of the developed NDFA is presented in Fig. 1,a. It consists of two amplification stages. Each stage consists of a 7 m-long neodymium-doped fiber which is pumped bi-directionally by two 808 nm pump laser diodes. To combine signal and pump radiation, two wavelength division multiplexers are used in each amplification stage. Two signal isolators at the input and the output of the amplifier are used for uni-directional operation. The active neodymium-doped fiber is an all-solid microstructure with a glass diameter of 126 µm and a micro-structure pitch of 6.6 µm. The core glass is a mixture of Nd^{3+} doped, fluorine doped and pure silica components where the original Nd^{3+} doped glass was produced by Optacore SA and was co-doped with 0.75 mol Al_2O_3. The Nd^{3+} ion concentration creates a small signal absorption of 57 dB/m at 808 nm as measured by Optacore SA from a slice of the glass rod. This amplifier design has been described previously [8], but here, we use a higher total pump power of 1.4 W from four diodes to achieve higher net gain. The measured NF and gain of the NDFA for -10 dBm input signal power is shown in Fig. 1,b. The amplifier features overall NF of 5-6.2 dB and gain in the range of 10-14 dB in the investigated region where the transmission is performed. The amplifier performance in terms of gain and NF is recorded with accuracy of 0.2 dB of two standard deviations. The gain peak of the amplifier is around 1398 nm. Due to the increased loss of G.652.D fiber in the E-band, when compared to the conventional C-band, the NDFA only partially compensates the loss of the fiber.

The setup of the E-band data transmission experiment is presented in Fig. 2. The transmitter (Tx) is comprised of a tuneable laser (TL) operating from 1405-1430 nm and a DP-IQ modulator driven by a digital-to-analog

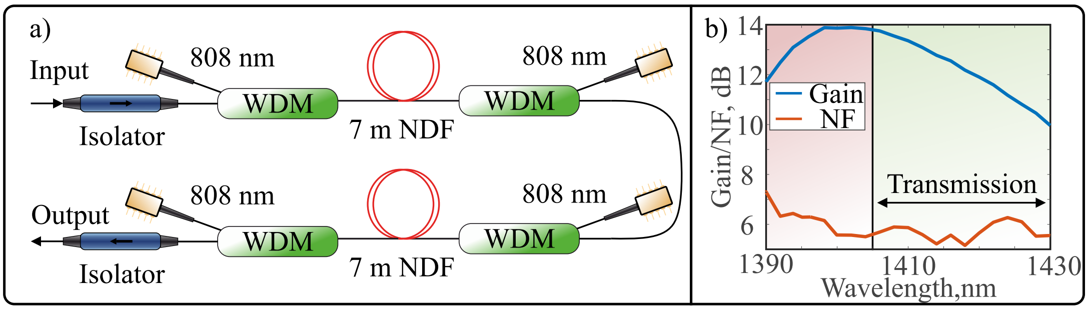

Fig. 1. (a) Schematic of neodymium-doped fiber amplifier (NDFA); (b) gain and NF of the developed NDFA.

converter (DAC) to generate a 30-GBaud DP-16-QAM signal. After the modulator, the signal is combined with two CWDM channels (1410 nm and 1430 nm) and then amplified by an in-house BDFA designed for E- and S-band operation [7]. Two extra dummy-channels are used to increase the spectral load on the in-line NDFA. After amplification the variable optical attenuator (VOA) is used 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 G.652.D fibre and then amplified by the in-line NDFA under test.

In all B2B and transmission experiments, after the OBPF, the signal is attenuated to a fixed input power of -20 dBm in all measurements, and then amplified by a receive BDFA. The receive BDFA is based on doped fiber reported previously [10], and has a similar design to the booster amplifier. The input power to the coherent receiver is fixed by another VOA to 8 dBm. A second TL operating from 1405-1430 nm is used as the local oscillator (LO) for 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 [11].

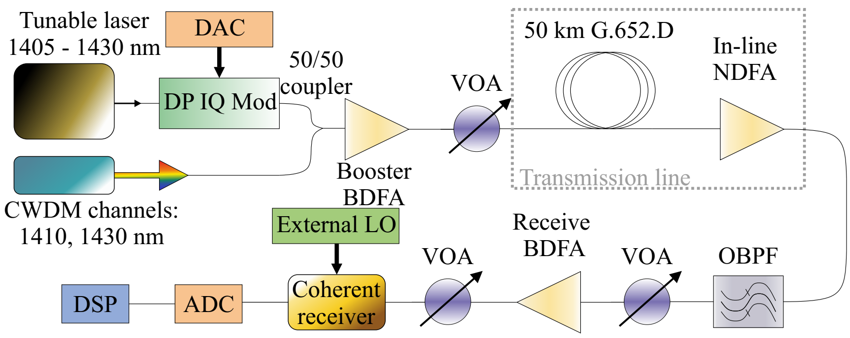

Fig. 2. Experimental setup of the transmission over 50 km-long G.652.D.

3. Results

To perform the measurements across the selected spectral interval, the operation wavelength of the input TL and the external local oscillator TL are appropriately controlled. In this work we experimentally measure system performance at six wavelengths: 1405, 1410, 1415, 1420, 1425, and 1430 nm. After the wavelength is tuned, as the first step B2B performance is recorded. The B2B performance for each wavelength is presented in Fig. 3,a in red. After measurements of the B2B performance, the transmission line is assembled. The launched power at the input to the transmission line is changed with a VOA to allow study of the performance at different launched powers. The power sweep of the launched input signal power was performed at each wavelength in the range of -6 to 4 dBm and the resultant dependence of the SNR on launched power per channel to the line at 1430 nm is presented in Fig. 3,b. Generally, the change of the SNR with the launched power adheres to the following pattern: the SNR grows with an increase of launched power per channel, until an optimal point (the launched power with the highest SNR). After the optimal point the SNR decreases with the increase of the launched power due to the nonlinear effects that lead to nonlinear signal distortions.

The power sweep measurements at all wavelengths are performed in a way to determine an optimal launched power but here we present only the performance at 1430 nm as an example. The power per channel was cal-

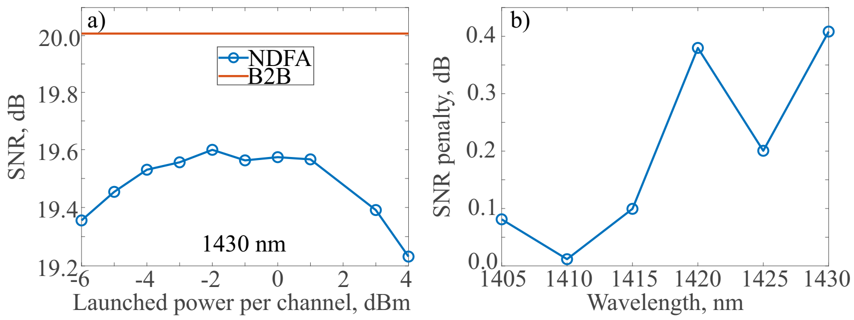

Fig. 3. The dependencies of the SNR of the transmitted signal on the launched power per channel and B2B SNR at 1430 nm (a); wavelength dependence of SNR penalty at optimal launch power (b).

ibrated to be the same among the three launched channels. After determining the highest value of the SNR at each wavelength, it is compared to the B2B performance to determine the SNR penalty of transmission. The SNR penalty is presented in Fig. 3,b. Each SNR value at each launched power per channel is an average of 10 traces. The variations of SNR in both B2B and transmission along 10 traces is usually less than 0.2 dB. The overall performance is better towards the lower wavelength range, where the NDFA features higher gain and relatively lower NF (as seen in Fig. 1,b). The lowest SNR penalty of 0.02 dB is achieved at 1410 nm. The highest SNR penalty of 0.4 dB is achieved at 1430 nm. The main limitations of the transmission bandwidth in this work are the degraded performance of the transmitter and receiver previously discussed in [12], and decreasing gain of the BDFAs not allowing sufficient launched power bandwidth to determine the optimal launched power point. Despite these challenges, here we demonstrate the first coherent transmission supported in-line by a NDFA.

4. Conclusion

In conclusion, for the first time, we performed a coherent transmission of a 30 GBaud DP-16-QAM signal over 50 km of SMF in the E-band supported by neodymium-doped fiber amplifier based on a dual-stage scheme. The amplifier features 13.5 dB gain and 5 dB NF in the investigated region. The achieved SNR penalty of transmission is below 0.4 dB in the whole range of the conducted measurement (1405-1430 nm). Such small penalty confirms the potential of using a NDFA for telecommunication applications.

5. Acknowledgment

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