50 Gbaud QPSK E-band Transmission Using Bismuth Doped Fiber Amplifiers

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Abstract: We experimentally demonstrate 35nm E-band transmission through 60km SSMF using 50Gbaud QPSK signals with Q^2 factor penalties less than 2.75dB enabled by a bismuth doped fiber amplifier with 29.8dB gain and 6.25dB noise figure. © 2022 The Author(s)

1. Introduction

The information transmission rate has been incessantly growing for the last 40 years, and it is not expected to stop in the near future. Thus, optical networks continuously require novel technical solutions to meet this increasing demand. Multi-band transmission (MBT) is one of the most promising practical approaches, allowing maximization of the return-on-investments in existing infrastructures [1]. The critical challenge for MBT is to develop efficient optical amplifiers beyond the currently used C-band [2]. Currently available commercial MBT systems typically target transmission in the C+L-band window, expanding current erbium-doped fiber amplifier (EDFA) technology. However, to extend the operation of optical networks, novel amplifiers in O-, E-, S-, and U-bands must be developed and deployed. One of the most promising amplification technologies is the bismuth-doped fiber amplifier (BDFA) as it provides gain in all aforementioned spectral bands [3, 4].

Recent advances in O- [5–7], E- [5, 6, 8], and S-bands [9] demonstrate the performance of BDFAs potentially comparable to EDFAs in terms of gain and noise figure (NF). There have also been recently reported demonstrations of BDFA-based the on-off keying (OOK) signal transmission in the O-band [10], the non-return-to-zero (NRZ) transmission in the E-band [11, 12], and the pulse amplitude modulation 4-level (PAM4) transmission over 1 km of hollow core fiber in the O-band [13]. However, there have been no studies of SP-QPSK signal transmission (or higher order modulation format signals that also require coherent detection) in SSMF in the E-band using bismuth-doped fiber amplifiers.

Thus, here for the first time, we report a 50 Gbaud single polarization (SP)-QPSK WDM transmission through 60 km of SSMF amplified solely by BDFAs. The receive amplifier has maximum gain of 29.5 dB and NF lower than 6.25 dB, and enabled almost zero-penalty transmission in the spectral band from 1415 nm to 1450 nm. Additionally we successfully transmitted a 30 Gbaud SP-32-QAM signal through 60 km of SSMF at 1430 nm to demonstrate compatibility of the setup with higher order modulation formats.

2. Experimental Setup

The experimental setup is presented in Fig.1. The output optical signal from the tuneable laser (TL) operating in the spectral range from 1340-1480 nm was modulated with a 50 Gbaud SP-QPSK signal by the I-Q modulator. The booster BDFA was used to amplify the modulated channel due to the high internal loss of the I-Q modulator (14 dB). This amplifier operated with high forward pump power (300 mW) to allow low NF operation [8]. The detailed description of this amplifier is not presented here as it was used solely for channel equalization, achieved using a variable optical attenuator (VOA) to adjust the power of the modulated signal to that of the other channels. Next, the signal was combined with an optical signal of the continuous wave laser diodes in a 3 dB optical fiber coupler. The optical signal of four laser diodes operating at the wavelengths of 1410, 1430, 1450, and 1470 nm was combined in a multiplexer (MUX). The total input signal power before the SSMF was 8 dBm. The transmission line comprised a 60 km long span of SSMF, followed by another BDFA. The receive BDFA had a bi-directional pumping scheme with 350 mW pump powers of both diodes at 1320 nm to enable high gain and low NF operation. Fig.1 also shows the input spectrum before the SSMF span and the output spectrum after the receive-side BDFA (from -20 dB coupler output). An optical bandpass filter was used to filter out the signal. Due to sufficient gain

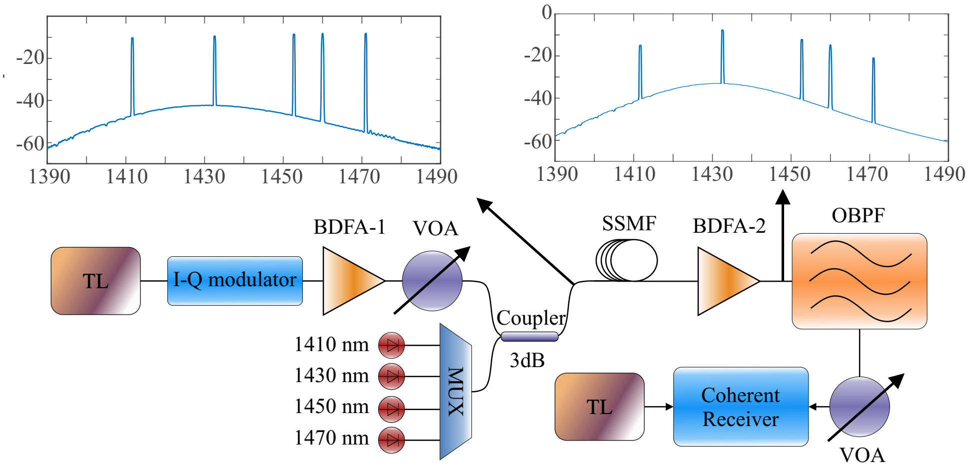

Fig. 1. Setup of coherent transmission experiment through 60 km of SSMF and BDFA. Input and output spectra from -20dB coupler output are presented at the top. TL: tunable laser; MUX: multiplexer; VOA: variable optical amplifier; BDFA-1: Booster Bi-doped fibre amplifier (BDFA); BDFA-2: receive BDFA; OBPF: Optical Bandpass Filter.

of the amplifier (Fig. 2(a)) no additional amplifier was required in the receiver line and another VOA was used to limit the signal to less than 6 dBm. Then, the signal passed on to the coherent receiver where the signal was received with an 80 GSa/s, 36GHz bandwidth oscilloscope and processed by an offline digital signal processing, as described in further detail elsewhere [14].

3. Results

The gain and NF of the developed amplifier were measured by switching the wavelength operation of the TL and are presented in Fig.2(a). The amplifier features a maximum gain of 29.8 dB with a 3 dB bandwidth of 35 nm for -15dBm signal power. The NF is as low as 5 dB and does not exceed 6.25 dB. The amplifier is based on 330 m long Bi-doped fiber, fabricated in FORC, Moscow, Russia, and two pump diode lasers operating at 1320 nm wavelength, with a setup similar to one described in [8].

The transmission performance of the 50 Gbaud SP-QPSK signal was measured every 5 nm from 1415 nm to 1450 nm, except 1445 nm. Due to unavailability of an additional TL that could be used for the local oscillator at 1445 nm, the measurement at this wavelength was skipped. Even though tuneable sources were available to reach outside the 1415-1450 nm range, measurements in that spectral region were not possible due to insufficient gain of the BDFA. First, the back-to-back (B2B) Q^2 factor of the transceiver setup was measured at the desired wavelengths and is shown in Fig.2,b with black squares. This measurement was conducted without the 60 km SSMF span and the receive BDFA. The average Q^2 factor in the operating range was around 18 dB and has a very flat performance in the spectral range from 1415 to 1440 nm. The decreased performance at 1450 nm can be explained by a limitation of the power of the local oscillator that was only 3 dBm in comparison to 10 dBm for all other wavelengths.

The spectral dependence of the Q^2 factor after a single span of SSMF and BDFA amplification is presented in Fig.2(b) with red circles, well above the HD-FEC limit of 8.5 dB for QPSK, but showing a more significant spectral dependence than the B2B performance. The Q^2 factor penalties are presented in Fig.2(c) indicating 2dB penalty in the spectral range 1420-1440 nm. The penalty increase at the edges of the measurement correspond to increased NF and decreased amplifier gain in these spectral regions. It is important to highlight that the experiment was conducted using a transmitter and receiver systems designed for operation in C- and L-bands. The measurements were conducted without the use of any extra recently reported techniques, such as nonlinear transmitter pre-distortion, that can improve the transmission performance in the E-band with the use of conventional C+L equipment [15, 16]. In general, the penalty in the E-band is mainly attributed to the low OSNR of the transmitted SP-QPSK signal due to imperfections of the transceiver system. Nevertheless, the output signal quality allowed us to achieve error-free transmission in the 1415-1450 nm spectral band.

As a last step, an additional experiment was conducted to examine the performance of the BDFA-based system with a higher order modulation formats. The experimental setup was the same as for the SP-QPSK transmission experiment, however, measurements on data transmission fidelity were taken only at the peak of the gain, at 1430 nm. The developed system and amplifiers supported the transmission of 30 Gbaud SP-32-QAM signals through 60

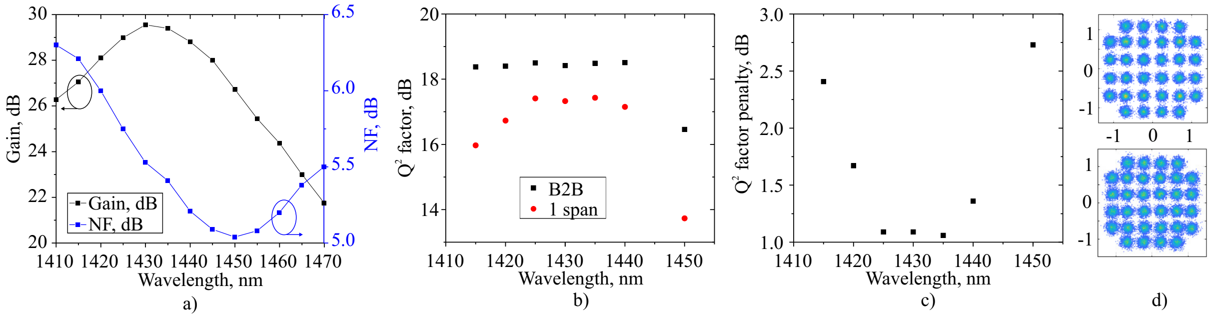

Fig. 2. a) Spectral dependence of the gain and NF of the receive BDFA; b) Spectral dependence of Q^2 factors for B2B and single span measurements for SP-QPSK signal; c) Spectral dependence of the Q^2 penalties for SP-QPSK signal; d) SP-32-QAM constellations for B2B measurement (top) and single span transmission measurement (bottom).

km fiber. In Fig.2,d the constellations for the B2B case (top picture) and the single span case (bottom picture) are presented. The SNR penalty for SP-32-QAM signal was measured to be 1.5dB which in combination with good quality of constellations indicate acceptable error-free system performance assuming the availability of standard FECs. To the best of our knowledge, this is the highest order modulation format transmitted to date in the E-band using BDFAs.

4. Conclusion

We have experimentally demonstrated 5-channel E-band transmission through 60 km SSMF using a BDFA with a 35 nm 3 dB bandwidth and a peak gain of 29.8 dB. We report error free transmission of 50 Gbaud SP-QPSK signals with Q^2 factor penalties in the range of 1-2.7 dB with respect to B2B performance. In addition, we experimentally showed that the developed system and amplifier is suitable for transmission of higher order modulation formats by successfully transmitting and recovering a 30 Gbaud SP-32-QAM signal.

5. Acknowledgment

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