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195-nm Multi-Band Amplifier Enabled by Bismuth-doped Fiber and Discrete Raman Amplification

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Abstract *We report a first-time ultra-wideband transmission through 70-km long fiber enabled by hybrid amplifier based on bismuth-doped fiber and discrete Raman amplification. The experiment features 195-nm 30 GBaud PM-16-QAM signal amplified with 15 dB gain and 6 dB NF.*

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[1]. Thus, optical networks continuously require novel technical solutions to meet this increasing demand. Multi-band transmission (MBT) is one of the promising practical approaches that allows to maximize the return-on-investments in existing infrastructures[2]. The critical challenge for MBT is the availability of efficient optical amplifiers beyond the currently used C-band to extend operation of optical networks in O-, E-, S-, and U-bands.

There have been recent significant advances in development of various doped-fiber amplifiers[3],[4], Raman amplifiers[5], fiber optical parametric amplifiers[6], and semiconductor optical amplifiers[7] operating in different telecommunication bands from O- to U-bands. However, demonstrations of ultra-wideband data transmission beyond S-, C-, L-bands lags behind the progress in amplifiers[8]–[10]. To the best of our knowledge, there has been no report yet combining bismuth-doped fiber amplifiers (BDFAs) with other types of amplifiers for MBT.

Here, therefore, we present a first-time implementation of an ultra-wideband amplifier based on a combination of a discrete Raman amplifier (DRA) for the S-, C-, and L-bands and a BDFA for the E-band. The MB amplifier performance was characterized in terms of gain - average 15 dB, and noise figure (NF) - 6 dB. Moreover, a 70 km, 195 nm transmission of dual polarization (DP) 30 GBaud 16-QAM signals is realized using this MB amplifier. Our experimental results show a low Q^2 factor penalty (less than 3.5 dB) for all the transmission bands. Moreover, two further BDFAs were used in the booster and receive stages to enable E-band transmission, showing comparable performance with commercially available amplifiers used for the same function in S-, C-, and L-bands

Experimental Setup

The schematic of the ESCL-band amplifier is presented in Fig. 1,a. It comprises two separate optical paths, with a BDFA operating in the E-band and a dual-stage DRA operating in the SCL-bands. These bands are separated by a filter WDM (FWDM), with transmission and reflection bands of 1410-1457 nm and 1470-1620 nm. After band-splitting, the E-band signal follows the upper path in Fig. 1,a passing via an isolator to a 300 m long Bi-doped fiber that is bi-directionaly pumped via a pair of WDM couplers by two pump diodes at 1260 nm (forward) and 1310 nm (backward). Additionally two isolators are used to ensure unidirectional propagation of the signal. The Bi-doped fiber used in this paper is the one reported in[11]. The SCL-band signal follows the lower path in Fig. 1,a where the first stage of the amplifier targets S-band amplification, and consists of an isolator, 7.5 km-long inverse dispersion fiber (IDF), WDM, a pump combiner and three pump diodes at 1365 nm, 1385 nm, and 1405 nm. The second stage amplifies the C- and L-bands and consists of the same set of components with the exception of pump combiner and pump laser diodes at 1425 nm, 1445 nm, 1464 nm, 1485 nm, and 1508 nm[10]. Finally both amplified signals are combined with 1410-1457nm/1470-1620nm FWDM.

The measured gain and noise figure (NF) of the amplifier are presented in Fig. 1,b, showing a maximum gain of 18 dB and minimum NF of 5.9 dB. The E-band BDFA was pumped at only 200 mW to enable matching gain with the DRA. The reduced gain at 1460 nm is explained by the lower efficiency of the BDFA in this region at this relatively low pump power level. The minimum of the

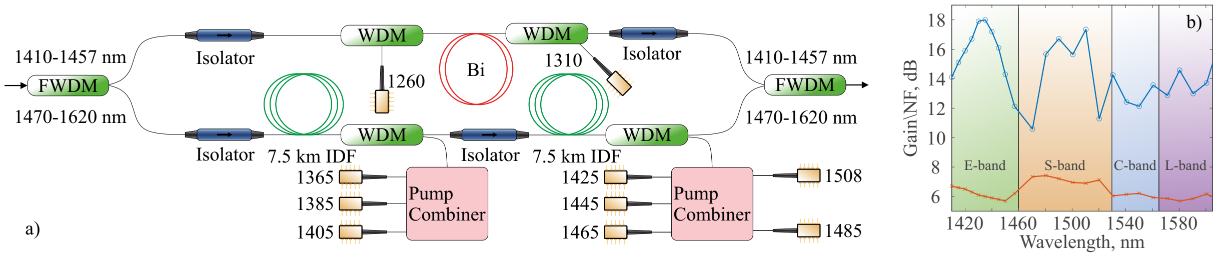

Fig. 1: Experimental setup E-,S-,C-,L-band amplifier enabled by active Bi-doped fiber and discrete Raman amplification.

NF is at 1450 nm which corresponds well with the behavior reported previously[11]. The DRA has increased gain in S-band except gain in vicinity of 1470 nm and 1520 nm due to high attenuation values, inter stimulated Raman scattering (ISRS) power transfer to the C and L band signals, and limitations of the pump. The NF was found to be lowest in the C-band with a minimum value 5.9 dB NF. The DRA has flat gain (with variations less than 3dB) from 1520 nm to 1605 nm with average gain of 13 dB covering whole C and L bands.

The setup of the data transmission experiment is presented in Fig. 2,a. The E-, S-, C-, L-band WDM grid consists of 143x100 GHz ASE-emulated channels in the S-, C-, and L-bands, plus three E-band laser diodes at wavelengths of 1411 nm, 1432 nm, and 1451 nm (Fig. 2,b,c,d). The S-band channels (1470-1520 nm) are generated using a supercontinuum source and a commercial wavelength selective switch (WSS) for channel spacing and flattening followed by a thulium doped fiber amplifier (TDFA). There are also two guard bands of 4 nm and 6 nm around each of the longest wavelength pumps at 1485 nm and 1508 nm, respectively. The S-band channels are combined together with a flat channelized C and L-band ASE noise extending out to 1608 nm, generated using C and L-band EDFAs and two WSSs for equalization and flattening. The data carrier signal is generated using different tuneable lasers operating from 1410 to 1605 nm, which are modulated by a dual-polarization IQ modulator (DP IQ Mod) driven by a digital-to-analog converter (DAC) to achieve 30 GBaud 16 QAM signal. The signal after the modulator is amplified by a booster amplifier (in-house BDFA for E-band, commercial TDFA for S-band, and commerical EDFAs for C- and L-bands). For power equalization of the data channel with WDM grid, a variable optical attenuator (VOA) is used ahead of a 90/10 coupler. As WDM grid is dense in S-,C-,L- bands, the WDM channel corresponding to the data carrier signal is turned off by WSS to avoid channel overlap. In the case of back-to-back (B2B) transmission the signal then is directed to an optical bandpass filter (OBPF), where the data carrier is filtered. When the transmission is performed, the signal is directed into a 70 km-long SMF-28 fiber and then amplified by the developed hybrid MB amplifier. In both cases, after the data carrier is filtered by OBPF it is amplified by an appropriate receive amplifier, similarly to the booster. The input power to the coherent receiver is controlled by another VOA, and a set of external tuneable lasers operating from 1410-1605 nm is used as a local oscillator for the coherent detection system. Channel reception is completed by a standard set of 80 GSa/s analog-to-digital converters (ADCs). The digital signal processing (DSP) chain used for analysis of the received signal has been described previously[12].

Results

The recorded results of the transmission experiment are presented in Fig. 3. The wavelength dependence of the Q^2 factor of a DP 30 GBaud 16 QAM signal is recorded by tuning the wavelength of the tuneable lasers (signal and local oscillator) across 195-nm bandwidth from 1410 to 1605 nm. The wavelength dependencies of the Q^2 factor (average between X and Y) for B2B and 70 km-long transmission are presented in Fig. 3,a. The Q^2 factor was calculated from the signal-to-noise ratio obtained from the recovered constellations[13].

The transmission performance of the DRA in the L-band features a Q^2 factor penalty no higher than 2.2 dB and the lowest Q^2 factor penalty for the whole DRA of just 1 dB (Fig. 3,b). The C-band shows the best B2B performance achieved in the experiment enabled by commercial EDFAs. The DRA has the maximum Q^2 factor penalty of 1.7 dB in this region. The B2B performance in the S-band shows similar performance to the L-band. However, a noticeable decrease of the S-band B2B performance at around 1470 nm is due to the relatively high NF of the TDFA in this region. The performance of the DRA in the S-band has a maximum penalty of 3.3 dB and the minimum of 2 dB. The substantial increase of the Q^2 factor

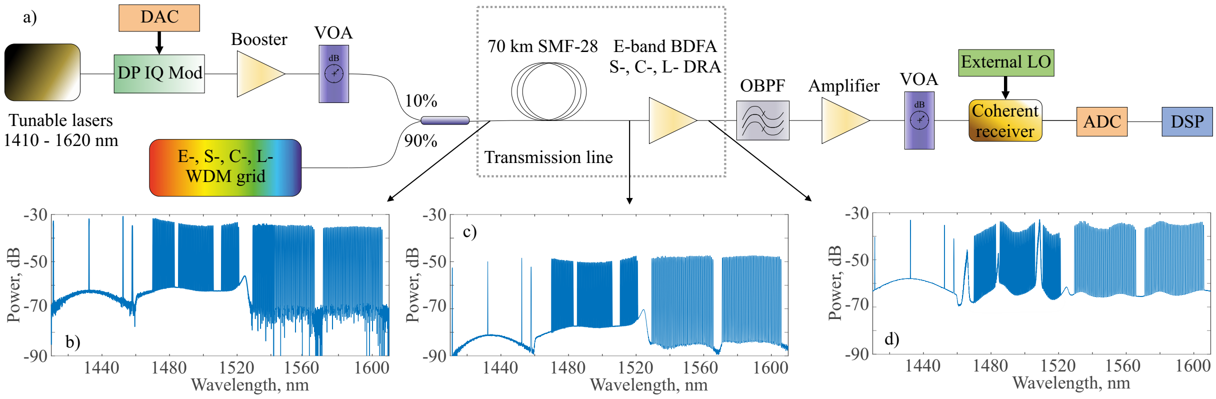

Fig. 2: a) Experimental setup of a B2B and transmission experiment; spectra of the WDM grid and E-band data carrier signal at 1457 nm at (b) input to the span, (c) end of the span, (d) after the amplifier.

penalty at 1470 nm can be explained by the high NF of the DRA at this wavelength of operation.

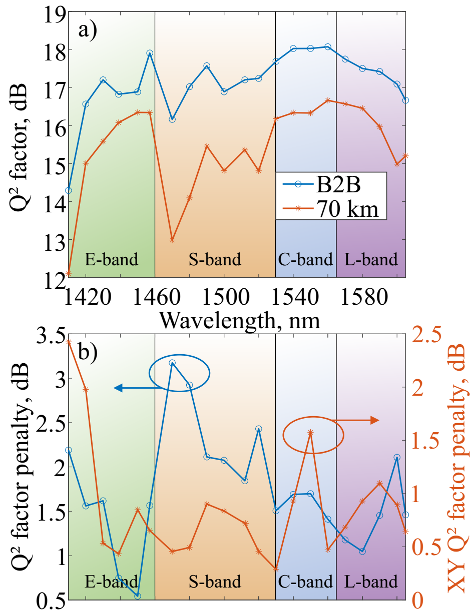

Fig. 3: a) Wavelength dependency of the Q^2 factor for B2B case and 70-km long transmission; b) wavelength dependency of Q^2 factor penalty between B2B case and transmission (blue line with circles) and X and Y polarization Q^2 factor imbalance (orange line with stars)

The E-band B2B measurement was enabled by two in-house-made BDFAs that will be reported elsewhere. The general B2B performance level is similar to the L-band case. However, there is a significant decrease of the performance at 1410 nm. This can be explained by substantial limitations of the optical hybrid in terms of polarization balance starting at 1420 nm. The X and Y polarization imbalance penalty is presented in Figure 3,b. There is a significant increase of the X and Y impairment below 1430 nm. The commercial optical hybrid used in this experiment was optimized for operation in the C- and L- optical bands. Despite the limited operation bandwidth, the X-Y impairment is lower than 2.5 dB in the whole region from 1430 to 1605 nm. The E-band transmission features the lowest Q^2 factor penalty of just 0.5 dB. Otherwise, the general performance of the in-line BDFA is similar to C- and L- band DRA. The increase of penalty towards 1410 nm is explained by both rising NF and decreasing gain of the amplifier. Based on the discussed results, here we report one of the record transmission bandwidth for coherent transmission lines with 195 nm and total of 34.2 Tbits/s (2 x 4 bits x 30GBaud x 143 channels)[14]–[16].

Conclusion

In conclusion an ultra wideband amplifier was developed and demonstrated with maximum gain of 18 dB and minimal NF of 5.9 dB. The amplifier was enabled by Bi-doped fiber in E-band and discrete Raman amplification in S-,C-,L-bands. A transmission experiment of 195 nm dual polarization 30 GBaud 16 QAM signal through 70 km was conducted to study further the performance of the developed amplifier. The overall performance of the amplifier was investigated and the average Q^2 factor penalty is around 1.7 dB through investigated bands. The minimal Q^2 factor penalty of just 0.5 dB at 1450 nm was achieved by amplification in Bi-doped fiber. We believe that our results show a great potential of using Bi-doped fiber amplifier in combination with discrete Raman amplifier for ultra wideband transmission in E-, S-, C- and L-bands.

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