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38 dB Gain E-band Bismuth-doped Fiber Amplifier

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Abstract *We experimentally demonstrate a novel single-stage bismuth-doped fiber amplifier with record E-band 38 dB gain and 4.5 dB NF operating from 1384 nm to 1484 nm. The amplifier features 28% power conversion efficiency and 3 dB gain bandwidth of 74.7 nm.*

Introduction

The Multi-band transmission (MBT) utilizing currently unused spectral bands of deployed single-mode fiber (SMF) has potential to be a short to medium term solution for increasing capacity of optical communication systems. The MBT solution offers an attractive return-on-investments in the existing infrastructures[1],[2]. The main challenge of the MBT approach is a requirement for novel power and cost efficient solutions for signal amplifications in the telecommunication bands beyond C- and L-bands[3]. There are several possibilities for providing broadband amplification that are under active study, including the development of various doped-fiber amplifiers[4],[5], Raman amplifiers[6], fiber optical parametric amplifiers[7], and semiconductor optical amplifiers[8] operating within the telecommunication O- to U-bands. These amplifiers have specific advantages and drawbacks and it is also possible that different optical communication sectors will require different solutions. One of the promising approaches that allows amplification in O-, E-, S-, and U- bands is a bismuth-doped fiber amplifier(BDFA)[4],[9]–[11]. Such spectral flexibility is provided by different co-dopants that can be used to form different Bi-related active centers in the core of the fiber. The phosphosilicate glass shifts the gain to the O-band[4],[11], the silicate glass with low concentration of germanium features gain in E- and S-bands[9],[10] and germanosilicate fibers make it possible to achieve amplification in U-band[12]. Note a growing number of publications demonstrating a great potential of BDFAs: O- and E- wideband amplifier[4]; 40-dB gain BDFA in O-band[11]; QPSK transmission in E-band[13].

Here we report a BDFA operating in the E-band that has a record (for E-band BDFA) gain and noise figure (NF). The amplifier features a maximum gain of 38.3 dB and a minimal noise figure (NF) of 4.5 dB. The amplifier operation performance was measured in the spectral range of 1384-1484 nm and the maximum 3 dB bandwidth is 74.7 nm. The amplifier performance is investigated for different pump and signal powers. Moreover, we show a significant increase in power conversion efficiency which is close to that of the commercially available EDFAs.

Experimental Setup

The schematic of the developed BDFA along with the experimental setup of gain and NF measurement is presented in Fig. 1. The developed amplifier consists of two thin-film filter wavelength division multiplexers (TFF-WDMs) used for multiplexing and demultiplexing of radiation at pump (1250-1330 nm) and signal (1350-1500 nm) wavelengths. The TFF-WDMs have very steep and flat transmission and reflection bands, thus, provide consistent loss over a wide spectral bandwidth. Two isolators centered at 1320 nm are used to avoid back reflection of radiation to the pump diodes, and two 1440 nm isolators are used for unidirectional transmission of the signal.

The signal was supplied by a tuneable laser operating in the wavelength range of 1384-1484 nm. A variable optical attenuator (VOA) was used for the control of the input signal power. 1% of the radiation was coupled with a fused silica fiber coupler to the power meter (PM) for the measurement of the input power. The signal was launched in the BDFA comprising a 400-m-long piece of the active Bi-doped germanosilicate fiber with approximately 6 μm fiber core diameter and a cut-off wavelength at around 1 μm. Two 1320-nm pump diodes controlled by a laser diode driver and a thermoelectric cooler controller were used for the bi-directional pumping of the Bi-doped fiber. After signal amplification, the signal is split with 99/1 coupler for a simultaneous measurement of optical spectrum with an optical spectrum analyzer (OSA) and optical power with a PM.

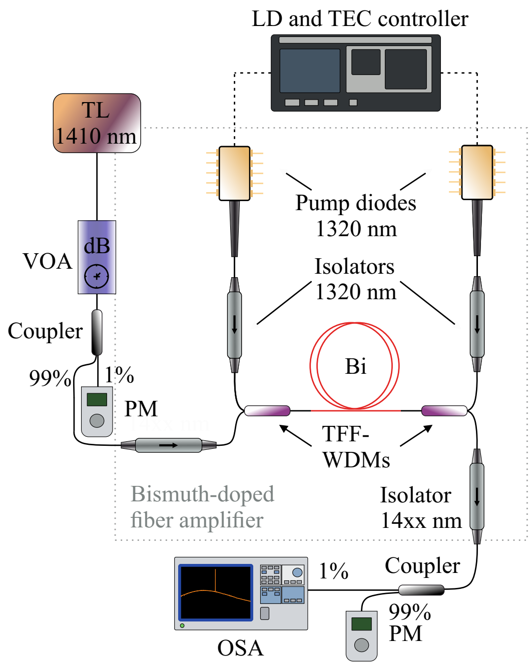

Fig. 1: Experimental setup of the gain and NF measurement along with experimental setup of the developed BDFA. TL: tuneable laser, VOA: variable optical attenuator; PM: power meter; OSA: optical spectrum analyzer.

The gain is found as a relation of the portion of the output power corresponding to the signal power (obtained from the optical spectrum) and input power determined from the measured input power and experimentally measured coupling ratio of the input coupler. The noise figure (NF) is estimated using the noise substraction technique and the following equation[14]:

$$NF = 10\log_{10}\left(\frac{\rho_{noise}}{Gh\nu} + \frac{1}{G}\right), \qquad (1)$$

where ρ_{noise} is the noise spectral density at the output of the amplifier, G is the gain, h is the Planck constant, and ν is the photon frequency. As the signal-to-noise ratio of the input signal is higher than 70 dB, the input noise is negligible. The noise spectral density is calculated from the optical spectrum by approximating of the spectral noise level on the signal wavelength. Moreover, the noise spectral density is calibrated in regard to the power received by the output PM.

Results

First, the amplifier performance is measured for different wavelengths, input signal powers (-20 dBm, -10 dBm, and 0 dBm), and maximum total pump power. The pump power is calibrated to be the same for forward and backward laser diodes with total value of 930 mW. The wavelength dependencies of the gain and NF for this case are presented in Fig. 2. The amplifier features a max-

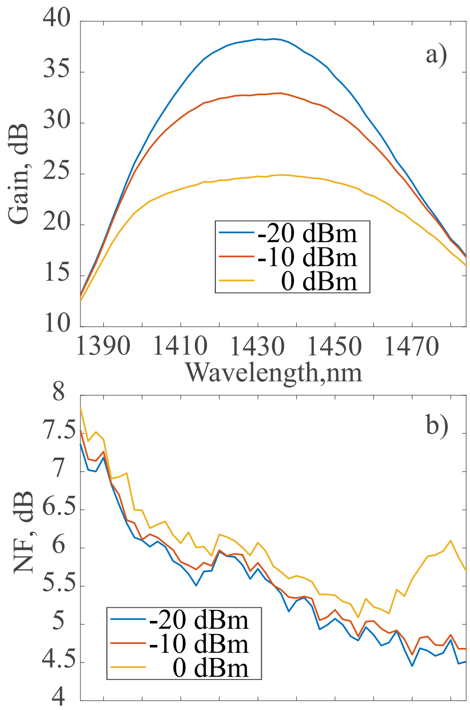

Fig. 2: a) Wavelength dependency of the gain (a) and the NF (b) for three input signal power levels: -20 dBm, -10 dBm, 0 dBm at maximum total pump power of 930 mW.

imum gain of 38.3 dB at 1430 nm for -20 dBm signal power and minimal NF of 4.5 dB shifted towards longer wavelength (1470 nm). The gain gradually decreases with increase of the signal power along with a shift of the gain peak from 1430 nm (-20 dBm) to 1436 nm (-10 dBm and 0 dBm). The increase of the signal power also increases the NF and 3 dB gain bandwidth from 4.5 dB to 5.2 dB and 34.7 nm to 74.7 nm, respectively. Three highlighted parameters (maximum gain, minimal NF, and 3 dB gain bandwidth) for different input signal powers are also presented in Table 1.

Tab. 1: Comparison of the main amplifier parameters for different signal powers and total pump power of 930 mW.

P_s dBm	Gain	Bandwidth	NF
-20 dBm	38.3 dB	34.7 nm	4.5 dB
-10 dBm	32.9 dB	63.7 nm	4.6 dB
0 dBm	24.9 dB	74.7 nm	5.2 dB

In the next step, the performance of the amplifier at different pump powers is investigated. The pump power dependencies of the gain and the NF for different signal powers at the wavelength of 1430 nm are presented in Fig.3. The increase of the pump power increases the gain and decreases the NF. After about 500 mW of total pump power, the NF is saturated and the increase of the performance is minor, especially for -20 dBm and -10 dBm. The gain features a nonlinear regime for pump powers less than 400 mW and changes to

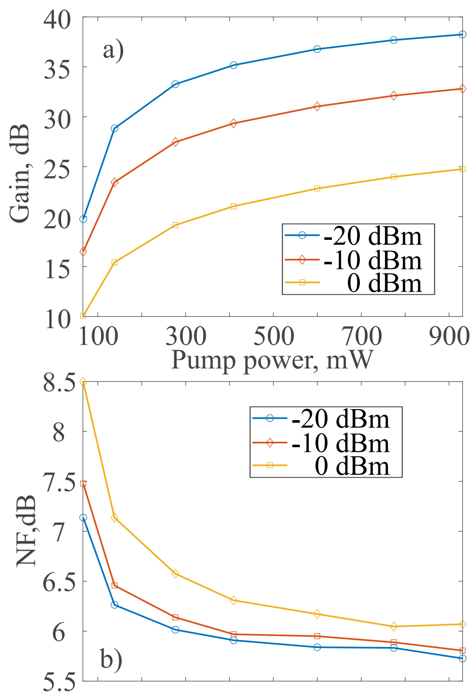

Fig. 3: a) Pump power dependency of the gain (a) and the NF (b) for three input signal power levels: -20 dBm, -10 dBm, 0 dBm at 1430 nm.

an almost linear dependency after 400 mW. The similar performance of the gain and the NF from the pump power at other wavelengths can be observed, thus, they are not presented here.

Another important characteristic of the optical amplifier is power conversion efficiency. It is calculated as a relation of the the portion of the output power related to the signal (obtained from the OSA and the output PM) and the total pump power. The obtained relation between power conversion efficiency in % to pump power and signal power at the wavelength of 1430 nm is presented in Fig. 4. The amplifier provides the maximum power conversion efficiency of 28% at 0 dBm input signal. The power conversion efficiency saturates for the pump power higher than 400 mW and the 0 dBm input signal. However, the power conversion efficiency significantly drops to 5% and 16% with the decrease of input signal power to -20 dBm and -10 dBm, respectively. This can be explained by less effective interactions between the signal radiation and Bi-doped related centers due to a lower signal power density in the core of the fiber. It is important to note that 28% power conversion efficiency is higher than the previously reported E-band amplifier in our previous paper[10], and is higher than the typical power conversion efficiency for L-band EDFAs, which is around 20%[15]. Moreover, it is close to commercially available C-band EDFAs 30% power conversion efficiency for 980 nm pumped EDFAs[16]. Further optimization of the amplifier setup in terms of the active fiber length might potentially increase the power conversion efficiency even higher by keeping moderate gain (higher than 30 dB) and low NF (lower than 5 dB). This might ensure similar costs per bit by utilizing multi-band transmission for traffic operators.

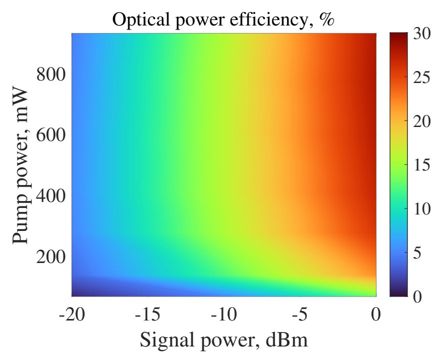

Fig. 4: Color map of power conversion efficiency in % against pump power and signal power.

Conclusion

To conclude, we developed a single-stage E-band bismuth-doped fiber amplifier with, to the best of our knowledge, record parameters for E-band BDFA of 38 dB gain and 4.5 dB NF. The amplifier was characterized in terms of gain, NF, 3 dB bandwidth, and power conversion efficiency. Moreover, the developed amplifier has comparable performance in terms of power conversion efficiency with commercially available EDFAs. Additional optimization of the amplifier fiber length might potentially increase the power conversion efficiency while keeping moderate gain and NF. This might ensure similar costs per bit by utilizing multi-band transmission for traffic operators.

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