Pump Optimization of E-band Bismuth-Doped Fiber Amplifier

Aleksandr Donodin[1]*, Egor Manuylovich[1], Vladislav Dvoyrin[1], Wladek Forysiak[1], Sergei K. Turitsyn[1]

[1]*Aston Institute of Photonics Technologies, Aston University, Birmingham, UK*

a.donodin@aston.ac.uk

Abstract: We experimentally investigate different bi-directional pumping schemes of an E-band bismuth-doped fiber amplifier. Best performance is achieved with 1320nm pumps, and features 38.9dB gain, 4.7dB NF, and 32.6% power conversion efficiency.

1. Introduction

Multi-band transmission (MBT) is considered as a promising mid-term solution for expanding the capacity of optical networks [1]. While currently commercial networks are being upgraded to support L-band along with the already massively deployed C-band, the interest to the next potential band to be exploited is rising. Even though the S-band may be seen as a natural next step with commercially available TDFAs, the performance of the S-band TDFAs are far from perfect [2]. Moreover, transmission in the S-band impacts significantly the performance of the C-band due to inter-channel stimulated Raman scattering [3]. Therefore, E-band can also be considered as a potentially feasible solution for MBT supported with emerging bismuth-doped fiber amplifiers.

Recent progress in E-band BDFAs has demonstrated their great potential for expanding optical communication networks. They feature high gain ($>$ 38 dB) [4, 5], low noise figure (NF) ($<$ 5 dB) [5, 6], high power conversion efficiency ($>$ 20%) [5], and their applicability for coherent transmission including multi-band scenarios [7, 8]. However, even though a number of studies have focused on spectroscopic properties of E-band BDFAs [9, 10], there has been limited work on optimization of pumping schemes (PSs) for E- and S-band BDFAs [6]. Thus, here for the first time, we report a comparison of the impact of different pumping schemes on the performance of the E-band BDFA. We examine three pump wavelengths of 1260 nm, 1310 nm, 1320 nm enabled by commercially available laser didoes with 500 mW output power. The optimal amplifier configuration features 38.9 dB gain, 4.7 dB NF, and 32.6% power conversion efficiency (PCE), which are, to the best of our knowledge, record characteristics for an E-band BDFA. The results presented here show further the great potential of BDFAs for amplification in multi-band optical communication networks.

2. Experimental Setup

The experimental setup of the BDFA and the automatic measurement design are presented in Fig. 1. The experimental setup consists of components that are automatically controlled. The first element of the setup is a tuneable laser (TL), that operates in the wavelength range of 1355-1485 nm. The output power of the TL is kept constant with the wavelength sweep, and an external variable optical attenuator (VOA) is used to control the input signal power. To correctly set the signal power, a power meter (PM) is used after a 30/70 coupler that in combination with the characterized splitting spectra of the coupler can correctly measure the real value of the input signal power. The splitting spectra is required as the fused couplers are usually applied in quite narrow spectral bandwidth (around 40 nm), and the coupler used in the experiment is designed for operation at 1550 nm.

After the input signal power is correctly calibrated, the signal radiation is directed into the BDFA which is controlled by a LD and TEC controller. The BDFA consists of two signal isolators and two thin-film-filter wavelength-division-multiplexers (TFF-WDMs). The 173-m long active bismuth-doped fiber has 6 µm core diameter and 125 μm cladding diameter. The refractive index difference (Δn) is around 0.004. The fiber core consists of 95 mol% SiO_2, 5 mol% GeO_2 and <0.01 mol% of bismuth. The cutoff wavelength (λ_c) of the fiber is measured to be around 1000 nm. Pump diodes at three different wavelengths are used for bi-directional pumping: 1260 nm, 1310 nm, and 1320 nm. The temperature of the pump diodes is kept constant at 20°C, and the pump laser output power is fixed at 500 mW. After the signal is amplified, it is split by a 99/1 coupler, and a 99% portion is recorded by the PM, and 1% is received by optical spectrum analyzer (OSA). After all the necessary data is recorded, it is used to obtain the main amplifier parameters: gain, NF, and power conversion efficiency (PCE). The method of NF measurement is the noise substraction technique [11].

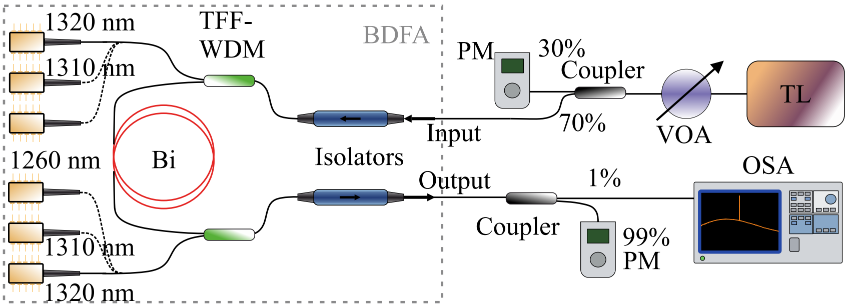

Fig. 1. Setup of the automatic measurement of the main parameters of BDFA. Three different pump wavelengths are used in each direction: 1320 nm, 1310 nm, 1260 nm.

3. Results

The measurements of the gain, NF and PCE spectra are performed with all nine combinations of pump wavelengths. The 500mW pump power of each laser diode leads to a total pump power of 1 W. The characterization is performed with two levels of input signal power: 5 dBm and -25 dBm. The results of the measurements and the comparison between different PSs in terms of the maximum gain, minimal NF, and maximum PCE is presented in Table 3. The first and second number in the column "Pumping scheme" indicate the wavelength of the forward and backward pump laser diode, respectively.

Pumping	Gain, dB		PCE,%		Minimal NF, dB	
scheme, nm	5 dBm	-25 dBm	5 dBm	-25 dBm	5 dBm	-25 dBm
1320-1320	20.2	38.9	32.6	2.5	6.4	4.7
1320-1310	19.8	38.6	30.2	2.4	6.3	4.8
1310-1320	19.5	38.4	27.7	2.3	5.8	4.9
1310-1310	19.6	38.8	29.4	2.5	5.8	4.8
1260-1310	18.2	37.3	21.0	1.9	6.3	4.9
1310-1260	18.5	37.9	22.6	2.0	6.7	4.9
1260-1320	18.7	37.9	23.0	2.0	6.2	4.8
1320-1260	19.0	37.9	27.5	2.0	6.7	4.8
1260-1260	15.7	35.1	12.8	1.0	6.8	5.0

Table 1. Comparison of the main characteristics of BDFA for different pumping schemes and two levels of input signal powers: 5 dBm and - 25 dBm

Overall, the performance of the amplifier with the PSs containing only 1320 nm and 1310 nm pumps perform better than those PSs that include 1260 nm pump. Thus, due to the limited space available, we will present a further analysis of only four representative PSs including the best performing ones: 1320-1320 nm, 1310-1310 nm, 1310-1320 nm, 1260-1260 nm. The maximum gain for both signal powers is achieved with the 1320-1320 nm PS and the gain is 20.2 dB and 38.9 dB for 5 dBm and -25 dBm input signal power, respectively. The maximum PCE is also achieved for this PS, and is 32.6% for 5 dBm, and 2.5% for -25 dBm. In contrast, the minimal NF of 5.8 dB for the 5 dBm signal is achieved with both 1310-1320 nm and 1310-1310 nm PSs and the minimal NF of 4.7 dB for -25 dBm signal is achieved with 1320-1320 nm PSs. It is notable that 32.6% PCE achieved with the 1320-1320 nm pumping scheme is higher than that of the previously reported E-band amplifier [5], and is higher than the typical power conversion efficiency of 20% for L-band EDFAs [12]. Moreover, it is comparable to the 30% PCE of commercially available, 980 nm pumped, C-band EDFAs [13].

The comparison of gain and NF spectra for the four aforementioned PSs is presented in Fig. 2. The gain spectra of the amplifier with 5 dBm input signal power is presented in Fig. 2a. The maximum gain of 20.2 dB is achieved with 1320-1320 nm pumping. The 1310-1310 nm PS allows improvement of the gain at shorter wavelengths with 12 dB at 1384 nm in comparison to 10 dB for all other PSs. The NF spectra for 5 dBm input signal power are shown in Fig. 2b. The lowest NF of 5.8 dB is achieved with both 1310-1310 nm and 1310-1320 nm PSs. However, the 1310-1320 nm PS has the worst NF at short wavelengths. In contrast, the 1320-1320 nm PS features almost flat NF in the region from 1400-1484 nm with the NF predominantly being in the range of 6.4-7.1 dB.

The comparison of the gain spectra for -25 dBm input signal power is presented in Fig. 2c. The gain performance

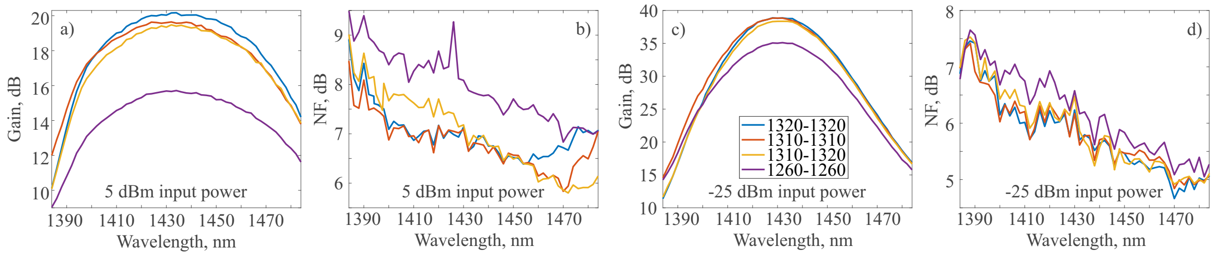

Fig. 2. Gain and NF spectra for four representative PSs at two input signal powers. a) Gain and b) NF for 5 dBm input power; c) gain and d) NF for -25 dBm input power.

is similar to the 5 dBm case with the highest gain of 38.9 dB achieved with the 1320-1320 nm PS. As for the higher input power, the gain in the blue-part of the spectrum is more pronounced for the 1310-1310 nm PS. Fig. 2d shows the NF spectra for the four PSs. In general, the NF performance of all PSs is similar, with the lowest NF of 4.7 dB achieved with the 1320-1320 nm PS. Finally, the 1260-1260 nm PS performs worse than all other PSs in terms of gain and NF. However, it has a similar effect on the gain as 1310-1310 nm PS leading to its slight shift toward shorter wavelengths. This behavior is observed with all PSs with no 1320 nm pumps. It is important to note that even though the performance of 1260-1260 nm PS is the worst of all, in combination with other pumping wavelengths, 1260 nm pumping can be used to achieve acceptable performance.

4. Conclusion

We have performed an experimental comparison of different BDFA bi-directional pumping schemes enabled by combinations of three pumping wavelengths: 1320 nm, 1310 nm and 1260 nm. The highest gains were achieved with the 1320-1320 pumping scheme, 20.2 dB and 38.9 dB, for input powers of 5 dBm and -25 dBm, respectively. The best NF performance for the 5 dBm signal was achieved with the 1310-1310 nm pumping scheme, with a lowest NF of 5.8 dB. For -25 dBm signal, the lowest NF of 4.7dB was achieved with 1320-1320 nm pumping scheme. The maximum PCE is 32.6% which is comparable to C-band EDFAs with 980 nm pump.

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