1255-1355 nm (17.6 THz) Bandwidth O-band Bismuth Doped Fiber Amplifier Pumped Using Uncooled Multimode (MM) 915 nm Laser Diode

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Abstract: We report BDFA with >20 dB gain over 1255-1355 nm bandwidth (17.6 THz) with maximum gain of 29.3 dB and corresponding NF of 4.6 dB (λ=1300 nm, Pin=-20 dBm). The BDFA has electrical power consumption of 8.1-9.6 W over 20-70 ºC.

1. Introduction

Bismuth doped fiber amplifiers have been demonstrated to provide gain in O-, E- and S- transmission bands [1-8]. Recently a BDFA that has more than 20 dB gain between 1345-1460 nm (17.6 THz) covering parts of the O- and E-bands have been demonstrated [1,2] using two single mode pump laser diodes. Despite the impressive bandwidth of 17.6 THz, it is allocated away from the wavelength range standardized for pluggable transceivers (1265-1345 nm) [9]. Moreover, approx. 20% of the demonstrated bandwidth overlaps the OH absorption peak, which reduces the BDFA gain, and increases the noise figure. Amplification over the standardized parts of the O-band has also been demonstrated [3-5], although with lower gain compared to the results presented in [1,2,7] and narrower bandwidth. Two main drawbacks of BDFAs operating over 1265-1345 nm range are lower BDF power conversion efficiency, compared to the longer wavelengths, and pump wavelength location within 1190-1200 nm range. This wavelength falls in between InGaAs and InP semiconductor technologies and at present single-mode (SM) pump can only be realized using quantum dot (QD) laser technology that make these pumps less power efficient, more expensive and limited in supply. In this paper we present a BDFA operating over the standardized part of the O-band with gain of more than 20 dB over 1255-1355 nm range (-20 dBm input signal power) and typical noise figure below 5.2 dB, pumped by a single commercial-of-the-shelf (COTS) high-brightness uncooled multimode laser diode via ytterbium doped fiber (YDF) based conversion stage. We demonstrated that the amplifier can operate over 20-70 ºC temperature range with overall power consumption similar to or better than SM diode pumped amplifier operating over half of the achieved bandwidth (Tab 1). We also confirmed that the amplifier is suitable for data transmission by amplifying 50 Gbaud/s PAM-4 signals from a pluggable module. To the best of our knowledge this is the first amplifier that can provide more than 20 dB gain over the 1255-1355 nm (17.6 THz) wavelength range and the first O-band amplifier pumped using a single MM laser diode. The results of previous relevant works are summarized in Tab. 1.

Tab. 1. Comparison of relevant BDFA works. Reviewed BDFAs have BDF length of 150-220 m.

Ref.	Wavelength range (nm)	> 20 dB G BW (THz)	P_{in} (dBm)	Peak G/ min NF (dB)	Pump type	Pump power into BDF (W)	Total LD+TEC PC (W)		
							20 ºC	45 ºC	70 ºC
1,2,7	1345-1460	17.6	-23	31/4.8	2×SM	0.85	N/R	N/R	N/R
3-5[M]	1280-1330	8.8	-20	23/5.5	2×SM	1	9	15	>39
TW	1255-1355	17.6	-20	29.3/4.6	1×MM	2	8.1	8.6	9.8

TW: this work; N/R: not reported; LD: laser diode; TEC: thermo-electric cooler; BW: bandwidth; G: gain; NF: noise figure; PC: power consumption, assuming 100% LD/TEC controller efficiency; M: if the parameter was not reported in the original publication, it has been measured (note, Refs.3-5 has been co-authored by authors of this paper).

2. Amplifier and fiber design

The amplifier consisted of a multimode uncooled pump laser diode (LD), pump wavelength conversion and O-band amplification stages (Fig.1A and B). YDF is used to convert the 915 nm output of a MM pump diode into SM 1150 nm wavelength to pump BDF. Around 30 meters of double clad OFS Yb 6/125 fiber was spliced between the high reflection (HR) and output coupler (OC) fiber Bragg gratings (FBG) written with 1 nm 3-dB bandwidth and

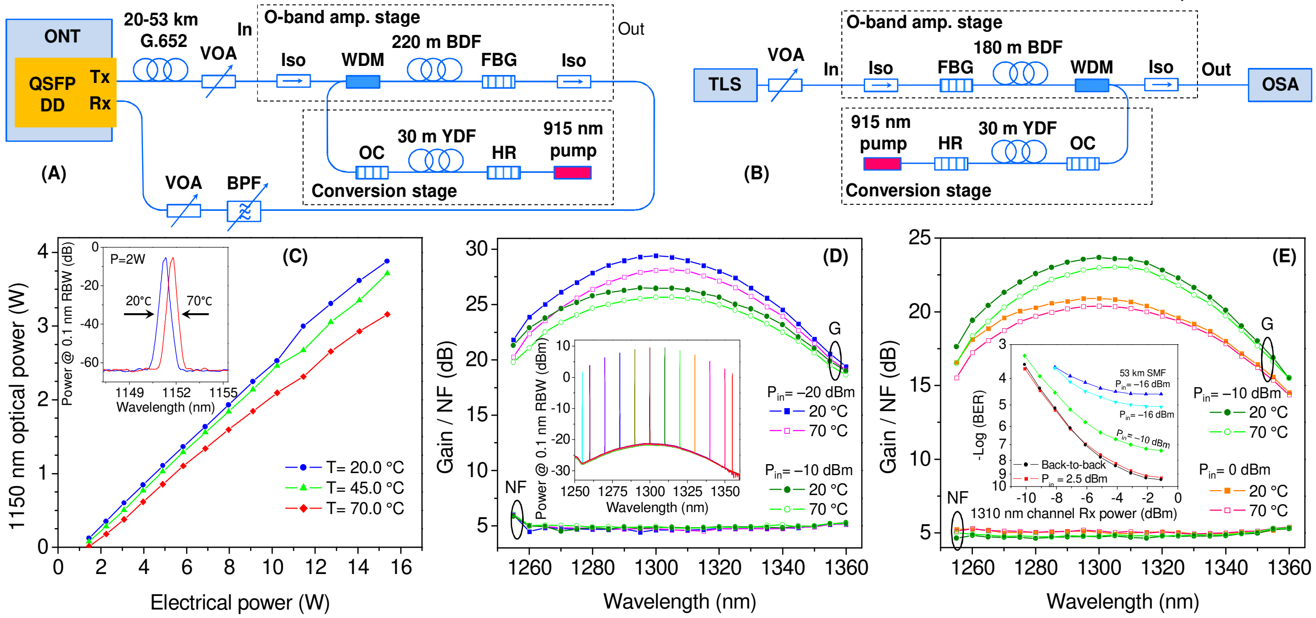

Fig 1. (A): Forward pumped BDFA and transmission setup; (B): Backward pumped BDFA and characterization setup; (C): Conversion stage output optical vs electrical power. Inset: Conversion stage optical spectra Pout=2W; (D): G and NF of forward pumped BDFA at -20 and -10 dBm input power. Inset: a set of BDFA output spectra for -20 dBm input power (0.1 nm resolution bandwidth (RBW)); (E): G and NF of backward pumped BDFA at -10 and 0 dBm input power. Inset: transmission results. WDM: multiplexer; ISO: isolator; VOA: variable optical attenuator; TLS: tunable laser; OSA: optical spectrum analyzer.

99.9% and 75% reflectivity respectively. A 915 nm 10 W rated MM pump laser was spliced directly to the HR grating. At 20 ºC the pump laser has a threshold current of 510 mA and an LI-slope efficiency of 0.88 that are degraded to 630 mA and 0.82 at 70 ºC. Relatively small laser performance reduction can be explained by selection of operation point below 50% of laser nominal range. The overall electrical to optical power conversion efficiency for the 20-70 ºC temperature range was 0.25-0.20 for 2W of 1150 nm power (Fig 1C). The conversion stage operates kink-free up to 2.25 W of output power and the kink is caused by pump laser power jump. To generate 2 Watts of 1150 nm power the pump LD current and voltage were 4.6 A and 1.77 V and 5.3 A and 1.84 V for 20 and 70 ºC respectively. The output spectra of the conversion stage at 2 W output power for 20 and 70 ºC is shown in inset of Fig 1C. The spectra have ASE level at 57 dB while there is also 0.5 nm temperature induced wavelength shift.

For O-band amplification we considered forward (220 m of BDF, Fig. 1A) and backward pumping (180 m of BDF, Fig. 1B) schemes for low noise and high-power applications respectively, with a single thin film filter based WDM and two isolators (iso). An additional FBG with 99% reflectivity at the pump wavelength is spliced opposite the WDM to prevent pump leakage and improve the amplifier gain and noise figure by approximately 1 dB and 0.3 dB respectively.

The O-band amplifier stage gain fiber is a bismuth-doped phosphosilicate glass core prepared by modified chemical vapor deposition (MCVD). Core and cladding diameters of the gain fiber are 8 µm and 125 µm respectively. The gain fiber numerical aperture is around 0.13 with cutoff wavelength at 1180 nm, providing single-mode operation in the O-band. The fiber loss at the pump wavelength (1150nm) is 0.3 dB/m measured by a cut-back method.

3. Amplifier characterization

Both forward and backward pumped BDFAs have <0.15 dB PDL and <0.3 ps DGD. To evaluate the BDFA gain and noise figure we used an ASE spectral interpolation method. As shown in Fig. 1A, the signal from a low-noise tunable laser source (TLS) was launched into the BDFA under test. At the output of the BDFA the optical spectrum was recorded using an optical spectrum analyzer (OSA) and gain and noise figure were computed. The 1150 nm pump power was set to 2W. Fig 1.D shows gain and noise figure for forward pumping BDFA. For -20 dB input signal power the BDFA demonstrated above 20 dB gain for the 1255-1355 nm (17.6 THz) bandwidth. The inset in Fig. 3 shows a set of output spectra for -20 dBm input signal power. The gain peak of 29.3 dB was at 1300 nm with the corresponding noise figure of 4.6 dB. Over entire range the noise figure was below 5.2 dB except for 1255 nm wavelength where the measured noise figure was 6 dB due to sharp WDM loss rise. For -10 dBm input power the gain was 2.7 dB lower and the noise figure 0.2 dB higher compared to -20 dBm input signal. When the amplifier temperature was increased to 70 ºC the gain peak shifted to 1305 nm, the gain was reduced by 1.1 dB maximum, and the noise figure was increased by 0.3 dB maximum across the wavelength range.

The backward pumped amplifier demonstrated maximum output power of 21 dBm at 1300 nm for an input power of 0 dBm with corresponding noise figure of 5.1 dB (Fig. 1E). The maximum thermal gain and noise figure degradation were 0.6 and 0.2 dB respectively.

To demonstrate that BDFA is suitable for data transmission we performed a real-time transmission experiment using 400 Gb/s LR4 QSFP-DD pluggable module with 10 km nominal distance. The module was inserted into an optical network tester (ONT) that generated 16x25 Gb/s 2^{31}-1 PRBS data lanes (Fig 1). Inside the module, lanes are converted to 4x50 Gbaud/s PAM signals and encoded onto 4 CWDM channels (1272, 1292, 1310, 1330 nm) using external modulators. This baud rate and modulation format were chosen due to their high sensitivity to noise. At the receiver side of the QSFP-DD, WDM channels were separated by optical filters with 38 nm 3-dB bandwidth and converted back into electrical OOK signals.

Firstly, we investigated the sensitivity of BDFA to conversion stage noise. Due to space limitations, we only present the forward pumping transmission results. We note that this pump scheme may be more susceptible to noise since pump and signal are propagated in the same direction. The impact of ASE was minimized by putting an external band-pass filter (BPF) with 1.1 nm 3-dB bandwidth in front of the QSFP-DD receiver. Note, while all four channels were amplified, in this experiment we only measured BER of 1310 nm channel, and therefore in this paragraph the power was measured only for the signal wavelength, while the total power was approx. 6 dB higher. 1310 nm signal power at the input of the BDFA was set to 2.5 dBm to further reduce ASE. The waterfall curves in inset of Fig. 1E for amplified and back-to-back (unamplified) transmission have small difference down to 5×10^{-10}, indicating that there is no noise associated with this pumping scheme. Inset of Fig. 5E also shows waterfall curves for -10 dBm BDFA input power at 1310 nm wavelength (Pin) and for Pin=-16 dBm with and without 53 km of G.652 fiber (loss 18.5 dB). The smooth waterfall curves are another indicator that the conversion stage noise is negligible. To prove that the amplifier is suitable for WDM amplification we removed the BPF and placed 20 km of G.652 fiber. The total input power into the BDFA was 0 dBm. The average BER for all four CWDM channels over 8 hours operation at 6 dBm receiver signal power was 2.5×10^{-6}.

4. Power consumption and summary

We demonstrated for the first time BDFA that can provide more than 20 dB gain over 17.6 THz bandwidth allocated over the standardized part of the O-band (1255-1355 nm) with peak gain and corresponding noise figure of 29.3 dB and 4.6 dB respectively. For 0 dBm input power, the backward pumped amplifier provides up to 21 dBm output power with 5.1 dB noise figure. For the first time O-band amplifiers were pumped by a single COTS MM 915 nm laser diode with electrical power consumption of 8.1 W at 20 ºC and 9.8 W at 70 ºC via an YDF conversion stage. Compared to previous works (Tab. 1), the electrical power consumption at 20 ºC is similar to SM laser diodes pumped BDFAs with >20 dB gain over 1280-1330 nm bandwidth (i.e. half of bandwidth demonstrated in this work), and 1.7 and > 3.5 times lower at 45 and 70 ºC respectively.

5. References

[1] Wang, N. K. Thipparapu, D. J. Richardson and J. K. Sahu, "Broadband Bismuth-Doped Fiber Amplifier with a Record 115-nm Bandwidth in the O and E Bands," 2020 Optical Fiber Communications Conference and Exhibition (OFC), 2020, pp. 1-3.

[2] Y. Wang, N. K. Thipparapu, D. J. Richardson and J. K. Sahu, "Ultra-Broadband Bismuth-Doped Fiber Amplifier Covering a 115-nm Bandwidth in the O and E Bands," in Journal of Lightwave Technology, vol. 39, no. 3, pp. 795-800, 1 Feb.1, 2021, doi:

[3] V. Mikhailov et al., "Amplified Transmission Beyond C- and L- Bands: Bismuth Doped Fiber Amplifier for O-Band Transmission," in Journal of Lightwave Technology, vol. 40, no. 10, pp. 3255-3262, 15 May15, 2022, doi: 10.1109/JLT.2022.3169172.

[4] Y. Wakayama et al., "400GBASE-LR4 Transmission Over Field-Deployed Fibre Link Supported by Bismuth-Doped Fibre Amplifier," 2021 European Conference on Optical Communication (ECOC), 2021, pp. 1-4, doi: 10.1109/ECOC52684.2021.9606147

[5] Y. Wakayama et al., " Over 90-km 400GBASE-LR8 Repeatered Transmission with Bismuth-doped Fibre Amplifiers," Accepted for publication at 2022 European Conference on Optical Communication (ECOC), 2022.

[6] A. Donodin, V. Dvoyrin, E. Manuylovich, L. Krzczanowicz, W. Forysiak, M. Melkumov, V. Mashinsky, and S. Turitsyn, "Bismuth doped fibre amplifier operating in E- and S- optical bands," Opt. Mater. Express 1, 127-135 (2021).

[7] Y. Ososkov, A. Khegai, S. Firstov, K. Riumkin, S. Alyshev, A. Kharakhordin, A. Lobanov, A. Guryanov, and M. Melkumov, "Pump-efficient flattop O+E-bands bismuth-doped fiber amplifier with 116 nm –3 dB gain bandwidth," Opt. Express 9, 44138-44145 (2021).

[8] F. Maes, M. Sharma, L. Wang, and Z. Jiang, "High power BDF/EDF hybrid amplifier providing 27 dB gain over 90 nm in the E+S band," in Optical Fiber Communication Conference (OFC) 2022, Technical Digest Series (Optica Publishing Group, 2022), paper Th4C.8.

[9] "IEEE Standard for Ethernet," in IEEE Std 802.3-2022 (Revision of IEEE Std 802.3-2018), vol., no., pp.1-7025, 29 July 2022, doi: 10.1109/IEEESTD.2022.9844436.