Simple Broadband Bismuth Doped Fiber Amplifier (BDFA) to Extend O-band Transmission Reach and Capacity

V. Mikhailov(1), M.A. Melkumov(2), D. Inniss(1), A.M. Khegai (2,3), K.E. Riumkin(2), S.V. Firstov (2), F. V. Afanasiev(4), M.F. Yan (1), Y. Sun(1), J. Luo (1), G.S. Puc (1), S.D. Shenk(1), R.S. Windeler (1), P.S. Westbrook (1), R.L. Lingle (1), E.M. Dianov (2), D.J. DiGiovanni(1)

1. OFS Laboratories, 19 Schoolhouse Rd., Somerset, New-Jersey, 08873, USA
2. Fiber Optics Research Center, Russian Academy of Sciences, 38 Vavilov St., Moscow, Russia
3. A General Physics Institute, Russian Academy of Sciences, 38 Vavilov St., Moscow, Russia
4. Institute of Chemistry of High-Purity Substances, Russian Academy of Sciences, 49 Tropinin St., Nizhny Novgorod, Russia
vmikhailov@ofsoptics.com

Abstract: We developed a simple silica-based BDFA with 80nm 6-dB gain-bandwidth flexibly centred within 1305-1325nm, and parameters comparable to EDFAs. The amplifier can extend 400GBASE-LR8 transmission (8×26.6 Gbaud/s PAM-4 channels) beyond 50 km of G.652 fiber.

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1. Introduction

O-band is extensively used for low cost data transmission. The advantage of O-band is that the transmitter wavelength(s) are located near the fiber's zero dispersion wavelength (λ_0), thus neither optical nor electronic chromatic dispersion compensation is required. Recently O-band transponder aggregate bit rate was increased to 425 Gb/s, for example by using 8 LAN WDM 26.6 Gbaud/s PAM-4 modulated channels [1]. The use of WDM and complex modulation format reduces both per-channel power at the receiver and receiver sensitivity, thus making optical amplification desired. Semiconductor optical amplifiers (SOA) can be used to boost O-band signals but they introduce significant distortion due to self- and cross- gain modulation [2] and although amplification of a large number dispersion broadened channels has been demonstrated [3], SOAs are not suitable for transmission of intensity modulation formats like PAM-4 operating near λ_0 with relatively small channel count. Praseodymium doped fiber amplifiers (PDFA) with 1280-1320 nm bandwidth were demonstrated [4], but they require non-silica host glass that makes PDFA complicated and expensive. Recently O-band amplification in Bismuth doped silica fibers has been studied in detail [5]. A 150 m long BDFA with 1320-1360 nm bandwidth was reported using complex dual wavelength pumping scheme with transmission of only 6×10 Gb/s OOK channels [6]. However, neither of these fiber amplifiers operates over the 1272-1310 nm wavelength range specified in the recent industry standards [1], nor has O-band amplified LAN WDM data transmission over 100 Gb/s capacity been demonstrated.

In this paper we present a simple single-stage Bi-doped silica fiber amplifier with more than 80 nm 6-dB gain bandwidth. The gain peak can be flexibly centered over 1305-1325 nm by pump wavelength selection. The amplifier has up to 19 dB gain, 20 dBm output power, 25% power conversion efficiency (PCE) and 5 dB noise-figure, similar to an EDFA of the same complexity. The amplifier can extend 425 Gb/s 400GBASE-LR-8 transmission (LAN WDM 8×26.6 Gbaud/s PAM-4 channels) to 50 km distance with 6×10^{-5} BER, below KP4-FEC limit (2.4×10^{-4} BER). We also showed that 4 long wavelength channels can be transmitted up to 81.5 km with BER 3×10^{-5}.

2. Fiber design and amplifier characterization

The core of the active fiber consisted of phosphosilicate glass doped with bismuth (<0.01 mol%) produced by using the MCVD process. A Heraeus F300 tube formed the cladding of the preform, while all components of the core including Si, P and Bi were deposited from the gas phase. The index difference between the fiber core and the cladding was approx. 6×10^{-3} and the cut-off wavelength was near 1.1 µm. Since 7 µm fiber core diameter provided good splice ability with silica-based fibers, standard splicer with automatic program was used to splice Bi- and G.652 fibers. To study emission properties, 80 meters of Bi-fiber was subsequently pumped by 1155, 1175, 1195, 1215 and 1235 nm pump lasers via a broadband 3 dB coupler (Fig. 1(a)), while results have been normalized to the loss of coupler, isolators and connectors. Fig. 1(b) shows ASE spectra for all five pump wavelengths at 275 mW pump power. In contrast to EDFAs there is a significant shift of ASE intensity peak with the pump wavelength at the rate of 0.5 nm per 1 nm pump. Each ASE spectra have 3 and 6 dB bandwidths of at least 60 and 85 nm respectively. Next, 1272-1380 nm 8 channels comb was used to characterize the fiber amplification. The dependency of gain (-2 dBm input power), saturated output power and PCE (10 dBm input power) from pump wavelength (pump power 400 mW) are shown in Fig. 1(c). The amplifier yielded 19-16 dB gain, 20 dBm saturated output power and 27-23% PCE for 1195-1235 nm pump wavelengths, while all parameters decayed sharply for shorter pump wavelengths.

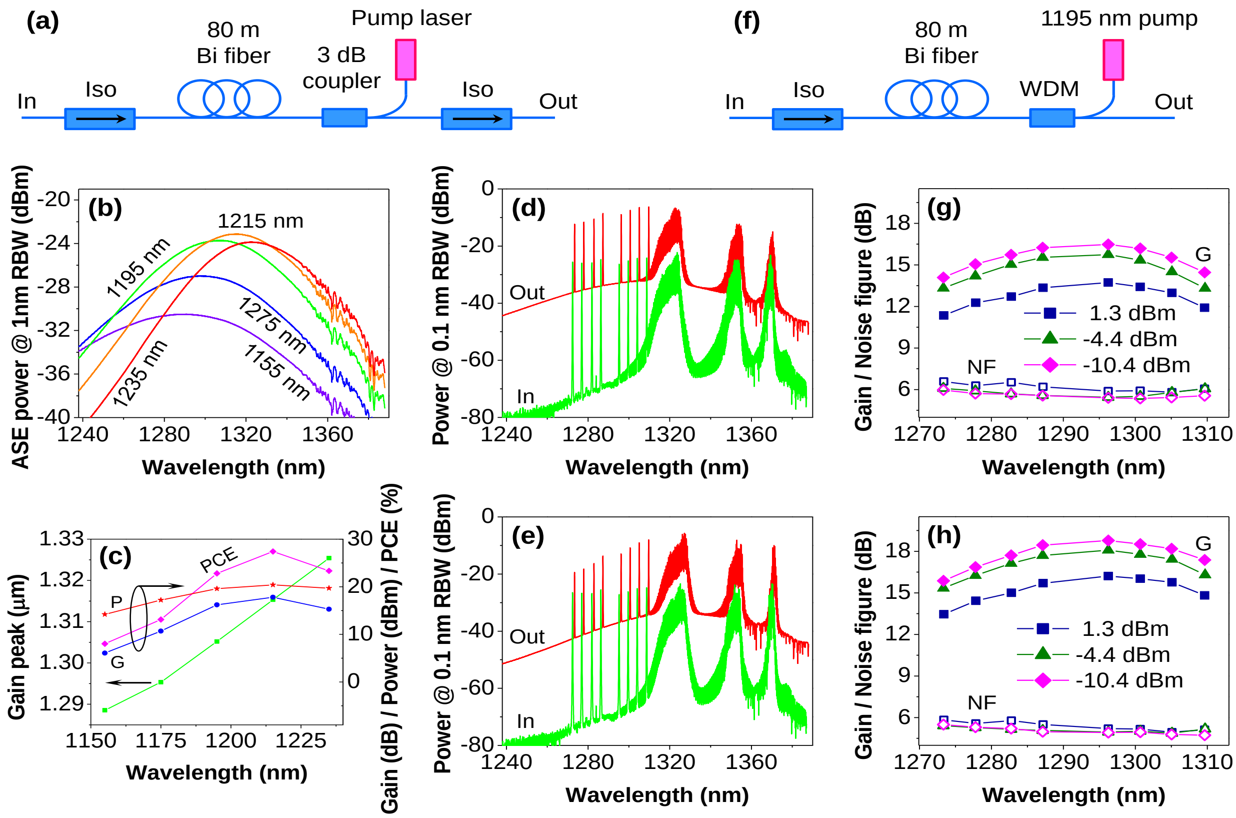


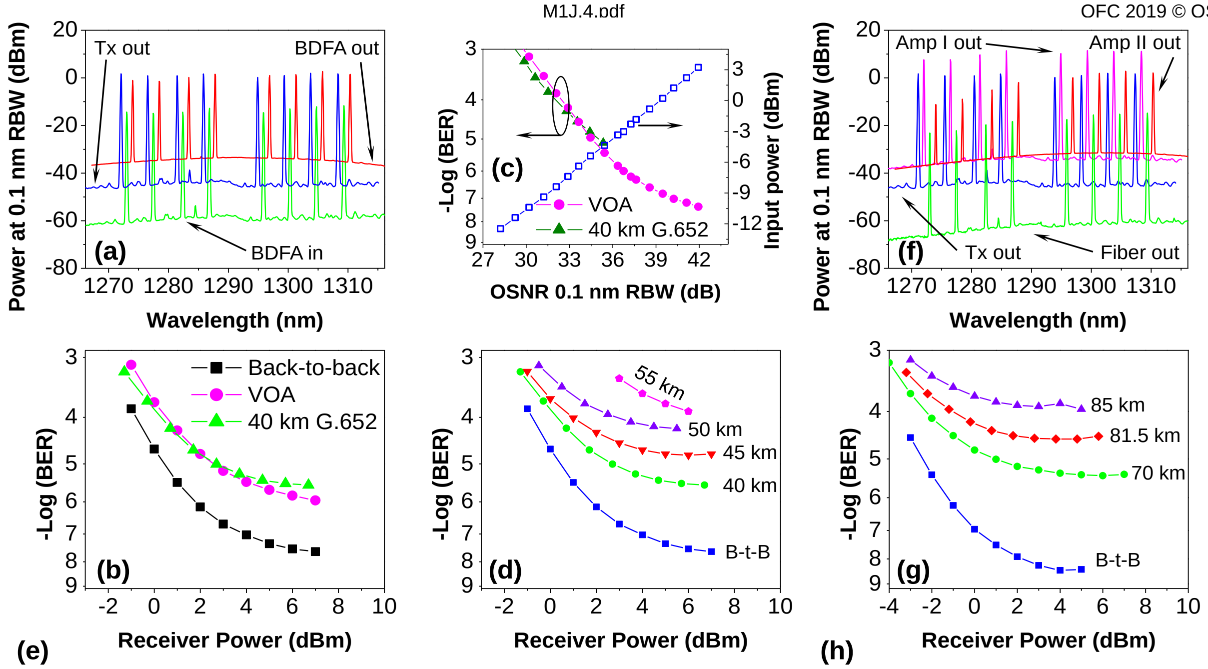
Fig. 1. (a) – Bi-fiber characterization setup. (b) – ASE spectra for 1155-1235 nm pump wavelengths. (c) – Gain peak position, gain (G), output power (P) and PCE as a function of pump wavelength. (d, e) – Spectra before and after amplification for 1195 and 1235 nm pump wavelengths respectively. (f) – BDFA scheme. (g,h) – BDFA gain and noise figure for a set of input powers at 500 mW (g) and 800 mW (h) pump power.

To measure gain bandwidth, we constructed 1272-1380 nm signal source by combining LR-8 transceiver and three Fabry-Perot lasers, since proper comb source was not available. The input (-6 dBm total power) and output spectra were measured for 1195, 1215 and 1235 nm pumps. The results are shown in Fig's 1 (d,e) for 1195 and 1235 nm pumps. As can be predicted, the gain peak coincides with ASE peak wavelength and for 400 mW pump power amplifier has at least 16 dB peak gain with 6 dB gain bandwidths exceeding 80 nm for all three pump wavelengths.

To amplify the LR8 signals we built a simple counter-pumped amplifier (Fig. 1(f)). WDM central wavelength was selected at 1272 nm to induce up to 4 dB loss at long wavelengths, while 1195 nm pump wavelength was chosen to increase the gain of the short wavelength channels. Fig's. 2(g,h) shows gain and noise figure (NF) at 500 and 800 mW pump power. Note since these measurements represent the performance of a complete amplifier results were not normalized to the components and connector loss. Over 1272-1310 nm wavelength range, the amplifier has maximum 19 dB gain, 2 dB gain flatness and 5 dB typical noise figure with 5.5 dB peak value at around 1272 nm.

3. Transmission performance over G.652 fiber

To evaluate the BDFA transmission performance a Finisar 400GBASE-LR8 transceiver and a Viavi ONT-604 tester were used. The tester generates 16×26.6 Gb/s 2^{31}-1 PRBS OOK data lanes at the transmitter side and detects BER for each of 16 receiver side lanes. The LR8 combines 16 OOK data lanes into 8×26.6 Gbaud/s PAM-4 channels and transmit them using the set of eight directly modulated lasers. At the receiver side, eight WDM channels are demultiplexed (filter width >4 nm), detected and converted into 16 digital signal lanes. The transceiver signal (11.7 dBm) was launched into 40-55 km of G.652 fiber (loss 0.33 dB/km @ 1310 nm, λ_0=1312 nm) or variable optical attenuator (VOA) and post amplified by the BDFA. Another VOA was placed after the BDFA to control power at the receiver. The optical spectra after the transmitter, 40 km fiber span and amplifier are shown in fig. 2(a). Note, a wavelength shift was added to increase visibility. The average fiber loss was 14.6 dB (incl. connectors) while short wavelength channels suffer up to 2 dB higher loss compared to the long wavelength channels. To make results more practical the pump power was restricted to 500 mW. Average BER as a function of signal power for 40 km transmission and 14.6 dB VOA are shown in Fig. 2(b). The power penalty at 2.4×10^{-4} BER (KP4-FEC threshold) was less than 1 dB for both VOA and fiber, while long-term (>8h) BER for 40 km distance was 5×10^{-6}. As seen from the table in Fig. 2(e), short wavelength channels have the highest BER and the channel's BER decreases with



(e)

Lane #	0	*1*	2	*3*	4	*5*	6	*7*
BER	3.4E-8	*5.8E-5*	2.5-8	*6.5E-6*	8.4E-9	*9.7E-6*	1.9E-9	*1.4E-6*
Lane #	8	*9*	10	*11*	12	*13*	14	*15*
BER	1.8E-9	*5.2E-7*	3.1E-9	*5.0E-7*	5.4E-10	*9.0E-8*	9.1E-11	*3.3E-8*

(h)

Lane #	8	*9*	10	*11*
BER	5.3E-8	*2.0E-5*	3.8E-8	*9.9E-6*
Lane #	12	*13*	14	*15*
BER	1.1E-8	*2.2E-6*	3.2E-10	*2.4E-6*

Fig. 2. (a) 40 km transmission spectra; note wavelength shift was added to increase visibility. (b) BER vs total receiver power for 40 km distance. (c) BER vs OSNR for 40 km distance. (d) BER vs power for 40-55 km distance; note 55 km was measured using BDFA pre-amplifier after the transmitter. (e) 40 km lane-by-lane BER. (f) 80 km transmission spectra; (g) BER vs power for 70-85 km distance. (h) 70 km lane-by-lane BER.

the wavelength. This can be explained by higher accumulated dispersion in the short wavelength channels, as well as 3 and 2 dB lower received power and OSNR respectively.

To investigate BER degradation from OSNR and estimate link loss margin (Fig. 2(c)) a VOA was inserted between the fiber and BDFA. The total receiver power was maintained at optimal 6 dBm level with 3 dB difference between best and worst channels. It can be calculated, that for transmitter power of 11.7 dBm and 40 km fiber span (14.6 dB loss) up to 6.8 dB loss can be added before KP4-FEC BER threshold is reached. It was possible to measure BER in all lanes for up to 55 km's (Fig. 2(d)), while the error floor increases with the distance to 1.3×10^{-4} level.

To further increase the span length, the signal was pre-amplified by another BDFA with the total output power of 20.8 dBm (pump wavelength and power are 1215 nm and 800 mW respectively). Only 8-15 data lanes were included in BER calculation while channels 1-4 where still transmitted as shown on the spectrum in Fig 2(f). Fig. 2(g) shows BER measurements for 70, 81.5 and 85 km lengths of G.652 fiber. The distance was again limited by performance of the short wavelength channels (Fig 2(h)) and measured 81.5 km long-term error floor was 3×10^{-5}.

In summary, we have presented a single stage 80 m long Bi-doped O-band fiber amplifier with 19 dB gain, 20 dBm output power, 5 dB noise figure and 25% PCE. The amplifier has more than 80 nm 6 dB bandwidth while the gain peak can be positioned between 1305-1325 nm by selecting the pump wavelength within 1195-1235 nm range. The single span amplified transmission distance for the signal from a commercially available 400GBASE-LR8 transceiver was 40-55 km for 425 Gb/s and 70-85 km for 213 Gb/s with measured BER below KP4-FEC limit. To the best of our knowledge, this is the first fiber amplifier operating over IEEE standardized part of O-band (1272-1310 nm) with parameters comparable or exceeding commercially available EDFAs of the same complexity.

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