A 16 m High Bismuth-Doped Fiber Amplifier Provides 47.9 dB Gain in E+S-band

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Abstract: We report a bismuth-doped fiber with high bismuth active center concentration and low unsaturable loss, demonstrating a record 16m E+S-band bismuth-doped fiber amplifier with 47.9dB gain and gain per unit length of 4.06dB/m at 1450nm.

1. Introduction

Bismuth-doped fiber (BDF) is currently widely regarded as a promising active medium for expanding transmission bandwidth and improving existing fiber data transmission capabilities due to its excellent ultra-wideband luminescence characteristics in near-infrared. The outside electrons of Bi atoms are highly susceptible to the external crystal field environment, which provides a prerequisite for bismuth atoms to exhibit different luminescence bands. Currently, the binding form and luminescence mechanism of bismuth active centers (BACs) cannot be fully clarified, but the widely accepted view is that low valence bismuth and oxygen defects together form the near-infrared BACs in silicate matrices. The binding form and luminescence range of BACs in silicate matrices can usually be tuned by co-doping with Al, P, and Ge elements, however effective methods have not been found to promote the conversion of bismuth atoms doped in fibers to specific BACs before completing fiber drawing, this due to the difficulty in controlling the valence state and binding form with surrounding substances of bismuth atoms in the high-temperature environment of fiber preparation [1]. Most of the bismuth atoms in BDF cannot be converted into BACs, which makes the gain efficiency of BDF still at a relatively low level so far and leads to the use of BDF with a length of over 100 m in relevant bismuth doped fiber amplifier (BDFA) before 2022 [2-4]. In addition, an increase in the concentration of BACs is also accompanied by a significant increase in unsaturable loss (UL), which instead leads to a decrease in gain efficiency [5, 6]. This is also one of the main limitations for the increase of BACs concentration in BDF. How to achieve high BACs concentration with low UL in BDF is an important and unresolved challenge. Recently, the usage length has been shortened to 35-50 m by increasing the concentration of BACs in BDF without significant UL deterioration, the absorption and UL at 1310 nm were 1.16-1.25 dB/m and 15.5-16.1%, respectively [7, 8]. The maximum gain reported of ~40 dB and a gain per unit length of ~1.14 dB/m were obtained through a double-pass amplifier scheme and 35 m BDF [7]. However, BDFs with higher BAC concentration and lower UL have not been reported so far.

In this paper, we report a BDF with high BACs concentration and low UL, the 1310 nm absorption and UL were 3.27 dB/m and 10.2%, respectively. 16 m in-house BDF was used to construct two simple amplification schemes: single-pass and double-pass, to demonstrate the gain performance of the in-house BDF fully. To the best of our knowledge, this is the first BDFA that can provide more than 47 dB gain at 1450 nm and uses only 16 m in-house BDF. The maximum gain per unit fiber length was up to 4.06 dB/m at 6 m BDF, more than 3.5 times the reported record of previous relevant works [7].

2. Properties of the BDF

The BDF used in this paper was prepared by the modified chemical vapor deposition (MCVD) combined with the solution doping technique. The core/cladding diameter of BDF was set to 8/125 μm during the drawing process. The refractive index difference (Δn) was measured by PK2650 Preform Analyzer (Photon Kinetics Inc., USA) as ~0.007, and the contents of GeO_2 and Bi element were measured by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS, Agilent 7850) was 7.5 wt.% and 0.12 wt.%, respectively. The absorption of 1310 nm was tested according to the cutback method by PK2500 Fiber Analyzer (Photon Kinetics Inc., USA) as 10.2 dB/m, the UL at 1310 nm was measured by adequate pumping and calculated to be 10.2%. The cutoff wavelength of the fiber was measured to be around 1160 nm.

3. Experimental Setup

Two different amplification schemes of single-pass and double-pass were set up as shown in Fig. 1(a) and (b), respectively. It should be explained that the input signal power, pump conditions and fiber length are consistent in the two amplification schemes. For the experimental setup of the BDFA, a 7-channel comb-like signal source covering 1390 nm to 1510 nm with ~20 nm spacing as a signal source and the power of each channel can be controlled independently. Before the gain test, the output power of the signal source needed to be adjusted to ensure that the total input signal power entering the BDF was regulated as -20 dBm and the input power of the 7 wavelengths remained basically consistent. Isolators were placed at the output port of the light source and the input port of optical spectrum analyzer (OSA), respectively, to protect the testing instruments. The OSA (the resolution is set to 0.2 nm) was used to record the signal spectrum and calculate the gain and noise figure (NF). A thin-film-filter wavelength division-multiplexer (TFF-WDM) was used to separate and combine the signal light and pump. A 1360 nm laser diode (LD) was used to provide forward pump. The same 16 m BDF was used in both single-pass and double-pass schemes. Compared with the single-pass scheme, two circulators were added in the double-pass scheme to amplify the signal light through the BDF twice, so as to improve the overall gain.

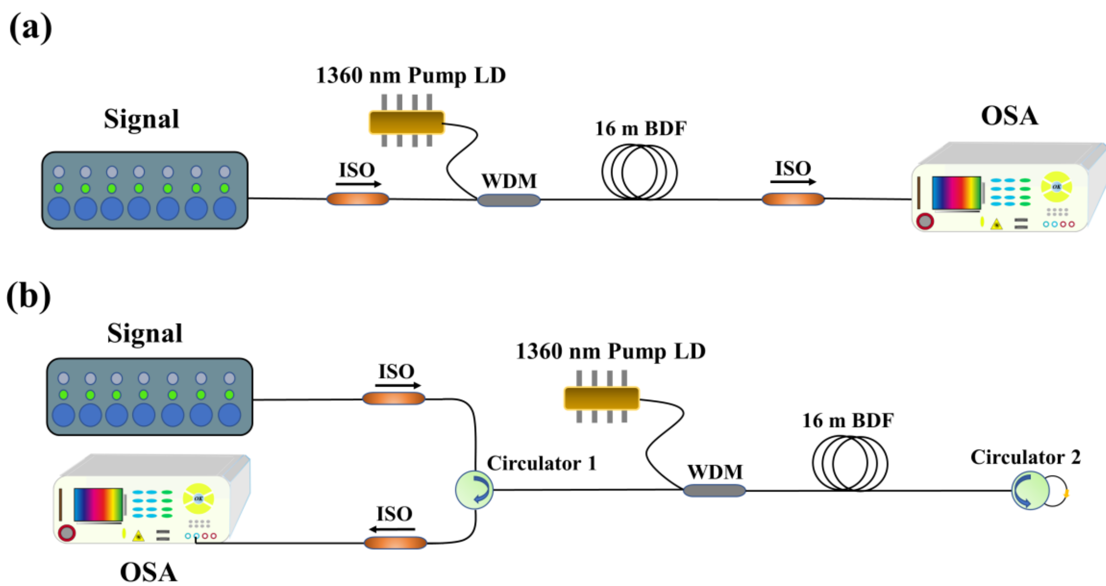

Fig. 1. Experimental Setup of the BDFA: (a) Single-pass scheme; (b) Double-pass scheme.

4. Results and discussion

The gain and NF of BDF in the range of 1390~1510 nm under the single-pass and double-pass schemes were tested firstly when the input signal power, pump power and fiber length were kept at -20 dBm, 590 mW and 16 m respectively, as shown in Fig. 2(a). The maximum gain of the single-pass scheme at 1430 nm was 38.7 dB, and the corresponding NF was 3.7 dB. When the double-pass scheme was adopted, the maximum gain wavelength was red-shifted to 1450 nm due to the reabsorption of the signal light. At this time, the maximum gain increased to 47.9 dB and the corresponding NF was 6.1 dB. The maximum gain and NF increased by 9.2 dB and 2.4 dB, respectively. This result indicates that both signal light and amplified spontaneous emission have been further enhanced in the double-pass scheme compared to the single-pass scheme. In order to demonstrate the gain per unit pump of BDF, we tested the gain performance of the BDF variation with pump power under the double-pass scheme, as shown in Fig 2(b). It can be seen that the gain at 1450 nm was always higher than that at 1430 nm under different pump powers. By calculating the maximum curve slope, the maximum gain per unit pump at 1450 nm was 0.2 dB/mW under the input signal of -20 dBm and double-pass scheme.

Then, the power conversion efficiency (PCE) variation with input signal power under the two schemes was tested. During the calculation of PCE, the output signal power was the result of eliminating the amplified spontaneous emission power in the total output power as much as possible. With the increase of input signal power, it can be observed that PCE increases monotonously in both schemes. When the input signal power was 12.3 dBm, the PCE was 14.1% in single-pass and 23.6% in double-pass. Next, we measured the gain performance of the two schemes under different fiber lengths, and calculated the gain-to-length ratio for each test length. It can be seen that with the increase of fiber length, the gain increased gradually and reached the maximum at ~16 m. The gain per unit length decreased with the increase of the length, and reached the maximum at ~6 m, which was 3.41 dB/m and 4.06 dB/m in the single-pass and double-pass schemes, respectively. It is worth noting that the gain efficiency per unit length of 4.06 dB/m is more than 3.5 times that reported record this year.

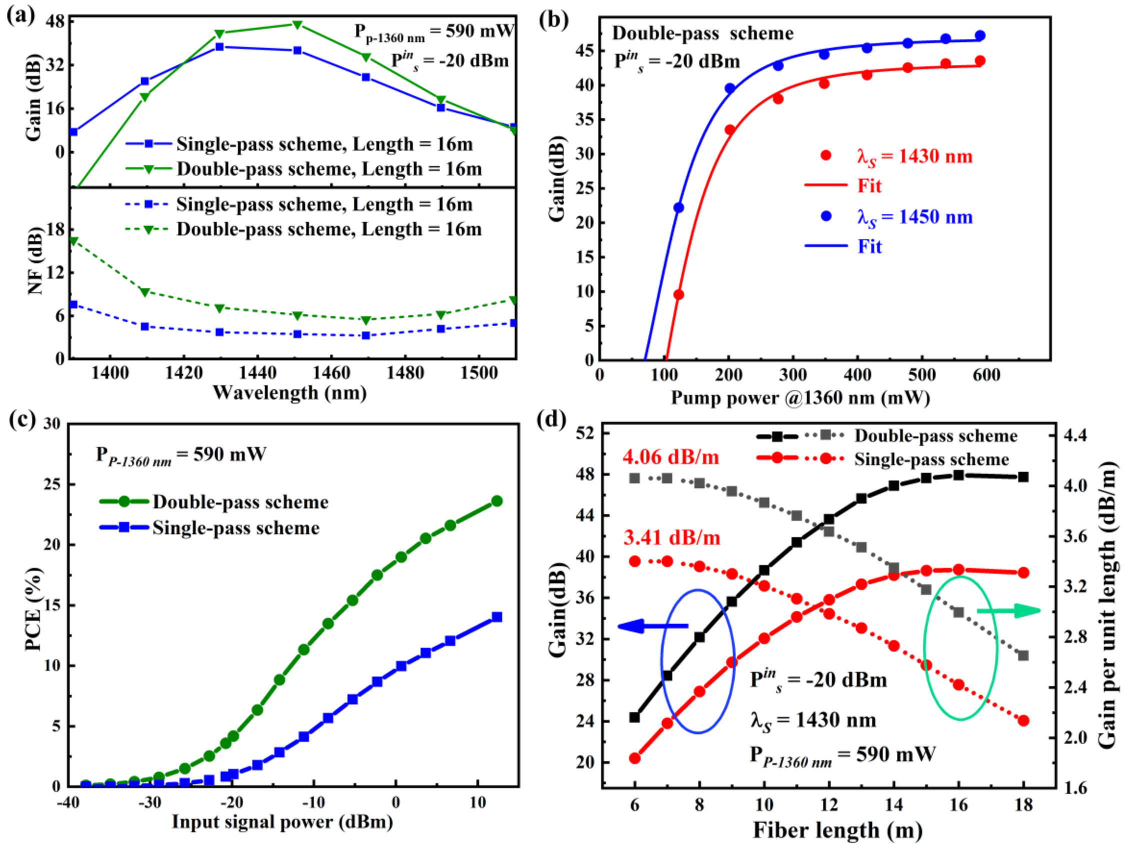

Fig. 2. (a) Gain and NF spectrum for a -20 dBm signal at two amplification schemes; (b) Gain with various pump power for a -20 dBm input signal power at 1430 nm and 1450 nm under the double-pass scheme; (c) Relationship between PCE and input signal power for two amplification scheme; (d) Gain and gain per unit length variation with length for a -20 dBm input signal power at two amplification schemes.

5. Conclusion

This work reports a BDF with high bismuth active center concentration and low UL, a single-pass amplifier and a double-pass amplifier were constructed using the 16 m BDF to demonstrate its high-efficiency E+S-band amplification. For a -20 dBm input signal, the gain at 1430 nm was 38.7 dB and the unit length gain was 3.41 dB/m in the single-pass scheme. In the double-pass scheme, the gain at 1450 nm and unit length gain were up to 47.9 dB and 4.06 dB/m, respectively. Through the in-house BDF, we have created multiple records simultaneously including the shortest length, maximum gain, and maximum gain per unit length. We also believe that this work opens important prospects for the high gain efficiency and integration of BDFA. It is expected that there is still foreseeable space for optimizing the preparation process of BDF to further increase the concentration of BACs and reduce UL.

6. References

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