O-Band Bismuth-Doped Fiber Amplifier With Double-Pass Configuration

S. F. Norizan, W. Y. Chong, S. W. Harun, and H. Ahmad

Abstract—**A Bismuth-doped fiber amplifier (BDFA) in a double-pass configuration is proposed and demonstrated. The BDFA consists of a Bismuth-doped phosphogermanosilicate (BiPGeSiO2) fiber pumped by a Titanium–Sapphire source at 810 nm. The BDFA has an amplified spontaneous emission (ASE) spectrum with a 3-dB bandwidth from 1220 to 1490 nm. The maximum gain of the proposed BDFA is 2.0 dB at an input signal wavelength of 1340 nm and is a gain enhancement of 100% over a similarly configured single-pass BDFA. The proposed BDFA has a higher gain enhancement of 1.7 dB at low input signal powers but decreases to as low as 0.5 dB as the input signal power increases.**

Index Terms—**Bismuth-doped-fiber, double-pass, O-band, Ti-sapphire.**

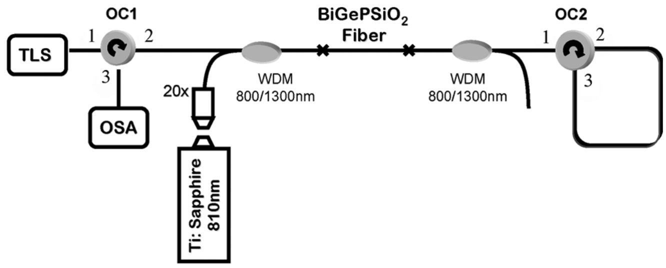

Fig. 1. Experimental setup of Bismuth-doped fiber amplifier in a double-pass configuration.

I. Introduction

INCREASING demands for telecommunication bandwidth has resulted in substantial research efforts towards extending the current telecommunication windows from the 1550 nm wavelength band towards the 1310 nm region, where silica fibers exhibit zero dispersion characteristics. A key focus is the development of fiber amplifiers capable of operating in the 1310 nm region [1] and subsequently broadband fiber amplifiers covering the entire optical fiber transmission bands [2]. With the recent introduction of Fiber-to-the-Home (FTTH) that operates with wavelengths at 1550, 1490 and 1310 nm, there is an immediate need to have a low-cost amplifier to support future requirements. Currently, amplifiers in this range are based on Pr-doped halide glasses [3] that are quite difficult to handle and cannot be spliced to standard telecommunications fibers. The other important issue is concerning the hydroscopic nature of fluoride fibers, which is a serious problem for countries within the equatorial region. As such, a new type of fiber is required such as Bismuth Oxide (Bi_2O_3) doped in silica fibers.

Bi_2O_3 is a potential candidate for providing amplification in the 1310 nm region due to its broadband near-infrared luminescence as reported in reference [4] for the case of $92SiO_2 \cdot 7.0Al_2O_3 \cdot 1.0Bi_2O_3$ (SAB) glass when exited at 808 nm. It has a broad fluorescence covering a wavelength range of 1100 to 1700 nm [4], [5]. Furthermore, the broad emission band of the Bismuth Doped Fiber (BDFs) covers the O-, E-, S-, C- and L-band (1260–1620 nm) [6], [7] allowing for the possible development of fiber amplifiers that covers a broad spectral region. The absorption spectra of various bulk glasses doped with Bi in combination with Al are presented by broad bands at wavelengths of 300 (for silicate glass), 500, 700, 800, and 1000 nm [8]. Although BDFs exhibit broad luminescence in the Near-Infrared (NIR) region, Exited State Absorption (ESA) as well as unsaturated pump absorption limits the available gain [9]. Various approaches have been put forward to overcome these problems, including the use of different excitation wavelengths [10] and active cooling of the fiber [11]. While these approaches have met with limited success, O-band signal gain of more than 13 dB is reported using BDF excited at 1230 nm [12]. This reporting could be the gain achieved due to a combination of Raman amplification and bismuth centre emissions. Earlier work indicated a net gain of about 1 dB with similar configurations, whereby the pump wavelength and amplification wavelength band is about 100 nm away [13]. It will be cost-effective for Bismuth-based optical amplifiers to be pumped using low cost laser diodes such as those at 800 nm.

In this letter, we report a gain of 3 dB using a double-pass configuration [14]–[17] for the case Bismuth Doped Fiber Amplifiers (BDFAs). This is a cost-effective approach and allows a compact unit to be realized. The double-pass configuration shows an improvement in the gain performance as compared to a single-pass setup. The characteristics of BDFA for different excitation powers, signal input powers and signal wavelengths in the O-band are studied.

II. Experimental Setup

The experimental setup of the double-pass BDFA is shown in Fig. 1. It resembles a fundamental fiber amplifier setup with two additional optical circulators to facilitate the amplifier input/output (OC1) and as a reflector (OC2). Port 1 of OC1 is connected to an O-band Tunable Laser Source (TLS) with a wavelength tuning range between 1260–1360 nm, while port 3 of OC1 is connected to an Optical Spectrum Analyzer (OSA) for

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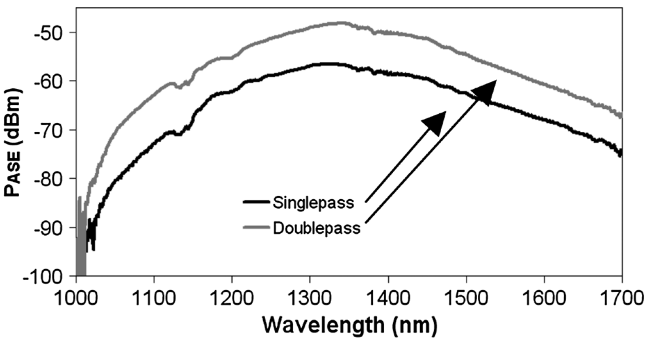

Fig. 2. ASE spectra of single- and double-pass BDFA.

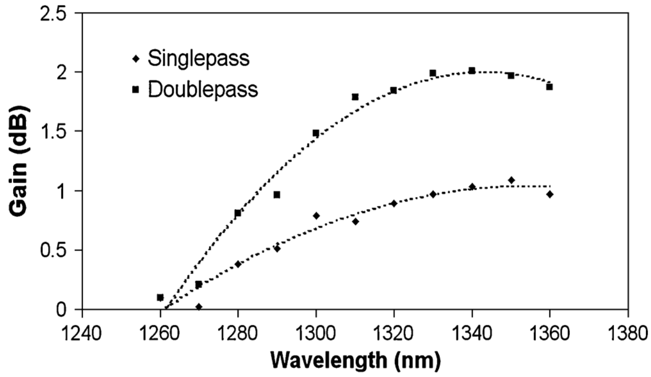

Fig. 3. Signal gain for single- and double-pass BDFAs at different signal wavelengths.

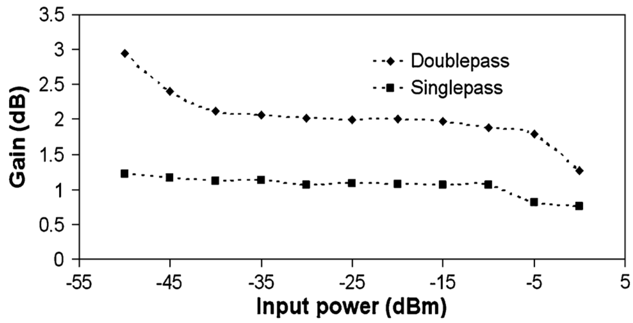

Fig. 4. Signal gain of the single- and double-pass BDFAs at different input powers.

signal analysis. OC2 is configured to loop the optical signal from the output Wavelength Division Multiplexer (WDM) back into the BDFA by connecting Port 2 to Port 3. The excitation source used is a Titanium Sapphire (Ti: Sapphire) laser operating at wavelength 810 nm. The excitation source output is directly coupled into the input of the WDM using a 20X magnification objective lens.

The direct coupling of the excitation source into the WDM minimizes the fiber mode mismatch as compared to when the excitation source is coupled into a separate fiber. The coupling efficiency is more than 60%. A 4 m Bismuth doped phospho-germanosilicate $(\mathrm{BiPGeSiO_2})$ fiber with core and cladding diameters of 8.3 μm and 110 μm respectively is used as the active fiber. The core and cladding diameters were measured using Image-J image analysis software. The signals generated by TLS are coupled into the amplifier configuration through Port 1 of OC1. The signal and excitation beam are coupled into the BDF via the WDM coupler. At the end of the BDF the second WDM coupler splits the signal and excess excitation power. The excess pump is measured using optical power meter while the signal is looped back into the BDF through OC2. Due to a 1 dB insertion loss induced by OC2, the reflection of the optical circulator is limited to 80%. The amplified signal emerging from Port 3 of OC1 is analyzed using the OSA.

III. Results and Discussion

Fig. 2 shows the Amplified Spontaneous Emission (ASE) spectra of the BDFA from a single- and double-pass configuration. The OSA resolution is set at 2 nm [18] and the excitation power is fixed at 360 mW for both cases.

Both the single- and double-pass configurations exhibit a similar ASE profile. The peak power level of the double-pass BDFA is -48 dBm at 1340 nm, which is 8 dB higher than that of the single-pass. The 3 dB bandwidth for the double-pass BDFA ASE is about 270 nm, stretching from 1220 to 1490 nm. The ASE bandwidth is limited by the transmission windows of the optical circulators; the 3 dB bandwidth of the ASE is expected to be wider if optical circulators with broader flat transmission ranges are used.

The signal gain of the BDFA is measured by comparing the signal power with and without the presence of excitation source as given in [19]. The signal gain for single- and double-pass BDFA at different signal wavelength is shown in Fig. 3. The input signal power and excitation power are set at -30 dBm and 270 mW respectively. The maximum signal gain is obtained at 1340 nm with 1.0 dB for single-pass and 2.0 dB for double-pass. The double-pass BDFA shows a 1 dB gain improvement over the single-pass BDFA between 1310 nm to 1360 nm.

The longer measurement wavelength range is limited by the TLS that has tuning range from 1260 nm to 1360 nm only. The gain enhancement as a result of the double-pass configuration reduces below 1260 nm, which is largely due to the transmission behavior of OC2. Therefore, the gain enhancement in the shorter wavelength is limited by the transmission bandwidth of the components used in the configuration.

The study of the gain characteristic at different input power levels is important as to understand the dynamic behavior of the BDFA. The gain of the BDFA at different signal input power levels are measured at an input signal wavelength of 1340 nm and this is shown in Fig. 4.

The gain of the single-pass configuration is about 1.2 dB from an input signal level of -40 to -10 dBm. For the double-pass, the gain is about 2.2 dB in the same input power range, giving a gain enhancement of 1 dB. Taking an input power level of -50 dBm, a gain enhancement of 1.7 dB is achieved, whereas at a high input signal level of 0 dBm, the gain enhancement is only 0.5 dB. The larger gain enhancement obtained at the small signal is due to the low extraction of energy from the gain medium in the first-pass and hence there is still energy stored in the form of the population inversion that is made available for the second-pass in the case of the double-pass BDFA. On the other hand, at higher input signals, the reduction of the gain enhancement

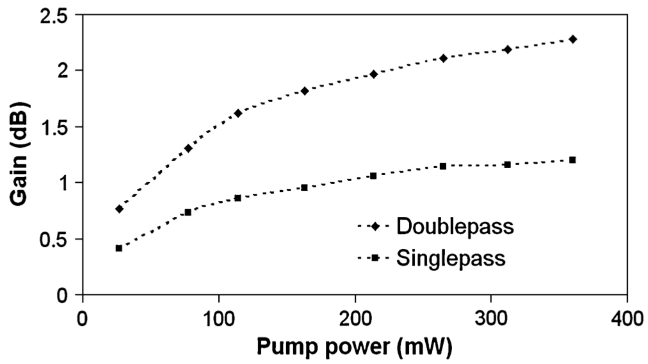

Fig. 5. Signal gain against input pump power of the BDFA.

is due largely to the less energy available for extraction in the second-pass, which is due to the gain saturation.

The signal gain variation against the pump power is shown in Fig. 5 taken at a signal wavelength of 1340 nm with an input power level of −30 dBm.

Gain enhancement increases from 0.4 dB to 1.1 dB as the pump power increased from 27 mW and 360 mW. A higher gain enhancement can be achieved with a longer length BDF, which in our case is limited to 4 m only. As reported in the single-pass gain study, a longer BDF length will give a higher gain [10]. As a summary, in this demonstration of double-pass configuration, a gain enhancement by as much as 1 dB can be achieved, which is an improvement of 100% for small signals. The gain can be further improved by having a longer length BDF. This is the first demonstration of gain improvement in a BDF using the double-pass technique.

IV. Conclusion

A $BiPGeSiO_2$ fiber amplifier in a double-pass configuration is demonstrated. A wide ASE spectrum with a 3 dB bandwidth from 1220 to 1490 nm is obtained when the BDFA is pumped at 810 nm. A maximum gain of 2.0 dB is obtained for a 1340 nm input signal, giving a gain enhancement of 100% over a single-pass configuration under similar circumstances. The double-pass configuration also exhibits a higher gain enhancement of 1.7 dB at lower input signal powers, but reducing to only 0.5 dB at high input signal powers. Increasing the pump power or using a longer BDF length can improve the gain enhancement.

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