Highlights

Multipass Amplification of Linearly-Polarized Signal in O-band Based on Non-Birefringent Bismuth Doped Fiber

- First experimental demonstration of an all-fiber 4-pass amplifier
- In the context of Bismuth Doped Fiber Amplifier, we have compared 2-pass and 4-pass configuration
- 4-pass configuration offers the best performance in term of gain (35.2 dB gain has been reached) at low wavelength of 1310 nm with a pump power limited to 165 mW
- 4-pass configuration provide a high power conversion efficiency for low input power: 16.7% for an input power -15 dBm.

Multipass Amplification of Linearly-Polarized Signal in O-band Based on Non-Birefringent Bismuth Doped Fiber

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Abstract

We present a multipass Bismuth-Doped Fiber Amplifier (BDFA) design delivering a linear polarization state with a home-made non-polarization maintaining Bismuth-Doped Fiber (BDF). The BDFA can operate in 2-pass or 4-pass configuration. The performances of both configurations operating at 1310 nm highlight that the gain, the optical-to-optical power conversion efficiency and the output power are higher with the 4-pass amplifier. To the best of our knowledge, this is the first experimental demonstration of such an all-fiber 4-pass amplifier. This configuration with a unique pump laser diode allows to reach a high gain of 35.2 dB and a high conversion efficiency of 16.7% for an input power of -25 dBm and -15 dBm, respectively.

Keywords: Bismuth doped fiber (BDF), Bismuth doped fiber amplifier (BDFA), Polarization Maintaining, Multipass Amplifier

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1. Introduction

Following the report of Murata et al. [1] in 1999 on the extremely broadband spectral emission of a Bismuth-doped glass, Bismuth-doped silica fibers have established themselves as a credible complement to rare-earth-doped silica fibers, particularly in spectral windows not covered by the latter, such as in the O-band (1260-1360 nm). Driven by the needs of the Telecom market, numerous groups have conducted work on Bismuth-Doped Fibers (BDF) to understand their spectroscopic properties for different core glass compositions and improve their amplification properties in the O-, E- (1360-1460 nm) S- (1460-1530 nm) and U- (1625-1675 nm) bands. For instance, one can cite the work by Thipparapu et al. reporting in 2019 a high gain of 39 dB at 1360 nm in a double-pass amplifier architecture [2]. An extremely high gain of 41.8 dB at 1325 nm was also presented by Wang et al. in 2023 for a total pump power of 1050 mW and an input signal power of -34 dBm [3]. In 2024, a group from OFS laboratories proposed an interesting design in which a 915 nm multimode diode was used as a primer pump. With this design a maximum gain of 29.3 dB at 1300 nm was reached [4]. In 2025, our group also reported the achievement of a gain up to 29 dB for a ~~total~~ input signal of -20 dB in the first half of the O-band (1280-1320 nm) [5]. This work was based on a homemade BDF presenting a limited non-saturable absorption. While these results are very promising, the technology based on BDF still suffers from different drawbacks like a low Power Conversion Efficiency (PCE), the lack of Polarization-Maintaining (PM) fibers or the cost of the used technology.

All the above-mentioned works are based on non-PM fiber and, to the best of our knowledge, only one group reported on a Polarization-Maintaining BDF (PM-BDF) [6, 7]. The lack of PM fiber or at least of PM gain section may be a limiting factor for some applications like laser development (non-PM designs makes them theoretically environmentally sensitive), nonlinear frequency conversion or nonlinear microscopy. Besides this, the power consumption of an amplifier is a relevant criterion, especially for space and submarine applications for which the input power is usually low. The optical-to-optical conversion efficiency of Bismuth-Doped Fiber Amplifiers (BDFA) operating in the O-band is generally around 3 to 5% in a single-pass amplifier design for a moderate input power of -10 dBm [8]. This PCE is low compared, for example, to that of co-doped Erbium/Ytterbium fiber amplifiers for which it can reach up to 32% [9]. So as to improve the PCE value of BDFA, one can use multipass or multistage approaches similarly to what has been done for EDFA [10]. For instance, it has been demonstrated that using a 2-pass amplifier architecture, the PCE value increases from 0.3% to 13.7% [2]. For a fiber amplifier, up to four passes can be made along the same gain fiber by taking advantage of the propagation direction and polarization characteristics. Nevertheless, to date, only one paper reports an experimental proof of such a concept [11]. In this case, the amplifier is built with some free-space elements making it less robust. Moreover, the free-space coupling induces also high loss leading to a PCE smaller than for a 2-pass amplifier. Simulations however show that the PCE can go up to 91% with the 4-pass design without losses. Regarding the wall-plug efficiency (WPE), the value drops then down to 0.02% [4]. Mikhailov et al. proposed then an efficient design based on YDF conversion stage pumped by a multimode 915 nm laser diode. The WPE value with this amplifier design is 0.1%. The pump power conversion stage is a laser at 1150 nm that requires a double cladding splice (making the design more complex to manufacture compared to the one based on a standard single mode pump) making the design more complex to manufacture than the one based on a standard single mode pump. This complexity might be a bottleneck for a ~~large~~ production context. The low PCE of BDFA in O-band has led the researchers to use one to two pump diodes emitting 700 mW average power around 1240 nm [3-5]. These diodes are so far the most expensive part of the O-band BDFA and make the technology less attractive than Praseodymium-Doped Fiber Amplifiers (PDFA) that are pumped with standard pump diodes emitting at 976 nm. In this context, the use of a unique low power pump diode emitting at 1240 nm appears a relevant approach. With this mindset, Khegai et al. achieved 18.5 dB gain at 1310 nm using 250 mW average-pump power at 1256 nm together with a low OH BDF [12].

In the present paper, we report on a BDFA design that circumvents the non-PM, low-efficiency, cost-efficiency drawbacks of the BDFA technology. For that purpose, an all-fiber multipass amplifier was designed using a single pump diode, a home-made non-PM BDF, a Polarization Beam Splitter (PBS) as the input/output coupler and a Faraday Mirror (FM). The standard setup is a 2-pass amplifier architecture but by adding a circulator looped on itself at the output of the amplifier, it has been extended to a 4-pass amplifier. The performances of these two configurations are compared in terms of gain, PCE and output power. To the best of our knowledge, this is the first experimental demonstration of an all-fiber 4-pass amplifier adapted to the amplification of a linearly-polarized signal.

2. Experimental setup

The experimental setup of the amplifier is shown in Figure 1. It is inspired by the linear architecture that has already been reported but to our knowledge never been published [11]. The signal is produced by FBG-stabilized laser diodes operating at 1310 nm. Light is injected through a circulator to protect from feedback for both configurations and extract the amplified signal in the 4-pass configuration. The signal is then injected into the amplifier via a PBS with a polarization extinction ratio of 28 dB. The different passes in the gain medium are respectively depicted in Figure 1.a and Figure 1.b for the 2-pass and 4-pass configuration.

The passes inside the amplifier are differentiated according to the polarization states for the 2-pass amplifier (the first pass and the second pass are cross-polarized) and to the polarization state (the first/third pass and the second/fourth pass are cross-polarized) and the propagation direction for the 4-pass amplifier. The polarization of each pass is controlled by the

PBS and the FM. This component induces a polarization rotation of 90° (with a rotation tolerance of 2°). Therefore, the part of the light that propagates linearly-polarized along one axis towards the FM comes back cross-polarized and vice versa. The small linear birefringence of the non-PM fiber and thus the optical path difference between the two components of polarization are then fully compensated after the backpropagation through the fiber (assuming that there is no non-reciprocal effect along the optical fiber [13]).

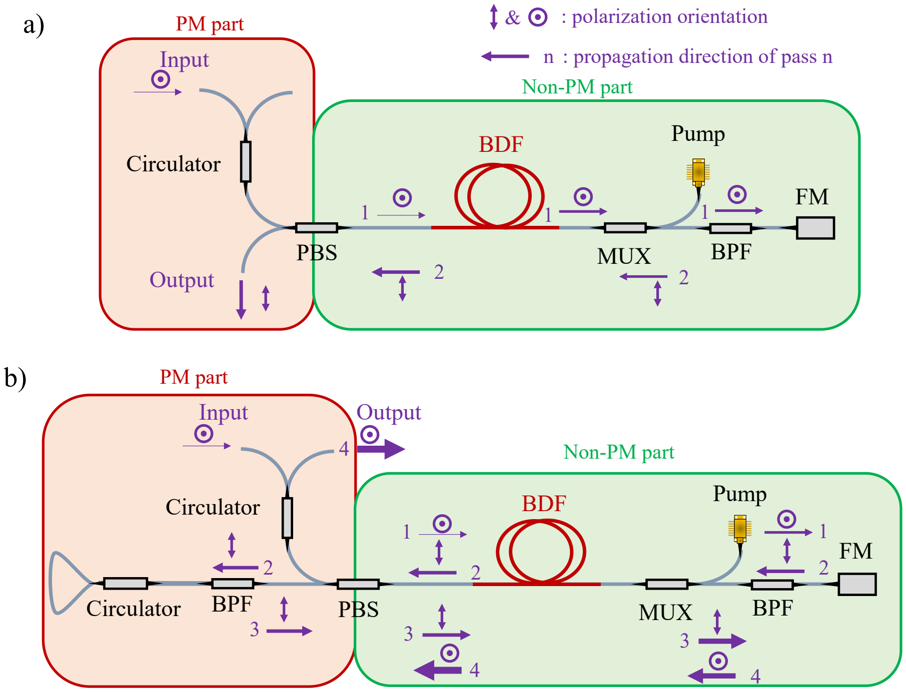

Figure 1: Experimental setup of the proposed BDFA for (a) the 2-pass configuration and (b) the 4-pass configuration.

Another theoretical advantage of the use of FM is the cancellation of environmental sensitivity because any change in linear birefringence induced by environmental effects like temperature or mechanical stress is compensated after a round trip in the amplifier [14]. This point was not analyzed in the present case, even though we observed good reproducibility of results from one day to the next. The gain medium is a 283 m long home-made non-PM BDF with core diameter of 7.6 µm and Numerical Aperture (NA) about 0.13. It was drawn from a preform made by Modified Chemical Vapor Deposition (MCVD) method with all-gas phase deposition, including for Bismuth doping. The core is made of phosphosilicate glass and exhibits an absorption of 0.16 dB/m at 1240 nm. The fiber is pumped at 1240 nm with 430 mW power delivered by an FBG-stabilized laser diode and injected through a pump signal Wavelength Division Multiplexer (WDM). The BDF and the WDM are inserted between the PBS and the FM. The signal propagating through the BDF is alternating between backward and forward pumping. The WDM is placed at the opposite of the output in order to minimize the Amplified Spontaneous Emission (ASE). A 2 nm bandwidth at -0.5 dB Band-Pass Filter (BPF) is placed between the WDM and the FM. This filter is used to block wavelengths out of the signal band so the generated out-of- band Amplified Spontaneous Emissions (ASE) is not re-amplified between passes which prevents self-lasing of the amplifier. This configuration is quite modular because the amplifier is a 2-pass or 4-pass amplifier depending on the addition of two components: a looped circulator acting as a mirror and an additional BPF playing the same role as the first one. Note that the length of BDF is kept the same for 2-pass and 4-pass amplifiers. Indeed, we have tried a cutback for both configurations but the gain and the output power decrease with decreasing the BDF length. It may be possible that the optimal length is longer than 283 m but this is the longest length we have available.

3. Experimental results

First, the performances of the 2-pass amplifier were investigated. The optical spectrum was measured for 430 mW pump power (see Figure 2) with different input signal power (from -30 dBm to 0 dBm). These measurements are intended to control the presence of a parasitic laser effect which manifests itself by the appearance of secondary peaks or a fluctuation of the amplified signal. As can be seen, no parasitic peaks are observed on the optical spectrum which also remains stable over the time. The amplified signal at 1310 nm clearly emerges above a wide ASE background extending from 1265 nm to 1500 nm. A 4 nm bandwidth plateau is visible on the blue edge of the signal and is attributed to the residual ASE generated along the first pass and not blocked by the BPF. Considering this plateau, the Optical Signal-to-Noise Ratio (OSNR) is around 18 dB for an input power of -30 dBm.

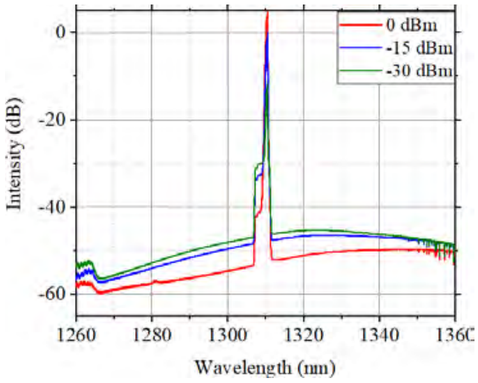

Figure 2: Amplified output spectra for different input powers in 2-pass configuration.

The average output power of the amplified signal and its gain were calculated from the optical spectra to avoid any source of error from the ASE contribution. These parameters are respectively represented in Figure 3.a and Figure 3.b as a function of pump power. As can be seen, the gain and the output power increase with the pump. A maximum of 33.5 dB gain is obtained for an input power of -30 dBm and the maximum pump power of 430 mW. Considering the short signal wavelength and the use of a single pump diode, the achieved gain is remarkably high. The maximal output power increases from 3.5 dBm (-30 dBm input power) to 18.8 dBm (0 dBm input power) with the pump power and does not appear to reach saturation.

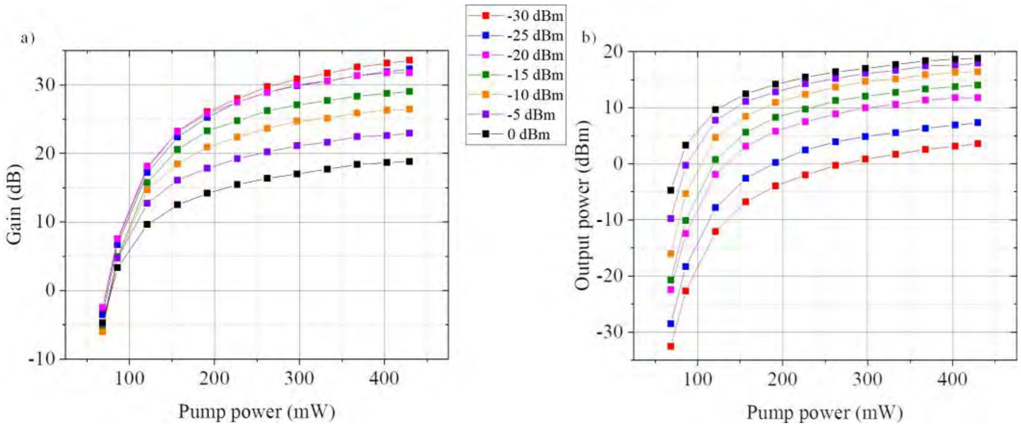

Figure 3: a) Evolution of the average output power of the amplified signal as a function of the pump power for different input signal powers. b) Evolution of the gain with the pump power for the different input signal powers. Results obtained for a 2-pass configuration.

The same measurements have been performed for the 4-pass architecture.

Here, the minimal input power for which the amplifier is operating without parasitic self-laser effect is limited to -25 dBm for a pump power of 165 mW. As suggested in a previous work on multipass fiber amplifiers, the limiting factor is the PBS extinction ratio (optical power ratio between the correct port and the unwanted port) that should be higher than the amplifier single- pass gain [11]. When this condition is respected, the power parasitic light leaking into the 4-pass arm (with circulator and BPF) and experiencing an extra amplification pass is kept low. However, PBS extinction ratio is not the only limiting parameter and the unperfect polarization rotation of the FM is also a source of parasitic leaking light. Indeed, the FM rotates the polarization with an angle ~~comprised~~ between 88° and 92° and part of the light does not undergo a change of polarization when it is reflected by the FM [15]. This leads to the creation of parasitic leaking light that experiences a different optical path compared to the rest of the light. Regarding the optical spectrum (see Figure 4), it resembles that of the 2-pass amplifier except that ASE outside the BPF bandwidth looks flatter and about 10 dB lower due to the increase of the power at each pass. In the BPF bandwidth however, ASE is increased slightly leading to a small degradation of OSNR from about 32 dB to about 31 dB for an input power of -15 dBm.

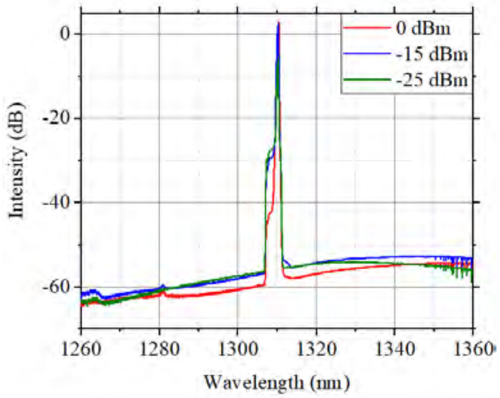

Figure 4: Amplified output spectra for the different input powers in 4-pass configuration.

The average output power of the amplified signal and its gain are reported in Figure 5.a and Figure 5.b. The gain value increases with pump power until it reaches its maximal value of 35.2 dB for -25 dBm (165 mW pump power) or -20 dBm input signal power (255 mW pump power). The gain is clamped to this value beyond which parasitic self-laser effects are observed. These effects induce power and spectrum instability and may lead to fiber component damaging; therefore, the pump power is limited for these input power. To the best of our knowledge, this is the highest reported gain value for this signal wavelength and such a low pump power. This highlights the benefit of the 4-pass configuration compared to the 2-pass one. The highest output power is 18.9 dBm and is obtained for -5 and 0 dBm input signal power with maximum pump power (430 mW). The amplifier in 4-pass configuration can deliver higher output power and it seems limited by the available pump power.

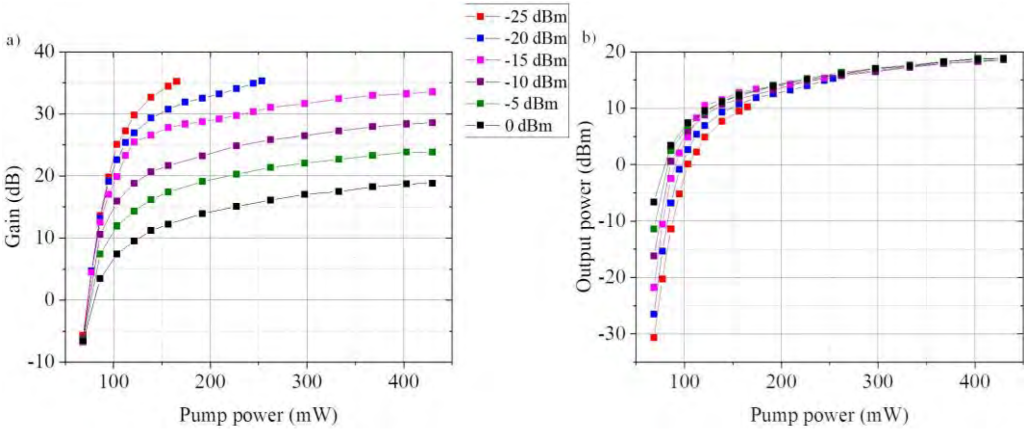

Figure 5: a) Evolution of the average output power of the amplified signal as a function of the pump power for different input signal powers. b) Evolution of the gain with the pump power for the different input signal powers. Results obtained for a 4-pass configuration.

4. Comparison and discussion

The highest obtained gain and output power are plotted in Figure 6 as a function of the input power for both amplifier configurations. The gain and output power are higher for the 4-pass amplifier than for the 2-pass one, except for the 0 dBm input power for which they are equal. The differences between the two configurations tend to decrease with the input power. These better performances prove the added-value of the 4-pass amplifier compared to the 2-pass one. The plateau on the gain curve (Figure 6.a) for the 4-pass amplifier is not a saturation of the gain but a limit related to the imperfection of some optical component (PBS and FM). Indeed, when an increase of the gain via an increase of the pump power is attempted, a self-lasing effect is observed. The use of a PBS with a polarization extinction ratio of 35-40 dB or a FM with a rotation tolerance of 1° or even 0.5° should permit to increase the gain beyond 35.2 dB. For the 4-pass configuration, a saturation of the output power starting from -15 dBm input signal power is observed (Figure 6.b). It seems related to a limitation of the available pump power. Indeed, the output power evolves with the pump power without saturation of the gain (see Figure 5.b). With a pump diode delivering higher power, one may expect for the highest input power values, higher gain and output power values.

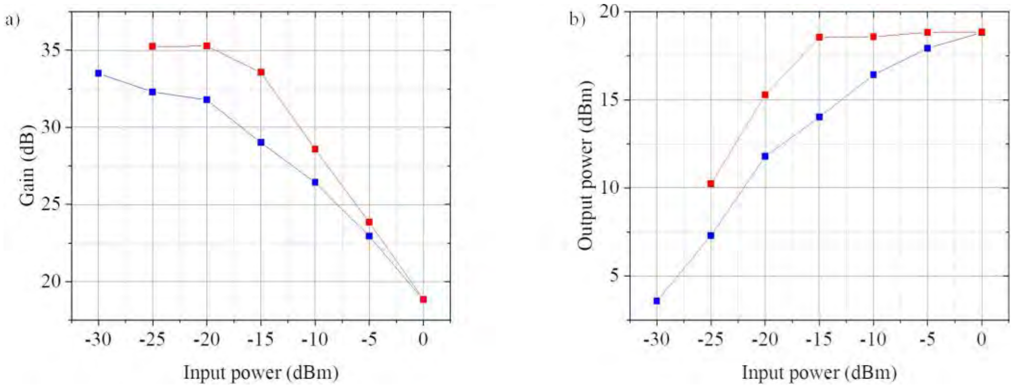

Figure 6: a) Highest gain and (b) output average power as a function of input power for 2-pass (blue curve) and 4-pass (red curve) configurations.

The optical-to-optical power conversion efficiency is computed for both configurations and is reported in Figure 7. PCE value is higher for the 4-pass amplifier than for the 2-pass one, except for the input power of 0 dBm for which they are equal. For this parameter, the amplifier seems limited by the available pump power. The maximum conversion efficiency is 17.8% for 0 dBm input power. The overall PCE values reported here for the 4-pass amplifier are notably higher than those in the literature, especially for low input power [8]. The WPE for 18.9 dBm output power is higher than 0.6%. Note that the power consumption of the electronics driving the pump laser diode is 12.6 W, TEC-power included for the highest pump power value. This is considerably high compared to the efficiency reported by Mikhailov et al. [4]. Once again, this highlights the benefit of the 4-pass configuration.

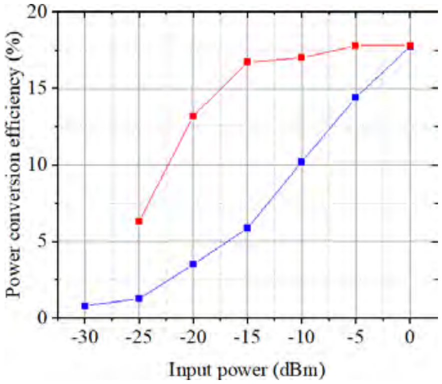

Figure 7: Evolution of the optical-to-optical power conversion efficiency as a function of the input power for 2-pass (blue curve) and 4-pass (red curve) configuration.

It should be noted that no gain saturation effect is observed for both configurations which suggests that the gain, the output power and PCE should be further increased using more pump power.

5. Conclusion

In this work, an efficient amplification of linearly polarized signal based on a non-PM BDF is demonstrated. The proposed amplifier can operate both in a 2-pass or a 4-pass configuration. This is the first experimental demonstration of an all-fiber 4-pass amplifier. An extensive study highlights that the gain and PCE values are improved when using the 4-pass architecture. This configuration allows to reach 35.2 dB with a pump power limited to 165 mW. The reported optical-to-optical power conversion efficiency for the 4-pass amplifier ranges from 6.3 to 17.8% which, for a BDFA, is remarkably good with regards to the low input power and used pump power. These results prove the real interest of this amplifier design. Possible ways to further improve performance of the 4-pass BDFA rely on the use of a FM with an angle close~~d~~ to 90° and a PBS with higher extinction ratio.

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