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Gain Behavior of E+S band Hybrid Bismuth/Erbium-doped Fiber Amplifier Under Different Conditions

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Abstract: *A hybrid amplifier employing bismuth-doped and erbium-doped fibers is demonstrated which provides over 27 dB gain from 1431 nm to 1521 nm. Furthermore, we demonstrate that gain inhomogeneity occurring in bismuth-doped fibers is significantly more pronounced than in erbium-doped fibers. ©2022 The Author(s)*

Background

Taking advantage of new wavelength transmission bands is considered among the most promising approaches to increase the capacity of the telecommunication network and address the ever growing demand for bandwidth [1]. To that extent, expanding the networks spectral coverage beyond the currently used C and L-bands and into the E and S-bands is deemed as the most straightforward implementation. Indeed, E and S-band telecommunication also benefits from the low propagation loss of standard singlemode optical fibers and can therefore rely on the same telecommunication network architecture as C and L-band telecommunication. However, the scarcity of powerful and cost-effective amplification systems rivalling the performance of erbium-doped fiber amplifiers (EDFA) in the C and L-bands currently constitutes a significant hurdle for the use of the E and S-bands in fiber telecommunication.

To address this issue, we have proposed a bismuth-germanium-doped fiber (BGDF) and erbium-doped fiber (EDF) hybrid amplifier (BEHA) that is able to provide gain in the E and S-bands, from 1431 nm to 1521 nm [2]. In this paper, we follow up the work in [2]. The BEHA is shown to provide a small signal gain larger than 27 dB as well as a total output power of 24.5 dBm, while a power conversion efficiency of 8.7 % is achieved for a total signal input power of 0 dBm. The system's performance is also tested in a reconfigurable gain scenario which revealed that the system's gain ripple over 90 nm is below 12 dB. Finally, this investigation shows that the BDGF gain is significantly affected by gain inhomogeneity which can lead to gain deterioration in excess of 7 dB.

Experimental setup

The BEHA employs two different active fibers in order to provide amplification in the 1430 nm to 1520 nm spectral range. A commercial erbium-doped fiber (EDF) is used to provide gain for wavelengths mainly > 1500 nm. The EDF possesses a 976 nm pump and 1530 nm signal absorption of 12 dB/m and 21 dB/m, respectively. Amplification for wavelengths < 1500 nm is provided by a bismuth-germanium-doped fiber (BGDF). The BGDF possesses a 7 µm core and 123 µm cladding diameter along with a 0.137 numerical aperture (NA). The small-signal absorption of the fiber at 1310 nm was measured to be 0.265 dB/m.

The BEHA architecture is schematized in Fig. 1 (a) and is composed of 4 amplification stages. The 1st and 3rd stages are composed of 200 m of BGDF whereas the 2nd and 4th stages are composed of 1.5 m of EDF. The lengths of the active fibers were chosen to provide over 23 dB of gain over the E+S bands while minimizing the gain ripple [2]. The BGDF stages are bi-directionnally pumped using single-mode

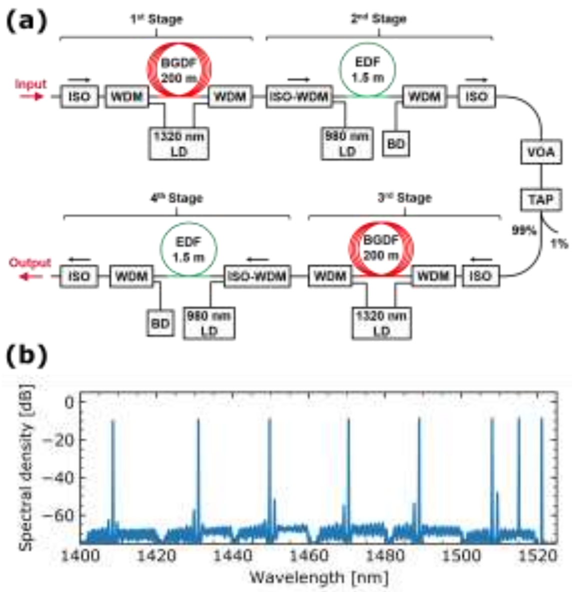

Fig. 1: (a) Schematic of the BEHA architecture and (b) input signal spectrum. ISO, isolator; WDM, wavelength division multiplexer; LD, laser diode; ISO-WDM, hybrid ISO and WDM; BD, beam dump; VOA, variable optical attenuator; TAP, 99/1 fused coupler tap.

1320 nm laser diodes while the EDF stages are pumped in the forward direction using 976 nm laser diodes. A variable optical attenuator (VOA) is used between the 2nd and 3rd stages in order to allow reconfigurable gain operation of the BEHA. The amplification performance of the BEHA is characterized using a comb source composed of 8 laser lines spanning the 1431 nm to 1521 nm wavelength range, as shown in Fig. 1 (b).

Results and analysis

The BEHA is firstly characterized when each amplification stage is fully pumped, i.e. 560 mW of 1320 nm pump power in both the forward and backward direction for the BGDF stages and 500 mW of 976 nm pump power in the forward direction for the EDF stages. Fig 2 presents the gain and noise figure spectra of the BEHA for different total input powers ranging between -20 dBm and 0 dBm. From the gain spectra it is clearly seen that the peak of the gain provided by the BGDF is around 1450 nm whereas the EDF provides gain for wavelengths beyond 1500 nm. The average gain over all the wavelengths is seen to decrease from 35.8 dB to 22.6 dB when the input power increases from -20 dBm to 0 dBm. At the same time, the noise figure is seen to be fairly constant with an average value between 5.3 dB and 5.1 dB. Only the 1431 nm wavelength noise figure undergoes a large variation from 6.8 dB at -20 dBm of input power to roughly 5 dB at 0 dBm input power. A maximum power conversion efficiency (PCE) of 8.7 % is achieved for the input power of 0 dBm.

Next, the BEHA is tested in a reconfigurable gain scenario where the output power of the system is fixed at 19.5 dBm and the gain is tuned from 27.5 dB to 22.5 dB. To that extent, the input signal power was switched from -10 dBm to -5 dBm while the attenuation produced by the VOA is switched from 0 dB to 5 dB. The pumping power supplied to the stages is 2 x 560 mW at 1320 nm in the 1st stage, 250 mW at 976 nm in the 2nd stage and 235 mW at 976 nm in the 4th stage for both gain settings. A similar gain tilt was achieved for both gain settings by tuning the 1320 nm pump power supplied to the 3rd stage. The gain and noise figure spectra measured during the reconfigurable gain experiment are presented in Fig. 3. The target average gains of 27.5 dB and 22.5 dB (with similar gain tilt) are achieved by tuning the 3rd stage's pump power from 2 x 235 mW to 2 x 200 mW, although non-negligible gain tilt differences have been witnessed in the shorter wavelength range where gain is provided by the BGDF. On the other hand, the noise figure remains fairly constant and does not exceed 6 dB for both gain settings. It should be noted that for the 27.5 dB average gain setting, a minimum gain of 22.9 dB is achieved at 1508 nm whereas a maximum gain of 34.2 dB is achieved at 1450 nm. This amounts to a peak gain ripple of 11.3 dB, a figure that can be easily compensated using a gain flattening filter (GFF).

Finally, the inhomogeneous behaviour of the BGDF was investigated in order to determine its magnitude. To that extent, the gain of the 1st BGDF amplification stage was recorded for different signal input powers. The flat input spectrum was composed of 5 laser lines in the 1430 nm to 1508 nm wavelength range and its power was tuned from 0 dBm to -20dBm using a VOA. For each input signal power, the bidirectional pump power is tuned so as to obtain an identical gain value at 1508 nm.

The recorded gain spectra as well as the gain discrepancy, i.e. gain for the given input power subtracted by the reference gain (taken for -20 dBm of signal input power), are shown in Fig. 4 (a) and (b), respectively. The -20 dBm gain curve was chosen as the reference gain since

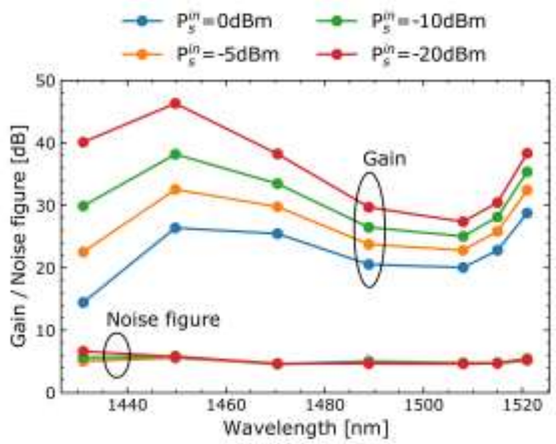

Fig. 2: Gain and noise figure spectra for different signal input powers when the BEHA is fully pumped.

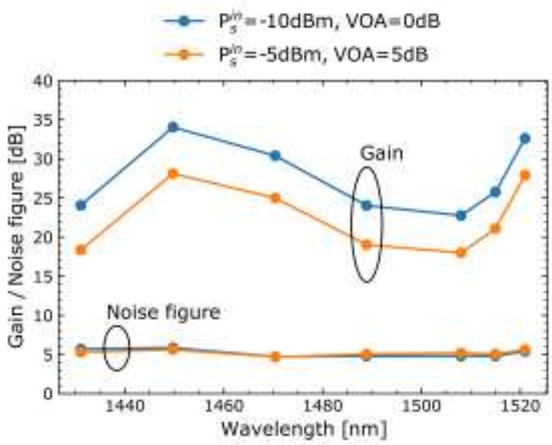

Fig. 3: Gain and noise figure when the BEHA is operated in a reconfigurable gain scenario.

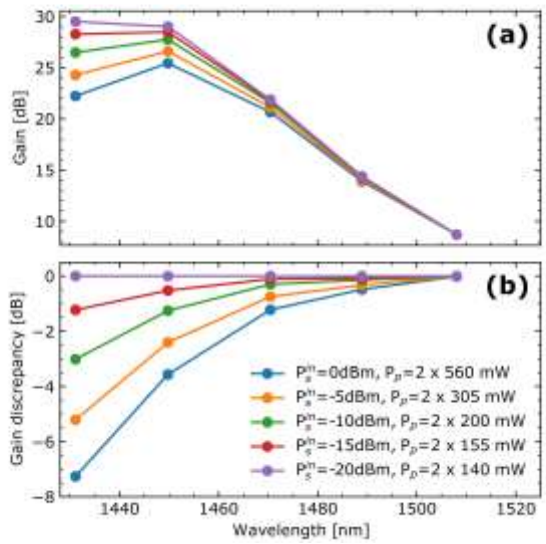

Fig. 4: (a) BEHA gain for different signal input ($\boldsymbol{P_s^{in}}$) and pump powers ($\boldsymbol{P_p}$) and (b) gain discrepancy w.r.t. the $\boldsymbol{P_s^{in}}$ = -20dBm gain spectra.

gain inhomogeneity scales with signal input power and we therefore expect little inhomogeneity to occur for this low input power. From Fig. 4 (a) the gain is seen to decrease for all wavelengths as the input power is increased, except for the 1508 nm wavelength since the experiment was designed to maintain the gain constant at this wavelength. Moreover, the gain deterioration can be in excess of 7 dB for the 0 dBm signal input power and decreases slowly as the signal wavelength shifts out of the BGDF's amplification band, as shown in Fig. 4 (b). It should be noted that the output amplified spontaneous emission (ASE) was affected in a similar way by gain inhomogeneity as the amplified signals. Finally, Fig. 5 presents the gain discrepancy as a function of input signal power for the different wavelengths of the input signal spectrum. Gain deterioration increases slowly for low signal input powers up to -10 dBm, a power above which the gain deterioration becomes linear with input signal power.

Discussion

The previous results highlight the inhomogeneous nature of the BGDF gain and supports earlier reports of gain inhomogeneity in other bismuth-doped fibers [3,4]. Furthermore, looking back a Fig. 4 (b) it appears that increasing the input signal power leads to the creation of a wide and large spectral hole in the BGDF gain with a trough located outside of the investigated wavelength range. This observation is reminiscent of spectral hole burning (SHB) observed in EDFs [5], although this same phenomena has been observed in several types of lasers and amplifiers. Indeed, strong saturation tones produce SHB holes in EDFs having widths

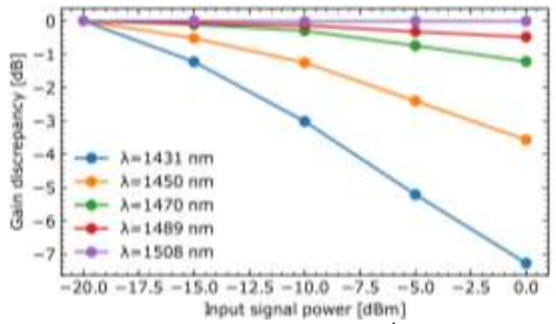

Fig. 5: (a) Gain discrepancy w.r.t. the $\boldsymbol{P_s^{in}}$ = -20dBm gain spectra as a function of the total signal input power.

up to 10 nm and depths generally lower than 2 dB [5,6]. Additionally, although the peak of the spectral hole generally occurs at the same wavelength as the saturation tone, non-resonant SHB can occur where the saturation tone produces a hole having a peak wavelength shifted by up to 3 nm [7]. In comparison, SHB in BGDFs appears to be more dramatic as the hole in Fig. 4 (b) seems to have a width of several tens of nm along with a depth much greater than 7 dB. Furthermore, the BGDF is potentially more prone to non-resonant SHB, assuming the hole's peak is located outside of the investigated wavelength range. Further experimental measurements are required to validate these conclusions and elucidate the inhomogeneous gain behaviour of BGDFs.

Although the BGDF's gain inhomogeneity had a limited impact on the gain tilt of the BEHA during the reconfigurable gain experiment, it will become an issue for BDF based amplification systems where flat and constant gain is expected for different input signal loading schemes. Therefore, investigating approaches to mitigate inhomogeneity in BDFs, such as gain clamping and/or pump wavelength tuning [4], is paramount for the demonstration of practical BDF based amplification systems. The development of numerical models able to accurately predict the gain in BDFs can also contribute to this effort.

Conclusion

We have demonstrated a BGDF/EDF hybrid amplifier providing > 27 dB gain over 90 nm in the E+S bands. The system is able to generate a total of 24.5 dBm of output power along with a PCE of 8.7 %, and to operate in a reconfigurable gain scenario. A study on the BGDF's gain inhomogeneity was undertaken and has revealed that the effect is significantly more pronounced than in EDFs. Future work will be devoted on further investigating gain inhomogeneity in BGDFs and finding mitigation strategies that will allow the development of practical BGDF based amplification systems operating in the E+S bands.

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