Feasibility Validation of “Hyper C-band” BDF/EDF Hybrid Amplifier with 9 THz Gain Bandwidth

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Abstract *We demonstrate that the bismuth doped fiber can assist to expand the gain bandwidth of a super C-band (6 THz) EDFA by 50% to the hyper C-band (9 THz). Design considerations and optimized performances are discussed.*

Introduction

Utilizing new transmission windows in optical telecommunication networks, such as the S band and the U band [1], is considered as one of the promising solutions to increase the transmission capacity. However, a whole set of new optical hardware platform is required to support various functionalities in the new wavelength ranges. The investments in end-to-end industrial chains will then be large and the commercial drive for this solution is somehow insufficient in consequence. In contrast, improving/expanding the technologies based on the C/L band and in the meantime reusing the existing hardware platform are more attractive from a practical perspective.

The development of the commercial amplifier technology is following this path. Erbium-doped fiber amplifiers (EDFAs) have recently evolved from the conventional C-band (4 THz) to the *super C-band* (6 THz) [2], as well as from the conventional L-band (4 THz) to the *super L-band* (6 THz) [3]. State-of-the-art EDFAs have already pushed the EDFs close to their performance limit, but whether there exist other ways to further expand the *super C-/L-* band still remains open-ended.

Recently, the bismuth-doped fiber amplifier (BDFA) technology starts to show complementary effects to the EDFA technology [4]. Bismuth-doped fibers (BDFs) provide gains in O/E/S band, depending on the host glass and the pumping wavelength. More importantly, the gain bandwidth of a BDF usually crosses multiple wavelength bands [5]: the phosphor-silicate BDF peaks at the O band and extends to the E-band; the germano-silicate BDF peaks at the E band and extends to the S- and even the C-band; the germano-silicate BDF with > 50 mol% GeO_2 centres at the U-band and extends to the L-band. The combination of the bismuth gain and the erbium gain in one amplifier opens up various possibilities. The BDF/EDF hybrid amplifiers (BEHAs) covering the E+S band [6] and C+L+U band [7] have been experimentally demonstrated. Accordingly, the idea of using BDF to further extend the bandwidth of *super C-band* EDFA looks natural and intuitive. However, in-depth investigations of this type of amplifier have never been reported.

The objective of this work is to validate the feasibility of using EDF/BDF hybrid structure to make a *hyper C-band* amplifier (9 THz, 1502~1572 nm). We mainly checked two basic aspects/parameters of the amplifier: the external gain ripple and the noise figure (NF), under different arrangements of the BDF and EDF in the setup and under different pump tuning strategies. The former parameter is equivalent to the depth of the gain flattening filter (GFF). It can’t be too large otherwise the fabrication of the GFF will become technically difficult. The latter is a well-known key parameter of an amplifier that impacts significantly the OSNR of the telecom link.

Amplifier Design

The BDF used throughout this paper is a commercial Ge-BDF [6]. The EDF is from CorActive (L1500). The optical gain profiles of both EDF and BDF can be estimated by the analytical equation derived from the Giles model: $G = [(\alpha + g^*)N_2 - \alpha] \times L$, where α is the absorption coefficient, g^* is the emission coefficient, N_2 is the averaged inversion level of the active ions (either the Er^{3+} ions or the bismuth active centres (BACs)) and L is the fiber length [8]. When the BDFA stage and the EDFA stage are cascaded in series, the total gain is assumed to be their linear summation: $G_{\text{total}} = [(\alpha_{\text{BDF}} + g^*_{\text{BDF}})N_2^{\text{BDF}} - \alpha_{\text{BDF}}] \times L_{\text{BDF}} + [(\alpha_{\text{EDF}} + g^*_{\text{EDF}})N_2^{\text{EDF}} - \alpha_{\text{EDF}}] \times L_{\text{EDF}}$. Then, the fiber lengths (L_{EDF} and L_{BDF}) and the inversion levels (N_2^{EDF} and N_2^{BDF}) are optimized simultaneously to obtain the minimum gain ripple, defined by $(G_{\max} - G_{\min})/G_{\min}$, where $G_{\max}$ and $G_{\min}$ are the maximum and the minimum gain values on the gain curve. This design methodology is not very precise because of BDF’s strong gain inhomogeneity [9,10] as well as of the interplay between the BDF gain and the EDF gain (as will be seen in the following experiments), but it is still generally usable for the initial rough design of an amplifier.

Fig. 1 plots the gain profiles after optimization. The length of the EDF is fixed at 1 m for simplicity. The optimized length ratio between the BDF and the EDF is ~200. The combination of the BDF gain (red curve in Fig. 1) and the EDF gain (blue)

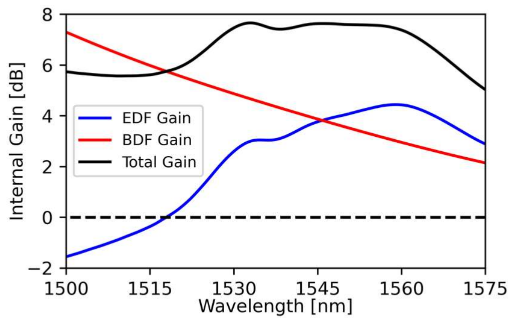

Fig. 1: Designed gain profiles of the BEHA

generates a gain (black) that covers the *hyper C-band*. The fiber internal gain ripple is 38.9%, which looks promising but may not be exactly the same as the experiment. This design is only used as the start point of the experiment investigation. The gain level is ~ 5.5 dB, which can be further scaled in the experiment by increasing the lengths of the BDF and the EDF.

Experiments

Fig. 2(a) shows the structure the BEHA. It cascades two amplification stages, based on two different active fibers (Fiber 1 and Fiber 2, can be either the BDF or the EDF). The total insertion loss of all the passive devices is ~ 1.9 dB. Two amplifier architectures are investigated. The first one is to put the BDF in the first stage (BDF-EDF). The second one is to put the EDF in the first stage (EDF-BDF). The EDF is forward-pumped by 976 nm laser while the BDF is forward-pumped by 1320 nm laser. The input signal is a combination of three laser sources (Fig. 2(b)). The one in *super C-band* (1524.50 ~ 1571.65 nm) is a filtered ASE comb source with total power of 6 dBm. A saturation tone (TLS1) with wavelength of 1501.57 nm and power of 3 dBm is used to mimic the multi-channel signal at 1502.98 ~ 1522.98 nm, corresponding to the same spectral power density as those in the *super C-band*. A probe laser (TLS2, ~ -30 dBm) is wavelength swept to measure the gain in this wavelength range.

The length of the BDF is fixed at 366 m which is the maximum available in our lab. The initial length of the EDF is chosen based on the designed length ratio (200), *i.e.* ~ 1.83 m. However, because the design is just for the purpose of a general guide, we modify the EDF length in the experiment until we could achieve the minimum gain ripple. The optimized EDF length is eventually chosen to be 3 m.

The 1320 nm pump power for the BDF is fixed at its maximum of 560 mW. This is because the BDF has low gain compared to the EDF and we need to keep the BACs at sufficient high inversion level to obtain enough gain in the short wavelength side of the *hyper C-band*. The external gains and NFs (the impact of the passive devices is included so as to have a practical evaluation of the amplifier performance) of the BDF-EDF and the EDF-BDF structures are measured and recorded at 976 nm pump powers of 50, 100, 200, 400 and 800 mW.

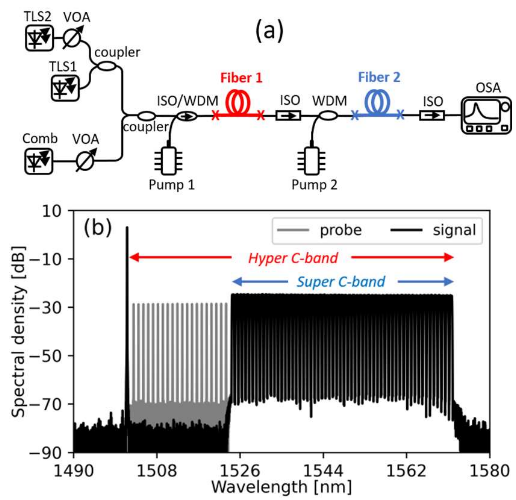

Fig. 2: (a) Experimental setup and (b) input spectrum. TLS, tunable laser; VOA, variable optical attenuator; ISO, isolator; WDM, wavelength division multiplexer; ISO/WDM, hybrid ISO and WDM.

Results and Discussion

The measured gain spectra are plotted in Fig. 3(a). The solid curves are for the BDF-EDF structure while the dashed lines are for the EDF-BDF structure. It can be seen that, for the BDF-EDF structure, the gain over the whole *hyper C-band* increases continuously as the 976 nm pump power increases. The gain ripple as well as the gain tilt changes in a moderate way. This indicates that, in the BDF-EDF structure, the interaction between the BDF gain and the EDF gain is weak. In contrast, when applying EDF in the first stage, the interaction becomes much stronger. As the 976 nm pump power increases, the gain below 1520 nm decreases dramatically. This is because, when the EDF is placed in front of the BDF, the optical signal above 1520 nm acquires large gain from the EDFA stage before being injected into the BDF. At this moment, the signal above 1520 nm is much stronger than the one below 1520 nm, it immediately depletes the inversion level of the Si-BACs, resulting in a significant gain saturation below 1520 nm. Nevertheless, if putting the BDF in first stage, the above depletion effect in the BDF won't happen since the gain above 1520 nm is provided by the EDF which is placed after the BDF stage.

In order to show clearer of this phenomenon, the gains at the first (1501.57 nm) and the last (1571.65 nm) wavelengths, in function of the 976 nm pump power, are shown in Fig. 4(a) (EDF-BDF) and (c) (BDF-EDF). For EDF-BDF, the first signal gain starts to drop significantly from 50 mW pump power while the gain of last channel keeps increasing with the 976 nm pump power. In comparison, for BDF-EDF, both the first and the last signal gains increase progressively with the pump power.

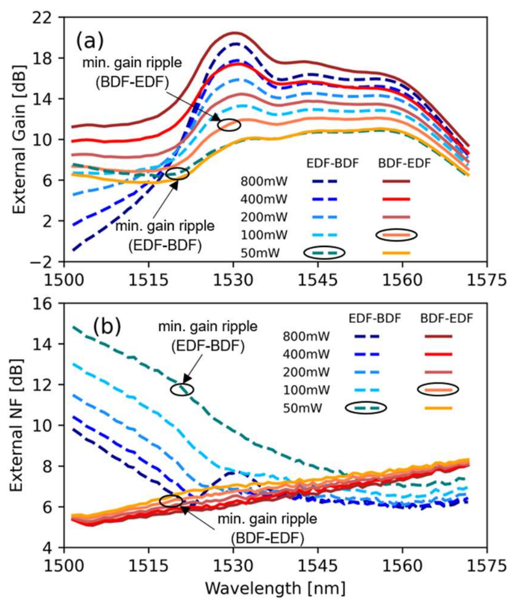

Fig. 3: Gain spectra (a) and NFs (b) of EDF-BDF and BDF-EDF hybrid amplifier under different pump powers.

In terms of the NF performance, the BDF-EDF structure is also much better than the EDF-BDF structure. As shown in Fig. 3(b), the NF of the EDF-BDF structure undergoes a very large degradation in the 1501 to 1524 nm wavelength range. This is because that the EDF is at the first stage and its gain in this region is too low compared to those in the *super C-band* and it can even be negative under low pump power. On the other hand, for the BDF-EDF structure, the NF is much better. It is below 6 dB at the shorter wavelength side but increases up to ~ 8 dB at the longer wavelength side due to the insufficient BDF gain in the *super C-band* region.

In theory, the NF can always be improved by pushing the BDF/EDF onto higher inversion levels, but it would then be in the cost of the gain ripple. Fig. 4(b) and (d) exhibit the maximum external NF across the whole spectrum with respect to the gain ripple. Generally speaking, in both EDF-BDF and BDF-EDF, the NF decreases exponentially with gain ripple. The smallest gain ripple of 71.6% and minimum gain of 6.34 dB are obtained at 50 mW pump power by using EDF-BDF combination. Nevertheless, the maximum NF is found to be 14.3 dB which is too large for practical amplifier application. Conversely, the overall NF is much smaller in BDF-EDF structure. At pump power of 100 mW, the smallest gain ripple of 76.8% and the maximum NF of 8.19 dB are obtained. The minimum gain of the optimized amplifier is 6.84 dB. Although it is much lower than the gain of a real telecom amplifier (because we have limited length of BDF in our lab), it is enough for demonstrating the general performance of such a *hyper C-band* amplifier. The gain of the amplifier can be scaled by enlarging the lengths of the gain fibers and by cascading more amplification stages, meanwhile the gain ripple and the NF will not deviate much from this two-stage demo.

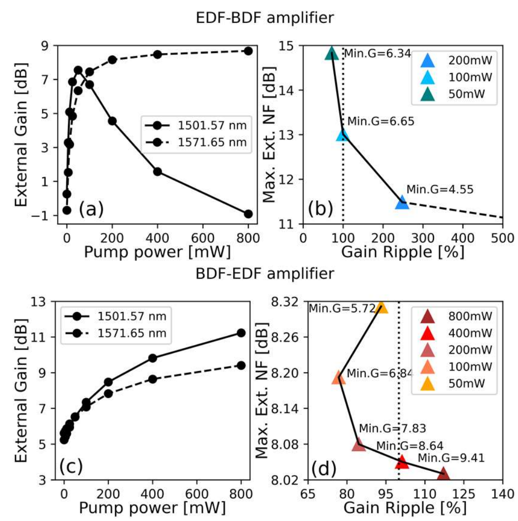

Fig. 4: External gain w.r.t. pump power at first and last wavelengths for EDF-BDF (a) and BDF-EDF (c). Relationship between maximum external NF and gain ripple for EDF-BDF (b) and BDF-EDF (d) amplifiers, under different pump powers.

Conclusions

The gain behaviours of cascaded BEHA for *hyper C-band* are investigated. The BDF-EDF amplifier structure is found to be the better one due to the less interaction between the BDF and the EDF gains as well as to the lower NF. The two key parameters of the optimized amplifier, the gain ripple and the worst NF, are 76.8 % (deep but still acceptable) and 8.2 dB (higher than conventional EDFAs) respectively. This indicates that *hyper C-band* amplifier based on BEHA is technically feasible, but great effort is still needed to make its performance be closer to the commercial EDFAs.

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