Bandwidth-Dependent Gain Deviation in E+S band Bismuth Doped Fiber Amplifier under Automatic Gain Control

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Abstract: Although bismuth doped fiber amplifier could provide ultra-wideband gain, the gain inhomogeneity might ultimately restrict its applicable bandwidth. This work explores this limitation through experimental measurements of signal dependent gain deformation.

1. Introduction

The continuous growth of the Internet services and cloud computing requires optical communication systems to have larger data transmission capacity. Utilizing new transmission windows such as the E- and S- band in future optical communication network is one of the promising solutions for which a compatible fiber amplifier technology is crucial.

Since the first experimental demonstration in 2006 [1], the bismuth-doped fiber amplifier (BDFA) has attracted increased attention. The advantages of the BDFA are multi-fold: it shows potential to provide ultra-wide an amplification bandwidth, the center of the gain can be tailored by modifying the composition of the glass matrix, it is based on silica glass which is compatible with the installed transmission fibers, *etc.*. Our recent theoretical analysis, based on published data, has shown that the germano-silicate BDFA could provide close to 100 nm bandwidth within the E+S band with the assistance of erbium-doped fibers (EDFs), output signal power well-above watt-level and noise figures (NF) close to the 3 dB quantum limit [2]. In parallel, we experimentally demonstrated a BDF/EDF hybrid amplifier with 27 dB gain, 90 nm bandwidth, 24.5 dBm output power, and NF of ~ 5.5 dB [3].

One remaining problem of the BDFA is the gain inhomogeneity, *i.e.*, the spectral hole burning effect (SHB). Since the bismuth ions do not have the 4-f electron shield as the Er^{3+} ions, they are more vulnerable to the local fields in the glass matrix, and it is expected that SHB could be stronger than in EDFs. Our preliminary experiment [4] shows that, when the signal input power drops, a gain "hole" in the E-band with a depth of several dB can be created close to the absorption peak of the BDF, and extending to almost the whole S-band. The deployment of amplifiers with such high gain inhomogeneity in ultra-wideband optical communication link is questionable. The gain deviation would accumulate over cascaded amplifiers and lead to the failure of the whole link in some channel loading scenarios.

In this paper, we investigate the gain deviations of the BDFA under automatic gain control (AGC), when operated in different wavelength ranges within the E+S band. The main purpose is to shed light to the SHB performance of the BDFA in the E- and S- band, as well as to find out the most applicable operation wavelength range for the BDFAs.

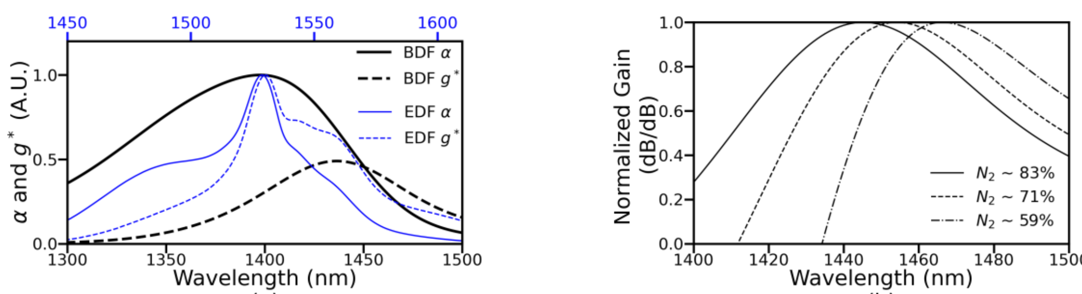

Fig. 1. (a) Normalized absorption and gain coefficients of the BDF and EDF; (b) gain curves of the BDFA corresponding to three different bismuth active center (BAC) inversion levels, which will be close to the target BDF gain profiles in the following experiments.

2. Properties of the BDF

The BDF used in the experiment is based on germane-silicate glass with GeO_2 content of ~ 5 mol%. Fig. 1(a) plots the BDF's absorption (α) and gain (g^*) coefficients, normalized to the absorption peak at ~ 1400 nm. The α and g^* of a typical alumino-silicate EDF are also plotted together in Fig. 1(a) and are intentionally shifted in wavelength (top axis) for the purpose of comparison. Fig. 1(b) plots the normalized gain curves using $G = (\alpha + g^*)N_2 - \alpha$, which is based on the assumption of an homogeneous gain profile. Although BDF has strong gain inhomogeneity, this relation still works well for the coarse determination of the gain bandwidth. The three gain curves in Fig. 1(b) correspond to amplification bandwidth of 1410~1490 nm, 1430~1490 nm and 1450~1490 nm respectively.

3. Experimental Setup

For the investigation of BDFA gain inhomogeneity in a DWDM scenario (with 50 ~ 200 GHz channel spacing), a reconfigurable comb-like signal source is needed (the power of each channel should be controlled independently). By randomly performing "add-drop" among all the DWDM channels, as well as locking the average gain to the target level (AGC), the gain deviations can be measured by using the "spectral subtraction technique" [5], *i.e.* the difference of the gain profiles between the partial-loading and the full-loading conditions. Here, due to experimental constraints, we use CWDM sources with wavelength spacing of 20 nm to "simulate" the above-mentioned condition. Since the spectral width of the "hole/bump" in the gain profile, created by the BDFA's SHB effect, occupies several tens of nanometers, this approximation is valid for the purpose of estimating the gain profile under AGC. The wavelength of each CWDM source is considered as the center of a "sub-band" with a width of ~ 20 nm, while their power is proportional to the total sub-band power from the number of equivalent DWDM channels within that band. The DWDM channel add-drop is simulated by applying random optical attenuations to the CWDM sources through variable optical attenuators (VOAs) in Fig. 2. (a) Experimental setup(a). The amplifier is a single stage BDFA under 1320 nm forward pumping. The full-loading gain is firstly measured: the VOAs are set to get a flat input signal spectrum, as shown in the top figure of Fig. 2. (a) Experimental setup(b); two optical spectrum analyzers (OSAs) are synchronized to monitor the input and output optical spectra; the pump power is tuned until the gains of the first and the last wavelengths are identical, which is defined as the target gain (gain flattening filtering is implemented offline). Then the partial-loading gains are measured: the total input signal power is reduced to 10, 20 and 30% of the full-loading input; the attenuations are randomly distributed among the CWDM sources; the averaged gain (after the offline gain flattening) is locked to the target gain. Three amplification ranges are investigated: 1410~1490 nm, 1430~1490 nm and 1450~1490 nm. The total input signal powers under full-loading are respectively -5.24, -1.21 and -2.46 dBm and the target gain levels are 14.8 dB (200 m BDF), 11.5 dB (200 m BDF) and 17.2 dB (366 m BDF). The precision of the AGC is $\pm$0.05 dB. For each amplification range, 120 random partial-loading cases are tested.

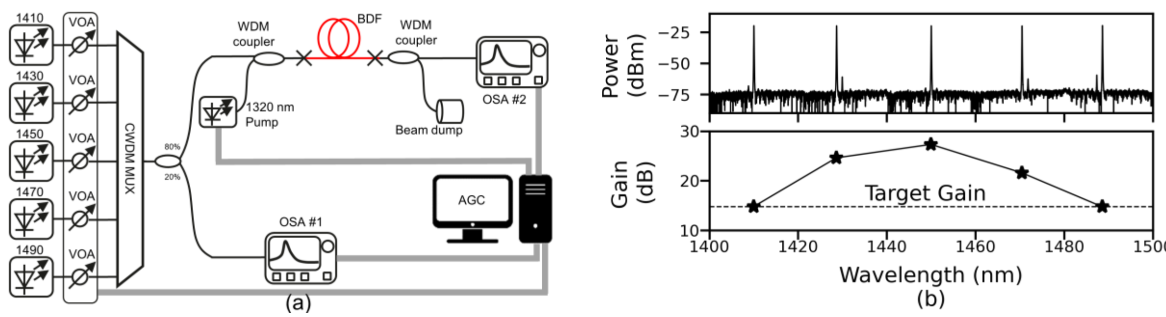

Fig. 2. (a) Experimental setup; (b) *upper*: the input signal spectrum for the range 1410~1490 nm, measured by OSA #1; *lower*: the gain spectrum of full-loading for the range of 1410~1490 nm.

4. Results and Discussion

Fig. 3 plots the summary of the results. Fig. 3(a), (b) and (c) are for the spectral range of 1410~1490 nm; (d), (e) and (f) are for 1430~1490 nm; (g), (h) and (i) are for 1450~1490 nm. Take the case of 1410~1490 nm as an example, the black and the red curves in Fig. 3(a) are the output spectra of one specific partial-loading case and of the full-loading case. The dark blue star markers are the gain deviations of the CWDM signals. The signal at 1430 nm is absent because it is fully "dropped" in this random case. It can be clearly seen that the shapes of the ASE pedestal are significantly different. According to [5], the shape of the output ASE spectrum mimics that of the signal gain. By subtracting the two ASE pedestals (full-loading and partial-loading), we obtain a curve (light-blue) that is similar to the gain profile deformation under partial-loading. In this case, a maximum of ~2.7 dB of gain deviation is observed for 14.8 dB of target gain. Fig. 3(b) plots together the gain deviations of 120 cases in the unit of percentage w.r.t. the target gain. The gain deviation can be as large as ~ 18% for the amplification range of 1410 ~ 1490 nm. Referring to the histogram in Fig. 3(c), the average gain deviation is ~ 12%.

By comparing Fig. 3(a)~(c) with Fig. 3(d)~(f) and Fig. 3(g)~(i), it is obvious that the gain deviation decreases as the center wavelength of the gain range moves toward the S-band. For the range of 1430~1490 nm, the gain deviation reduces to ~ 8% average (~16% max). For the range of 1450~1490 nm, it further reduces to ~ 2% average (~3% max). A hypothesis to explain the lower gain deviation over the 1450~1490 nm is the following. The SHB effect of the BDF mainly happens in the vicinity of 1410 nm. Any lightwave, including the signal and the ASE light in this region could induce a gain hole on top of the homogeneous gain profile. The red tail of this hole extends into the longer wavelength side of the spectrum. For the full-loading case, the signal power in the longer wavelength side is relatively strong, the lightwave in the vicinity of 1410 nm is therefore weak, and the gain hole is shallow. When the signal power reduces to 10~30%, the lightwave in the vicinity of 1410 nm becomes stronger, and then the gain hole becomes deeper. As a result, the gain profile will have a positive tilt (lower gain in the shorter wavelength side). In addition, the averaged signal gain becomes lower than the target gain. Under AGC, the signal gains are increased to catch up with the target gain. The additional gain will apply a negative tilt. Finally, as the AGC finishes, the gain profile presents a residual negative gain tilt. A similar phenomenon was also observed in the L-band EDFA [6] for which, after AGC, the gain profile can be recovered very close to that of the full-loading case and the residual gain deviation can be neglected.

Generally speaking, for the C-band EDFA, the gain deviation under AGC is about 2%~4%, depending on the specific gain bandwidth. Our experiment shows that BDFAs working in the wavelength range beyond 1450 nm would have similar magnitude of gain deviation as that in the C-band EDFA. Beyond 1490 nm, the gain can be enhanced by cascading a section of EDFA to the BDFA. A BDF/EDF hybrid amplifier that covers the whole S-band and part of the E-band (1450 ~ 1520 nm, in total 70 nm bandwidth), would thus be practically feasible.

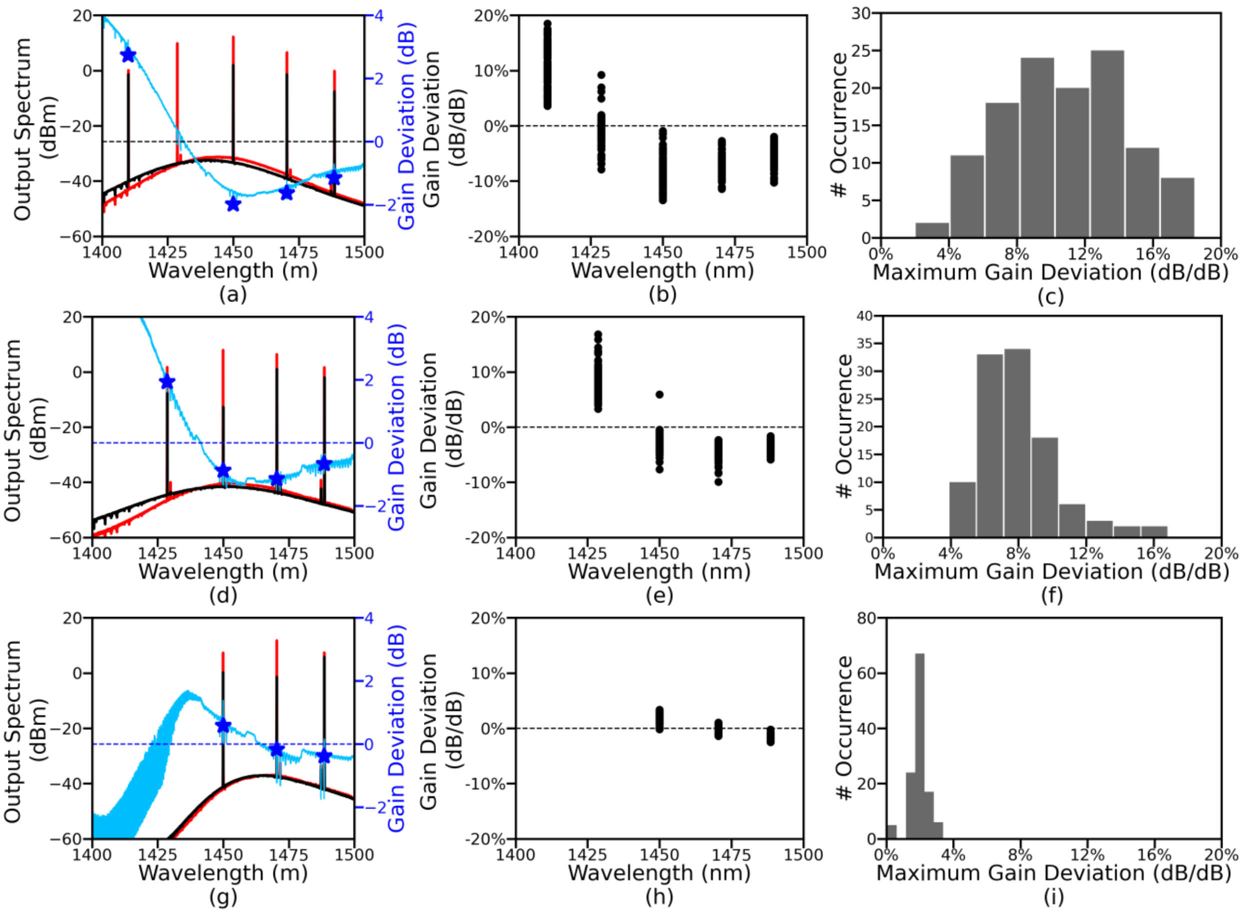

Fig. 3. The experimental results for the spectral windows of (a)~(c) 1410~1490 nm, (d)~(f) 1430~1490 nm and (g)~(i) 1450~1490 nm.

5. Conclusion

Under AGC, the residual gain deviation of the E+S band BDFA depends on the specific operating range. The gain deviation reduces from ~18% to ~4% when the shorter wavelength edge is displaced from 1410 nm to 1450 nm.

6. References

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