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Accurately control and flatten gain spectrum of L-band erbium doped fiber amplifier based on suitable gain-clamping

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ABSTRACT

The increasing traffic with dynamic nature requires the applications of gain-clamped L-band erbium-doped fiber amplifier (EDFA). However, the weak or over clamping may lead the unexpected gain-compression and flatness-worsening. In this article, to enhance practicality, we modify the partly gain-clamping configuration and utilize a pair of C-band fiber Bragg gratings (FBGs) to non-uniformly compress the gain spectrum of L-band. Through a comprehensive test and comparison, the suitable gain-clamping region for the amplified signals is found, and the gain in L-band is accurately controlled and flattened under the matched central wavelength of FBGs. The experimental results show that, our designed L-band EDFA achieves a trade-off among the output gain, flatness and stability. The ±0.44 dB flatness and 20.2 dB average gain are together obtained in the range of 1570–1610 nm, with the ±0.1 dB stability of signals in over 30 dBm dynamic range.

1. Introduction

To date, erbium-doped fiber amplifier (EDFA), with high gain and low cost, has always been one of the key equipments and widely applied as pre-, post- and inline-amplifier in a dense-wavelength-division-multiplexing-based optical communication system [1–3]. The continuous increasing traffic requires the operating band of EDFAs to be extended from C-band (1525–1565 nm) to S-band (1460–1510 nm) and L-band (1570–1610 nm). Comparatively, because of practicability, L-band EDFAs have received more attention in terms of gain-enhancement, flatness-improvement and gain-clamping[4–10]. According to [6–8], the two-stage and dual-pass (with higher noise figures) configurations are proved to efficiently guarantee the high output gain, and its flatness also can be obviously improved by parameter optimization, filters and gratings [11–14]. Besides, in gain-clamping, the all-optical technique based lasing-control is more popular than electrical and hybrid methods due to its simplicity [9,10,15,16]. But the penalty is to surely generate a clear loss at the lasing-wavelength, which may lead the unexpected gain-compression and flatness-worsening [17–19].

So guaranteeing high output gain and flatness in gain-clamping L-band EDFAs is still an open issue. To enhance output gain, Harun introduces a wideband fiber Bragg grating (FBG) to reflect more residual L-band amplified spontaneous emission (ASE) [20], Xia and Xiao propose the partly gain-clamping to reduce the compressed gain [8,17]. Also, to improve flatness, the clamping capability is constrained and the C-band lasers/seed-lights/FBGs are frequently used in the linear- and ring-cavity configurations [5,13,14,18,21,22]. The shortcoming is to lack of a comprehensive evaluation on the key parameters of FBGs (e.g., central wavelength and reflectivity). Hence, the inaccurate lasing-control brings a weak or over clamping on gain spectrum of L-band, and the un-flatness reaches ~2.5 dB and the output gain is merely 8–17 dB in the reported literatures.

In this article, we modify the partly gain-clamping scheme and use a pair of C-band FBG to non-uniformly compress the gain spectrum of L-band. Then through a comprehensive test and comparison, the suitable gain-clamping region for the amplified signals is found, and the gain in L-band is accurately controlled and flattened under the matched central wavelength of FBGs. Consequently, by our designed L-band EDFA, the small un-flatness (< ±0.44 dB) and the acceptable average gain (> 20 dB) are together obtained in the range of 1570–1610 nm, with the ±0.1 dB stability of signals in over 30 dBm dynamic range. To the authors' knowledge, it is unreported to simultaneously meet the demands of L-band EDFA in terms of output gain, flatness and stability by such simple and practical scheme.

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2. Principles of suitable gain-clamping

In order to maintain high output gain, the partly gain-clamping scheme is adopted. As shown in Fig. 1, our designed linear-cavity L-band EDFA consists of two stages of erbium-doped fiber (EDF). In the first stage, a short EDF is selected to generate the C-band ASE with high gain-efficiency. Moreover, this C-band ASE and pump will together enter the second stage to enhance the output gain in L-band. In the second stage, we place a pair of FBG at the two ends of a long EDF to form a Fabry–Perot (F–P) cavity. Then a lasing-resonance at the central wavelength of FBGs will be generated in such F–P cavity and the output gain of amplifier is automatically stabilized but with the expense of gain–loss [13,17,18,21,22].

Further, we assume the two FBGs with narrow line-width have the same central wavelength (λ_B), and their reflectivities are r_1 and r_2, respectively. Then according to Ref. [23], the optical gain in the second stage can be depicted as

$$G(\lambda) = e^{\{[\alpha(\lambda)+g^*(\lambda)]\bar{n}-[\alpha(\lambda)+l(\lambda)]\}L} \tag{1}$$

where α, g^*, l and L are the absorption, emission coefficients, background loss and length of EDF, respectively, λ is the wavelength of signal, $\bar{n}$is the average population inversion number and can be written as

$$\bar{n} = \frac{\alpha(\lambda_B)+l(\lambda_B)}{\alpha(\lambda_B)+g^*(\lambda_B)} + \frac{(-10\log\sqrt{r_1 r_2}+\delta_c)/L}{4.34\gamma[\alpha(\lambda_B)+g^*(\lambda_B)]} \tag{2}$$

where δ_c is called splicing loss, and γ is a constant and equal to 2 in linear-cavity configuration. Combining Eqs. (1) and (2), it is obvious that $G(\lambda)$ is negative proportional to the product of r_1 and r_2 for a given L. And the minimum $G(\lambda)$ would be gotten at $\lambda=\lambda_B$ because of the energy consumption from lasing (see Fig. 1). While, when λ is drifted from λ_B, the compressed gain (dot line) will be quickly reduced, and the FBG-pair can be viewed as a narrow-band filter in this case. From [19], at $\lambda=\lambda_B$, the gain may lose ~50% due to gain-clamping. But in L-band, the real gain spectrum is monotonically decreased with the rise of λ, and the gain difference is less than 30%. So λ_B must be limited in C-band in our amplifier, which makes the compressed curve of gain in L-band has the monotone increasing feature. Therefore, based on symmetrical compensation, the gain spectrum of L-band can be flattened by the compressed gain through accurately adjusting the key parameters of FBGs (i.e., λ_B, r_1 and r_2). For simplicity, we can fix r_1 and r_2, and let $r_1=r_2$. Then our work simply focuses on finding a matched λ_B to avoid the weak or over gain-clamping.

3. Experiments and results

Fig. 2 illustrates the experimental setup of our designed L-band EDFA. The input signals are generated by a tunable laser source (TLS), and cover the whole L-band with the interval ($\Delta\nu$) of 5 nm. We set the dynamic range of the input power of signals (P_s) is from −40 dBm to 0 dBm. Two DFB-type laser diodes, with central wavelengths at 974 nm and 1478 nm, are used as pumps in the two stages, and their output power are 30 mW and 70 mW, respectively [8]. The 11 m- and 40 m-EDFs (EDFC-980-HP by Nufern) are respectively placed in the first and second stages, and other key parameters of EDF are given in Table 1.

Furthermore, the isolators (ISO), wavelength division multiplexers (WDM) and coupler (C) have the abundant pass-band for the pump lights, C-band ASE and L-band signals, and their connecting loss is smaller 0.2 dB. The output signals will be recorded by optical spectrum analyzer (OSA, Agilent 81642B) and power meter (NewPort 1830c). In addition, the working temperature is kept at 23 ± 0.2° Celsius and the whole experimental setup is placed in an optical stable platform to avoid the unexpected interference. Then to find the suitable gain-clamping region, we first select four pairs of C-band FBGs with a small difference of λ_B ($\sim\pm0.2$ nm) in experiments, and their central wavelengths are approximately equal to 1529.3 nm, 1538.8 nm, 1550.2 nm and 1558.9 nm, respectively. The reflectivity of FBGs is ~99% and the 3 dB-line-width is less than 0.5 nm by an experimental test.

We then tune P_s and conduct the experiments and evaluation in term of gain-stability under the various C-band FBG-pair. From Fig. 2(a) and (b), we observe that the gain-stability is not ideal when λ_B (=1529.3 or 1538.8 nm) is far away L-band. Due to the weak capability of clamping, the ±0.1 dB stability (G_s) only can be obtained in the dynamic range of less than 20 dBm although the output gains of signals are higher than 25 dB. Moreover, from the subfigures, the gain fluctuation in L-band reaches ~30% in these two cases. In values, the gain differences (ΔG) are 9.3 dB and 8.7 dB, respectively. This means, except for high output gain, the demands on flatness and stability cannot be guaranteed in the weak gain-clamping region. With the rise of λ_B (=1550.2 or 1558.9 nm), the gain-stability is obviously improved in Fig. 3 (c) and (d) because of the continuously increased capability of

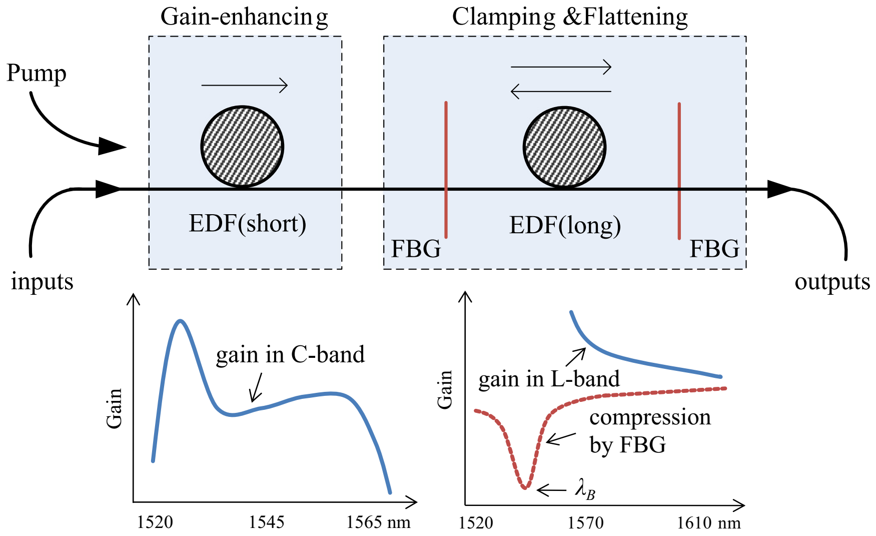

Fig. 1. Basic principle of suitable gain-clamping technique with two-stage configuration, EDF: erbium-doped fiber, FBG: fiber Bragg grating, λ_B: central wavelength of gratings.