Gain equalization of EDFA using a loop filter with a single polarization controller

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Received November 7, 2011; accepted January 18, 2012; posted online March 28, 2012

A Sagnac loop filter with two pieces of high birefringence fiber having equal lengths, and spliced together at a fixed angle of 30^o displacement between the two principle axes, is proposed in this letter. Gain equalization of erbium-doped fiber amplifiers (EDFAs) is implemented by tuning only the polarization controller in the loop filter. Experimental result shows that there remains a deviation of ±1 dB in the region of the flattened profile with the useful bandwidth of about 23 nm, thereby demonstrating the effectiveness of the method. An effective mathematical model and mechanism is also given for further explanation.

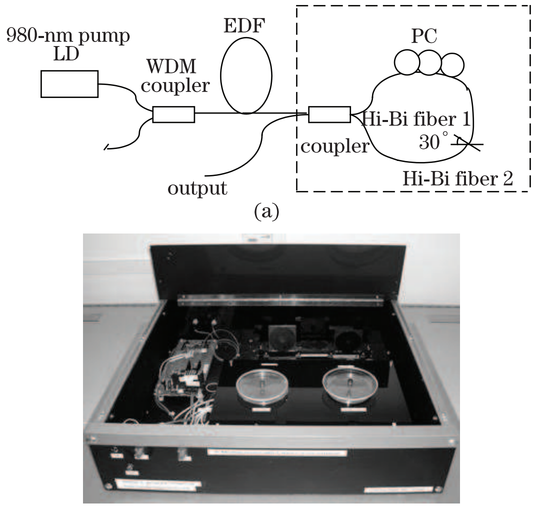
OCIS codes: 060.2320, 060.2280, 260.1440.
doi: 10.3788/COL201210.070604.

Gain equalization of erbium-doped fiber amplifiers (EDFAs) is a critical issue for wavelength-division multiplexing (WDM) communication systems[1]. This is because gain un-equalization of the amplifier creates undesirable non-linear effects, such as the cross and self-phase modulation, wave mixing, Brillouin and Raman scattering, and signal overloading and crowding out by noise, all of which can potentially hamper the performance of the WDM system. In general, the gain profile of EDFAs can be flattened by modifying the material composition in the erbium-doped fiber (EDF), or by using optical filters to compensate for the variations in the gain spectrum. Various kinds of optical filters are demonstrated for the application, including the long-period gratings, fiber acousto-optic tunable filters, and fiber Bragg gratings (FBGs) technologies[2−9]. Different from other interferometers, such as the Mach-Zehnder, the light intensity transfer function (TF) of the Sagnac interferometer is independent of the input polarization state if there are no non-reciprocity components and polarization-dependent components used[10]. Fang *et al.*[11] have reported a Sagnac loop with high birefringence (Hi-Bi) fiber, which can function as a filter that can be used as a wavelength-division multiplexer. This Sagnac loop can also be used in fiber lasers[12,13]. Li *et al.*[14] have employed this type of loop to the gain equalizer and a circulator in the fiber amplifier, using two independent polarization controllers (PCs) and two independent segments of Hi-Bi fiber. In using this type of loop, there are too many structure parameters that must be adjusted to adapt the demand of EDFAs with high gain equalization.

In this letter, we demonstrate the construction of a Sagnac interferometric loop with only one PC and two segments of Hi-Bi fiber spliced together as an EDFA gain-flattening filter. The two Hi-Bi fibers have equal lengths and are coupled at a fixed angle of 30° displacement between the two principle axes, making them easier to adjust which, in turn, results in high performance experimentally. In our experiment, the output beam is from the transmission port of the loop, instead of the circulator or isolator. Different from the reflective port of the loop, the transmission port may not induce the lasing oscillation without the circulator or isolator.

The portion with the dotted lines shown in Fig. 1(a) demonstrates the Hi-Bi loop that serves as an optical filter. The principle of the Hi-Bi fiber loop filter is as follows. The input beam from a 3-dB 50:50 coupler made from a single-mode fiber (SMF) is split into two counter-propagating beams, each of which is decomposed into four beams after traveling through the two Hi-Bi fiber sections that are effectively two polarimetric interferometers connected in a series. The input polarization state of the light into these interferometers can be controlled by adjusting the PC. The intensity of the light coupled back to the output depends on the phase differences among the interfering beams in terms of the-birefringence, the length of the Hi-Bi fiber sections, and the couple angle between the two sections of Hi-Bi fiber. In general, a Hi-Bi fiber loop filter with n-sections can produce a spectrum of a 2^n-beam interferometer. When the lengths of the Hi-Bi fiber are chosen appropriately, the transmission spectrum of the Hi-Bi fiber loop filter can be matched with the EDFA gain profile to produce an overall gain flattening. A photograph of the EDFA gain equalization experimental set up used in this letter is shown in Fig. 1(b).

The typical EDFA gain profile generated from a 15-m EDF pumped at 88 mW was used in the experiments. The gain peak at the wavelength of around 1 530 nm had a gain of 12 dB above that of the flat portion from 1 535 to 1 560 nm, which was difficult to flatten. Ideally, if the gain can be flattened, the entire EDFA gain bandwidth can be utilized to realize light amplification, and the useful gain bandwidth of the EDFA spectrum is normally around 36 nm, ranging from 1 523 to 1 559 nm. Figure 2 shows the ideal filter gain profile that allows a good equalized output over the broad gain spectrum of the EDFA. The equation of the gain profile of the



(a)

(b)

Fig. 1. (a) Schematic of EDFA gain equalization using Sagnac interferometric filter; (b) photograph of the EDFA gain equalization experimental setup.

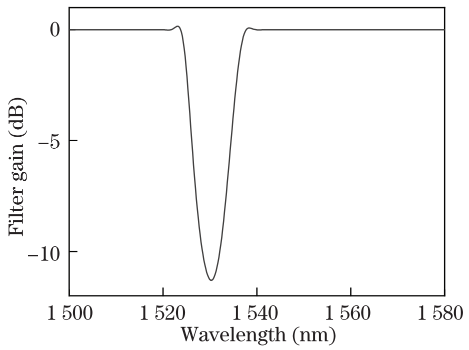


Fig. 2. Ideal filter gain profile of the Hi-Bi loop.

gain-flattening loop is given by

$$\text{Gain}_{\text{EDFA}} \times \text{Gain}_{\text{Filter}} = \text{Constant}.$$

If this ideal profile can be achieved (Fig. 2), the useful bandwidth of the EDFA is maximized, i.e., achieving a totally flattened gain over a wide bandwidth. However, it is extremely difficult to achieve this in practice.

The gain-flattening experiment first started off with single-segment Hi-Bi fiber loop filter. It had a similar structure with its two-segment counterpart, except that the Sagnac loop was formed by a single Hi-Bi fiber segment with a length of 8 cm. The best gain profile achieved was a mere ±3-dB peak deviation, which was far from our objective of ±1 dB. To achieve better gain flattening, research was extended into using a two-segment Hi-Bi fiber loop filter from the single-segment one, based on the same principle of the Sagnac interferometer.

The gain-flattening Sagnac loop filter with two Hi-Bi fiber segments was connected together with the EDFA to form the gain-flattening circuit (Fig. 1(a)). This circuit was characterized with different levels of pump power to determine the resultant profiles of the loop filter and the EDFA gain. The pump power was gradually increased in steps of the laser pump current with 10 mA. As the pump current increased from 30 to 190 mA, the equivalent pump power also increased from 5 to 88 mW, respectively.

The approach that we used for this Hi-Bi loop filter device was to first choose the geometric parameter of the fiber. This was done to obtain an initial coarse correspondence of the period spacing of the comb filter matching the EDFA gain bandwidth as well as a notch valley of approximately −12-dB attenuation, with a wavelength of 1 530 nm. Adjustments were done to match the EDFA bandwidth by conducting experiments with different lengths of the Hi-Bi fiber, l_1 and l_2, together with the PC to optimize the profile of the filter.

After conducting experiments with different lengths of two-segment Hi-Bi fibers, the filter loop was constructed with $l_1 = l_2 = 8$ cm, with modal birefringence $B = 3.8 \times 10^{-4}$, and the two Hi-Bi fibers coupled at $\theta = 30°$. The transmission spectrum of the Hi-Bi filter loop was characterized to determine the gain profile of the filter, which was then inputted with ANDO AQ4321D tunable laser between 1 520 to 1 560 nm at 1 mW (0 dBm). Figure 3(a) shows the intensity transmission profile of the filter, in which the first paddle of the PC is tuned near the coupler (No. 1) and the middle paddle (No. 2). By adjusting the PC, the rotation angle less than 90° of polarization plane increased from the left to the right as shown in the curve in Fig. 3(a) The profile is appropriately matched in terms of the spectra bandwidth of the EDFA; at the same time, the notch of the profile aligns at the peak value of the EDFA gain with around 1 531 nm. This suggests that the length of the two Hi-Bi fibers and the coupling angle of 30° are quite suitable. The notch position can also be optimized for its wavelength and depth to achieve the required amount of attenuation.

Figure 3(b) shows that the filter gain profile is approximately the same as the ideal gain profile shown in Fig. 2.

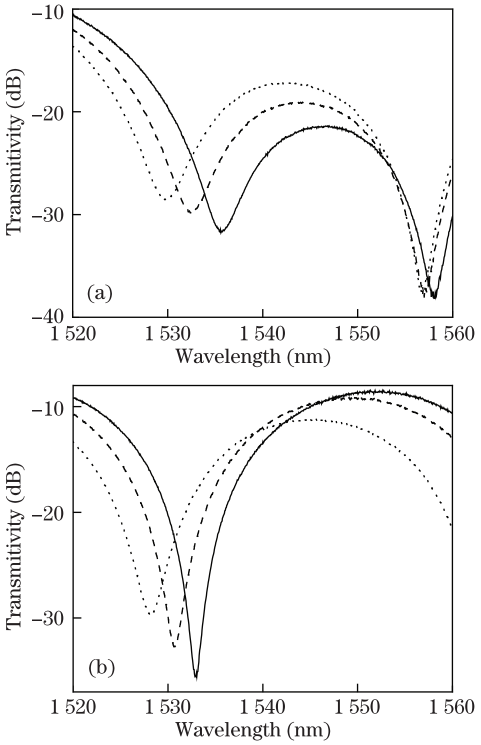


Fig. 3. Sagnac interferometric filter transmission spectra with tuning paddle (a) Nos. 1 and 2 and (b) Nos. 2 and 3 of the PC.

The wavelength and depth of the notch can be aligned by turning the PC. The rotation angle with more than 90° of polarization plane increases from the left to the right as shown in the curve in Fig. 3(b). The insertion loss of the Hi-Bi loop is approximately 7.5 dB. Majority of the loss is contributed by the 6 fusion splices, especially those between the SMF and the Hi-Bi fiber. Moreover, two FC connectors were used in the circuit construction, and these must be improved in the future work.

No EDFA gain profile can be observed below the pump power of 5 mW (Fig. 4). When the pump power increases to above 5 mW, the EDFA gain profile becomes visible with a non-flattened gain. The EDFA gain increases significantly by adjusting the pump power from 5 to 42 mW, and the profile remains flattened in the region between 1 530 and 1 553 nm, with a deviation of ±1 dB. Above the 42-mW pump level, the EDFA gain starts to saturate, and thus, the Hi-Bi loop filter output shows no significant increment, merely fluctuating at the peak level of −24 dBm. However, the gain profile remains stable as the pump current increases from 42 to 88 mW (Fig. 4). Experimentally, we achieved the best gain equalization of around ±1 dB, with the bandwidth of 23 nm.

The wavelength-dependent intensity TF for non-reciprocity port of the Sagnac loop filter can be expressed as

$$\mathrm{TF} = 1 - 4\left\{|s_{11}|^2 + [\mathrm{Re}\,(|s_{12}|)]^2\right\}, \tag{1}$$

where s_{11} and s_{12} are the first row elements of a 2×2 matrix, respectively, which denote the Jones propagation matrix of the Sagnac loop in a counter-clockwise direction. For the setup in Fig. 1(a), the TF could be further rewritten as

$$\begin{aligned}\mathrm{TF} =& \sin^2\alpha\cos^2\theta\left[1-\cos^2\left(\frac{2\pi}{\lambda}Bl\right)\right]+\cos^2\alpha\sin^2\theta \\ &\cdot\sin^2(\delta/2)+\sin 2\alpha\sin 2\theta\sin(\delta/2)\sin\left(\frac{2\pi}{\lambda}Bl\right),\end{aligned} \tag{2}$$

where λ is the wavelength, B is the model birefringence of the Hi-Bi fiber, l is the length of each piece of Hi-Bi fiber, θ is the angle between the two principal axes of the Hi-Bi fibers, and α and δ are the rotation angles of the polarization plane by the PC and the induced birefringence phase with the PC, respectively. First, we set the rotation angle α of PC to 90°. The simulation results of the TF with different θ values are shown in Fig. 5(a). As can be seen, the notch is located at 1 530 nm.

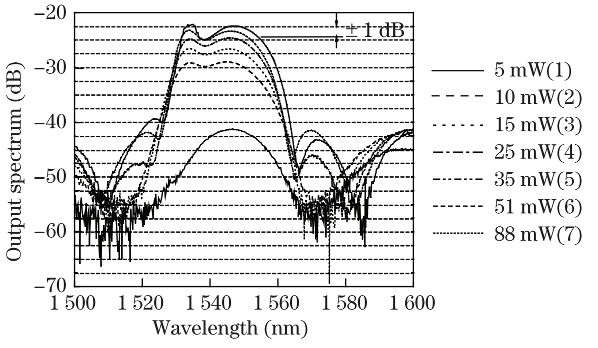


Fig. 4. (Color online) Resultant output profiles of the EDFA employing the Hi-Bi loop filter with different pump power levels.

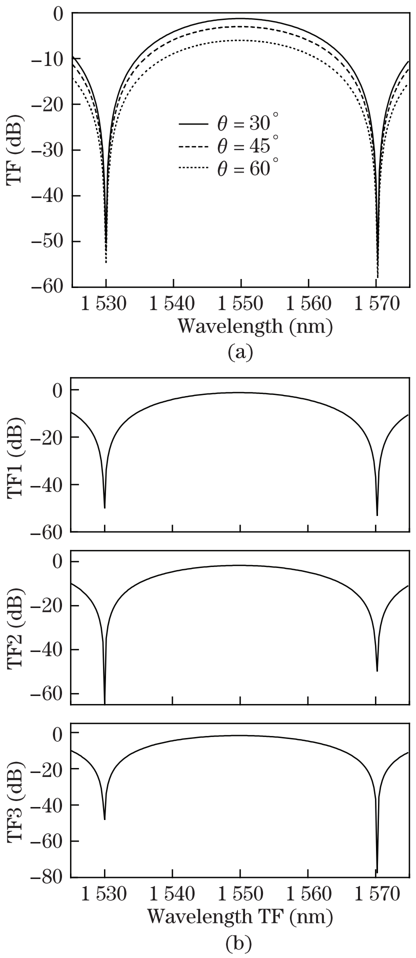


Fig. 5. (a) Simulation results of the loop filter TF with (a) different θ values when α is set at 90° and (b) different α values when θ is set at 30°.

We considered the influence of the third term in Eq. (2), and δ was given a small value. From top to bottom, Fig. 5(b) shows the TFs when the third term of Eq. (2) is zero, negative and positive, respectively. We assumed $\sin^2\alpha = 0.9$ for the last two curves in Fig. 5(b). The notch depth can be adjusted with different α and δ values; moreover, the notch wavelength can be modified given that δ is also wavelength-dependent.

A good level of EDFA gain equalization can be achieved with this type of configuration; specifically, the two segments of the Hi-Bi fibers with equal lengths and the appropriate coupling angle between the two-segment Hi-Bi fibers must be carefully selected. Given that the coupler consists of the SMF, due to its small core imperfection and ability to easily induce birefringence caused by stress and bending, the coupler can inherently affect the state of the polarization of the beams propagating in the loop. In particular, since the portions of SMF near the PC controls the launch angles of the propagating beams in the loop, it could easily affect the phase shift between the interfering beams, thus resulting in the gain profile instability.

In conclusion, we demonstrate the flattened gain profile of the EDFA spectrum with ±1-dB peak deviation and bandwidth of about 23 nm using the Sagnac Hi-Bi loop filter as a gain profiling filter, in which the band-stop notch is tuned to 1 530 nm, with an attenuation of 12 dB. Characterization of the Sagnac interferometirc Hi-Bi loop filter as an EDFA gain equalization optical filter is also presented. The Hi-Bi loop filter is combined with the EDF with a length of 15 m, using a 980-nm pump source to form an optical amplifier. The output is generated at different pump power levels ranging from 42 to 88 mW. We choose the original gain profile with 12-dB peak at 1 530 nm, which is more difficult to flatten. Compared with the result of a previous work[14], the loop filter proposed here only has the Hi-Bi fiber length as the parameter that must be modified and one PC that must be tuned. A mathematical model is also established, through which the effective simulations are presented. Moreover, different from the reflective port of the loop used a previous work[14], we employ the non-reciprocity port of the Sagnac loop here and do not use any isolators or circulators. To the best of our knowledge, this is the simplest and most convenient method for flattening the gain of EDFAs. This is also useful for wide bandwidth sources and fiber multi-wavelength lasers.

The authors wish to thank Teck Heng Tan and Wai Chung Poon for their contributions to our experiments.

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