Optimization of the two-stage single-pump erbium-doped fiber amplifier with high amplification for low frequency nanoscale pulses

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Abstract. We report the two-stage single-pump configuration of an erbium-doped fiber amplifier, in which a Sagnac interferometer is introduced to reduce the most important contribution of amplified spontaneous emission (ASE) noise, providing significant improvement on the amplifier performance. A Sagnac interferometer, made from a high-birefringence fiber loop, is included between the first and second stages. It is designed to provide transmittance with a period of 46 nm that allows us to adjust the minimum transmission around 1530 nm (peak of ASE noise) and maximum transmission at 1550 nm (signal wavelength). For optimizing the configuration, we measure the erbium-doped fiber parameters and simulate the amplification of the signal along the fiber. In the experiment, a significant absorption coefficient for pump and signal is found. The absorption looks to be too strong for the background absorption, and we suppose that it may be caused at least partly by excited-state absorption (ESA). Including the absorption coefficient allows very good correspondence between simulation and experiment. Experimental results show that with a simple configuration, we obtain up to 53-dB amplification with only 73 mW of pump power. [DOI: 10.1117/1.2823495]

Subject terms: erbium-doped fiber amplifiers; optical filters; Sagnac interferometer.

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1 Introduction

The field of erbium-doped fiber amplifiers (EDFAs) has received a great deal of attention since their development, due to their characteristics of high gain, polarization independent amplification, and low intrinsic optical noise. Therefore, these devices have been permanently improved and adapted to new requirements.

Several techniques have been proposed to enhance signal gain and pump conversion efficiency. One of these brings the double propagation of the signal beam into the amplifier by using mirrors at the output end of the erbium-doped fiber (EDF).[1–4] Another suppresses the unwanted amplified spontaneous emission (ASE) noise,[5–7] providing significant improvement in signal gain. Also, optical isolators and optical filters have been inserted to avoid ASE noise, causing fast saturation in the EDF.[4–8]

In spite of the abundance of scientific and technical information in this field, new configurations of the amplifiers still can be suggested following the new applications. In this work, we present a two-stage single-pump erbium-doped fiber amplifier design, in which a Sagnac interferometer filter is introduced to reduce the most important contribution of ASE noise (peak around 1530 nm), providing significant improvement on the amplifier performance. The amplifier was designed for the study of nonlinear phenomena in optical fiber with ns-pulse pumping, where it was used for amplification of the signal from a mW-power directly modulated distributed feedback (DFB) laser to tens of watt pulses, convenient for nonlinear phenomena in optical fibers.

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2 Amplifier Configuration

The amplifier configuration that we propose is shown in Fig. 1. The design for this amplifier is based on a two-stage configuration with a single-pump laser diode and interstaged components, such as an optical circulator and an optical bandpass filter to optimize the signal gain. The first stage is a conventional double-pass configuration deployed as an optical preamplifier to provide high gain with a low ASE noise by using a fiber Brag grating (FBG), where reflectivity is near 100% for a 1550-nm wavelength, placed at the output end of EDF 1 to allow the signal to undergo double propagation.

The optical circulator connects the first stage (EDF 1) with the second stage (EDF 2), and avoids ASE originated in the second stage to cause saturation in the first stage. Nevertheless, backward ASE originated in EDF 1 causes saturation in EDF 2, degrading its optical gain. To overcome this problem, we inserted an optical filter based on the Sagnac interferometer to reduce the unwanted ASE noise suppressing the ASE peak at 1530 nm. The second stage is a conventional single-pass configuration deployed

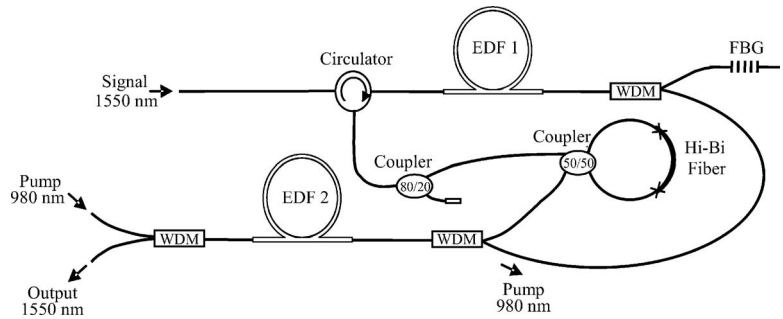

Fig. 1 Amplifier configuration.

as a power amplifier. One specific feature of our amplifier is the use of a single 980-nm pump diode to supply both the first and second stages.

The principle of the Sagnac interferometer filter can be described as follows. The input light introduced at the 50/50 coupler is split into two counterpropagating beams. After propagating through the high birefringence (hi-bi) fiber, both of the beams separate into fast and slow axis components. They finally propagate again into the 3-dB coupler and interfere at the output end. Therefore, the transmission of the Sagnac can be described as follows,[9]

$$I_{\text{out}}\alpha(I_{\text{cw}}+I_{\text{ccw}})\{1+\cos[\delta\phi(\lambda)]\}, \tag{1}$$

where I_{cw} and I_{ccw} are the intensity of the light in the clockwise and counterclockwise path, respectively, and $\delta\phi(\lambda)$ is the phase difference between the fast and slow axis components, which can be described by the following formula

$$\delta\phi(\lambda)=\frac{2\pi BL}{\lambda}, \tag{2}$$

where B is the birefringence, L is the length of the hi-bi fiber, and λ is the wavelength.

Based on the previous analysis, it is clear that the Sagnac interferometer provides a periodic transmittance that can be used as a bandpass filter by selecting properly the hi-bi fiber length. For the amplifier configuration, we choose a 15-cm-long hi-bi fiber to have a half period equal to 23 nm that allows the minimum transmission at about 1530 nm (peak of the noise) and maximum transmission at 1550 nm (signal wavelength). The maximum transmittance of the Sagnac interferometer is 0.6, and it was determined mostly by the splice losses between standard and hi-bi fibers. The position of the maximum and minimum of the transmission could be adjusted by temperature of the hi-bi fiber controlling the electric current of a thermo-electric cooler (TEC), as is shown in Fig. 2.

3 Simulation Model

We simulate amplifier performance by solving the propagation and rate equations of a two-level EDF model[10] by numerical simulations. This model assumes that erbium ions are homogeneously broadened, and effects such as excited-state absorption (ESA) are not considered. After a few algebraic manipulations in a steady-state situation, the population density $N_2(z)$, as a function of position z along the fiber, is given by

$$N_2(z)=\frac{\dfrac{\tau\sigma_s^{(a)}\Gamma_s P_s(z)}{ah\upsilon_s}+\dfrac{\tau\sigma_p^{(a)}\Gamma_p P_p(z)}{ah\upsilon_p}+\sum_j\dfrac{\tau\sigma_j^{(a)}\Gamma_j P_{\text{ASE}}(\upsilon_j)}{ah\upsilon_j}}{\dfrac{\tau(\sigma_s^{(a)}+\sigma_s^{(e)})\Gamma_s P_s(z)}{ah\upsilon_s}+\dfrac{\tau(\sigma_p^{(a)}+\sigma_p^{(e)})\Gamma_p P_p(z)}{ah\upsilon_p}+\sum_j\dfrac{\tau(\sigma_j^{(a)}+\sigma_j^{(e)})\Gamma_j P_{\text{ASE}}(\upsilon_j)}{ah\upsilon_j}+1}N, \tag{3}$$

where N is the total erbium ion density. $\sigma_s^{(a)}$, $\sigma_s^{(e)}$, $\sigma_p^{(a)}$, and $\sigma_p^{(e)}$ are the absorption and emission cross sections for signal and pump, respectively. $\Gamma_{s,p,j}$ are the integral overlap factors for signal, pump, and ASE. a is the effective area of erbium ion distribution. $\upsilon_{s,p,j}$ are the light frequencies corresponding to signal, pump, and ASE. h is Planck's constant. τ is the lifetime for transitions from level 2 to level 1, and $P_{s,p,\text{ASE}}(z)$ are the optical power for the signal pump and ASE beams as a function of position along the fiber.

To simulate the amplifier performance, it is necessary to determine all parameters in Eq. (3). Nevertheless, there are some limitations because of the complicated measurements to determine all required parameters. To overcome this problem, these parameters are grouped in a new set of parameters, which can be measured in an easy way, which we call the A,B,C,D parameters. The parameters can be grouped as follows:

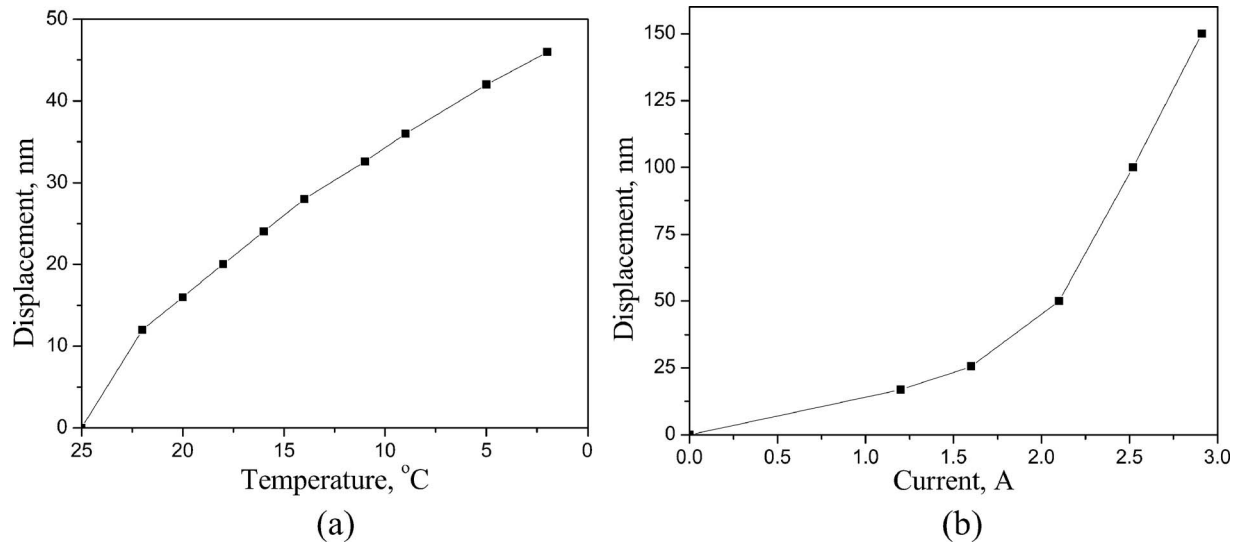

Fig. 2 Dependence of wavelength displacement on (a) temperature and (b) electric current through TEC.

$$A(\lambda) = \frac{\tau\sigma_p^{(a)}}{ah\upsilon_p}\Gamma_p, \quad B(\lambda) = N\sigma_p^{(a)}\Gamma_p,$$

$$C(\lambda) = \frac{\tau\sigma_s^{(a)}}{ah\upsilon_s}\Gamma_s, \quad D(\lambda) = N\sigma_s^{(a)}\Gamma_s. \tag{4}$$

The signal, pump, and ASE propagation equations are then written in terms of the A,B,C,D parameters as

$$\frac{dP_p}{dz} = \left[\frac{N_2}{N}(1+\eta_p) - 1\right]BP_p - \alpha_p P_p, \tag{5}$$

$$\frac{dP_s}{dz} = \left[\frac{N_2}{N}(1+\eta_s) - 1\right]DP_s - \alpha_s P_s, \tag{6}$$

$$\frac{dP_{\mathrm{ASE}}^{+}(\upsilon_j)}{dz} = \left\{\frac{N_2}{N}[1+\eta(\upsilon_j)] - 1\right\}D(\upsilon_j)P_{\mathrm{ASE}}^{+}(\upsilon_j) + 2\frac{N_2}{N}\eta(\upsilon_j)D(\upsilon_j)h\upsilon_j\Delta\upsilon_j - \alpha_j P_{\mathrm{ASE}}^{+}(\upsilon_j), \tag{7}$$

$$\frac{dP_{\mathrm{ASE}}^{-}(\upsilon_j)}{dz} = -\left\{\frac{N_2}{N}[1+\eta(\upsilon_j)] - 1\right\}D(\upsilon_j)P_{\mathrm{ASE}}^{-}(\upsilon_j) - 2\frac{N_2}{N}\eta(\upsilon_j)D(\upsilon_j)h\upsilon_j\Delta\upsilon_j + \alpha_j P_{\mathrm{ASE}}^{-}(\upsilon_j), \tag{8}$$

where $\eta_{s,p,\upsilon j}$ are the ratio between emission and absorption cross section spectrum for signal, pump, and ASE, respectively, which is obtained by the McCumber relationship.[10] $\alpha_{p,s,j}$ are the absorption coefficients for pump, signal, and ASE, respectively. P_{ASE}^{+} and P_{ASE}^{-} are the optical powers of ASE in forward and backward directions, respectively.

The A,B,C,D parameters are measured considering high and low power regions in Eqs. (3), (5), and (6). For these conditions, the solution of the signal and pump propagation equations show that by measuring the output power of the signal and pump beams in the EDF, we obtain a graphic whose slope provides information to obtain the A,B,C,D parameters. For a detailed explanation of this method, see Ref. 11.

For the experiment, we used a High Wave Optical Technology erbium-doped fiber, model EDF510, with the following characteristics: absorption at 1532 nm=9.21 $\times 10^{-3}$ cm^{-1}, absorption at 980 nm=7.6$\times 10^{-3}$ cm^{-1}, background loss at 1200 nm=1.31$\times 10^{-5}$ cm^{-1}, cut-off at 870 nm, mode-field diameter at 1550=5 μm, cladding diameter=125±1 μm, and erbium concentration of 1000 ppm. The result of the measurements is the following: B=6.98$\times 10^{-3}$ cm^{-1}, B/A=5.61$\times 10^{-6}$ W/cm, D=3.73 $\times 10^{-3}$ cm^{-1}, and D/C=2.07$\times 10^{-6}$ W/cm. We found strong absorption coefficients α_p=0.59$\times 10^{-3}$ cm^{-1} and α_s=0.94$\times 10^{-3}$ cm^{-1} for pump and signal, respectively.[11] The absorption looks to be too strong for the background absorption, and we suppose that it may be caused at least

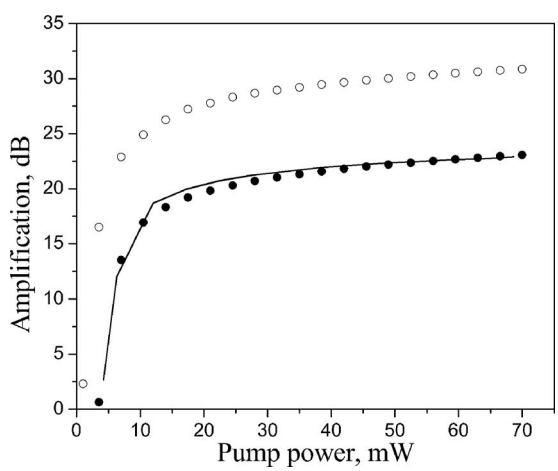

Fig. 3 Comparison between experimental results (solid line) and simulations introducing the absorption coefficients (•) and without introducing the absorption coefficients (◦).

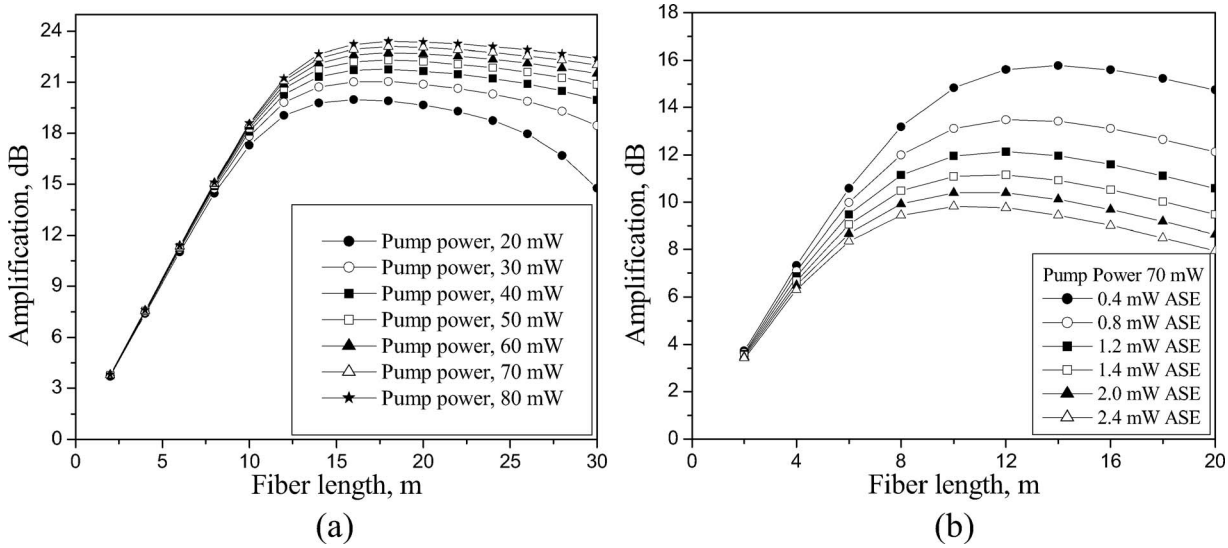

Fig. 4 Simulation amplification as a function of EDF length: (a) for the first stage, and (b) for the second stage, considering the effect of different ASE noise powers coming from the first stage.

partly by the ESA. However, the use of Eq. (3) without ESA gives reasonable agreement between the simulation based on A,B,C,D parameters and experimental results (see later). We have measured the amplification of the EDF fiber and compared experimental results with the simulation using the experimentally measured parameters. We found that it is very essential to include in the equations the absorption coefficients both for pump and signal to obtain good agreement between the simulation and experimental results. Figure 3 shows the effect of introducing the absorption coefficients in the simulations of a signal gain in a 20-m-long EDFA.

From Fig. 3 it is clear that the best agreement between simulation and experimental results is obtained by introducing the absorption coefficients in the simulations.

4 Selection of the Erbium-Doped Fiber Lengths and Experimental Results on the Two-Stage Amplifier

To obtain the optimum fiber length for the EDFA, we simulate the amplification as a function of EDF length for the first and second stage, as is shown in Fig. 4. For the first stage, we found that the amplification grows strongly with the EDF to approximately 15 m in length, and for longer fiber lengths the amplification begins to decrease. The maximum amplification in one direction is about 23 dB for the 15-m EDF fiber, and gain difference for pump powers between 30 and 80 mW is only about 2 dB. Therefore, it is not necessary for high pump powers to optimize amplifier gain. For these reasons, the best candidate is 15 m of EDF

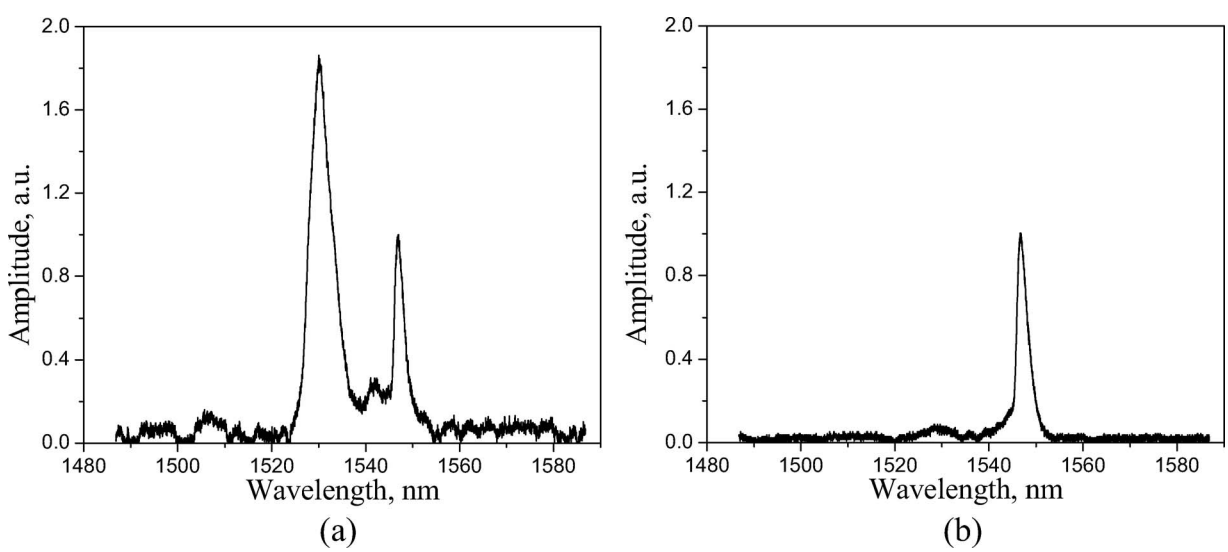

Fig. 5 Spectral dependence of (a) ASE noise and (b) filtering of ASE noise by the Sagnac interferometer.

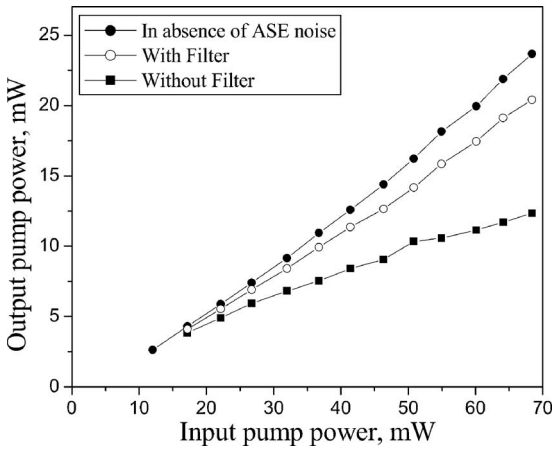

Fig. 6 Effect of introducing the Sagnac interferometer to enhance output pump power.

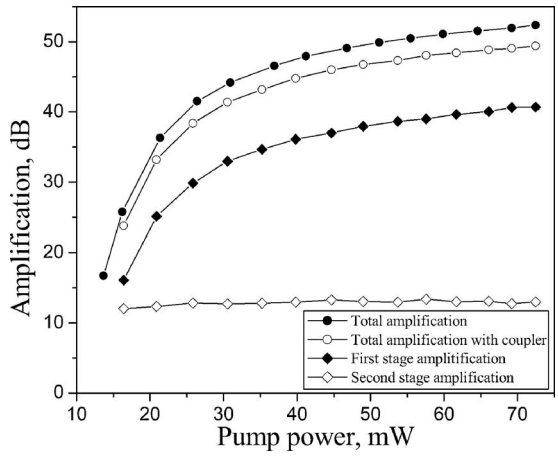

Fig. 7 Amplification of the first stage, the second stage, and total amplification.

to provide high amplification with low pump power. For the second stage, the optimal length is obtained considering the effect of the backward ASE coming from the first stage into the second stage. We found that the backward ASE ranges from 0.2 to 2 mW for pump powers between 5 and 25 mW. Figure 4(b) shows the simulation amplification for different EDF lengths at the 70-mW pump, introducing different input backward ASE powers from the first stage to estimate the optimal length in the presence of ASE noise. We have found from the simulation that the optimal length of the EDF in the second stage decreases when the ASE power grows; however, the fiber length in the range from 9 to 16 m can be appropriate for any ASE power, with penalty in the amplification less than 2 dB.

We measured the spectral dependence of the ASE at the output of the first stage and found that there are two strong maxima: one about 1530 nm and another about 1550 nm. The first one coincides with the maximum of the amplification, and the second coincides with the FBG. To improve gain and pump absorption, a Sagnac interferometer filter (described in Sec. 2) is introduced to suppress the most important contribution ASE (peak at 1530 nm). Figure 5 shows the spectrum of the ASE before and after the filter. The strong decrease of the ASE at 1530 nm can be clearly seen. Both dependencies were scaled to have equal maxima at 1550 nm.

Another effect of the ASE noise is to reduce the pump power that passes through the second stage and enters the first stage. The use of the filter in our configuration helps to increase the pump power at the second stage output. As a reference, we obtained output pump power from the second stage in absence of ASE noise to determine the maximum pump power provided from this stage. After that, the first stage was connected and the output pump power was measured with and without the Sagnac filter. Figure 6 shows the effect of introducing the Sagnac filter to enhance output pump power for a 9-m-long EDF.

Since ASE noise is reduced by inserting the Sagnac interferometer filter, EDF length for the second stage can be selected considering low ASE noise coming from stage one. In our case, 9 m is the best option because the difference of the gain maximum is not significant (less than 2 dB), considering low ASE noise into the fiber and also because shorter lengths provide higher pump power to stage one.

The 0.2/0.8 coupler between the first and second stages of the amplifier (Fig. 1) allows the separate measurement of the amplification of the first and second stage. Experimental results are shown in Fig. 7. As we can see, amplification is about 40 dB for the first stage because of double propagation of the signal beam. The second stage produces constant amplification of 13 dB due to the high population inversion in the fiber. Note that the total gain is not the sum of amplification in both stages because of losses in the 0.2/0.8 coupler and the Sagnac interferometer, where transmission is 0.6. The losses degrade the total gain by at least 3 dB. Finally, by eliminating the 80/20 fiber coupler, the total signal is obtained. This figure shows that the amplifier exhibits very good gain performance, achieving a signal gain of about 53 dB for a pump power of 73 mW.

5 Conclusions

We investigate a simple two-stage erbium-doped fiber amplifier using a Sagnac interferometer filter to improve amplifier performance. Experimental results show that by inserting the Sagnac interferometer filter with the hi-bi fiber as the spectral filter between the first and second stage, it is possible to avoid a fast saturation in the second stage and to improve pump conversion efficiency. As a result, only a single pump power is enough to supply both stages, and with a simple configuration to obtain 53-dB amplification with only 73 mW of the pump power. The amplifier proves to be very useful for nonlinear investigation in optical fibers.

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Biographies and photographs of the authors not available.