Double-pass ytterbium-doped fiber amplifier with high gain coefficient and low noise figure

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We have proposed and demonstrated a double-pass ytterbium-doped fiber amplifier using an optical circulator and a fiber Bragg grating as reflector. When the signal has passed through the ytterbium-doped fiber once, it reflects off a 0.2-nm passive fiber Bragg grating filter. This reduces amplified spontaneous emission (ASE) noise from the first pass. The input signal light is amplified both forward and backward through ytterbium-doped fiber. With this double-pass configuration, 1053.15-nm unsaturated signal gain of 28 dB, gain coefficient of 1.1 dB/mW, and noise figure of less than 4 dB are achieved at 977-nm pump power of 68 mW. It is also found that this double-pass configure provides enhancing gain coefficient and improving noise figure by comparison with single-pass configuration.

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Ytterbium-doped silica fiber, with its broad gain bandwidth, high output power, excellent power conversion efficiency, and large saturation fluence, represents an extremely attractive medium for both the regeneration and the subsequent amplification of ultrashort optical pulses[1,2]. There is also a wide range of possible pump wavelengths ($\sim 860-1064$ nm), allowing a variety of pumping schemes, including the use of diode lasers or even high-power Nd lasers[3]. Possible applications of ytterbium-doped fiber amplifiers (YDFAs) include power amplification at special wavelengths, small-signal amplifiers in fiber sensing applications, free-space laser communications, and chirped-pulse amplification of ultrashort pulses which can be produced in an ytterbium-doped fiber (YDF) laser, as demonstrated[4]. High peak power laser systems (such as those for fusion or high field physics) require low power input pulses for amplification. Because many of these systems use Nd:phosphate glass, sources and signal amplifiers are needed around 1053 nm[5]. Those laser systems run near peak power damage limits imposed by self-phase modulation and filamentation in large optics. We must therefore make the signal-to-noise ratio (SNR) high enough to limit instantaneous power perturbations due to mixing of signal and amplified spontaneous emission (ASE) in the amplifier.

To achieve a better utilization of pump energy and thereby increase the gain coefficient of the amplifier, some double-pass (DP) erbium-doped fiber amplifiers (EDFAs) have been proposed[6,7]. These are of the reflective type using a mirror and an optical circulator, where signal and pump light are reflected from one end of the amplifier. The necessary inclusion of an optical circulator is however expected to lead a more noisy performance of the amplifier. Using a 3-nm band-pass filter (BPF) between erbium-doped fiber (EDF) and mirror to remove the ASE improved the noise performance[8]. Using an optical circulator placed within the EDF and a reflector, a new DP-EDFA with enhanced noise figure characteristics has been demonstrated compared to the previous DP-EDFA[9].

Here, we have developed a low noise DP-YDFA using an optical circulator and fiber Bragg grating (FBG) as reflector. The effect of double passing the signal is demonstrated by comparing the gain and noise figure of the DP system with a single-pass (SP) system.

Our analysis is based on a rate equation model, and includes signal stimulated emission and absorption, spontaneous emission, and scattering losses. The power $P^{\pm}$ propagates along the positive (the plus superscript) or negative (the minus superscript) z direction. The fiber core supports a mode at the signal wavelength λ_s and is doped with a dopant concentration N (average over the core cross section) that is constant. The time-dependent rate equations satisfy[10]

$$\pm\frac{\mathrm{d}P^{\pm}(z,t,\lambda)}{\mathrm{d}z}=\Gamma_s\left[(\sigma_a(\lambda)+\sigma_e(\lambda))\cdot N_2(z,t)-\sigma_a(\lambda)N\right] \cdot P^{\pm}(z,t,\lambda)-\alpha(\lambda)P^{\pm}(z,t,\lambda) +\Gamma_s\sigma_e(\lambda)N_2(z,t)P_0(\lambda), \quad (1)$$

where the positive coefficient α represents scattering loss, Γ_s is the power filling factors for signal, and $N_2(z,t)$ is the upper lasing level population density. The functions $\sigma_a(\lambda)$ and $\sigma_e(\lambda)$ are the emission and absorption cross section, respectively. The power density per unit wavelength $P_0(\lambda)$ represents the contribution of the spontaneous emission into the propagating mode.

In accordance with the experimental setup, schematically shown in Fig. 1, appropriate boundary conditions are imposed at beginning and at the end of the active fiber ($z=0$, L). For SP configuration, the boundary conditions

$$P_p^-(z=L)=P_p,\ P^-(z=L,\lambda)=P_s. \quad (2)$$

For DP configuration, the boundary conditions

$$P_p^-(z=L)=P_p,\ P^+(z=0,\lambda)=P_s,$$
$$P^-(z=L,\lambda)=R(\lambda)P^+(z=L,\lambda), \quad (3)$$

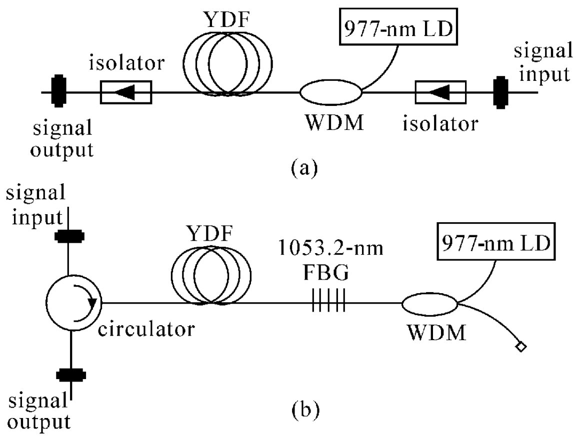

Fig. 1. YDFA configurations. (a) Conventional single-pass configuration; (b) double-pass configuration.

where $R(\lambda)$ is the power reflectivity of the FBG at $z = L$. Equation (1) can be solved iteratively with a convergence criterion that tests the convergence of the overall signal power.

The conventional SP-YDFA configuration is shown in Fig. 1(a). The optical isolator has a loss of 0.5 dB. The DP-YDFA configuration consists of a 20-meter YDF, an optical circulator, and a FBG as reflector, as shown in Fig. 1(b). In the experiment, the optical circulator has a loss of 2 dB and an isolation of over 30 dB. The FBG has a reflectivity of 98%, bandwidth of 0.2 nm, and center wavelength of 1053.15 nm. The FBG with its center wavelength tuned to the signal wavelength is employed which acts as a narrow-band reflector. The YDF has a doping concentration of 400 ppm, core diameter of 3.4 μm, numerical aperture (NA) of 0.2, and cutoff wavelength of 900 nm. The YDF is pumped with a 977-nm laser diode (maximum power 70 mW) through a 980/1053 nm wavelength division multiplexing (WDM) coupler. The amplified signal from the optical circulator is launched into an optical spectrum analyzer (OSA). The measurement of gain and noise is taken from the OSA (ADVANTEST Q8384), which is repeated for the SP-YDFA for comparison. The effect of the isolator and the circulator is not taken away from the measurement.

The signal gain characteristics for both DP and SP configurations of the 1053.15-nm signal against pump power are measured by varying the pump power from 40 to 70 mW as shown in Fig. 2. The power level of input signal is maintained at −40 dBm to avoid gain saturation. The gain for the DP-YDFA exceeds the SP-YDFA beyond the pump power of 61 mW. Below this pump power, the signal is absorbed at the output portion of the YDF, hence gain is reduced. The gain coefficient for the DP-YDFA configuration is estimated to be 1.1 dB/mW and the gain of 28 dB is obtained at the pump power of 68 mW. On the other hand, the coefficient for the SP-YDFA configuration is 0.8 dB/mW. It is confirmed that the DP-YDFA configuration can enhance the gain coefficient using the same YDF.

Figure 3 shows gain and noise figure with input signal power of 1053.15 nm at pump power of 68 mW. Because the input signal is amplified both forward and backward through YDF, signal gain for the DP-YDFA is higher than that for the SP-YDFA. For DP-YDFA, the unsaturated gain obtained is at about 28 dB and degrades as the input signal power increases. The difference, between these two gain values of DP and SP configurations, gradually decreases as the input signal power increases because of the effect of the homogeneous gain saturation. The noise figure equation is given by

$$\mathrm{NF} = \frac{1}{G} + \frac{P_{\mathrm{ASE}}}{Gh\nu\Delta\nu}, \qquad (4)$$

where G is a gain, P_{ASE} is ASE level, ν is a signal frequency and $\Delta\nu$ is the frequency bandwidth. From Eq. (4), noise figure shows a linear dependency to ASE level whereas with gain it has an inverse nonlinear relationship. The fiber grating as a noise filter is 0.2-nm bandwidth, reflecting the signal and reducing ASE power from the first pass where most of the ASE is generated. That causes the noise figure improvement in this DP-YDFA. Overall, noise figure for the SP-YDFA is higher than that for this DP-YDFA, and the noise figure for DP-DFA is measured to be less than 4 dB.

The input signal spectrum with power of −13.54 dBm at 1053.15 nm is shown in Fig. 4(a) measured with an 0.02-nm OSA resolution setting. The input signal is launched into the DP-YDFA pumped with 68 mW, and reflected from the FBG. The output spectrum with

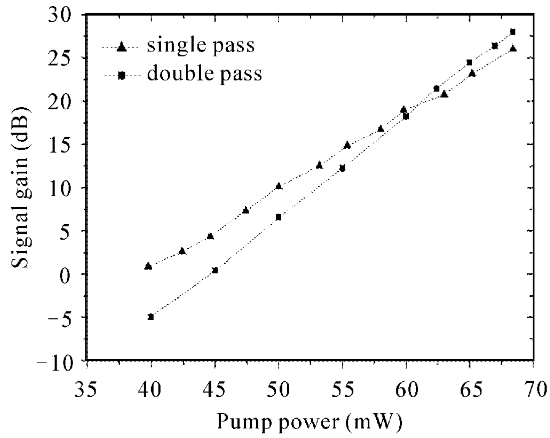

Fig. 2. Signal gain against pump power.

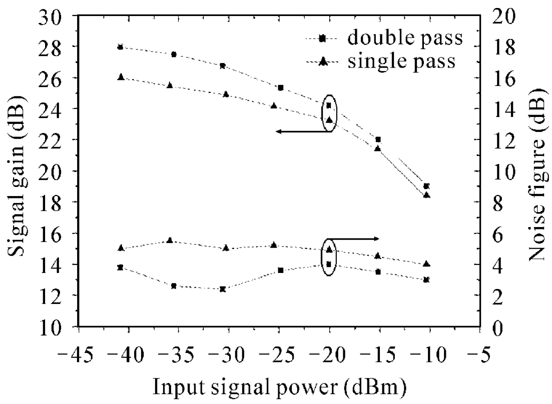

Fig. 3. Gain and noise figure against input signal power.

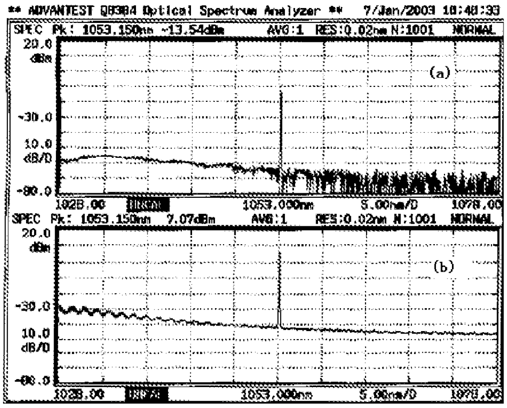

Fig. 4. Optical spectra of double-pass YDFA pumped with 68 mW. (a) Input signal power of −13.54 dBm at 1053.15 nm; (b) amplified output.

power of 7.07 dBm is shown in Fig. 4(b). From Fig. 4, the signal gain is 20.6 dB and noise figure is 3 dB with signal power of −13.54 dBm, which agrees with Fig. 3 well.

We have proposed and demonstrated a novel DP-YDFA using an optical circulator and a FBG as reflector. When the signal has passed through YDF once, it is reflected by a 0.2-nm FBG. This reduces ASE noise from the first pass. The input signal light is amplified both forward and backward through YDF. We achieve a gain coefficient of 1.1 dB/mW, noise figure of less than 4 dB. With this DP configure, 1053.15 nm unsaturated signal gain is 28 dB at 977-nm pump power of 68 mW. The effect of double passing the signal is demonstrated by comparing the gain and noise figure of the DP system with a DP system. It is also found that this DP-YDFA provides enhancing gain coefficient and improving noise figure.

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