GAIN AND NOISE FIGURE IMPROVEMENT OF 1,480 NM-PUMPED L-BAND EDFA USING EMBEDDED ISOLATOR

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Abstract

A new architecture of low-noise 1,480 nm-pumped long-wavelength band Erbium-doped fibre amplifier was persented. The enabling device was the isolator embedded between first-stage and second-stage amplifiers. The signal and pump lights could pass through the isolator that significantly reduced the insertion loss compared to the traditional approach. The isolator also suppressed the propagation of backward amplified spontaneous emission from the second-stage amplifier to the first-stage amplifier. Thus, gain improvement between 0.6 and 3 dB was obtained from 1,569.6 to 1,604.2 nm for -7 dBm input power. Consequently, the noise figure improvement up to 0.5 dB was observed at short wavelengths.

Keywords: Erbium, optical amplifiers, optical communications, wavelength division multiplexing

Introduction

Low-noise optical amplifiers are essential devices for long-haul transmission systems where they incorporate other vital elements such as dispersion compensating module and gain flattening filters. Low-noise and high-gain amplifier designs for long-wavelength band (L-band) have been reported for the past few years (Ono *et al.*, 1997; Park and Kim, 1999; Cordina *et al.*, 1999; Chung *et al.*, 1999). The most renowned architecture for low-noise amplifiers is the dual-stage structure with a midway isolator and 980 nm pump lasers are utilized in the first-stage amplifier. A low noise figure of 3.6 dB was achieved using a tapered fibre filter technology that suppresses the strong Amplified Spontaneous Emission (ASE) peak around the 1,530 nm band while allowing propagation of the 980 nm pump light (Cordina *et al.*, 1999). The best noise figure value ever obtained and published was 3.3 dB using the backward-pumped 980 nm laser (Chung *et al.*, 1999). However, both recorded noise figures are measured without any input isolator and coupler. It is impractical to use the proposed amplifier designs because of the presence of the multipath interference in the transmission fibre (Gimlett *et al.*, 1990).

In this paper, a low-noise L-band EDFA utilizing 1,480 nm pump laser as the pre-amplifier is reported. The unique solution for this less favourable pump laser is to incorporate an embedded isolator between the first-stage and

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second-stage amplifiers. The pump and signal lights can pass through it with minimal losses. Gain and noise figure improvements are observed due to the effectiveness of the embedded isolator suppressing the backward ASE.

Theory

The erbium ion is described with the energy level diagram shown in Figure 1. When pumping at 1,480 nm, the EDFA acts as a quasi-2-level laser system (Desurvire, 1994). The Er^{3+} ion is excited from the ground state level, $^4I_{15/2}$, to the upper level, $^4I_{13/2}$. The quasi-2-level system is possible where a crystal or ligand field induces a Stark effect, which results in the splitting of the energy levels. The population distribution between sub-levels is attributed to the Boltzmann's distribution that eventually makes it possible to consider each of them as a single energy level.

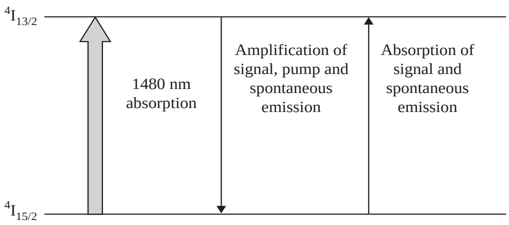


Figure 1. Erbium ions energy level laser systems.

The state where the ions are inverted to the upper level by the pump photons is termed as population inversion. The EDFA is described in a (r, ϕ, z)-cylindrical coordinate system with the z-axis as the fiber axis. Considering only LP_{01}-modes and circular symmetry for the EDFA, the steady-state population concentrations $N_1(r, z)$ and $N_2(r, z)$ in the ground and excited state respectively, are evaluated from the transition rates of pump, signal and spontaneous emission (Pedersen *et al.*, 1991):

$$N_1(r,z) = \rho_{Er}(r)\frac{R_{pe}(r,z) + W_{se}(r,z) + A_e}{R_{pa}(r,z) + W_{se}(r,z) + W_{sa}(r,z) + A_e}, \quad (1)$$

$$N_2(r,z) = \rho_{Er} - N_1(r,z), \quad (2)$$

where ρ_{Er} is the erbium concentration and $A_e = 1/\tau_e$ is the spontaneous emission rate, τ_e being the lifetime. W_{se} and W_{sa} represent the signal emission and absorption rates, respectively, whereas R_{pe} and R_{pa} represent the pump emission and absorption rates. With the transition rates and population distribution, the ordinary differential equations for signal (P_s), pump (P_p), forward ASE (S^+_{ase}) and backward ASE (S^-_{ase}) propagation are given as:

$$\frac{dP_s(z)}{dz} = \left[\gamma_e(\nu_s,z) - \gamma_a(\nu_s,z)\right]P_s(z), \quad (3)$$

$$\frac{dP_p(z)}{dz} = \left[\gamma_e(\nu_p,z) - \gamma_a(\nu_p,z)\right]P_p(z), \quad (4)$$

$$\frac{dS^-_{ase}(\nu,z)}{dz} = -2h\nu\gamma_e(\nu,z) - \left[\gamma_e(\nu_s,z) - \gamma_a(\nu_s,z)\right]S^-_{ase}(\nu,z), \quad (5)$$

$$\frac{dS^+_{ase}(\nu,z)}{dz} = +2h\nu\gamma_e(\nu,z) + \left[\gamma_e(\nu_s,z) - \gamma_a(\nu_s,z)\right]S^+_{ase}(\nu,z), \quad (6)$$

where the emission, γ_e (ν, z) and absorption, γ_a (ν, z), factors are determined from the emission and absorption cross-sections, respectively, and hn is the energy of a single photon.

Materials and Methods

The experimental configuration is shown in Figure 2. The amplifier architecture consists of a two-stage design with a single pump laser in forward-pumped configuration. In this experiment, the maximum pump power of 180 mW from the pump laser is used at two pump wavelengths; 980 and 1,480 nm. Erbium-doped fibre (EDF) used is characterized by 960 ppm of Er^{3+} ion concentration, a peak absorption of 13.3 dB/m at 1,530 nm, a cut-off wavelength of 920 nm and a numerical aperture of 0.22. The EDF lengths in the first and second-stage amplifiers are 3 and 20 m respectively. An isolator is embedded in between these two EDFs. The isolator can allow the 1,480 nm pump light to pass through with a minimal insertion loss of 0.8 dB in this work. The input and output couplers are deployed to tap only 5% of the signal powers. These tapped powers are used in the gain and noise figure measurements through the automated test bed. Moreover, the deployment of these couplers is also intended to imitate the real architecture in the field where the input and output signal conditions must be measured beforehand for automatic gain control and transient suppression approaches. The light sources used in the experiment are 42 WDM channels from 1,569.6 to 1,604.2 nm with 100 GHz spacing where the total signal powers are varied from -7 to 7 dBm. The specified signal power range is based on the average input signal powers into in-line amplifiers for transmission systems with or without distributed Raman amplifiers.

Results and Discussions

The first experimental work is carried out to identify the effectiveness of the embedded isolator for the 1,480 nm pumping scheme. For this case, the signal power is varied from -7 to 7 dBm with a 2 dB step and the pump power is fixed at 180 mW. The length of EDF in the first and second-stage amplifiers are 3 and 20 m respectively. Gain and noise figure for signal powers of -7 dBm are shown in Figure 3.

Referring to Figure 3, gain is improved between 0.6 and 3 dB in the signal wavelength range when the embedded isolator is implemented. As a result, the noise figure is also

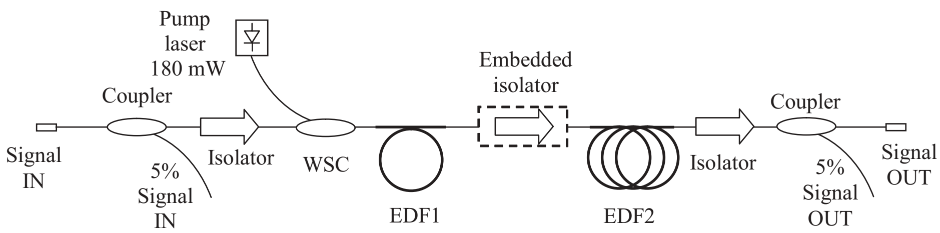


Figure 2. Experimental configuration of a dual-stage amplifier incorporating the embedded isolator.

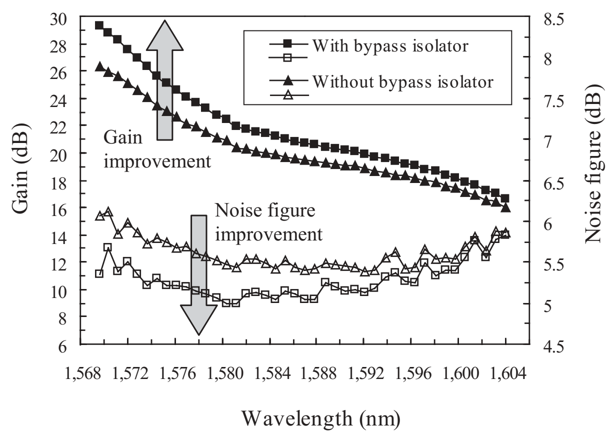


Figure 3. Gain and noise figure at -7 dBm total signal power with and without embedded isolators, pumped by 180 mW of 1,480 nm pump laser.

improved where the noise figure levels are lower as compared to the case without the embedded isolator. The noise figure of -7 dBm input signal power is around 4.8 to 5.8 dB including the input components insertion loss of 1.2 dB (the splicing loss between the single mode fibre and the EDF is estimated around 0.2 dB). Therefore, the proposed amplifier produces the internal noise figures between 3.6 and 4.6 dB from the 1,569 to 1,604 nm wavelength range (35 nm bandwidth). These values are reasonably good compared to the values obtained using the 980 nm pump laser (Cordina *et al.*, 1999). The improvement of gain and noise figure is attributed to the reduction of backward ASE from the second-stage amplifier into the first-stage amplifier. This phenomenon can be explained by showing the evolution of ASE power along the EDF as shown in Figure 4.

The embedded isolator is used to reduce the intensity of the backward ASE from the second-stage amplifier. Normally, the isolator has isolation of better than 30 dB in which the intensity of the backward ASE can be reduced by 1,000 times compared to the case of the conventional architecture (without the embedded isolator). The stronger the backward ASE is, the stronger its effect on energy extraction from the excited ions at the energy level, $^4I_{13/2}$. This situation creates a competition between the backward ASE and the signal photons over the limited number of excited ions at the energy level, $^4I_{13/2}$. Thus, the signal amplification is degraded at the input end of EDF. Hence, reducing the intensity of the backward ASE can improve the signal amplification at the input end of EDF that leads to better noise figures.

The analysis of gain and noise figure improvement over the signal power range as performed is depicted in Figure 5. In general, gain improvement is observed from -7 to -3 dBm signal power across the wavelength range. However, the benefit of implementing the embedded isolator is gradually diminished for signal power greater than -1 dBm. The signal gain is saturated in this power range and the remnant of pump light is low at the end of EDF1. Therefore, lesser pump lights can be used for signal amplification in EDF2. Furthermore, the inclusion of the isolator incurs a certain amount of loss to the pump light. Therefore, the signal amplification is deteriorated in the second-stage amplifier as compared to the case of the amplifier without the embedded isolator. A gain penalty of around 0.5 dB is obtained for signal power of 3 dBm. On the other hand, more than 75% of the channels experience noise figure improvement from -7 to -3 dBm signal powers. The value of noise figure improvement gradually reduces from short to long wavelengths. The maximum noise figure improvement of 0.5 dB is measured at -7 dBm signal power.

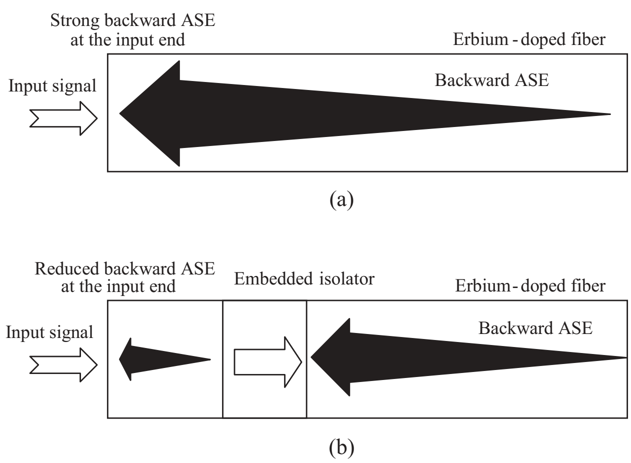
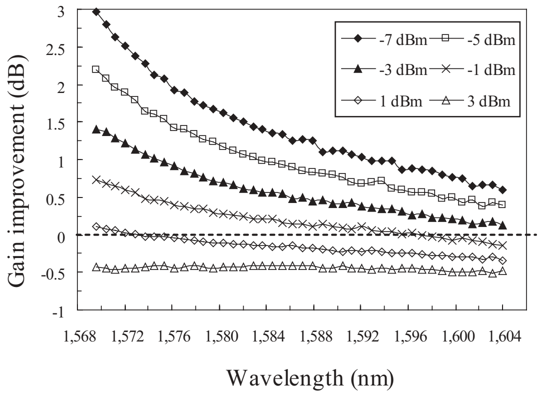
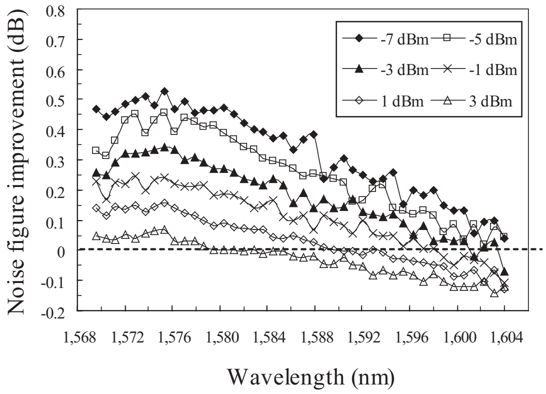


Figure 4. ASE power evolution in EDFA (a) without and (b) with the embedded isolator.



(a)



(b)

Figure 5. (a) Gain and (b) noise figure improvements against wavelengths at different signal powers, the pump power of 1,480 nm is fixed at 180 mW.

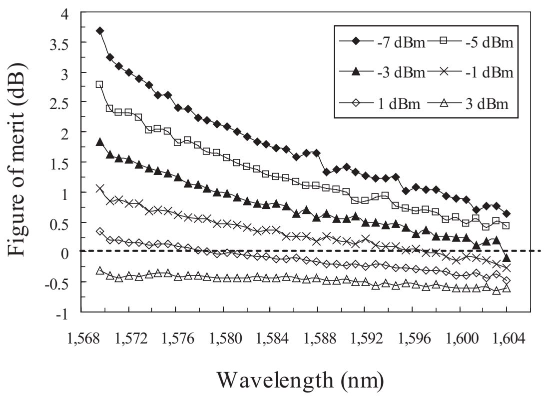


Figure 6. The contribution of gain and noise figure improvements against signal wavelengths at different signal powers.

Based on the findings, it shows that the embedded isolator effectively suppresses the backward ASE from the second EDF coil and hence reduces its saturation effect on the signals. The proposed amplifier configuration still shows some benefits for signal powers less than or equal to 1 dBm. The noise figure is improved for signal wavelength less than 1,589 nm and, for the rest of the signals, the noise figure penalty is very minimal with the maximum value of less than 0.1 dB. However, as the signal power increases the remnant pump power is inadequate to maintain high population inversion in the second EDF coil. In addition, the insertion loss of the embedded isolator becomes tangible and decreases the efficiency of the overall amplifier system. Therefore, the noise figure penalty is quite significant in this range of signal powers (> 1 dBm).

The best way to describe the behaviour of gain and noise figure is to calculate the gain improvement and noise figure improvement from the 1,480 nm pumping scheme. Then, a new parameter of Figure of Merit is defined in dB as;

$$\text{Figure of Merit} = \text{Gain improvement} + \text{Noise figure improvement} \quad (7)$$

to show the effectiveness of the 1,480 nm embedded isolator as shown in Figure 6.

Multi-stage amplifier noise is heavily influenced by the first-stage amplifier. In this case, the noise figure of the first-stage amplifier must be minimized and at the same time, gain of this first-stage amplifier must be maximized. Therefore, the contribution of both parameters must be taken into account to design low-noise optical amplifiers. Referring to Figure 6, the figure of merit shows that the gain improvement is dominant over the noise figure penalty. In this case, the noise figure penalty of having the 1,480 nm pump laser is minimal as compared to the greater gain obtained from this pumping scheme.

Conclusion

A new technique of designing low-noise L-band Erbium-doped fibre amplifiers utilizing an embedded isolator for 1,480 nm pumping scheme is successfully demonstrated. The embedded isolator acts as the blocking device to the backward propagating amplified spontaneous emission, and at the same time allows the 1,480 nm pump light to travel pass through. The noise figure obtained from this new amplifier architecture is lower compared to the standard approach without the embedded isolator. Low noise figure values of 5 to to 5.8 dB have been achieved over 35 nm bandwidth for -7 dBm signal power. This new approach reduces the necessity of decoupled/coupled light using wavelength selective couplers that increases the complexity of the amplifier design in terms of assembly time and reduces the insertion loss of the signals from the first-stage amplifier to the second-stage amplifier.

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