PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 66, No. 3
March 2006
pp. 539–545

Gain-clamping techniques in two-stage double-pass L-band EDFA

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MS received 9 March 2005; revised 31 May 2005; accepted 22 July 2005

Abstract. Two designs of long-wavelength band erbium-doped fiber amplifier (L-band EDFA) for gain clamping in double-pass systems are demonstrated and compared. The first design is based on ring laser technique where a backward amplified spontaneous emission (ASE) from the second stage is routed into the feedback loop to create an oscillating laser for gain clamping. The gain is clamped at 18.6 dB from −40 to −8 dBm with a gain variation of less than ±0.1 dB and a noise figure of less than 6 dB. Another scheme is based on partial reflection of ASE into the EDFA, which is demonstrated using a narrowband fiber Bragg grating. This scheme achieves a good gain clamping characteristic up to −12 dBm of input signal power with a gain variation of less than ±0.3 dB from a clamped gain of 22 dB. The noise figure of a 1580 nm signal is maintained below 5 dB in this amplifier since this scheme is not based on lasing mechanism. The latter scheme is also expected to be free from the relaxation oscillation problem.

Keywords. Gain clamping; optical amplifier; L-band EDFA; two-stage EDFA; double-pass EDFA.

PACS Nos 42.60.Da; 42.81.-i; 42.81.Wg; 42.81.Uv

1. Introduction

The long-wavelength band erbium-doped fiber amplifiers (L-band EDFAs) have been researched for many years because of its capability to expand the total capacity of dense wavelength multiplexed (DWDM) systems when it is used in a parallel configuration with the conventional-band (C-band) EDFA [1,2]. The use of the L-band EDFAs also reduces a four-wave-mixing problem in the transmission system with dispersion shifted fiber [3]. However, L-band EDFAs are relatively inefficient on the gain, as the operating wavelengths are far away from the peak emission band of erbium ion. Several efforts have been made to improve the gain in this band [4–6]. Of them, the double-pass amplifier [6] has given a significant gain improvement over the conventional single pass amplifier, but one drawback is the higher noise figure. Besides gain improvement, L-band EDFAs for DWDM system must also be able to maintain constant gain during channel add/drop or abrupt failure in the system. To satisfy the requirement of broadband transmission in DWDM systems, the gain clamping is an important characteristic for L-band EDFAs as well as C-band EDFAs. It make possible that the performances of EDFAs are independent of the input power of signals and the number of channels used in DWDM systems.

To date, various research efforts have been made to clamp the gain in L-band EDFAs [7,8]. In this paper, two new approaches for gain clamping in double-pass L-band EDFA are demonstrated and compared. The first scheme is based on ring laser technique where a backward amplified spontaneous emission (ASE) from the second stage is routed into the feedback loop to create an oscillating laser for gain clamping. The second scheme uses a narrowband FBG to reflect a portion of backward C-band ASE back into the EDFA for gain clamping.

2. Ring laser technique

A ring laser technique is one of the techniques to clamp the gain of L-band EDFA in double-pass system. The gain clamping is achieved by routing the backward amplified spontaneous emission (ASE) into the feedback loop to create a ring laser. Figure 1 shows the schematic diagram of the gain-clamped amplifier, which consists of two sections of erbium-doped fibers (EDF1 and EDF2). EDFs 1 and 2 having an erbium ion concentration of 400 ppm are optimised at 12 m and 50 m, respectively for a higher gain and lower noise figure. 980 nm laser diodes (P1 and P2) are used to pump both EDFs using a forward pumping scheme. P1 and P2 are fixed at 68 mW and 102 mW, respectively. Two 980/1550 nm wavelength selective couplers (WSCs) are used to combine the 980 nm pump from each laser diode with the test signal. A broadband fiber Bragg grating (FBG) with reflectivity of 92% and bandwidth of 44 nm centered at 1587 nm is employed at the output end of EDF2. It retro-passes the test signal back into the system for gain enhancing. The backward ASE from EDF2 is routed into the feedback loop via the circulator and C/L-band WSC, and passes through the FBG to form a complete ring cavity. A tunable laser source (TLS) is used for the evaluation of the amplifier performances in conjunction with an optical spectrum analyzer (OSA), which is located at the L-port of C/L-band WSC.

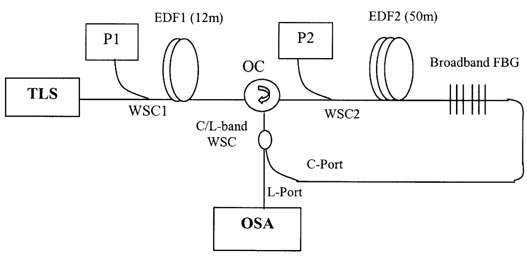

Figure 1. Gain-clamped double-pass L-band EDFA based on ring laser.

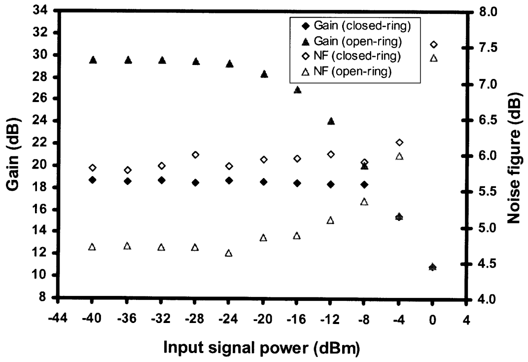

Figure 2. Gain and noise figure characteristics for the gain-clamped amplifier with ring laser.

The gain and noise figure characteristics for the proposed amplifier against input signal power is shown in figure 2. For comparison, the characteristics were also investigated for an unclamped amplifier, which is obtained by opening the ring. The signal wavelength is fixed at 1580 nm. For the open-ring (unclamped) amplifier, the unsaturated gain obtained is 29.6 dB and degrades as the input signal power increases. On the other hand, good gain clamping behavior is observed for the closed-ring amplifiers. The gain is clamped at 18.6 dB for all input signal powers from −40 dBm to −8 dBm with a gain variation of less than ±0.1 dB. This clamping effect is due to the fixed population inversion set by the laser at 1564 nm, which is oscillating in the closed-ring. The clamped gain level is relatively higher in this double-pass gain-clamped system than in the conventional single-pass gain-clamped EDFAs [7]. This is attributed to the fact that the test signal is amplified twice in different directions in the second stage of the system, and the total gain is significantly increased due to the increase in effective EDF length. The output power is measured to be in the range of −21.4 to +10.4 dBm as input signal power increases from −40 to −8 dBm.

On the other hand, the noise figure shows an increment in the gain-clamped amplifier compared to the unclamped amplifier. The noise figure penalty is due to the limited population inversion, which causes changes in inversion parameter $n_{\mathrm{sp}} = \{\sigma_{\mathrm{e}}(\lambda)N_2\}/\{\sigma_{\mathrm{e}}(\lambda)N_2 - \sigma_{\mathrm{a}}(\lambda)N_1\}$, where σ_{e} is the emission cross-section, σ_{a} is the absorption cross-section, N_2 is the population density of the upper state and N_1 is the population density of the lower state, which leads to noise figure degradation. The noise figure varies from 5.8 to 6 dB within the dynamic input signal power range, which is about 0.5–1.2 dB higher compared to that of the open-ring amplifier. For input signal powers within the dynamic range, the significant noise figure penalties are induced by the intense counter-propagating ring laser light passing through the EDF. However, for the input signal power above the dynamic range, the noise figures are primarily dominated by the self-induced saturation. The slight noise figure degradation at these input powers is attributed to the regenerative backward ASE. However, the noise figures are still relatively lower in the proposed amplifier compared to that of another double-pass amplifier [6] due to the incorporation of pre-amplifier (forward-pumped EDF1) in front of a

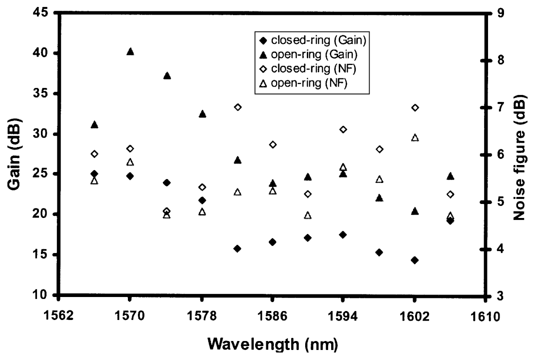

Figure 3. Gain and noise figure spectra for both amplifiers with open- and closed-ring.

double-pass amplifier. Since the circulator (OC) prevents the amplified signal and backward ASE from propagating into the EDF1, the population inversion of the input part of the amplifier is hardly affected by the intense lights, and therefore, the noise figure could be kept low.

Figure 3 depicts the gain and noise figure spectra of the amplifier with open- and closed-ring, where the diamond symbols represent the amplifier with closed-ring. The input signal power is fixed at −30 dBm in this experiment. As shown in the figure, the amplifier with closed-ring shows a lower gain compared to that of the open-ring, which is due to the extraction of the energy stored in the amplifier by the oscillating laser as described before. The oscillating laser also increased the amplifier's noise figure as depicted in the figure. The gain and noise figure fluctuation are observed for both the amplifier schemes due to the inconsistency of the FBG reflectivity.

3. ASE reflection technique

In the previous section, a highly efficient gain-clamped L-band EDFA is successfully demonstrated using a ring laser in double-pass system. However, the gain-clamped amplifier has two shortcomings resulting from the lasing mechanism. One is that it has a relatively high noise figure since the population inversion is clamped at low value. The other is that surviving channels have to experience transient power excursions due to relaxation oscillation. In this section, an all-optical gain-clamped L-band EDFA scheme based on the reflection of backward amplified spontaneous emission (ASE) into the EDFA is proposed and experimentally demonstrated using a fiber Bragg grating (FBG) at the input end of the second stage. Due to non-optical cavity structure, the proposed gain-clamped EDFA should be free from the two shortcomings.

Figure 4 shows the configuration of the proposed gain-clamped amplifier, which is almost similar to our previous scheme. In this set-up, the feedback ring is removed and replaced by incorporation of a narrowband FBG (NBFBG) at the input end of the second stage. The NBFBG has a reflectivity of 99.9% and a 3 dB bandwidth

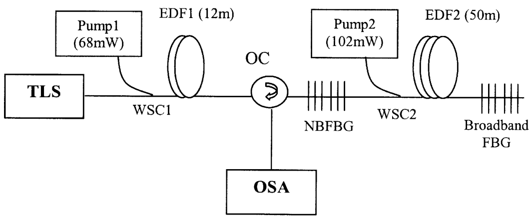

Figure 4. Gain-clamped double-pass L-band EDFA based on a partial reflection of ASE.

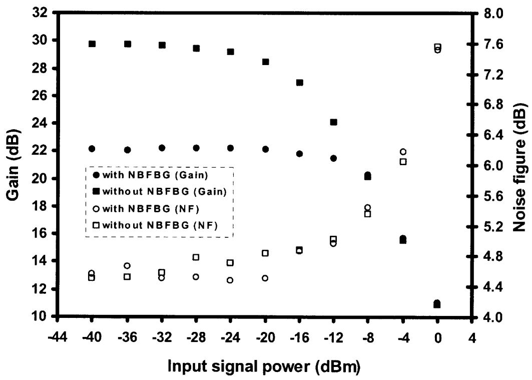

Figure 5. Gain and noise figure characteristics for the gain-clamped amplifier with NBFBG.

of 0.2 dB centered at 1560.7 nm. The NBFBG reflects a portion of backward ASE from EDF2 back into the amplifying stage for gain clamping. Both EDF length and pump laser powers are set at the same value as the previous scheme.

In order to evaluate the gain clamping and noise performances, the gain and noise figure are measured as a function of input signal power. The input signal wavelength is set at 1580 nm. As shown in figure 5, about 22 dB of a clamped gain is achieved by the proposed amplifier with a gain variation of less than ± 0.3 dB till input signal power increases up to -12 dBm. The output power is measured in the range of -17.9 to $+9.5$ dBm as input signal power increases from -40 to -12 dBm. The gain level is higher and the dynamic range is smaller in this scheme compared to the previous scheme. This is attributed to the gain clamping effect, which is stronger in the ring laser scheme. The clamping effect is dependent on the center wavelength of the NBFBG used. The center wavelength should be set as close as possible to the amplifier's operating wavelength for a better gain-clamping effect.

The gain clamping in this scheme is due to the incorporation of FBG that reflects a portion of backward ASE from the second stage. The reflected ASE goes back into the second stage EDFA and amplified while passing through the EDFA. Intensity of the reflected ASE is strongly dependent on the intensity of the externally applied signal. It is maximum when there is no external signal. When external signal is launched into the EDFA, it consumes a part of the amplifier gain, and then the intensity of backward ASE decreases. As a result, the intensity of the

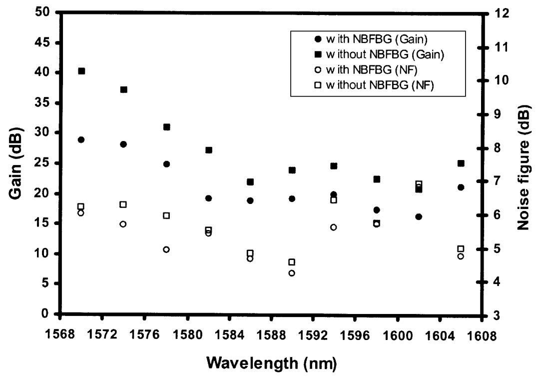

Figure 6. Gain and noise figure spectra for the gain-clamped amplifiers with and without NBFBG.

reflected ASE decreases. Because of this all-optical complementary property of the two-signal intensities up to some input intensity level of the externally applied signal, the total intensity remains constant automatically. Therefore, the amplifier gain can be fixed regardless of the externally applied signal intensity as shown in figure 5. Amplifier power loss due to the FBG is negligible because the proposed gain-clamped amplifier and the unclamped amplifier have the same gain for saturated input power range around 0 dBm.

Compared to the unclamped amplifier, the proposed amplifier has similar or a little better noise figure at input signals less than −12 dBm as shown in figure 5. This is attributed to the lack of population inversion degradation due to lasing mechanism in this scheme. The gain-clamped amplifier maintains the noise figure below 5.0 at input powers of less than −12 dBm. The gain and noise figure spectra of both amplifiers with and without NBFBG are shown in figure 6. The incorporation of NBFBG has reduced the gain due to the extraction of the energy stored in the amplifier by the reflected ASE. The noise figure is also slightly reduced by the incorporation of NBFBG as depicted in the figure. The proposed amplifier is also expected to have no relaxation oscillation-related power variation because it is not based on lasing mechanism.

4. Conclusion

Two gain-clamped double-pass L-band EDFA schemes are demonstrated and compared. The first design uses a ring laser which is generated by routing a backward ASE from the second stage into the feedback loop. The gain is clamped at 18.6 dB from −40 to −8 dBm with gain variation of less than ±0.1 dB. However, the noise figure penalty is observed in this amplifier compared to the unclamped amplifier. The latter scheme uses a narrowband FBG to reflect a portion of backward C-band ASE back into the EDFA for gain clamping. The gain is clamped at 22.0 dB with a gain variation of less than ±0.3 dB and dynamics input powers up to −12 dBm without any noise figure penalty. The noise figure of a 1580 nm signal is maintained below 5.0 dB in this amplifier since the latter scheme is not based on lasing mechanism. This amplifier is also expected to be free from the relaxation oscillation problem.

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