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GAIN CLAMPING IN SINGLE-PASS AND DOUBLE-PASS L-BAND ERBIUM-DOPED FIBER AMPLIFIERS

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Gain clamping is demonstrated in single-pass and double-pass long wavelength band erbium-doped fiber amplifiers (L-band EDFAs). A C/L-band wavelength division multiplexing (WDM) coupler is used in single-pass system to generate a laser at 1566 nm. The gain for the amplifier is clamped at 15.5 dB with gain variation of less than 0.2 dB from input signal power of −40 to −14 dBm with almost negligible noise figure penalty. However, the flatness of gain spectrum is slightly degraded due to the un-optimisation of erbium-doped fiber (EDF) length. The advantage of this configuration is that the oscillating light does not appear at the output port of the amplifier. A highly efficient gain-clamped L-band EDFA with improved noise figure characteristic is demonstrated by simply adding a broadband conventional band fiber Bragg grating (C-band FBG) in double pass system. The combination of the FBG and optical circulator has created laser in the cavity for gain clamping. By adjusting the power combination of pumps 1 and 2, the clamped gain level can be controlled. The amplifier gain is clamped at 28.1 dB from −40 to −25 dBm with gain variation of less than 0.5 dB by setting the pumps 1 and 2 at 59.5 and 50.6 mW, respectively. The gain is also flat from 1574 nm to 1604 nm with gain variation of less than 3 dB. The corresponding noise figure varies from 5.6 to 7.6 dB, which is 0.8 to 2.6 dB reduced compared to those of unclamped amplifier.

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1 Introduction

Dense wavelength division multiplexing (DWDM) technology with erbium-doped fiber amplifier (EDFA) has enabled todays fiber optic transmission systems and networks with several tens of DWDM channels. However, for satisfying the drastically increasing traffic of tomorrows Internet, interaction and multimedia services, more high-capacity DWDM systems with higher DWDM channel count are unavoidable. This trend of fast bandwidth consumption has resulted in the latest interest in EDFAs operating at long wavelength band (L-band). By integrating L-band in parallel with conventional band (C-band), a gain bandwidth of about 80 nm can be achieved [1]. Since the erbium emission cross section in the L-band is far from its peak value at 1531 nm, its gain coefficient and

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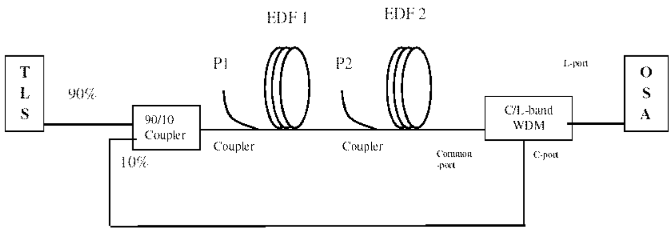

Fig. 1. Configuration of the proposed gain clamped L-band EDFA in single-pass system.

quantum conversion efficiency are much reduced from that of the C-band amplifiers. Therefore, the double-pass technique was introduced in our earlier work [2] to enhance the gain in this band. As the complexity of the networks increases in DWDM system, the control of the gain of EDFAs is necessary due to circumstances such as faults, adding and dropping of wavelengths and rerouting. In these cases, the gain media show different levels of population inversion resulting in fluctuation of the gain level. Thus, a gain clamping mechanism is desired. The gain clamping techniques have been extensively explored for C- and L-band EDFAs to control the dynamic gain variation, including use of optoelectronic feedback circuits [3] and gain clamping by an all-optical feedback loop [4-6].

In this paper, two gain clamping schemes in L-band EDFA are introduced. The first scheme uses a C/L-band wavelength division multiplexing (WDM) coupler to route the C-band portion of the amplifiers forward amplified spontaneous emission (ASE) into the ring cavity and generates lasing oscillation at 1566 nm. The second scheme incorporates a broadband fiber Bragg grating (FBG) in the double-pass amplifier system to clamp a gain.

2 Gain clamping in single-pass system

The configuration of the proposed gain clamped L-band EDFA in single pass system, which uses a ring laser cavity with a C/L-band WDM coupler is shown in Fig. 1. It consists of two sections of erbium-doped fibers (EDF1 and EDF2), two laser diodes (P1 and P2), two pump/signal wavelength division multiplexing (WDM) couplers and a C/L-band WDM coupler. Both EDFs have a length and nominal Er^{3+} -concentration of 50 m and 400 ppm, respectively. 980 nm laser diodes are used to pump both EDFs using forward pumping scheme. Both pump powers (P1 and P2) are fixed at 26.7 mW. Two pump/signal WDM couplers were used to combine of 980nm pump from each laser diode with the test signal. A C/L band WDM is used to separate C-band and L-band lights. The ring cavity is formed by connecting the C-port of the WDM coupler to the 10% port of the 90/10 coupler. A tunable laser source (TLS) was used for the evaluation of the amplifier performances in conjunction with an optical spectrum analyzer (OSA). The amplifier performance is also measured for the open-ring system for comparison purpose.

Fig. 2 shows the forward ASE spectrum at the C-port of C/Lband WDM for the

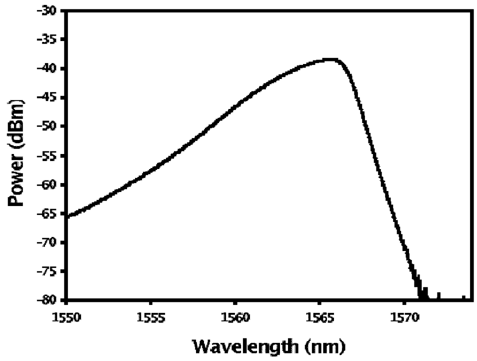

Fig. 2. Forward ASE at the L-port of C/L-band WDM with open-ring.

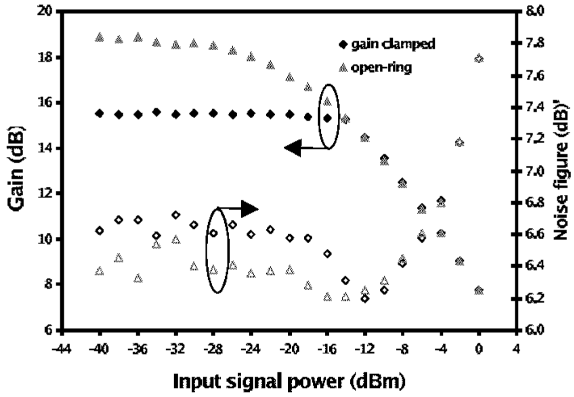

Fig. 3. Gain and noise figure against input signal power for single-pass system.

amplifier with open ring. The intense L-band forward ASE was excluded at C-port, and the peak value of the ASE appeared at 1566 nm. The ASE was fed back into amplifier via a 90/10 coupler to generate laser oscillation at the peak wavelength, which can extract the energy stored in the amplifier due to the homogeneous broadening [7]. The gain and noise figure characteristics as functions of input signal power at both open-ring and the gain clamped systems are shown in Fig. 3. Measurements of the gain and noise figure were performed at different input signal power levels, from −40 to 0 dBm at 1580 nm. For the amplifier with open ring, the unsaturated gain obtained at 18.9 dB and degrades as the input signal power increases. On the other hand, gain for the closed ring amplifier is clamped at 15.5 dB for all input signal powers from −40 to −14 dBm. Although the amplifiers gain reduces about 3.4 dB, a drop of 18 % compared to the open ring case, the flatness of the gain curve at small input signal power is very encouraging within 0.2 dB. This clamping is due to the fixed average population inversion set by the

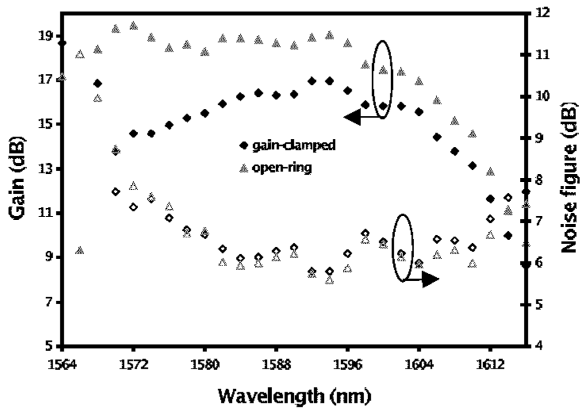

Fig. 4. Gain and noise figure as functions of input signal wavelength for single-pass system.

oscillating laser in the ring cavity. In a homogeneously broadened medium, the lasing action fixes the total population inversion. Any variation in other conditions, such as the input signal power, would be compensated by the adjustment of the lasing power [8]. This is especially true when the input signal power is low (lower than the laser output power level) as shown in Fig. 3. However, as the input signal power is increased, the laser power is decreased and becomes extinguished, hence the gain is no longer clamped.

Noise figures measured are about 6.6 dB in the gain clamped region with increment of 0.2 dB compared to the open ring case, as depicted in Fig. 3. The noise figure penalty is due to bi-directional operation of the laser that makes the population inversion at input end of the amplifier is lower. The noise figure can be improved by incorporating of optical isolator in the cavity. Fig. 3 also shows that the noise figure curve has a dip at high input power, especially at -12 dBm input signal power region. The dip is attributed to the interplay between self-saturation by backward ASE and signal-induced saturation [8]. The gain and noise figure spectra of the open and closed-ring amplifiers are compared in Fig. 4. The gain is reduced with the laser in the cavity due to the laser extracting the energy stored in the amplifier The gain flatness for the gain clamped amplifier is worse compared the open ring case due to the laser extracting more energy from nearer signal wavelength. The gains of 15 to 17 dB are obtained at wavelength from 1576 to 1604 nm. The noise figure is slightly degraded due to the same reason as explained above. The gain flatness can be improved by optimization of EDF length. The laser does not appear at the output port since it operates at wavelength of 1566 nm, which is outside of L-band region. This prevents the WDM system from being disturbed by the oscillating laser.

3 Gain clamping in double-pass system

The proposed configuration of gain clamped EDFA in double-pass system is shown in Fig. 5. It consists of two sections of EDF, two laser diodes, two WDM couplers, a

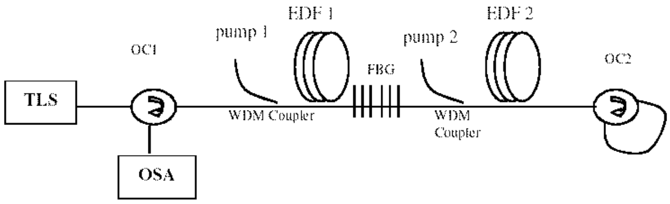

Fig. 5. Configuration of the proposed gain clamped L-band EDFA in double-pass system

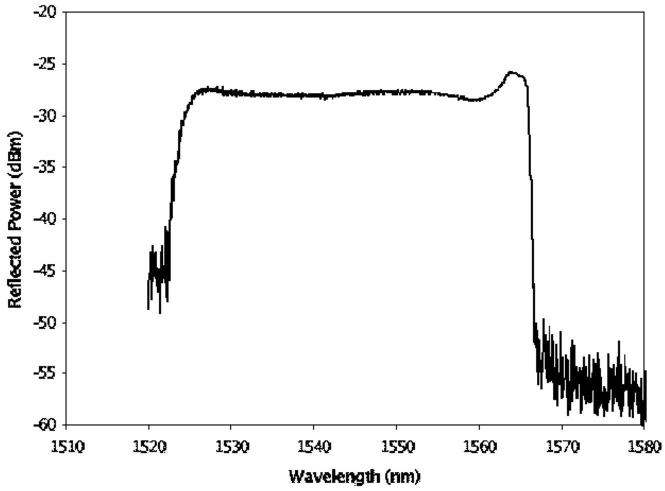

Fig. 6. Reflection characteristics of the broadband FBG

FBG and two circulators (OC1 and OC2). The EDFs used in the experiment have a similar length and Er^{3+} -concentration as the previous scheme. This scheme also uses 980 nm laser diodes with forward pumping. A broadband C-band FBG with a peak reflectivity at 1567nm is employed in between the two EDF sections to create a laser in the amplifier system. The reflection spectrum of the FBG is shown in Fig. 6. It has a reflectivity of about 99% and a bandwidth of 40nm centered at 1545 nm. At the amplifier output end, an optical circulator is employed which acts as a broad-band reflector to retro-pass the tested and laser signals back into the system. The amplifier performances is evaluated using an OSA, which is located at port 3 of optical circulator OC1. The amplifier performances are also measured for unclamped amplifier, which is modified from the gain-clamped case by removing the FBG, for comparison purpose.

Fig. 7 shows the gain and noise figure of 1580 nm signal with respect to a variation of input signal power for the gain-clamped (GC1 and GC2) and unclamped amplifiers. Pump 2 is fixed at 50.6 mW for both gain-clamped amplifiers. Pump 1 for GC 1 and GC

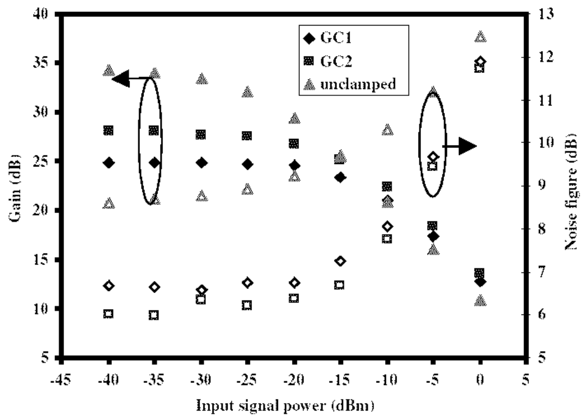

Fig. 7. Gain (closed) and noise figure (clear) as functions of input signal power for double-pass system.

2 are fixed at 48.6 mW and 59.5 mW, respectively. For the unclamped amplifier pumps 1 and 2 are fixed at 28.3 and 56.5 mW, respectively. Both GC amplifiers show a constant gain at small signal wavelength compared to unclamped amplifier. The gain is clamped at 24.9 dB and 28.1 dB for GC1 and GC2 respectively, with gain variation of less than 0.5 dB. The dynamic range of GC1 and GC 2 is -20 and -25 dBm, respectively. This clamping effect is due to the laser light at 1567 nm, which is formed by the existence of the FBG and OC2 in the amplifier system. This laser limits the population inversion in the amplifier. Therefore each signal wavelength experiences a constant gain, independent of pump and input signal power variations. In gain-clamped amplifier system, the laser light will reduce the clamped-gain value due to saturation effect. However, the clamped-gain is higher in this double pass gain-clamped system compared to those of single-pass amplifier. This is attributed to the tested signal is amplified twice in different directions in the double pass system, and the total gain is almost doubled due to the increase of the effective EDF length.

At larger input signals, both gain clamped amplifiers show a higher gain compared to those of unclamped amplifier as shown in Fig. 7. This is attributed to the incorporation of broadband C-band fiber Bragg grating that blocks the backward C-band ASE from EDF2 and increases the forward ASE level and thus the amount of energy available for transfer from short to long wavelength also increased. Noise figure on the other hand, shows a small reduction in gain-clamped amplifier. This improvement is due to the increased population inversion in the first stage, which is attributed to the broadband FBG that blocks the backward propagating ASE of the second stage. Fig. 8 shows a small signal gain and noise figure spectra for gain clamped and unclamped amplifiers. The small signal gain is reduced for the both gain clamped EDFA compared to those of unclamped amplifier due to the limited total population inversion. Compared to the unclamped amplifier, the flat-gain region of the gain clamped amplifier is shifted to the

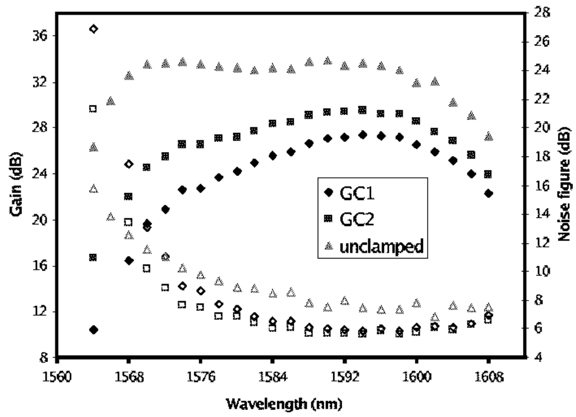

Fig. 8. Gain (closed) and noise figure (clear) as functions of input signal wavelength for double-pass system.

longer wavelength. For the GC2 amplifier the flat-gain is obtained at about 28dB with gain variation of less than 3 dB from 1574 nm to 1604 nm. The noise figure varies from 5.6 to 7.6 dB at this flat-gain region. The noise figure values are improved from 0.8 to 2.6 dB compared to those of unclamped amplifier due to the reason as explained above.

4 Conclusion

A new configuration of gain clamped L-band EDFAs in single-pass and double-pass systems have been proposed. A C/L-band WDM coupler is used in single-pass system to generate a laser at 1566 nm, which can be used for gain clamping. The gain for the amplifier is clamped at 15.5 dB with gain variation of less than 0.2 dB from input signal power of −40 to −14 dBm with a small noise figure penalty. However, the flatness of gain spectrum is slightly degraded due to the un-optimisation of EDF length. The advantage of this configuration is that the oscillating light does not appear at the output port of the amplifier. In double-pass system, a broadband C-band FBG is used in conjunction with an optical circulator to create laser in the cavity for gain clamping. In this amplifier, the clamped gain level can be controlled by adjusting the power combination of pumps 1 and 2. The amplifier gain is clamped at 28.1 dB from −40 to −25 dBm with gain variation of less than 0.5 dB by setting the pumps 1 and 2 at 59.5 and 50.6 mW, respectively. The gain is also flat from 1574 nm to 1604 nm with gain variation of less than 3 dB. The corresponding noise figure varies from 5.6 to 7.6 dB, which is 0.8 to 2.6 dB reduced compared to those of unclamped amplifier.

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