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EFFECT OF INJECTION OF C-BAND AMPLIFIED SPONTANEOUS EMISSION ON TWO-STAGE L-BAND ERBIUM-DOPED FIBER AMPLIFIER

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An effect of injection of conventional-band amplified spontaneous emission (C-band ASE) on a two-stage long wavelength band erbium-doped fiber amplifier (L-band EDFA) is demonstrated. It uses two circulators and a broadband fiber Bragg grating (FBG) to route unused C-band backward ASE from the second stage back to the input end of the first stage of the amplifier. The amplifier gain is clamped at 15.5 dB and the saturation power increases from −13 dBm to −8 dBm with injection of the C-band ASE. The gain level can be controlled to be in the range from 15.5 to 16.8 dB by varying the variable optical attenuator (VOA) loss from 0 to 20 dB without much variation in noise figure. These results show that the injection of C-band ASE can be used to clamp the L-band gain in a two-stage L-band EDFA, which has higher gain compared to a single stage.

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1 Introduction

Wavelength-division-multiplexing (WDM) techniques can very efficiently utilize the low loss transmission bandwidth of single mode fiber (SMF) to increase the transmission capacities of fiber systems. However, the transmission capacities of current 1.5 μm WDM systems are limited by the gain bandwidth of erbium-doped fiber amplifiers (EDFAs), which operate in the conventional wavelength band at 1529–1560 nm (C-band). Therefore the L-band (1568–1600 nm) is offered in addition to the conventional band (C-band) EDFA. Integration of L-band in parallel with C-band allows a gain bandwidth of about 70 nm to be achieved [1].

The excited erbium-doped fiber (EDF) will emit amplified spontaneous emission (ASE) in both forward and backward directions. The large amount of backward ASE at the input end of the EDFA system is totally unavoidable because ASE generation is quasi-random in direction. To date, there are many research efforts to enhance the amplification characteristics of the L-band EDFA by utilizing this unused C-band backward ASE [2–4]. In this letter, we demonstrate that the unused C-band backward ASE can be used to clamp a gain in the two-stage L-band EDFA. Gain clamping is very important for maintaining gain as the signal is added and dropped from the channels traveling through the L-band EDF.

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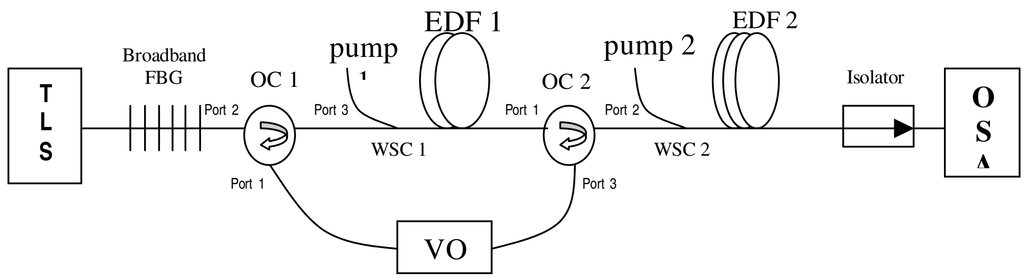

Fig. 1. Configuration of L-band EDFA.

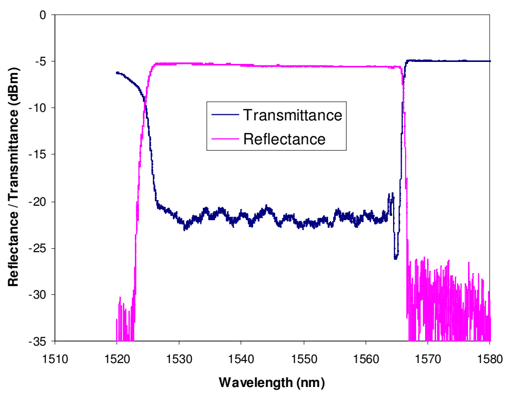

Fig. 2. Reflection and transmission characteristics of the FBG.

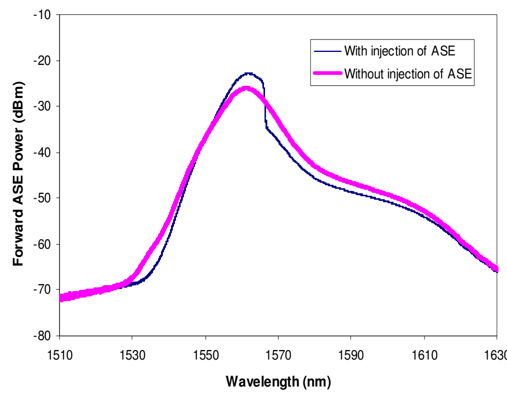

Fig. 3. Forward ASE spectra of the two-stage L-band EDFA.

2 Experiment

The experimental set up is shown in Fig. 1. The amplifier system is a two-stage EDFA with an optical circulator OC 2 placed in between. The EDFs used in the experiment are 30 m (first stage) and 20 m (second stage), which are commercially available and have a cut off wavelength of 950 nm and peak absorption of 5.6 dB/m at 1531 nm. Both are pumped at 980 nm and allotted 57 mW and 35 mW for the first and second stage, respectively. The wavelength selective coupler (WSC) combines the test signal and the 980 nm pump into a single fiber. The pumped EDF 2 will emit ASE in both forward and backward directions, whereby this backward ASE is directed into OC 2 and is then re-routed through port 3 to port 1 of OC1, via a variable optical attenuator (VOA). The backward ASE is then passed to the FBG, which has a center wavelength of 1545 nm and a 3 dB bandwidth of 40 nm with a nearly 100 % reflectivity. This FBG will then reflect the C-band backward ASE into the EDF 1 in a forward direction. Fig. 2 shows the reflection and transmission characteristics of the FBG. The VOA provides variation of the ASE power, needed to study the effect of injecting C-band ASE in this system. An optical isolator is located at output end of the system to prevent spurious backward reflection from disturbing the system.

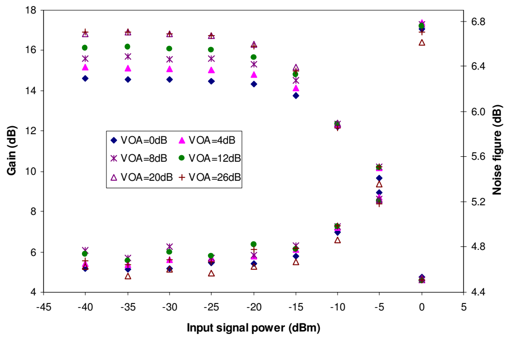

Fig. 4. Gain and noise figure against input signal power at various VOA.

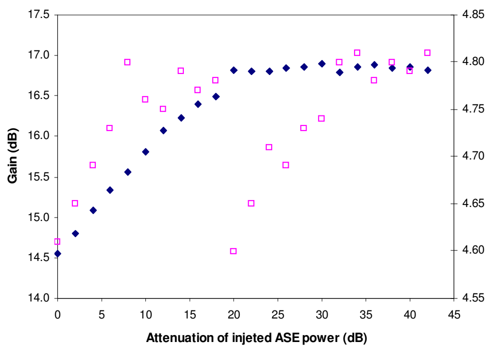

Fig. 5. Small signal gain (closed) and noise figure (clear) against VOA.

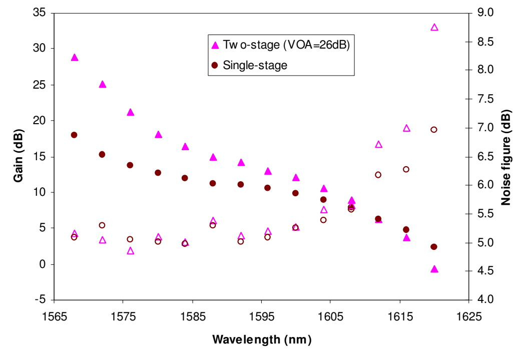

Fig. 6. Gain and noise figure at function of signal wavelength.

3 Results and discussions

Fig. 3 depicts the ASE spectra of the two-stage L-band EDFA with and without injection of C-band ASE, where the thin line represents the amplifier with injection of C-band ASE. As seen, the amplifier with C-band ASE injection shows a lower L-band ASE than that of the amplifier without C-band ASE injection, at L-band region (above 1567 nm). This reduction of L-band ASE is obtained due to the injection of C-band (1525 nm to 1567 nm) ASE that causes saturation at the longer wavelength region. The signal gain and noise figure at 1580 nm against input signal power for various VOA losses is plotted in Fig. 4. With the injection of C-band backward ASE from the second stage, the amplifier system shows a flatter gain curve at small input power compared to the amplifier without the C-band ASE injection (VOA = 26 dB). The saturation power also increases from -13 dBm (for VOA = 26 dB) to -8 dBm (for VOA = 0 dB). The L-band amplification mechanism is made possible by the intra-Stark-level multi-phonon transitions and re-absorption that transfer energy from the short wavelength (C-band) to the longer wavelength (L-band). Therefore, injecting a large amount C-band ASE into EDF 1 depletes number of ions in ground state. This limits the population inversion, which in turn reduces gain, thereby clamping the L-band gain. A lower VOA loss enables a higher injected signal power, which degrades the amount of available inversion. On the other hand, noise figure of the amplifier is relatively unchanged with injection of C-band ASE. The noise figure varies from 4.5 to 4.8 dB at small input signal power (< -15 dBm) for all VOA losses. The circulator, OC2, placed between the two-stages functions to re-route the C-band backward ASE from stage 2 as well as to allow forward C-band ASE from stage 1 to pass through. This arrangement prevents population inversion depletion by the backward ASE from stage 2, thereby preserving a good noise figure value below 5 dB.

Fig. 5 shows the small signal gain and noise figure against the VOA loss, when input signal power and wavelength are fixed at -30 dBm and 1580 nm, respectively. By varying the VOA from 0 to 20 dB, the small signal gain is controlled to be in the range from 15.5 to 16.8 dB as depicted in the figure. The gain is a monotonously increasing function of the attenuation from 0 to 20 dB. We find that when the VOA is above 20 dB, the optical gain becomes constant at 16.8 dB. In this region, the injected ASE power is very low. Therefore, the condition for clamping effect is not satisfied. On the other hand, the noise figure fluctuates between 4.6 and 4.8 dB for all VOA losses. Fig. 6 shows a comparison of gain and noise figure between the two-stage amplifier (VOA = 26 dB) and single stage amplifier at input signal power of -30 dBm. The EDF length and pump power of the single-stage amplifier are fixed at 50 m and 92 mW, respectively. As seen, the two-stage EDFA small signal gain is higher compared to a single-stage amplifier with similar total EDF length and pump power at wavelength from 1568 to 1604 nm, without any significant noise figure penalty. This is attributed to the dual forward pumping scheme that increases the efficiency of energy transfer from the short to long wavelength. The gain and noise figure is degraded in the wavelength longer than 1608 nm due to the ${}^4\mathrm{I}_{13/2} \rightarrow {}^4\mathrm{I}_{9/2}$ excited state absorption (ESA) that appears from 1600 nm [5].

4 Conclusion

The effect of injecting a C-band ASE from the second stage into the first stage of two-stage L-band EDFA is demonstrated. The amplifier gain is clamped at 15.5 dB and the saturation power increases from -13 dBm to -8 dBm with the ASE injection (VOA = 0 dB). The gain level can be controlled to be in the range from 15.5 to 16.8 dB by varying the VOA loss from 0 to 20 dB, without much variation in noise figure. This result shows that the injection of C-band ASE can be used to clamp L-band gain in two-stage L-band EDFA, which has an improved gain compared to single stage L-band EDFA.

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