Gain Enhancement in L-Band Loop EDFA Through C-Band Signal Injection

Ahmet Altuncu and Arif Başgümüş

***Abstract*—Gain enhancement provided in L-band erbium-doped fiber amplifier (EDFA) with loop configuration and through C-band signal injection is experimentally demonstrated and compared with conventional single-stage L-band EDFA design. Significant backward amplified spontaneous emission suppression in C-band and pump conversion efficiency increase in L-band were observed for varying C-band seed signal wavelength and power levels. Gain and noise figure (NF) performance of loop design L-EDFA is compared with the conventional bidirectionally pumped single-stage L-EDFA design. Gain and NF measurements in the loop configuration have resulted in an up to 9.5-dB increase in gain and up to 2.6-dB degradation in NF at a moderate signal wavelength of 1585 nm.**

***Index Terms*—Erbium-doped fiber amplifier (EDFA), L-band loop erbium-doped fiber amplifier (L-EDFA), wavelength-division multiplexing.**

I. Introduction

ERBIUM-DOPED fiber amplifiers (EDFAs) which have been initially developed for optical signal amplification in the conventional band (C-band, 1525–1565 nm) are now being utilized to cover the long wavelength band (L-band, 1565–1620 nm) with an inherent flat gain spectrum [1]. Combined C- and L-bands offer a much wider transmission window for the dense WDM systems. The lower EDFA gain in the L-band relative to the C-band can in principle be increased by using longer lengths and more heavily doped active fibers. Several different amplification methods have been proposed in order to improve the relatively low pump conversion efficiency (PCE) and, thus, enable a higher gain per unit fiber length in the L-band EDFA (L-EDFA). Specifically, a significant gain enhancement was achieved through external C-band (1550–1560 nm) seed signal injection [2]–[5], rereflection of the unused backward amplified spontaneous emission (ASE) to amplifier using fiber reflectors [5], circulators [6] or fiber Bragg gratings [7], the use of external ASE sources as a secondary pump source [8], the use of signal double-pass configuration [9], and using 1540-nm band pumping [10]. In this letter, gain enhancement provided in the L-band EDFA with loop configuration and through C-band signal injection is experimentally demonstrated and compared with the conventional single-stage bidirectionally pumped L-EDFA design. Loop EDFA design was previously investigated for the C-band [11], but not for the L-band EDFA. We find that, backward ASE spectral evolution as a function of the seed signal wavelength shows significant C-band backward ASE suppression through 1540–1560 nm seed signal injection with a power of higher than -15 dBm resulting in an increase in the PCE in L-band for both schemes. In addition, loop configuration of L-EDFA with respect to conventional design provides a significant gain improvement, although its noise figure (NF) performance deteriorates.

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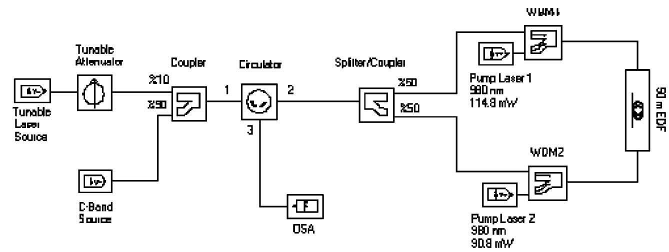

Fig. 1. L-band loop EDFA.

II. Experimental Setup

The loop design of bidirectionally pumped L-EDFA is shown in Fig. 1. In this configuration, a tunable laser source (TLS) with a variable optical attenuator was used as the L-band signal source. TLS output signal and the C-band injection signal at 1550 nm are combined via a 90/10 coupler and then the combined signal is applied to both of the loop and conventional designs of L-band EDFA pumped bidirectionally at 980 nm. In loop design, the combined signal is directed through a wide-band circulator and a 3-dB coupler while in the conventional design, an isolator is used only at the input of the L-EDFA to suppress lasing oscillations. EDF used in this experiment was 50 m long and its numerical aperture is 0.21, cutoff wavelength is 960 nm, core radius is 1.75 μm, background loss at 1310 nm is 8 dB/km, absorption loss at 980 nm is 10.46 dB/m, and emission loss at 1530 nm is 16.59 dB/m. The amplified signal at the L-EDFA output is observed with an Anritsu MS9710B optical spectrum analyzer, and gain and NF measurements performed systematically for 0.1-nm resolution. The maximum pump power applied in L-EDFA was 205.6 mW, with 114.8 mW in forward and 90.8 mW in backward directions giving a forward/total pumping ratio of 0.56.

III. Results and Discussion

First, the backward ASE spectrum measurements were performed for a conventional L-band EDFA as a function of seed signal wavelength and power. The backward ASE spectrum of forward-pumped conventional L-EDFA is shown in Fig. 2 as a

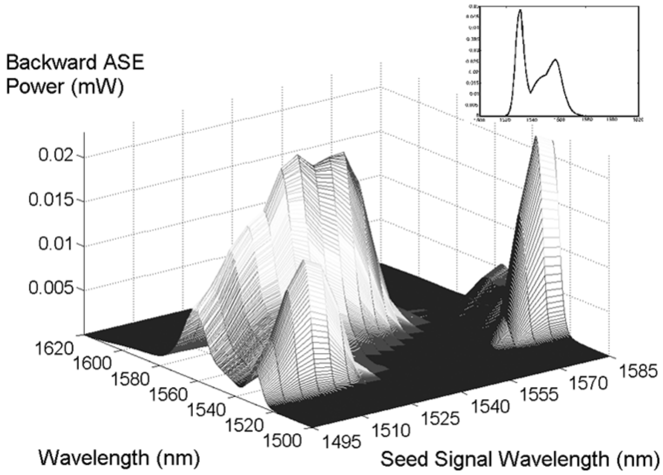

Fig. 2. Backward ASE spectrum of forward pumped L-EDFA as a function of seed signal wavelength. Inset: Backward ASE spectrum without seed signal.

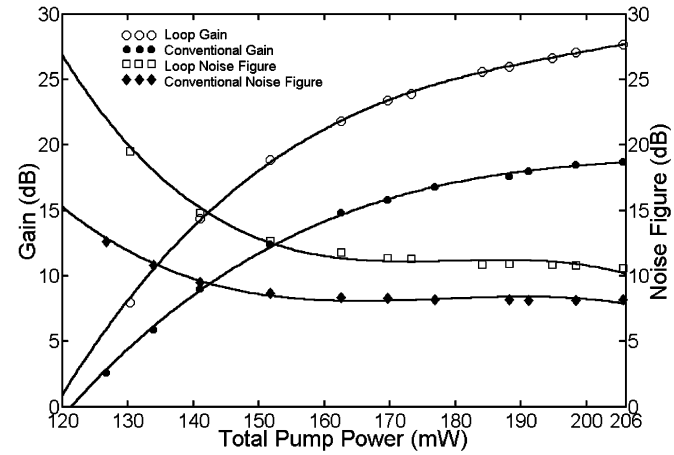

Fig. 3. Gain and NF variations as a function of total pump power for conventional and loop L-EDFA configurations. ($P_{\rm sig.in} = -30$ dBm, $\lambda_{\rm sig} = 1585$ nm).

function of seed signal wavelength with the inset showing the backward ASE spectrum of the amplifier without applying a seed signal. It can be seen in Fig. 2 that C-band backward ASE at around 1535 nm is significantly suppressed when the C-band seed signal wavelength is varied from 1540 to 1560 nm. The backward ASE spectrum of forward-pumped L-EDFA was also measured as a function of 1550-nm seed signal power. When the seed signal power is increased from -30 to -15 dBm, C-band backward ASE at around 1535 nm sharply decreases and diminishes. The effect of C-band seed signal injection in an L-EDFA can be explained by two mechanisms: First, the C-band backward ASE is suppressed at the input section of the EDF so that the pump power can be converted more efficiently to the L-band signal power. PCE enhancement of L-EDFA provided with the C-band seed signal injection depends on both of the seed signal wavelength and the injected power level. Second, the injected C-band seed signal is strongly amplified at the input section which is then used as a secondary pumping source at 1550 nm to the system. Using a longer length of EDF, maximum energy transfer from C- to L-band can be achieved, resulting in a higher gain and an extended gain spectrum.

Fig. 3 shows gain and NF performance of bidirectionally pumped conventional and loop designs of L-EDFA as a function of total pump power. The applied pump power was varied from 125 to 205 mW. It can be seen that, for both configurations, the gain increases and NF decreases with increasing pump power. In addition, the gain of loop L-EDFA at 1585 nm is significantly higher than conventional L-EDFA giving a net gain of approximately 27.8 dB and a gain improvement of up to 9.5 dB for the maximum provided pump power. On the other hand, the loop design of L-EDFA deteriorates NF performance causing an increase of up to 2.6 dB, resulting in an approximately 9.7-dB NF. The reason for a higher gain in loop design of L-band EDFA can be explained by the fact that both of the L-band signal and the injected C-band seed signal are split into two parts at the 3-dB coupler. The clockwise and the counterclockwise propagating parts of the L-band signal and the C-band seed signal are strongly amplified and reflected back to the same coupler. The backward ASE generated in both ends of the EDF is significantly suppressed due to the heavily amplified C-band seed signal. Backward ASE suppression and secondary pumping effects provided at both fiber ends result in an enhanced PCE and a significantly higher gain achievable in the L-band loop EDFA with respect to the conventional design. Additionally, the loop in this design acts as a dispersion-balanced fiber reflecting mirror due to 3-dB coupling ratio, uniform EDF, and pumping the amplifier with equal pump powers at both ends. The counterpropagating parts of the L-band signal pass the same optical path in the loop and then directed to the output port through the circulator. Therefore, they do not change their relative phases leading to any time delay. The reflection mechanism is due to constructive interference of the counterpropagating beams of the coherent input signal [11] which is evidenced by having a higher gain in loop design of L-band EDFA. Therefore, the loop L-EDFA can perform high-quality pulse amplification in both linear and nonlinear regimes. It has been shown theoretically that the scheme is quite tolerant of small variations in both the device and input pulse parameters such as the loop length, loop gain, coupler splitting ratio, input peak power, input pulse shape, initial frequency chirp, and higher order fiber effects [12].

On the other hand, the counterpropagating components of the generated ASE noise are nonpolarized independent random processes having random relative phases. Therefore, they interfere destructively yielding a reduced amount of ASE accumulation within the L-EDFA. The NF increase in loop design, however, can be explained by a double backward ASE coming from the loop and extra signal losses resulting from the 3-dB coupler and the circulator. Since the fiber length is not exactly optimized for this design, which is evident from the tendency of the gain variation with pump power, the gain and NF performance obtained could be improved if the pump power applied is further increased. This has also been confirmed by the simulations performed on the conventional L-EDFA design such that the optimum length of EDF is estimated about 44 m for the maximum provided pump power.

Fig. 4 shows the measured gain and NF spectrum of conventional and loop L-EDFA between 1565–1585 nm. The spectral gain and NF measurements were limited to 1585 nm at

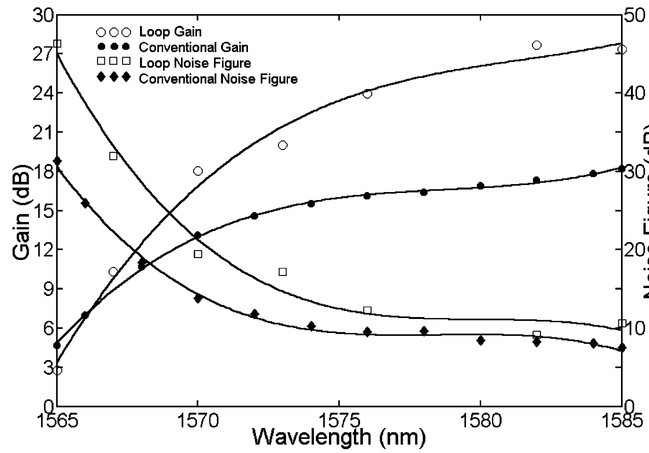

Fig. 4. Gain and NF variations as a function of signal wavelength for conventional and loop L-EDFA configurations. ($P_{\mathrm{sig.in}} = -30$ dBm, $P_{\mathrm{p.tot}} = 205.6$ mW).

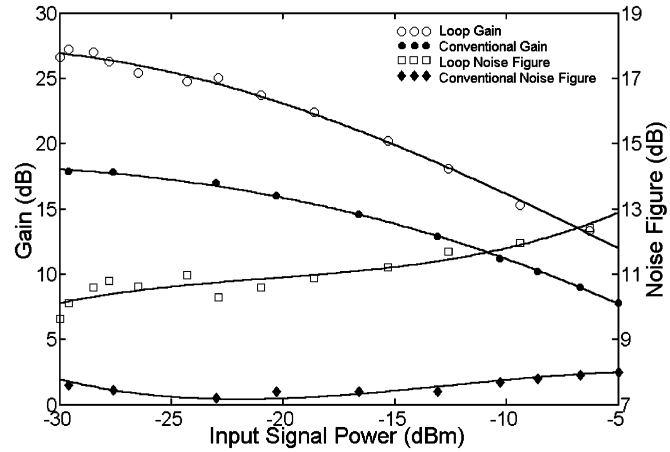

Fig. 5. Gain and NF variations as a function of input signal power for conventional and loop L-EDFA configurations. ($\lambda_{\mathrm{sig}} = 1585$ nm, $P_{\mathrm{p.tot}} = 205.6$ mW).

L-band, due to unavailability of the TLS operation beyond this wavelength. It can be seen from Fig. 4 that the loop L-EDFA gain increases more sharply with increasing wavelength up to 1585 nm. Both configurations have almost equal gains at the beginning of L-band (1565 nm). However, beyond 1570 nm, the loop L-EDFA gain increase with wavelength is much higher than conventional design giving a maximum gain enhancement of 9.5 dB. Although the NF performance of loop L-EDFA at 1565–1570 nm is worse, NF degradation in loop design gets reduced to 2.6 dB at 1585 nm signal wavelength. Loop EDFA gain and NF were measured as 27.8 and 9.7 dB, whereas conventional L-EDFA gain and NF were 18.3 and 7.1 dB, respectively. These results include two standard to angled FC/PC connector adapter losses used at the EDFA input and output. From the output ASE spectrum of L-EDFA observed on optical spectrum analyzer, the loop design is estimated to provide an approximately 40-nm gain bandwidth between 1570–1610 nm for saturating signal powers.

Fig. 5 shows gain and NF variations as a function of input signal power for both conventional and loop L-EDFA configurations. As seen in the figure, gain saturation occurs for both configurations together, with slightly faster saturation in the loop L-EDFA. At a saturating signal level of -5 dBm, gain improvement is reduced to 4.3 dB, yielding gains of 12 dB in loop configuration and 7.7 dB in conventional design. The NF difference, however, slightly increases to 5 dB giving NF values of 12.9 dB for loop configuration and 7.9 dB for the conventional design.

IV. Conclusion

A substantial gain enhancement was achieved in an L-band EDFA by using loop configuration and a C-band seed signal. Significant backward ASE suppression in C-band occurring due to C-band signal injection was observed through backward ASE measurements for seed signal wavelengths varying between 1540–1560 nm and powers higher than -15 dBm. Gain and NF performance of our loop L-EDFA design was compared with the performance of a conventional L-EDFA design. Gain and NF measurements in loop configuration have resulted in an up to 9.5-dB increase in gain and up to 2.6-dB degradation in NF, at a moderate signal wavelength of 1585 nm. In general, with its relatively high NF values, the loop design of L-EDFA can be used as a L-band booster amplifier not requiring minimized NF.

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