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A novel 3-stage structure for a low-noise, high-gain and gain-flattened L-band erbium doped fiber amplifier*

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Abstract: The configuration of the novel three-stage L-band erbium-doped fiber amplifier with very large and flat gain and very low noise figure presented in this paper uses the forward ASE (amplified spontaneous emission) from the first section of the EDF (erbium-doped fiber) and the backward ASE from the third section of the EDF (both serve as the secondary pump sources of energy) to pump the second EDF. To improve the pump efficiency, the power of the pump is split into two parts (with a ratio of e.g. 2:7). The characteristics of this L-band EDFA are studied on the basis of the Giles Model with ASE.

Key words: Erbium doped fiber amplifier, Three-stage, Pump, L-band, Fiber optical communication
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INTRODUCTION

Optical communications have been developed so rapidly that the conventional C-band transmission window (1520–1560 nm) cannot satisfy the requirements of a dense wavelength division multiplexing (DWDM) system. L-band EDFAs have attracted much attention (Massicott *et al.*, 1990; Lee *et al.*, 1999; Mahdi *et al.*, 2000; Harun *et al.*, 2002) since they can effectively increase the transmission bandwidth and reduce the FWM (four-wave mixing) in a system with dispersion-shifted fibers (DSFs). However, L-band EDFAs are relatively inefficient since they are operated at the tail of the erbium gain band. In order to improve the gain in the L-band, several schemes using various techniques such as C-band backward ASE (amplified spontaneous emission) (Lee *et al.*, 1999), 1550 nm-band signal injection technique (Mahdi *et al.*, 2000), and double-pass technique (Harun *et al.*, 2002) have been reported recently. The use of a 1550 nm laser source as a pump will increase the cost. Double-pass technique can improve the noise figure, but two optical circulators are needed and thus the cost increases. ASE pumping (serving as a secondary pump) is thus a very appropriate scheme to enhance the L-band EDFA gain.

In this paper, a novel three-stage structure is introduced to achieve a very large and flat gain and a very low noise figure. Both the forward ASE from the first section of EDF and the backward ASE from the third section of EDF serve as the secondary pump sources to pump the second section of EDF. A mid-way isolator is used to eliminate the backward ASE (which may disturb previous portions) and thus improve the noise figure (Yamashita and

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Okoshi, 1992). To improve the pumping efficiency, the power of the pump is split into two parts in an appropriate way (at a ratio of say 2:7).

THEORETICAL MODELING

EDFA configurations

In general, a 980 nm pump has higher gain and lower noise figure than a 1480 nm pump (with a high power). Furthermore, for a very long fiber, the backward pump gives worse signal gain than the forward pump (Becker *et al.*, 1999). A 980 nm forward pump is thus used in the present work. The schematic diagram of the suggested L-band EDFA is shown in Fig.1c, where the EDF1 length should be short enough in order to obtain highly reversed population at different energy levels. In this way, a large C-band forward ASE serving as a secondary pump (indicated by the dashed box in Fig.1c) at wavelength of about 1550 nm is obtained. The backward ASE from EDF3 also serves as a secondary pump source. The efficiency of the proposed L-band EDFA structure is compared with the efficiency of a conventional single-stage L-band EDFA shown in Fig.1a and the efficiency of the two-stage ASE pumping structure introduced by Lee *et al.* (1999) shown in Fig.1b. For comparison, the total pump power is kept at 90 mW in all the configurations. WDM$_{1,2}$ are wavelength-multiplexed couplers, and ISO$_{1,2,3}$ are optical isolators.

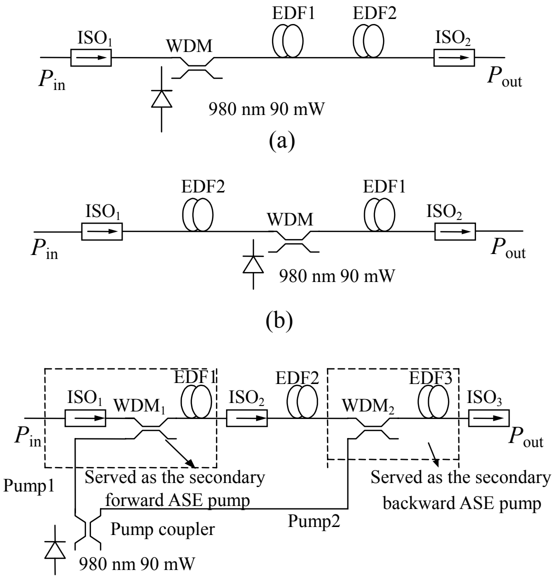


Fig.1 The configurations for 3 different designs of L-band EDFAs

(a) A conventional single-stage EDFA with a forward pump; (b) A structure introduced by Lee *et al.*(1999); (c) Our three-stage EDFA structure

Model

The EDFA pumped by 980 nm or 1480 nm laser can be modeled as the two-level model of Giles and Desurvire (1991). In the two-level model with ASE, the propagation equation for each light field (with index *k*) is

$$\begin{aligned} \mathrm{d}P_k^{\pm}(z)/\mathrm{d}z = &\pm(\alpha_k+g_k^*)\bar{n}_t^{-1}\bar{n}_2P_k^{\pm}(z) \\ &\pm mg_k^*\bar{n}_t^{-1}\bar{n}_2h\nu_k\Delta\nu_k \mp(\alpha_k+l_k)P_k^{\pm}(z)\,, \end{aligned} \tag{1}$$

where $P_k^{\pm}(z)$ is the light power at position z in the frequency bandwidth; $\Delta\nu_k$ denote the frequency step (which is about 125 GHz for a spectral bandwidth of 1 nm) used in the simulation to resolve the ASE spectrum; u_k is equal to +1 for a forward-propagating field and –1 for a backward-propagating field; α_k, g_k^*, l_k represent the spectral attenuation, gain and background loss of the considered EDF, respectively; and the factor m equals 2 due to the two polarization states of the lowest order mode. The population ratio $\bar{n}_2/\bar{n}_t$ for the upper energy level is

$$\frac{\bar{n}_2}{\bar{n}_t}=\frac{\sum\limits_k\dfrac{P_k^{\pm}(z)\alpha_k}{h\nu_k\zeta}}{1+\sum\limits_k\dfrac{P_k^{\pm}(z)(\alpha_k+g_k^*)}{h\nu_k\zeta}}\,, \tag{2}$$

where $\zeta=P_k^{\mathrm{sat}}(\alpha_k+g_k^*)/h\nu_k$ is the saturation parameter which can be obtained from a measurement of the fiber saturation power.

The noise figure is defined by (Becker *et al.*, 1999)

$$NF=10\lg\left(\frac{1}{G}+\frac{P_{\mathrm{ASE}}}{h\nu G\Delta\nu}\right), \tag{3}$$

where G the signal gain,

$$G = 10\lg(P_{\text{out}} / P_{\text{in}})\ . \tag{4}$$

For a given boundary condition, Eq.(1) can be solved easily by using the relaxation method. For example, for EDF1 we have $P^{+}_{\text{ASE}}\big|_{z=0}=0$ and $P^{-}_{\text{ASE}}\big|_{z=L}=0$, where L is the EDF1 fiber length. Boundary conditions for EDF2 and EDF3 can be given in a similar way. The absorption and emission spectra used in our simulation are shown in Fig.2. A commercial erbium doped fiber (type: MP 980) was used in our calculation. The other parameters for the EDFs are set as follows: cutoff wavelength λ_c=842 nm, absorption coefficient α (980 nm)=4.57 dB/m, emission coefficient g^* (980 nm)=0 dB/m, α (1530 nm)=5.86 dB/m, background loss l=0.91 dB/km, and bandwidth Δv=125 GHz.

NUMERICAL RESULTS

In general, the small signal gain spectrum of an EDFA can be well reflected by the corresponding ASE spectrum with no signal input (Desurvier, 1994). It is thus very convenient to determine the optimal parameters of an EDFA through its ASE spectrum. Fig.3 shows the ASE spectra for a conventional single-stage structure, the two-stage structure introduced by Lee *et al.*(1999) and our structure. The length of EDF and the corresponding pump power for these structures are listed in Table 1. Fig.3a is for a case without optimization and Fig.3b corresponds to the case with optimization. From Fig.3 one sees clearly that our structure can provide a higher ASE as compared to the other two structures (with or without optimization). Fig.3b shows that the EDFA parameters associated with curve 1 are a good set of parameters for a high performance L-band EDFA. These parameters are thus used in the following simulation. Fig.4 shows the gains and noise figures for various structures as the signal wavelength increases. The input signal is fixed at –30 dBm in the simulation. Fig.4a shows the relationship between the gain and the signal wavelength. Fig.4a shows that our L-band EDFA can achieve 28.9 dB gain with only about 1 dB gain ripple (from 1570 nm to 1605 nm) and this gain is at least 8 dB higher than the gains of the two other str-

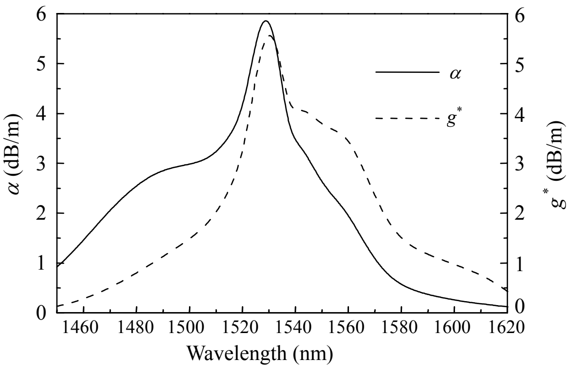
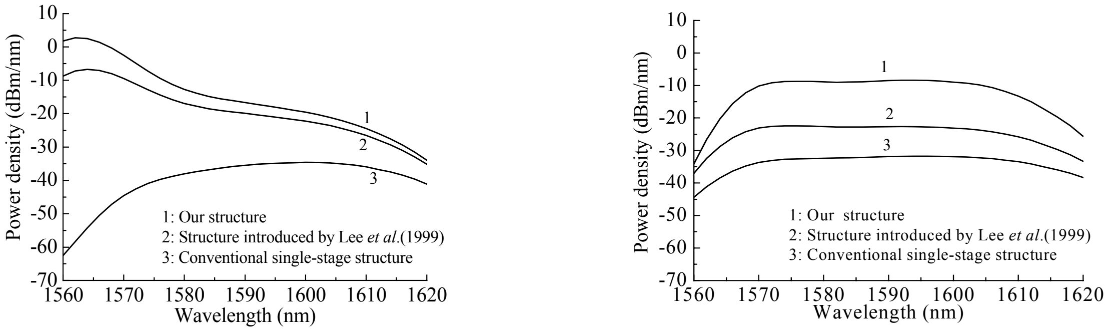


Fig.2 Spectra of α and g^*



(a) (b)

Fig.3 ASE spectra

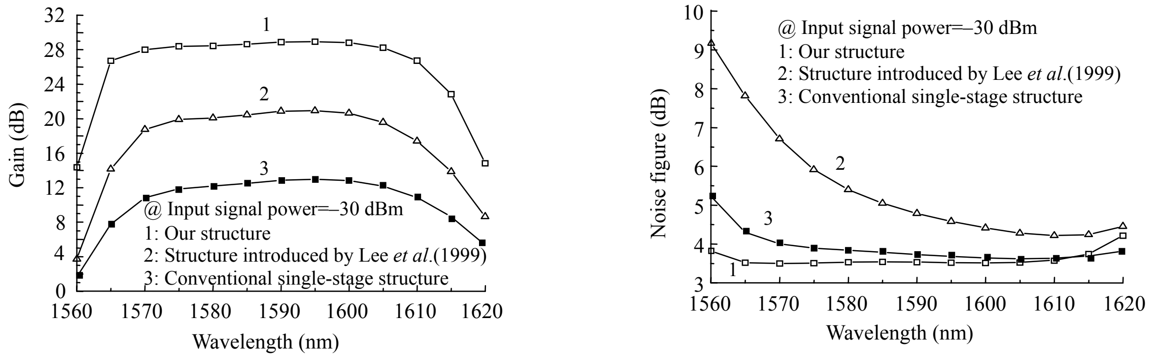
(a) for various structures without optimization, power ratio in our structure is 1:2;
(b) for various structures after optimization, power ratio in our structure is 2:7

uctures. Fig.4b shows the relationship between the noise figure and the signal wavelength. As shown in Fig.4b, the proposed L-band EDFA structure can provide less than 3.6 dB noise figure (from 1570 nm to 1605 nm), which is at least 0.2 dB lower than the noise figures of the other two structures. These simulation results showed that a high performance L-band EDFA (with simultaneously high gain, low noise and low gain ripple) could be realized by our novel structure. Comparing the spectra in Fig.4 to the corresponding ones in Fig.3, one sees that the ASE spectrum can reflect the small signal gain spectrum of the EDFA.

Fig.5 shows the gains and noise figures for different input signal powers. Fig.5a is for a single channel (1572 nm) signal input to our EDFA. Fig.5b

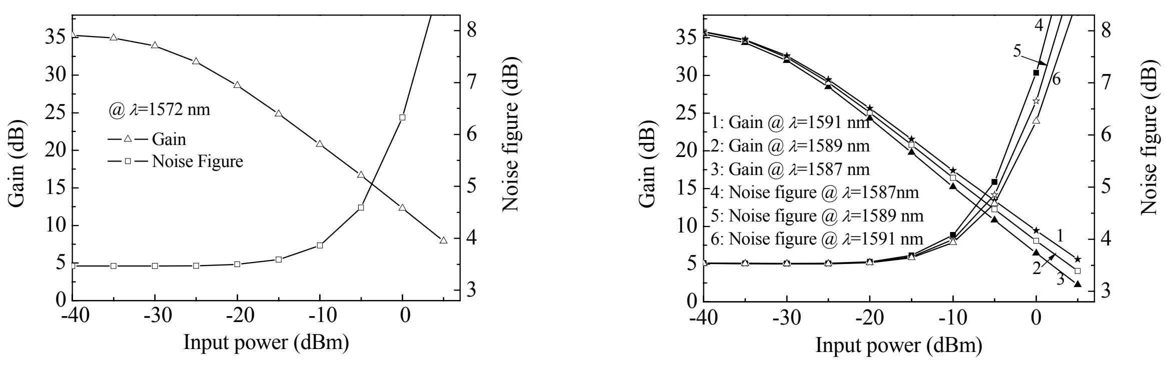
Table 1 Lengths of EDF sections and the corresponding pump powers (980 nm) for various structures shown in Fig.2

	Configuration in Fig.2	Length of EDF1 and the corresponding pump power	Length of EDF2 and the corresponding pump power	Length of EDF3 and the corresponding pump power
Without optimization	(a)	70 m/90 mW	10 m/0 mW	0
	(b)	10 m/90 mW	70 m/0 mW	0
	(c)	10 m/30 mW	10 m/0 mW	60 m/60 mW
With optimization	(a)	65 m/90 mW	5 m/0 mW	0
	(b)	99 m/90 mW	10 m/0 mW	0
	(c)	10 m/20 mW	10 m/0 mW	160 m/70 mW



(a) (b)

Fig.4 (a) Gain and (b) noise figure as the wavelength increases



(a) (b)

Fig.5 Gain and noise figure for different input signal power

(a) For the case of single-channel; (b) For multi-channel case is for multi-channel (1587 nm, 1589 nm, 1591 nm) signal input (with equal power) to our EDFA. The small signal gain and noise figure for the three channels of 1587 nm, 1589 nm and 1591 nm are 35.49 dB/3.54 dB, 35.74 dB/3.537 dB and 35.79 dB/3.534 dB, respectively. The maximal gain difference is 0.3 dB and the maximal difference in noise figure is 0.006 dB. When the power of the input signals increases, the EDFA gain decreases and finally reaches the saturation area. It shows again that our novel EDFA structure can provide excellent performance.

CONCLUSION

In summary, a novel three-stage L-band EDFA structure with ASE pumping has been proposed. Based on the Giles model with ASE included, numerical simulation showed that the present EDFA structure can provide 28.9 dB gain with only about 1 dB gain ripple and less than 3.6 dB noise figure (from 1570 nm to 1605 nm) when the input signal is fixed at –30 dBm. The present L-band EDFA structure can be optimized to achieve better performance by using e.g. a genetic algorithm (a global optimization method).

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