Design and Control of Gain-Flattened Erbium-Doped Fiber Amplifier for WDM Applications

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CONTENTS

ABSTRACT

A simple experimental method to design gain-flattened erbium-doped fiber amplifier is proposed and demonstrated based on the two linear relations between the output power and the pump power, and between the gain and the length of the erbium-doped fiber at the gain flattened state. The spectral gain variation of the erbium-doped fiber amplifier constructed by this method was less than 0.4 dB over 12 nm (1,545∼1,557 nm) wavelength region. The gain flatness is also controlled within 0.4 dB over the input power range of $-30 \sim -15$ dBm/ch through the feedback control utilizing the amplified spontaneous emission power in the 1,530 nm region.

I. INTRODUCTION

Wavelength division multiplexed (WDM) lightwave transmission offers the potential of upgrading transport network with high capacity long distance transmission systems. In particular, the successful demonstration of amplified WDM systems in the low-loss 1.5 μm fiber requires high performance optical amplifiers to be used as power booster, repeater and preamplifiers. In that respect, erbium-doped fiber amplifiers (EDFAs) have many attractive features such as high gain, low noise, and low polarization dependency that have pushed their investigation, development and utilization to a large scale. However, EDFAs exhibit the irregular emission and absorption spectra which not only change the gain and output power as a function of the operating wavelength but also yield variations in the optical signal-to-noise ratio (OSNR) among channels in case of WDM transmission. Moreover, for a given EDFA design, variation of total input signal power changes the channel-by-channel gain and the OSNR. These EDFAs make the WDM system more complicated and less efficient. For the robust operation of the WDM systems, EDFAs should be designed and controlled to a gain flattened condition for a given input power range.

In this paper, a simple method to determine the erbium-doped fiber length and the pump power of the EDFA offering the desired flat gain over a 12 nm wavelength from 1,545 nm to 1,557 nm is demonstrated. Also the control of the gain flatness is proposed and demonstrated by utilizing the amplified spontaneous emission (ASE) in the 1,530 nm region. In our scheme, the ASE power is coupled out by a fiber Bragg grating (FBG) reflector inserted at the end of the EDFA. In Section II, we described the procedure to determine the parameters of the EDFA from the simplified theory showing the relations between the erbium-doped fiber length and the flat gain and between the input (output) signal power and the required pump power. The control of the flat gain for the input power variation is demonstrated in Section III. Finally we concluded in Section IV.

II. DESIGN OF THE GAIN-FLATTENED EDFA

It is well known that the gain of the EDFA is represented as [1]

$$G = \mathrm{Exp}\{[g^*\overline{n_2} - \alpha(1-\overline{n_2})]L\}, \qquad (1)$$

or in dB scale,

$$G = \gamma_s L, \qquad (2)$$

where L is the length of the erbium-doped fiber; $\overline{n_2}$ is the upper level population which is normalized by the total population of the erbium-doped fiber and averaged over the entire erbium-doped fiber; α and g^* are the absorption and gain per unit length, respectively; and γ_s is the signal gain coefficient defined by $[g^*\overline{n_2} - \alpha(1-\overline{n_2})]$. The signal gain coefficient γ_s determines the gain spectrum of the EDFA regardless of the length of the erbium-doped fiber. Thus the gain in dB is proportional to the doped fiber length for a given gain spectrum [2]. On the other hand, the signal gain coefficient γ_s is again described in terms of the pump and the signal powers as follows [3] :

$$\gamma_s = g^* \frac{P_P/P_P^{th} - S}{1+P_P/P_P^{th}} \frac{1}{1+P_S/[P_{sat}(1+P_P/P_P^{th})]}, \quad (3)$$

where P_P is the pump power; P_P^{th} is the threshold pump power representing $h\nu_P A_P/[\alpha_P \tau]$; P_S is the output signal power; P_{sat} is the intrinsic saturation power representing $h\nu_S A_S/\ \{[\sigma_a(\nu_S)+\sigma_e(\nu_S)]\tau\}$, $S=\sigma_a(\nu_S)/\sigma_e(\nu_S)$ where $\sigma_e(\nu_S)$ and $\sigma_a(\nu_S)$ are the stimulated emission and the absorption coefficients of the erbium-doped fiber, respectively; h is Plank constant; and A_S, A_P and τ are mode field areas of signal, pump and the upper level life time, respectively. At the high pump powers, (3) could be simplified as follows after some calculation :

$$P_P = C_P \frac{\gamma_S}{g^* - \gamma_S} P_S, \quad (4)$$

where C_P is a constant representing P_P^{th}/P_{sat}. For a given gain spectrum (i.e, signal gain coefficient γ_s), the required pump power is proportional to the output signal power. Equations (2) and (4) give two linear relations: the gain versus the length of the erbium-doped fiber length and the output signal power versus the required pump. From these two relations, the length of the erbium-doped fiber and the required pump power giving the best flat gain over the transmission channel could be determined for a given input signal power and the gain of the EDFA.

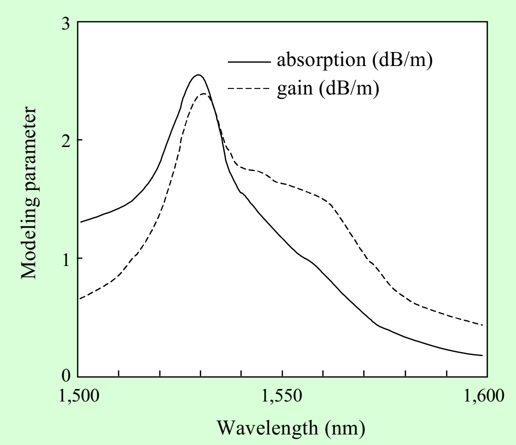
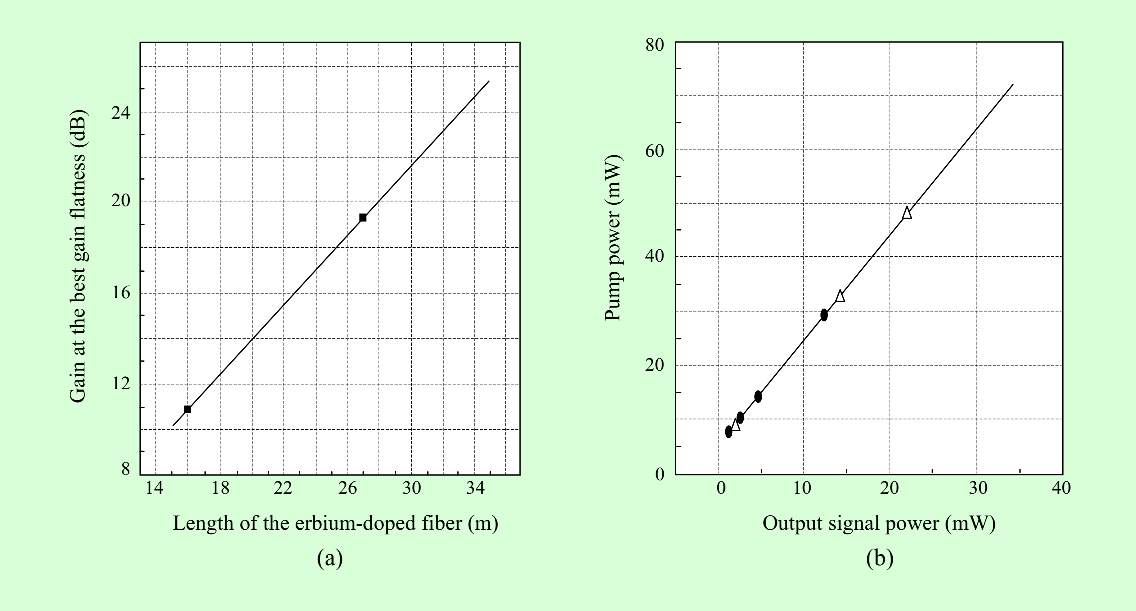


Fig. 17. The gain and absorption spectrum per unit length of the erbium-doped fiber used in the experiment.

For our system, the input signal of the EDFA is −23 dBm/ch., and the required gain is about 20 dB. The channels, the desired number of which is 16, are distributed with equal spacing at the wavelength range from 1,545 nm to 1,557 nm. The erbium-doped fiber is codirectionally pumped by using 980 nm LD. The maximum available pump power is about 70 mW. In the experiment, we used 4 channels of signal sources instead of 16 channels, where the input (output) power per channel is −17 dBm (3dBm), which gives the same result for the 16 channels with the input (output) power of −23 dBm/ch. (3 dBm/ch.).



(a)

(b)

Fig. 18. Two linear relations of (a) gain versus the length of the erbium-doped fiber and (b) the required pump power versus the output signal power of the EDFA at the best gain flattened condition. The solid line in (a) is linear fitting result and that in (b) is the numerical simulation result. The open triangle and the closed circle in (b) are the results for the erbium-doped fiber lengths of 16 m and 27 m, respectively.

The absorption and the gain per unit length of the erbium-doped fiber used in constructing the EDFA are shown in Fig. 1. The absorption per unit length for the 980 nm pump wavelength is 2.11 dB/m. From the numerical simulations, $\overline{n_2}$ at the best flat gain in the 1,545∼1,557 nm region is found to be about 68.6%.

Initially, we determine the above two linear relations exactly using two arbitrary lengths of the erbium-doped fiber without the knowledge of the constant g^*, C_P, or even γ_s at the best gain flattened condition. In the experiment, we used 16 m and 27 m lengths of the erbium-doped fiber. Figure 2(a) represents the gain versus the erbium-doped fiber length. The solid line is the linear fitting result of the data. The signal gain coefficient γ_s is found to be about 0.76. This value is also confirmed from the calculation with $\overline{n_2}$ of 0.68 and using the values of α and g^* which are averaged for the wavelength region from 1,545 nm to 1,557 nm, resulting in α of 0.263 and g^* of 0.376 in linear scale. The calculated γ_s is 0.762, which shows good agreement with the experimental result. The pump power and the related output power for those two lengths of the erbium-doped fiber is shown in Fig. 2(b). From the best fit of the experimental result, the slope coefficient is found to be 1.93. Using the values of γ_s and g^*

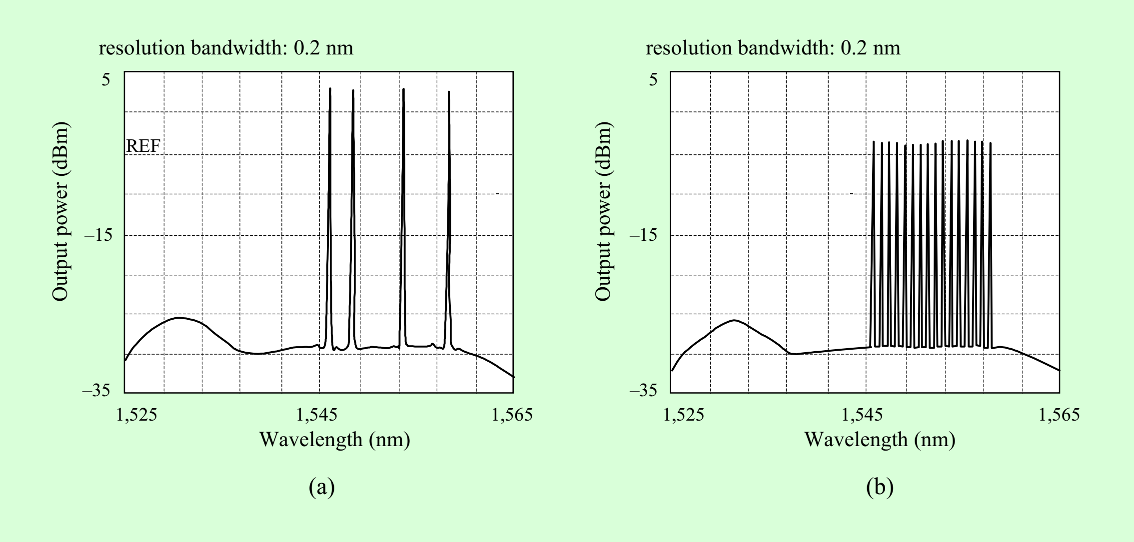


Fig. 19. (a) Output spectrum of the EDFA constructed by the parameters obtained from the relations in Fig. 3. The input signal is multiplexed four channels with input power of −17 dBm/ch., (b) represents the simulation result using the 16 channels of input signal with the power of −23 dBm/ch.

in linear scale, C_P is found to be about 2.2. The solid line is the numerical simulation result. In the numerical simulations, the values of the parameters A_S, A_P and τ are slightly adjusted so that resulting C_P coincides with the value obtained from the experiment. The experimental and simulation results show good linear relationship between the output signal power and the required pump power.

From the results of Fig. 2(a) and (b), we determine the length of the erbium-doped fiber and the required pump power at the desired condition, i.e, the gain of 20 dB and the output signal power of 9 dBm (8 mW). Considering the insertion loss of the devices in the EDFA such as isolators and pump-signal combining coupler, we determine the length of the erbium-doped fiber as 30 m which gives the flat gain of 21.5 dB. The required pump power is about 21 mW.

Figure 3(a) shows the output spectrum of the EDFA constructed by the above result. The gain flatness over the 12 nm (from 1,545 nm to 1,557 nm) is within 0.4 dB and the obtained gain is about 20 dB. Figure 3(b) is the numerical simulation result using the input signal source as multiplexed 16 channels. The spectral gain variation is about 0.4 dB with the gain of about 22.8 dB excluding the insertion loss of the isolators and the directional coupler [4].

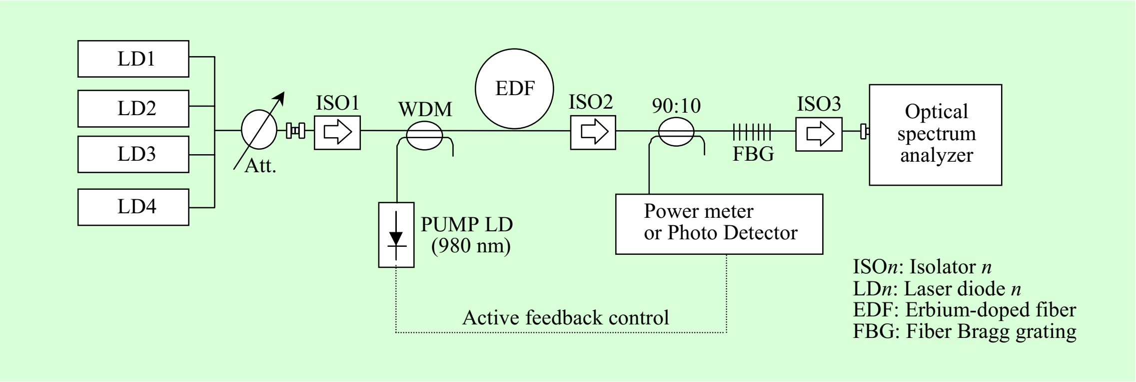


Fig. 20. Experimental setup of the gain flatness control and the configuration of the EDFA employing the feedback control of the gain flatness.

III. CONTROL OF THE GAIN-FLATTENED EDFA

Although the EDFA is constructed with optimum parameters giving the best flat gain condition at the fixed input (output) signal power, the spectral gain variation could be changed according to the input power variations due to the homogeneous broadening characteristics of the erbium ion [5]. Therefore it is necessary to maintain the gain flatness regardless of the input signal power. Gain flattening could be maintained by clamping the gain of the EDFA to a given value, based on (2). Optical feedback or the backward ASE power monitoring methods have been proposed and demonstrated to control the gain flatness based on the gain clamping [6], [7]. In this paper, we utilize the rejected ASE in the 1,530 nm region to control the gain since the ASE power in the given bandwidth is proportional to the gain [8]. The ASE in the 1,530 nm region is coupled out by using a fiber Bragg grating to prevent the saturation in concatenated silica-based EDFAs.

Figure 4 shows the experimental setup with the actively controlled EDFA configuration. The EDFA is constructed with the 30 m long erbium-doped fiber which is determined at the previous section. An FBG is inserted to reject the ASE component in the 1,530 nm region after the second isolator (ISO2). The maximum reflection and the 3 dB bandwidth of the FBG are 94% and 3 nm centered at 1,532 nm, respectively. The reflected ASE power from the FBG is monitored through a 90:10 fiber directional coupler. The last isolator (ISO3) is used to remove the possible reflection from the end of the connector which disturbs the ASE power detection at the photodetector. To measure the gain flatness, multiplexed four channels with wavelengths in the range of 1,545∼1,557 nm are also used. The incident power into the EDFA is controlled by using an attenuator.

Figure 5 shows the gain and the related spectral gain variation for different input signal powers with fixed pump power. The gain with best gain flatness is about 19.5 dB, which is slightly lower than the value obtained in the previous section due to the insertion loss of the FBG and the ISO3. For the input signal power of −30 ∼ −10 dBm/ch., the gain and the spectral gain variation change from 26.5 dB to 14 dB and from 1.6 dB to −1.6 dB, respectively. The monitored ASE power versus the spectral gain variation is represented in Fig. 6. The ASE power is measured with the input signal power of −30 ∼ −10 dBm/ch. for different pump powers. The monitored ASE power at the minimum spectral gain variation is about −22.5 dBm. The effect of the amplified transmission signal leakage to the monitor port is found to be negligible for the measured gain variation range.

By using the feedback control of the pump power to maintain the monitored ASE power at −22.5 dBm, the EDFA provides the best gain flatness regardless of the input signal power. Figure 7 shows the gain and the spectral gain variations versus the input signal powers with the feedback control. The gain variation is maintained within 0.4 dB for the input power range of −15 ∼ −30 dBm/ch. This input power range is limited by available pump power at the strong input signal region and can be extended with a strong pump. The actively controlled gain flatness of the EDFA can also be achieved even in the case of the channel add/drop.

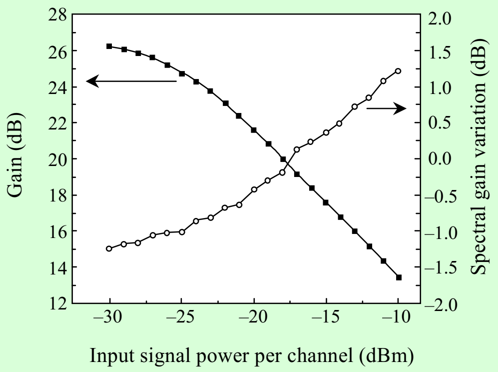


Fig. 21. Gain and related spectral gain variation in the 1,545 nm∼1,557 nm wavelength region versus the input signal power per channel with fixed pump power.

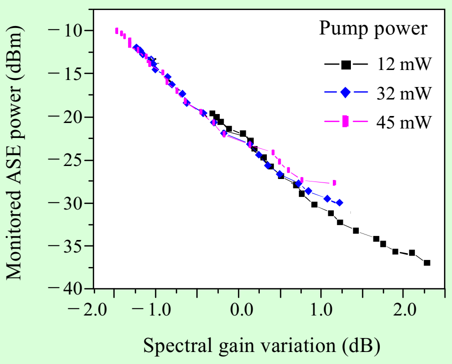


Fig. 22. Monitored ASE power versus the spectral gain variation measured by changing the input signal power from −10 to −30 dBm for various pump powers.

IV. CONCLUSION

A simple experimental method to design the gain flattened EDFA has been proposed and demonstrated utilizing the two

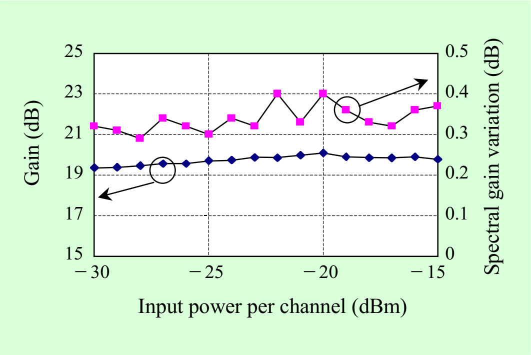


Fig. 23. Gain and spectral gain variation for different input signal power with the feedback control of the pump power using the monitored ASE power.

linear relations between the output power and the pump power, and between the gain and the length of the erbium-doped fiber at the desired gain flattened condition. For the EDFA constructed by using the proposed method, the spectral gain variation was less than 0.4 dB over the 12 nm wavelength region with total gain of about 20 dB.

We have also demonstrated the control of the gain flatness within 0.4 dB over the input power range of $-30 \sim -15$ dBm/ch through the feedback control utilizing the ASE power in the 1,530 nm region.

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