

A new compensation method for temperature-dependent gain tilt in L-band EDFA by adjusting only inserted VOA

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Received April 11, 2003

A novel compensation method for temperature-dependent gain tilt of L-band erbium-doped fiber amplifier (L-EDFA) is proposed, in which the attenuation between stages is the only parameter to be adjusted. A simple linear relationship between the attenuation and the erbium fiber coil temperature was derived theoretically. When the erbium fiber coil temperature cycles from 26 to 70°C, the gain tilt variation less than 0.3 dB is achieved experimentally by adjusting only the pre-inserted variable optical attenuator (VOA).

OCIS codes: 060.0060, 060.2320.

The recent tendency of wavelength-division-multiplexed (WDM) system involves more channel numbers, higher bit rates and longer distances, where L-band erbium doped fiber amplifier (L-EDFA) is required to double the transmission band. But, in L-EDFA, the temperature-dependent gain tilt is serious due to the temperature dependence of the absorption and emission cross sections of erbium ions. For example, the gain tilt can be as high as 3 dB in a 24-dB gain amplifier when the erbium fiber coil's temperature changes between 26 and 70°C. Many methods are proposed to compensate this temperature-dependent gain tilt such as using a hybrid cascade erbium-doped fiber (EDF)^[1], adopting 980-nm pump^[2] or adding a long period fiber grating with contrary temperature coefficient^[3]. But all these methods are complicate or only partly compensating. One more practical method is realized by co-operation of automatic gain control (AGC) and automatic temperature control (ATC)^[4], where a variable optical attenuator (VOA) is used to compensate the temperature effect and a complementary light has to be used to maintain the gain profile. Actually, the variation of inserted attenuation between stages could change the inversion level of the followed stages, so the gain spectrum will tilt with no pump power that adjustment required, in another word, when the temperature varies, the temperature-dependent gain tilt can be compensated via adjusting the attenuation if the control algorithm is proper. Based on this mechanism, we propose a novel temperature gain tilt compensation method in this paper, where the attenuation of inserted VOA is the only parameter to be adjusted. Starting from McCumber's relation, an approximate linear relation of attenuation increment of VOA versus temperature variation is derived theoretically, and the experimental demonstration results are also given.

According to McCumber's relation, the absorption coefficient $\alpha_K(\nu_K)$ and the emission coefficient $g_K^*(\nu_K)$ satisfy^[5]

$$g_K^*(\nu_K) = \alpha_K(\nu_K) \exp \left[\frac{\varepsilon(\nu_K, T) - h\nu_K}{kT} \right], \quad (1)$$

where $\varepsilon(\nu_K, T)$ is the absolute free energy when an erbium ion is stimulated from the energy level ${}^4I_{15/2}$ to ${}^4I_{13/2}$. $\varepsilon(\nu_K, T)$ can be considered as a temperature-

independent constant $\varepsilon(\nu_K)$ for normal considered temperature range^[6]. T is the temperature in degrees Kelvin, k is Boltzmann's constant and the subscript K is the index of signal or pump wavelength, respectively. $\alpha_K(\nu_K)$ can be approximated as^[6]

$$\alpha_K(\nu_K) = H(\nu_K) \exp[B(\nu_K)/kT], \quad (2)$$

where $H(\nu_K), B(\nu_K)$ are some functions, which can be obtained from two experimental gain spectra at different temperatures. Generally, the amplified spontaneous emission (ASE) power in L-band is small enough to be neglected, then the gain of EDFA can be written by using Eqs. (1), (2) and Giles model^[7] as (in linear scale)

$$G_K = \exp \left\{ \left[\left(\exp \left(\frac{B(\nu_K)}{kT} \right) + \exp \left(\frac{B(\nu_K) + \varepsilon(\nu_K) - h\nu_K}{kT} \right) \right) H(\nu_K) \frac{\bar{N}_2}{N_T} - \left(H(\nu_K) \exp \left(\frac{B(\nu_K)}{kT} \right) + l_K \right) \right] L \right\}, \quad (3)$$

where l_K is the background loss of the EDF, L is the EDF's length and \bar{N}_2/N_T is the average population inversion, respectively.

On the other hand, the average inversion level \bar{N}_2/N_T has a formula as^[7]

$$\frac{\bar{N}_2}{N_T} = -\frac{1}{L\zeta} \sum_K \frac{P_K^{\text{in}}}{h\nu_K} \times \left\{ \exp \left[\left((\alpha_K + g_K) \frac{\bar{N}_2}{N_T} - (\alpha_K + l_K) \right) L \right] - 1 \right\}, \quad (4)$$

where ζ is the saturation parameter.

For the normal situation, the input signal power is much smaller than the pump power, so \bar{N}_2/N_T is more dependent on the pump. Then, temperature dependent variation of \bar{N}_2/N_T can be neglected if 980-nm pump is adopted, because of the tiny temperature dependent effects of the pump's cross sections $\sigma_a(\lambda_p, T)$ and $\sigma_e(\lambda_p, T)$ ^[2]. Based on this assumption and Eq. (3),

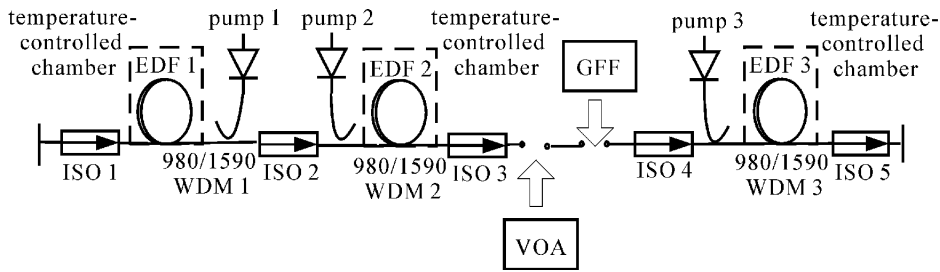


Fig. 1. The L-band EDFA set up used in the simulation and experiment.

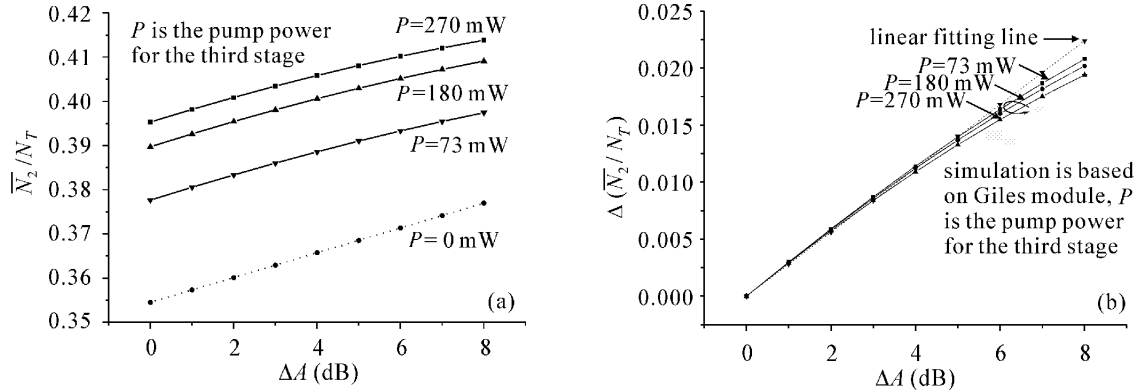


Fig. 2. The simulation results. (a) The relation of \bar{N}_2/N_T versus ΔA ; (b) the relation of $\Delta(\bar{N}_2/N_T)$ versus ΔA .

we can get gain variation ΔG_K with temperature variation ΔT (in logarithmic scale) as

$$\Delta G_K = \frac{4.343\alpha_{K_0}(\nu_K)L}{kT_0^2} \times \left\{ B(\nu_K) \left[1 - \frac{\bar{N}_2}{N_T} - \frac{\bar{N}_2}{N_T} \exp\left(\frac{\varepsilon(\nu_K) - h\nu_K}{kT_0}\right) \right] - \frac{\bar{N}_2}{N_T} [\varepsilon(\nu_K) - h\nu_K] \exp\left(\frac{\varepsilon(\nu_K) - h\nu_K}{kT_0}\right) \right\} \Delta T, \quad (5)$$

where $\alpha_{K_0}(\nu_K)$ is the value of $\alpha_K(\nu_K)$ at a medial temperature T_0 , e.g. room temperature. $H(\nu_K)$ has been eliminated by using Eq. (2).

It is well known that, the gain tilt could be changed if \bar{N}_2/N_T is varied^[7] even if the temperature is constant (in logarithmic scale)

$$\Delta G'_K = 4.343(\alpha_K + g_K^*)L\Delta(\bar{N}_2/N_T). \quad (6)$$

So, related Eqs. (5) and (6), one can compensate the temperature-dependent gain tilt by varying \bar{N}_2/N_T via some methods, such as changing the inserted attenuation between stages. In order to find out the relationship between the adjustment of attenuation ΔA and the variations of inversion $\Delta(\bar{N}_2/N_T)$, we numerically investigated a set-up shown in Fig. 1 by using Giles model. The set-up is a three-stage structure with a VOA and a gain flattening filter between the second and third stages, 980-nm LD pump and Lucent MP1480 L092202 EDF were used. A short pre-stage with counter propagating pump was used to generate seed ASE for pump efficiency enhancement. The EDF lengths and the pump powers for the first and second stages were 3.0 m, 60 mW and 40.0 m, 120 mW, respectively. For the third stage, the EDF

length was 7.3 m and the pump power was varied from 73 to 270 mW. The simulation results are shown in Fig. 2. Figure 2(a) illustrates the curves of \bar{N}_2/N_T versus ΔA (all solid lines) with a curve (dotted line) for a simplest situation, in which there was no pump input for the third stage and neglecting the differences of frequencies and attenuations for all the signals from stage 2 to stage 3. In order to see the effect of VOA clearer, we re-plotted Fig. 2(a) into $\Delta(\bar{N}_2/N_T)$ versus ΔA , here $\Delta(\bar{N}_2/N_T)$ is the difference between the average inversion values at any ΔA and $\Delta A = 0$ in the same curves, shown in Fig. 2(b). It can be seen from the curves that the relation of $\Delta(\bar{N}_2/N_T)$ versus ΔA is exactly linear for the virtual simplest situation, and nearly linear for the other cases with excursion at high ΔA end. In fact, under the assumption of simplest situation, a linear analytical relation can be derived from Eq. (4) (in logarithmic scale)

$$\Delta A = 4.343 \left[(\alpha_p + g_p^*)L - \frac{L}{L_3(\bar{N}_2/N_T)_3} \right] \Delta(\bar{N}_2/N_T), \quad (7)$$

where L_3 and $(\bar{N}_2/N_T)_3$ are the EDF length and the average inversion when ΔA is zero and pump power is zero for the third stage, respectively. Although an excursion rises due to the fact that pump power for stage 3 has to be supplied and the signal frequencies are different, we still have enough reason to use the approximate relation (7) for engineering application purpose, especially in the small ΔA range.

To realize temperature gain tilt compensation, the total gain variation due to temperature and attenuation variations should satisfy (in logarithmic scale)

$$\Delta G_K + \Delta G'_K - \Delta A \leq \varepsilon, \quad (8)$$

where ε is a small value represents the compensation level required. The value ε that can be reached is dependent on the intrinsic character of erbium ions, which is almost zero for L-band. Let ε be zero, comparison of expressions (5), (6), (7) and (8) gives a linear relation between ΔA

and ΔT (in logarithmic scale)

$$\Delta A = CL\Delta T, \quad (9)$$

where

$$C = \frac{4.343\alpha_K}{k\Delta T_0^2} \left\{ B(\lambda_K) \left[1 - \frac{N_2}{N_T} - \frac{N_2}{N_T} \exp\left(\frac{\varepsilon(\lambda_K) - hc/\lambda_K}{kT_0}\right) \right] - \frac{N_2}{N_T} [\varepsilon(\lambda_K) - hc/\lambda_K] \exp\left(\frac{\varepsilon(\lambda_K) - hc/\lambda_K}{kT_0}\right) \right\} \cdot \frac{1}{1 - \frac{(\alpha_K + g_K^*)}{(\alpha_K + g_K^*) - 1/[L_3(N_2/N_T)_3]}}. \quad (10)$$

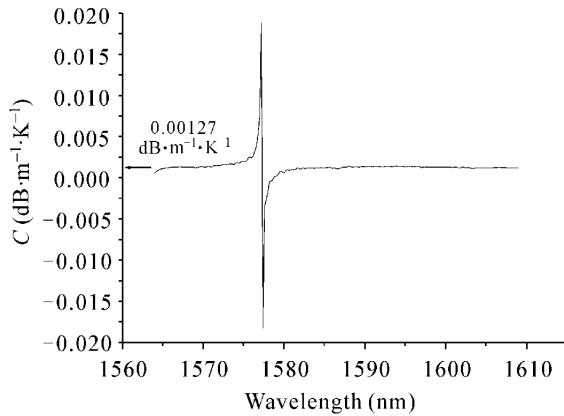


Fig. 3. The simulation value of C over the whole L-band wavelength range.

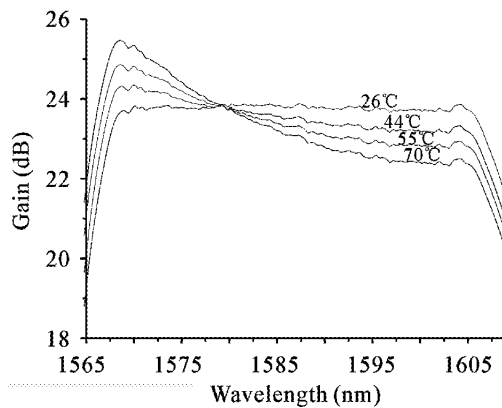


Fig. 4. The measured gain spectra of L-EDFA for temperatures of 26, 40, 55, and 70°C without attenuation variation.

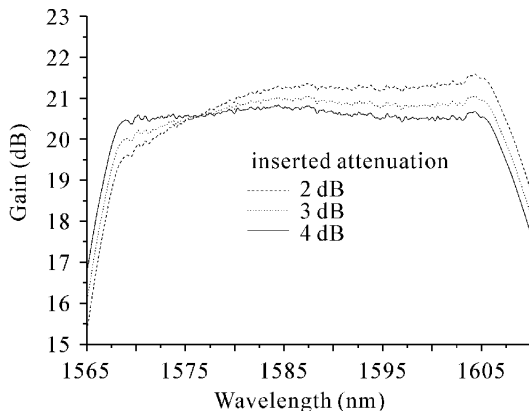


Fig. 5. The measured gain spectra of L-EDFA for attenuation of 2, 3, 4 dB at room temperature.

The linear relation (9) can be used for compensation control. It is worth to question that is C wavelength-dependent because some parameters in Eq. (10) are wavelength related. Shown in Fig. 3 is the calculated C at room temperature for different wavelengths by Eq. (10). For most wavelengths, C is almost constant with a value $C = 0.00127 \text{ dB}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, except a great break around 1577 nm. Further simulation and experimental results show that there is a singular point around 1577 nm, where ΔG_K and $\Delta G'_K$ are almost zero (see Figs. 4 and 5), the assumption of $\varepsilon = 0$ may cause singular and higher order approximation should be taken into account.

The experimental set up is the same as shown in Fig. 1. Equivalent saturation and broadband source method were used in gain spectrum measurement, the saturation power was -8.5 dBm at 1586 nm and the total power of broadband source were -23 dBm from 1565 to 1610 nm. The gain spectra in Fig. 4 were measured when the environment temperature of EDFs varied from 26 to 70°C

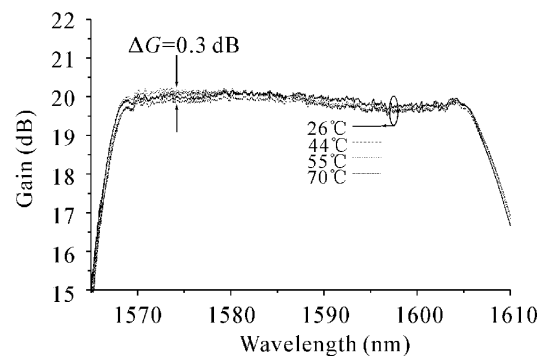


Fig. 6. The measured gain spectra at various temperatures with attenuation adjustment.

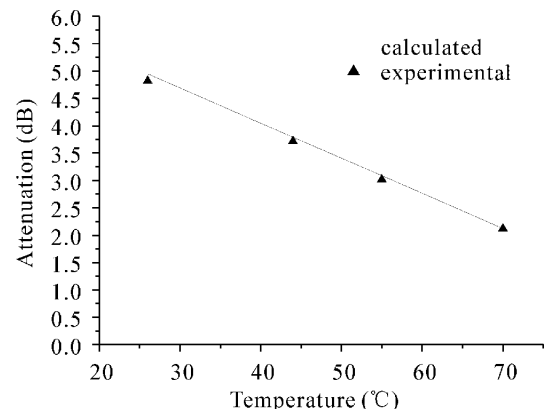


Fig. 7. The theoretical and experimental results of attenuation of VOA versus temperature.

without VOA adjustment. The gain spectra measured at room temperature with the VOA's attenuation of 2, 3 and 4 dB, respectively, are shown in Fig. 5. Comparison of Figs. 4 and 5 indicates that the temperature-dependent gain tilt can be compensated by adjusting the inserted attenuation. Figure 6 shows the gain spectra measured at temperature 26, 44, 55 and 70°C, with corresponding attenuation of the VOA 4.82, 3.72, 3.02 and 2.12 dB, respectively. It can be seen that the variation of all gain spectra is less than 0.3 dB. The attenuation value of VOA versus temperature is plotted in Fig. 7 with the calculation results (the solid line) from Eq. (9). It shows good linear relationship and good agreement between experiment and simulation.

In summary, a novel method for compensation of temperature-dependent gain tilt in L-EDFA is proposed. In this method, the only adjusted parameter is the attenuation of the pre-inserted VOA. Based on McCumber's relation, an approximately linear relationship of attenuation versus environment temperature was derived and demonstrated experimentally. The fluctuation of gain and gain tilt less than 0.3 dB was achieved by using the

proposed linear control when the erbium fiber coil temperature cycled from 26 to 70°C.

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