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Theoretical analysis on the transient characteristics of EDFA in optical fiber communication

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Abstract. Erbium laser amplifier has become one of the important components indispensable in optical fiber communication for its high gain, high pumping efficiency, polarization-independent and small crosstalk between signals, etc. The transient characteristic of the EDFA is an inevitable phenomenon based on the mechanism of EDFA amplification by stimulated emission of radiation. This paper focuses on the EDFA transient effects caused by the signal power, pump power , and gain saturation recovery time from the aspects of EDFA transient rate equation、the relation between the signal power and the output power、The relations between pump power and the output power and the transient effect caused by gain recovery time.

Introduction

In the future, optical fiber communication will occupy the leading position in the communication's industry inevitably as its large capacity, long distance, security and good performance of adaptability. While as a representative, Erbium laser amplifier has become one of the important components indispensable in optical fiber communication for its high gain, high pumping efficiency, polarization-independent and small crosstalk between signals, etc. However when a bunch of light pulses pass through an optical amplifier, the former pulse will have some impact on the amplification behavior of the latter one, even when it is a single light pulse, the leading edge will also affect the amplification behavior of the Trailing edge, which is an inevitable phenomenon based on the mechanism of EDFA amplification by stimulated emission of radiation, known as the transient characteristics of the EDFA.

The main reason causing the transient gain effect is the initial state of stimulated emission and the temporal correlation , the leading edge of signal pulse makes a large number of particles on the upper level transit by absorbing energy ,and then supply the lost particles for stimulated radiative transition on the upper level by the two means of transverse relaxation of the particles on the upper level and non-radiative transitions of a large number of particles in the pump energy level, in a sufficiently short period of time, if the number of particles in the upper level can't be replenished , there will be a gain difference between the former and the latter one of a series of pulses, or even the former and the latter edge of a pulse, causing changes in the output pulse waveform [1].

The main parameters of transient effects of EDFA are almost the same as the one of steady stat , both are associated with the pump power , signal power and noise -related gain of EDFA , the only difference is that the number of particles in the upper and lower levels is not certain value at transient changes, which changes with time, when the signal light passes through the EDFA , the transient power changes will cause the gain saturation phenomenon of EDFA, which is described by the EDFA gain recovery time. So when we analyze the transient changes of EDFA, we also need to analyze the recovery time of EDFA gain [2]. This paper focuses on the EDFA transient effects caused by the signal power, pump power, and gain saturation recovery time.

EDFA transient rate equation

Assume that the number of particles on the upper level is constant when the amplifier works at the steady state. However, the time-varying response of the number of particles on the upper level must be considered when it comes to the transient state, and the transient rate equation [3] should be adopted to analyze the characteristics of the amplifier. The level population change equation is as follows: (ignoring pump state absorption)

$$\frac{dN_1}{dt} = -(R_{13} + W_{12})N_1 + (W_{21} + A_{21})N_2 + R_{31}N_3 \tag{1}$$

$$\frac{dN_2}{dt} = W_{12}N_1 - (W_{21} + A_{21})N_2 + A_{32}N_3 \tag{2}$$

$$N_3(z,t) = N_t - N_1(z,t) - N_2(z,t) \tag{3}$$

Pumping rate R_{13}, stimulated emission rate W_{21} , spontaneous emission rate W_{12} are influenced by the signal power , pump power. So the level population is also affected by the pumping rate and signal power.

$$R_{13}(z,r) = \frac{\sigma_a(\upsilon_s)}{h\upsilon_p \pi\omega_p^2} P_p(z)\psi_p(r) \tag{4}$$

$$W_{21}(z,r) = \frac{\sigma_e(\upsilon_s)}{h\upsilon_s \pi\omega_s^2} P_s(z)\psi_s(r) \tag{5}$$

$$W_{12}(z,r) = \frac{\sigma_s(\upsilon_s)}{h\upsilon_s \pi\omega_s^2} P_s(z)\psi_s(r) \tag{6}$$

where, σ_a, σ_e, σ_s represents the pump absorption cross section, the stimulated emission cross section and the stimulated absorption cross section respectively. υ_p represents the frequency of the pump light, υ_s represents the frequency of the signal light , ω_p represents the mold spot radius of the pump light , ω_s represents the mold spot radius of the signal light , $\psi_p(r)$ represents the mode field envelope of the pump light in the fiber , $\psi_s(r)$ represents the mode field envelope of the signal light in the fiber.

The transfer equations of the pump signal and ASE power at transient stats are as following:

$$\frac{\partial P_P^{\pm}(z,t)}{\partial z} - \frac{1}{v_g}\frac{\partial P_P^{\pm}(z,t)}{\partial t} = \pm\alpha_p \Gamma_p (N_3 - N_1) p_p^{\pm}(z,t) \tag{7}$$

$$\frac{\partial P_s^{\pm}}{\partial z} - \frac{1}{v_g}\frac{\partial P_s^{\pm}(z,t)}{\partial t} = \pm\alpha_s \Gamma_s (N_3 - N_1) p_s^{\pm}(z,t) \tag{8}$$

$$\frac{\partial P_{ASE}^{\pm}(z,t)}{\partial z} - \frac{1}{v_g}\frac{\partial P_{ASE}^{\pm}(z,t)}{\partial t} = \pm\alpha_s \Gamma_s (N_3 - N_1) P_{ASE}^{\pm}(z,t) \pm 2\alpha_s \Gamma_s N_2 \eta_s P_0 \tag{9}$$

where, v_g is the group velocity, and assuming that the signal light and the pump light have the same group velocity; $\frac{d}{dz} = \frac{\partial}{\partial z} - \frac{1}{v_g}\frac{\partial}{\partial t}$, $\Gamma_{s,p}$ represent the overlap integral between the signal and pump mode field with the doped core area respectively. Other parameters have been described in previous chapters .

The stimulated emission rate W_{21} , spontaneous emission rate W_{12} are proportional to the power of the signal light, the pump light power R_{13} is proportional to the power of the pump light, which are all inversely proportional to the saturated output power of EDFA .

2 The relation between the signal power and the output power

The power transmission equation of the signal can be acquired by the rate equation and the power transmission equation of the level system. Replace the optical power by the number of photons, the output light power of the k- beam can be achieved

$$\overline{P}_k^{out} = \overline{P}_k^{in} \exp[-\alpha_k L + \frac{\overline{P}^{in} - \overline{P}^{out}}{\overline{P_{sat}}(\upsilon_k)}] \tag{10}$$

Where $\overline{P}^{\text{in,out}}$ is the total photon number of the input and output of the optical amplifier, $\overline{P_{sat}}(\upsilon_k)$ is the saturation power when entering the first k beam frequency, $\overline{P_{\text{sat}}}(\upsilon_k) = \frac{P_{\text{sat}}(\upsilon_k)}{h\upsilon_k}$.

Considering only the single-pump single-wavelength signal in the forward pump, (10) can be changed as follows:

$$\ln G_p = -\alpha_p L + (1 + G_P) P_P^{in} + (1 - G_s) P_s^{in} D(\lambda_s, \lambda_p) \tag{11}$$

$$\ln G_s = -\alpha_s L + (1 - G_s) P_s^{in} + (1 - G_p) P_p^{in} \frac{1}{D(\lambda_s, \lambda_p)} \tag{12}$$

We can know from the above ：

$$\ln G_s = -\alpha_s L + (1 - G_s) P_s^{in} + \frac{P_p^{in}}{D}[1 - \exp(D \ln G_s - D\alpha_s L + \alpha_p L) \tag{13}$$

Where $D(\lambda_s, \lambda_p) = \dfrac{(1+\eta_p)\alpha_p}{(1+\eta_s)\alpha_s}$

It can be achieved that the changes of signal gain is related with the input power and the length of the fiber. The relationship between the gain with the input power and the length of the fiber is shown in figure 1[4].

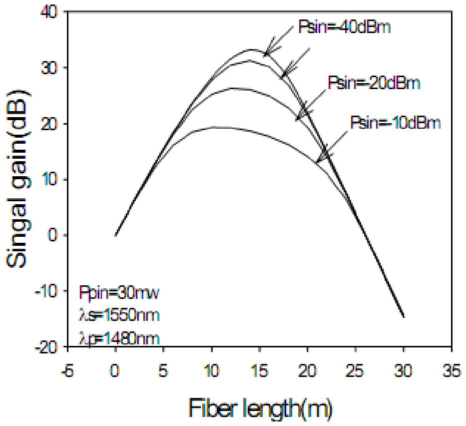

Fig 1 The relationship between the gain with the input power and the length of the fiber

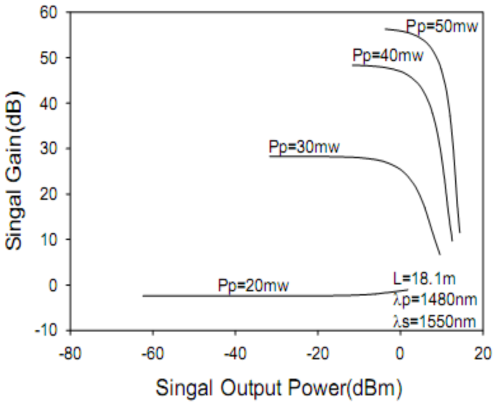

Fig 2. The relationship between the pump power and the signal output power

It can be seen from the figure that the gain is affected by the input power and the length of the fiber. For a given signal power, there is always an optimal fiber length which makes the maximum gain. While for a fixed fiber length, the gain increases as the input signal power [5].

The relations between pump power and the output power

The relation between input power and the output power is as following:

$$\ln(\gamma\frac{P_s^{out}(L)}{P_{th}}) - \ln(\gamma\frac{P_s^{in}(0)}{P_{th}}) + (\gamma\frac{P_s^{out}(L)}{P_{th}} - \gamma\frac{P_s^{in}(0)}{P_{th}}) = \frac{\alpha_s}{\alpha_p}[\frac{P_p(0)}{P_{th}} - 1 - \ln\frac{P_p(0)}{P_{th}}] \tag{14}$$

P_{th} is the power when G=0dB,which is called the pump threshold power; $\gamma = \upsilon_p / \upsilon_s$; $P_p(0)$, $P_p(L)$ represent the input and output normalized pump power respectively.

According to (14) and the relationship between gain G and the normalized input pump power $P_p(0)$ as well as the length L of the amplifier, it can be known that for a given input signal power ,when changing the pump power, the gain changes as the pump power. However the optical amplification of EDFA is due to the principle of stimulated emission, so the impact on the inversion population from the pump power will also affects EDAF gain [6] . When the input signal power is small , the pump increases, the gain will also increase. Until the pump power reaches a certain level, the gain no longer increases, which is due to the complete saturation of EDFA gain, the number of particles in he lower level are completely reversed at this time , there is little effect on the population inversion when increasing the pump power continuously, so the output power of the signal light hardly changes with pump light. However when the power of input signal light is larger, the front gain of the signal is larger, while the rear gain may decrease, which is also decided by the inversion population of EDFA, in which case the pump power is increased, the output power increases , which can slow down the gain reduction of the rear end . The relationship between the pump power and the signal output power is shown in Figure 2.

It can be seen from the figure that the amplifier is in the state of small signal amplification when the pump power is small, in which case the signal output power is almost constant. As the pump power increases, the signal output power increases, but the speed for EDFA to enter into saturation also increases, until the pump power increases to a certain value, it can be seen that the output power of the signal is into saturation, which is a fixed value that does not change with the increase of the pump power.

The transient effect caused by gain recovery time

Analysis on the change of EDFA inversion population should be done before the analysis on gain recovery time. Assuming that the input pump is uniform, and the signal light is pulse signal, the pump rate R_{13} , the stimulated emission rate W_{21} and the spontaneous emission rate W_{12} can be taken as constants, it can be obtained by the transient rate equation:

$$\frac{d}{dt}\begin{bmatrix}N_1\\N_2\end{bmatrix}=\begin{bmatrix}a_{11}&a_{12}\\a_{21}&a_{22}\end{bmatrix}\begin{bmatrix}N_1\\N_2\end{bmatrix}+\begin{pmatrix}1\\1\end{pmatrix}N_t \tag{15}$$

Where, $a_{11}=-(R_{13}+R_{31}+W_{12});\ a_{12}=W_{21}+A_{21}-R_{31};$ (16)

$$a_{22}=-(W_{21}+A_{21}+A_{32}) \tag{17}$$

$$a_{21}=W_{12}-A_{32}; \tag{18}$$

The eigenvalue of the solvable equations is : $\lambda_{1,2}=\frac{1}{2}\left[(a_{11}+a_{22})\pm\sqrt{(a_{11}+a_{22})^2-4(a_{11}a_{22}-a_{12}a_{21})}\right]$, then the form of the solution is that ： $N_i(t)=A_i e^{-t/t_1}+B_i e^{-t/t_2}+C_i$, where $t_1=-1/\lambda_1$, $t_2=-1/\lambda_2$ are time constant, A_i, B_i, C_i is the function about R_{13} , W_{21} , W_{12} [7], which can be brought into the function to solve the population of each level, Characteristic time constant can also be calculated : $t_1=\frac{\tau_{21}}{1+P_p+P_s}$, $t_2=\frac{\tau_{21}}{1+P_p}$;

（$\tau_{21}=1/A_{21}$ is the lifetime of the particles in the upper level). The lifetime of the particles in the excited state is much smaller than the one in metastable state, so it is ignored here. Then it can be obtained that: $N_2(t)=1-N_1(t)$, and the inversion population is $\Delta N(t)=N_2(t)-N_1(t)$,as is shown in figure 3：

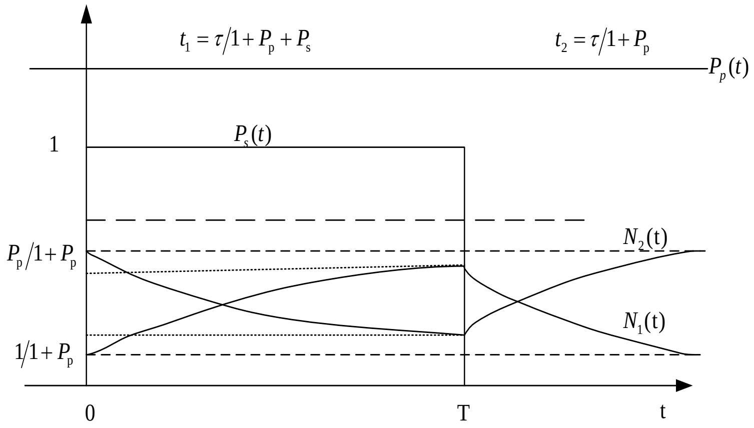

Fig 3 the diagram of the inversion population change

Assuming that the signal light is square wave pulse whose width is T, it can be seen from the diagram above that the signal light makes the population N_1 in lower levels increased, and the one in higher levels N_2 decreased, but for the case of pump light, it is just the opposite ,which makes N_1 decreased, and N_2 increased[8]. Under the interaction of the pump and signal light ,in the transmission paragraph of the signal, the inversion population is reduced due to saturation ,the saturation time $t_{sat} = \frac{\tau_{21}}{1+P_p+P_s}$ decreases with the increase of the signal power and the pump power. In the empty number segment of the signal, signal light power recover to 0, which do not consume the inversion population, and $\Delta N(t)$ begins to recover ,with the recovery time $t_{rec} = \frac{\tau_{21}}{1+P_p}$, and the ratio between recovery time and saturation time is $\frac{t_{rec}}{t_{sat}} = \frac{1+p_p+p_s}{1+p_p} > 1$, so the recovery time is always larger than the saturation time[9] . Therefore the frontier edge of the signal light pulse consume the inversion population, which may be insufficient because there is not enough time to replenish when the trailing edge comes, leading to the reduction of the trailing edge gain ,and a great distortion of the output waveform. Figure 4 shows the distortion waveform for a low frequency signal passing through the EDFA.

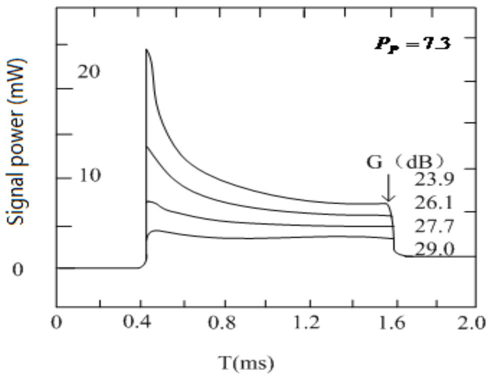

Fig 4 The distortion waveform for a low frequency signal

The figure above shows that there will be an amplification distortion when a square wave signal pulse of lower frequency passes through the EDFA system. It can be seen that the waveform of the signal light pulse will be deformed in the process of transmission through the EDFA system and amplification. This is because that in the transmission process, the signal has been consuming the particles in the upper levels , leading to that the inversion population is a variable that changes with time , finally resulting in that the frontier edge gain of the square wave pulse is higher than the trailing edge gain [10] . The size of the signal modulation frequency has some impact on the inversion population changes, and therefore it can be drawn that the modulation frequency of the signal light is related with the deformation of the pulse. In the case of the recovery time of EDFA gain, it can be analyzed by the change of EDFA output power in Figure 5.

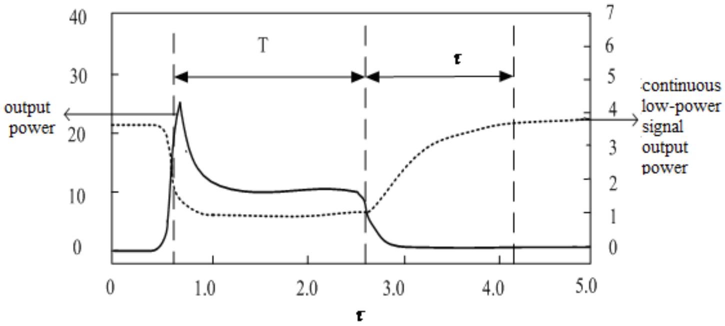

Fig 5 the output power changes of EDFA

The dotted line (continuous low-power signal light) indicates that when the input signal is not coupled with the optical pulse , EDFA is in the steady state , the continuous signal light output power is constant, when coupled with the input signal pulse of larger power, EDFA starts to be in the state of gain saturation , continuous signal output power decreases along. When the input pulse is over, the complementary carriers increase, the gain starts to slowly return to the initial value, which is the small signal gain of no saturation, and the output power is gradually return to stability. The solid line indicates that at the beginning of the entrance of the signal light, the gain is not saturated , the signal output power is high , the gain factor is large, then with the consumption of the inversion population by the input pulse, although by pump supplement, but the inversion population is not enough to compensate for the lost particles used for amplification before, leading to that the number of particles on the upper level decreases, the gain saturation occurs , the output power decreases until the pulse width $\tau = T$, the input pulse transmission of number is over, the output power is reduced to zero. Gain recovery time is the duration from the minimum gain value of the pulse end ($\tau = T_s$) to the value when the gain has been restored to the steady state.

We conclude that if the time constant t_{rec} is much smaller than the signal modulation cycle (modulation T>>t_{rec}), that is the signal symbol rate is low , the signal is low-speed long-pulse signal , the EDFA inversion population change is small, resulting in a weak graphic effects .

When the time constant t_{rec} is much larger than the signal modulation cycle (modulating T<<t_{rec}), that is the signal symbol rate is higher, for this narrow pulse signal , EDFA do not appear graphical effects basically.

When the time constant t_{rec} is several times of the period of the modulation signal （t_{rec}~T）, the frontier pulse waveform will be distorted and along comes the latter pulse , then the gain is not stabilized , the particles have not been pumped transitions , the gain of the latter pulse is 0 , as time increases , the gain slowly return . A larger effect of graphics generated at this time. The figure of waveform distortion should be as follows [2] Figure 6.

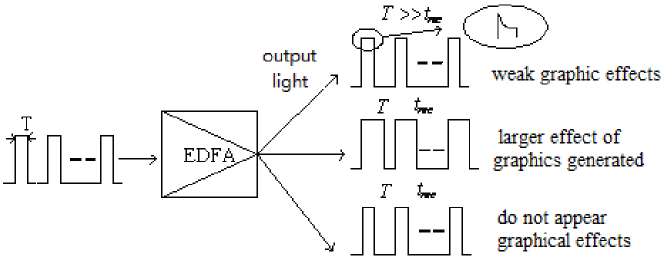

Fig 6 The figure of waveform distortion of EDFA signal for different pulse width

Conclusion

Due to the analysis above, the article determined the relationship between the signal output power, pump power and signal power. Based on the theoretical study and simulation, the article draws the following conclusions: When the pump power is fixed, as the input signal power increases, the gain recovery time increases, the saturation time slightly decreases. When the input signal power is fixed, with the increase of pump power, the gain recovery time and saturation time decreases. Modulation signal pulse width has an effect on the EDFA transient effect, only when the pulse width T and the gain recovery time is a particular value, the distortion is obvious. When t_{rec}>>T, it results hardly any graphic effect; when t_{rec}<<T, it results a weak graphic effects.

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