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Pulse amplification characteristics of multimode fiber amplifier

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ABSTRACT

Under small signal situation, the analytical expression for describing the output signal emitted from an Yb^{3+}-doped fiber amplifier with a Gaussian input pulse signal is deduced, by full considering both fiber guided modes' propagation constant and filling factor, which depend on the signal frequency. Pumped by continue wave (CW) source, the analytical expressions of the small signal gain and each guided mode's output power are obtained. Based on these analytical expressions, the various intensity distributions of output pulses amplified by the fiber amplifier with different Gaussian input pulse widths are analyzed.

1. Introduction

Fiber amplifiers are used to amplify not only the CW signal, but also pulse or pulse trains in most applications [1,2,3,4]. Due to the light that support for pulse amplification has certain line width, in recent years, a large amount of research has been done in the frequency characteristic of fiber amplifiers [5,6].

However, so far almost all the researches are focused on the analysis and discussed the effect of the main factor, i.e., the dispersion, on the pulse transmission in the amplifier [7,8]. But for waveguide devices, in fact, not only the propagation constant β depends on the light frequency, but also the field distribution does. This indicates that the filling factor Γ for describing the signal in the fiber core also depends on the frequency. That is to say, when a pulse is propagating in a waveguide device, the spectra with different frequencies may have different gains.

For single transverse mode fiber amplifier, pulse profile distortion is almost induced by dispersion, and that by Γ is relatively small. In order to stand out the effect of Γ on the pulse profile, the change of gain G due to the signal frequency is neglected. Under this assumption, we deduce that the analytical expression described the effect of Γ on the pulse profile, and then investigate the pulse profile distortion based on the analytical result.

For multi transverse mode fiber amplifier, the pulse propagates in the fiber in the form of two or more transverse modes depending on the fiber parameters as well as signal wavelength. In this case, each transverse mode contains above situation. However, as each transverse mode has different propagation velocity in the fiber, it will arrive at the fiber output end with different time. This phenomenon would induce pulse spread and is called as the modal dispersion. All the effects of these factors on the pulse would make the pulse propagation in a fiber much more complicate. In order to understand such situation more intuitive, we show the various output pulse profiles emitted from a multimode fiber amplifier with different pulse widths Gaussian input pulses.

2. Theoretical analysis

Assume that the transverse and temporal distribution of a single pulse injected into a fiber amplifier for amplifying are both Gaussian profile, then the expression for describing the pulse in the input fiber end is written as

$$E_{\text{in}}(0, r, t) = A_{\text{in}} \exp\left(-\frac{r^2}{2w_0^2}\right) \exp\left(-\frac{t^2}{2T_0^2}\right) \tag{1}$$

where w_0 is the beam width of the input pulse in the transverse distribution, T_0 represents the input pulse width, and A_{in} is the input pulse amplitude. As the input pulse in the transverse distribution is Gaussian profile, i.e., round symmetric distribution, the input pulse will be propagated and amplified in the form of LP_{0n} in the fiber amplifier [9]. The input pulse is thus given by

$$E_{\text{in}}(0, r, t) = \sum_n A_n F_n(r) \exp\left(-\frac{t^2}{2T_0^2}\right) \tag{2}$$

where $F_n(r)$ are LP_{0n} modes' transverse field distributions and are normalized in intensity, A_n are LP_{0n} modes' amplitudes. The

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expression of the input pulse in the frequency domain can be obtained by using Fourier transform, and is given below

$$\tilde{E}_{in}(0, r, \omega-\omega_0) = 1/\sqrt{2\pi}\sum_n A_n F_n(r)\int_{-\infty}^{\infty}\exp\left(-\frac{t^2}{2T_0^2}\right)\exp[i(\omega-\omega_0)t]dt$$
$$= \sum_n A_n F_n(r) T_0 \exp[-T_0^2(\omega-\omega_0)^2/2] \quad (3)$$

After propagating and amplifying in a fiber amplifier with a length of L, the expression of the output pulse in the frequency domain is given by

$$\tilde{E}_{in}(L, r, \omega-\omega_0) = \sum_n A_n F_n(r) T_0 \exp[(\Gamma_n G - \alpha_s L)/2 - i\beta_n L] T_0 \exp[-T_0^2(\omega-\omega_0)^2/2] \quad (4)$$

where β_n are LP_{0n} modes' propagation constants, α_s is the loss coefficient of signal radiation, Γ_n describes the power filling factors of the LP_{0n} modes radiations, which are calculated by the following equation:

$$\Gamma_n = \frac{P_{core}}{P_{total}} = \frac{\int_0^a [J_0(U_n r/a)/J_0(U_n)]^2 r dr}{\int_0^a [J_0(U_n r/a)/J_0(U_n)]^2 r dr + \int_a^\infty [K_0(W_n r/a)/K_0(W_n)]^2 r dr} \quad (5)$$

In Eq. (5), J_0 and K_0 are the zero order first kind and second kind of Bessel function, respectively, a is the fiber core radius, P_{core} is the power that propagates in the fiber core area, P_{total} is the total power that propagates in the fiber, U_n and W_n represent the normalized transverse propagation constants of LP_{0n} modes in the fiber core and cladding area, respectively.

The gain G is defined as

$$G = \int_0^L [\sigma_{ts} N_2(z) - \sigma_{as} N] dz \quad (6)$$

In Eq. (6), $N_2(z)$ is the upper population density function, N is the total Yb^{3+}-doped population density, $\sigma_{ts} = \sigma_{as} + \sigma_{es}$, σ_{as} and σ_{es} are the emission and absorption cross sections of signal radiation, respectively.

Using Fourier inverse transform in Eq. (4), we can obtain the following expression of output pulse in time domain

$$E_{out}(L, r, t) = 1/\sqrt{2\pi}\sum_n A_n F_n(r) T_0 \int_{-\infty}^{\infty}\exp[-T_0^2(\omega-\omega_0)^2/2] \exp[(\Gamma_n G - \alpha_s L)/2 + i\beta_n L]\exp[-i(\omega-\omega_0)t]d\omega \quad (7)$$

In order to analyze and investigate the effect of Γ_n on pulse in focus, we neglect the dependence of G on frequency and assume in the small signal situation, i.e., consider G as a constant value (G_0). Then, we write Γ_n and β_n through Taylor series expansion

$$\Gamma_n = \Gamma_{n\_0} + \sum_{q=1}^{\infty}\Gamma_{n\_q}(\omega-\omega_0)^q/q! \quad (8)$$

$$\beta_n = \beta_{n\_0} + \sum_{q=1}^{\infty}\beta_{n\_q}(\omega-\omega_0)^q/q! \quad (9)$$

where Γ_{n_0} and β_{n_0} are the filling factor and propagation constant in the central frequency located at ω_0, respectively. And

$$\Gamma_{n\_q} = d^q\Gamma_n/d\omega^q|_{\omega=\omega_0} \quad (10)$$

$$\beta_{n\_q} = d^q\beta_n/d\omega^q|_{\omega=\omega_0} \quad (11)$$

Assume that the pulse spectrum width is not very broad and the fiber length is not very long, then we can neglect the higher order terms and only hold the first term in the Taylor series of Eqs. (8) and (9), and rewrite them as

$$\Gamma_n = \Gamma_{n\_0} + \Gamma_{n\_1}(\omega-\omega_0) \quad (12)$$

$$\beta_n = \beta_{n\_0} + \beta_{n\_1}(\omega-\omega_0) \quad (13)$$

Substituting Eqs. (12) and (13) into Eq. (7), we get the following pulse expression at the fiber amplifier output end

$$E_{out}(L, r, t) = \sum_n A_n F_n(r)\exp[(\Gamma_{n\_0}G_0 - \alpha_s L)/2 + \xi_n^2/2T_0^2 - T_n^2/2T_0^2]\exp[i\phi_n(t)] \quad (14)$$

where

$$\phi_n(t) = \beta_{n\_0}L - \xi_n T_n/T_0^2 \quad (15)$$

and

$$\xi_n = \Gamma_{n\_1}G_0/2 \quad (16)$$

$$T_n = t - \beta_{n\_1}L \quad (17)$$

And the pulse intensity distribution at the fiber amplifier output end is given by

$$I_{out}(L, r, t) = \sum_n |A_n F_n(r)|^2\exp[\Gamma_{n\_0}G_0 - \alpha_s L + \xi_n^2/T_0^2 - T_n^2/T_0^2] \quad (18)$$

Given the fiber parameters, pump power and the initial signal power, in Eq. (14), the unknown quantity is just only the small signal gain G_0. The solving process of G_0 and amplified signal power is provided in detail in the next section.

3. Analytic solution of pulse amplification process

Using a forward end pumped Yb^{3+}-doped fiber amplifier to amplifier a pulse input signal, then the rate equations for describing this pulse amplification process are written as

$$\frac{\partial N_2(z,t)}{\partial t} = -[\sigma_{ts}N_2(z,t) - \sigma_{as}N]\frac{P_n(z,t)}{h\nu_s A} - [\sigma_{tp}N_2(z,t) - \sigma_{ap}N]\frac{P_p(z,t)}{h\nu_p A} - \frac{N_2(z,t)}{\tau} \quad (19)$$

$$N = N_1 + N_2 \quad (20)$$

$$\frac{\partial P_p(z,t)}{\partial t} + v_{gp}\frac{\partial P_p(z,t)}{\partial z} = \Gamma_p v_{gp}[\sigma_{tp}N_2(z,t) - \sigma_{ap}N]P_p(z,t) - \alpha_p v_{gp}P_p(z,t) \quad (21)$$

$$\frac{\partial P_n(z,t)}{\partial t} + v_{gs}\frac{\partial P_n(z,t)}{\partial z} = \Gamma_n v_{gs}[\sigma_{ts}N_2(z,t) - \sigma_{as}N]P_n(z,t) - \alpha_s v_{gs}P_n(z,t) \quad (22)$$