Numerical analysis of polarization character in Yb^{3+}-doped fiber amplifiers

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Polarization-dependent gain (PDG) and state of polarization (SOP) of the output signal light in Yb^{3+}-doped fiber amplifiers are studied by numerically stimulation, which showed that PDG of output signal light is not only changed with the input pump power and signal power, input polarization of pump and signal light, but also changed with the doping concentration, the cross-section anisotropy, the fiber length, the phase difference of the fiber, and so on. Moreover, SOP of the output signal light is studied. It is found that the polarization of output signal light is relative not only to the phase difference of the fiber, polarization of pump and signal light as the non-doped fiber, but also to PDG of output signal light, the cross-section anisotropy, the doping concentration, and so on, which is different to the non-doped fiber.

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Polarization hole burning (PHB) in rare-earth-doped glasses is a subject of longstanding interest. Some effects[1−7] have been made to understand the mechanism of polarization-dependent gain (PDG) and evaluate its impairment on the performance of long-haul optical amplified systems. The numerical modeling of the polarization properties of erbium-doped fiber amplifier (EDFA) was firstly performed by Wysocki[1], who partitioned the randomly orientated dipoles into a finite number of classes with different orientations. However, this approximation seems to converge rather slowly and requires a large number of classes to be taken into account. Wang[2] established a computing model that considers the anisotropy of the stimulated emission cross section and the absorption cross section, which explained much problems in a simple way, but it failed to explain the influence of the phase difference of the fiber on PDG of output signal light. Moreover, in order to obtain maximum coherent detection signals, the polarization of the signal of the local oscillator must be the same. It is, thus, necessary to control the output polarization of the fiber amplifier. Some effects[9−10] have been made to study the mechanism of state of polarization (SOP) of non-doped fiber, but few work studied the SOP of doped fiber theoretically.

In this paper we analyzed PDG and SOP output signal light in Yb^{3+}-doped fiber amplifiers with the theory of Leners[3], and numerically stimulated PDG of output signal light changing with the doping concentration, the cross-section anisotropy, the fiber length, the phase difference of the fiber and SOP of output signal light changing with the signal cross section anisotropy.

The gains $G_{//}$ and $G_{\perp}$ for two probes with the parallel and perpendicular SOP's relative to the output signal are given by[3]

$$G_{//}=\int_0^L \mathrm{d}z g_{//}=N\Gamma_s\sigma_s\int_0^L \mathrm{d}z(D_0-d_s)+N\Gamma_s\sigma_s\frac{1-\beta_s}{1+\beta_s}\times\int_0^L \mathrm{d}z[s_{1s}D_1+(s_{2s}\cos\phi_s+s_{3s}\sin\phi_s)D_2], \quad (1)$$

$$G_{\perp}=\int_0^L \mathrm{d}z g_{\perp}=N\Gamma_s\sigma_s\int_0^L \mathrm{d}z(D_0-d_s)+N\Gamma_s\sigma_s\frac{1-\beta_s}{1+\beta_s}\times\int_0^L \mathrm{d}z[s_{1s}D_1+(s_{2s}\cos\phi_s+s_{3s}\sin\phi_s)D_2], \quad (2)$$

where N is the doping concentration, Γ_s is signal transverse overlap integral, σ_s is emission cross-section of signal, the phase difference $\phi_s=(k_{sx}-k_{sy})z$, β_s is signal cross-section anisotropy, $D(z,t,\alpha)=D_0(z,t)+2D_1(z,t)\cos(2\alpha)+2D_2(z,t)\sin(2\alpha)$ is longitudinal variation of the average population inversion, α is the orientation of the cross-section ellipse with respect to the birefringence axes x and y, s_{1s}, s_{2s} and s_{3s} are three Stokes parameters.

We use Eqs. (1) and (2) to analyze PDG of the output signal light, the simulation parameters as follows: pump wavelength 975 nm, signal wavelength 1030 nm, the data of the emission and the absorption cross section of Yb^{3+}-doped fiber was used as that in Ref. [11], fluorescence lifetime of τ is 0.8 ms, the Yb^{3+} ion concentration, $N=10\times10^{24}$ m^{-3}. $\Gamma_s=0.6$, $\Gamma_p=0.6$, the fiber length was 8 m, the pump power 20 mW, the signal power 0.1 mW, the signal cross-section anisotropy 0.5, the pump cross-section anisotropy 0.9, the mode area 7 $\mu\mathrm{m}^2$, the beat length of the fiber for the wavelength of signal and pump light respectively, 1030 and 975 nm were 0.77 and 0.49 m.

From Figs. 1 and 2, we can find that PDG deceases with the increasing of the signal cross section anisotropy, and increases with the increasing of the pump cross section anisotropy. This result agreed with the measured data[7]. Figure 3 showed that PDG oscillate around a certain value, the reason is that PDG is the function of the triangle of the signal phase difference which has a cyclicity. And from Fig. 4 we can find that with the increasing of the doping concentration, PDG increases and saturates at the beginning of a value. The reason is with the increasing of the doping concentration, the fiber gain of the output signal of perpendicular and parallel SOP's to the input signal will saturate, so the PDG will saturate in the same way. PDG changed with the fiber length as seen in Fig. 5. From the figure, we can find the gain of the output signal of perpendicular and parallel SOP's to the input signal increase with the fiber length and saturate at a value, but they have a more difference at the beginning of 3 m. It can be estimated to be caused by the common effect of signal and pump power more apparently, because around this value, the signal and pump power become more similar value. PDG changing with the signal power and pump power was already discussed in Refs. [1 – 3], here, we will not discuss it.

Figure 6 shows the diagram of polarization azimuth orientation relative to the standard frame of reference, in which Ψ is the arc tangent of the ellipticity, ϕ is the angle of two revolution coordinate.

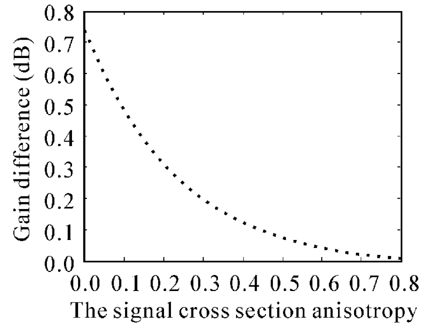

Fig. 1. PDG of output signal changed with the signal cross section anisotropy.

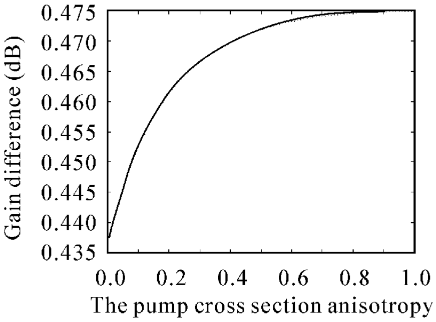

Fig. 2. PDG of output signal changed with the pump cross section anisotropy.

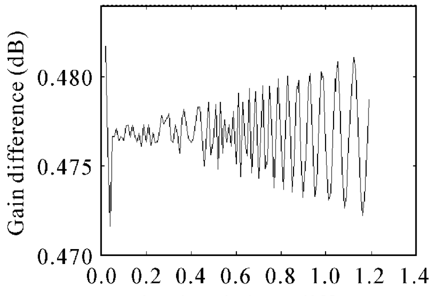

Fig. 3. PDG of output signal changed with the signal phase difference.

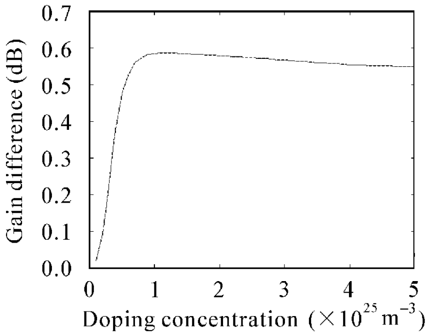

Fig. 4. PGD of output signal changed with the doping concentration.

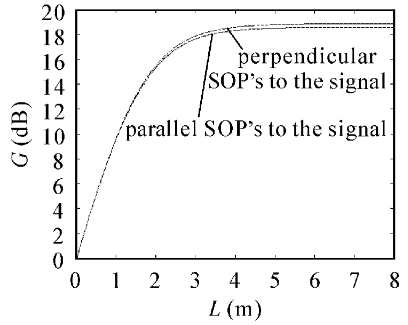

Fig. 5. The output signal of perpendicular and parallel SOP's to the input signal changed with the fiber length.

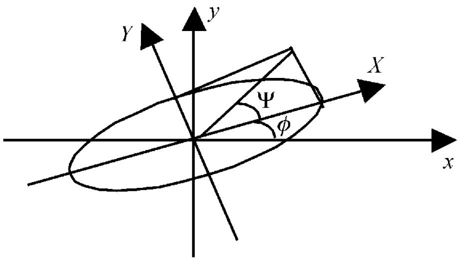

Fig. 6. The diagram of polarization azimuth orientation relative to the standard frame of reference.

The vector of signal normalized envelopes is

$$E = \begin{pmatrix} \cos\theta \\ \sin\theta e^{i\Delta} \end{pmatrix}, \tag{3}$$

where θ is the angle between the standard frame of reference and the field vector, Δ is the phase difference of the field component.

$$\tan(2\phi) = \tan(2\theta)\cos\Delta, \tag{4}$$

$$\sin(2\Psi) = \sin(2\theta)\sin\Delta, \tag{5}$$

here $\Delta = \pi/4 + \varphi_s$, $\tan\theta = G_{\perp}/G_{//}$.

Using the value of the Ψ and ϕ, we can describe more polarization parameter, for example: the Stokes vector, ellipticity, the extinction ratio and so on. Here we only simulate the value of the Ψ and ϕ changed with the signal cross-section anisotropy.

From Figs. 7 and 8, we can find that with the increasing of the signal cross section anisotropy, the φ and Ψ value will increase, the reason is the fiber will have more high polarization degree with the increasing of the signal cross section anisotropy. Of course, the value of φ and Ψ will also change with the signal and pump power, doping concentration, fiber length, the phase difference of the fiber, and so on.

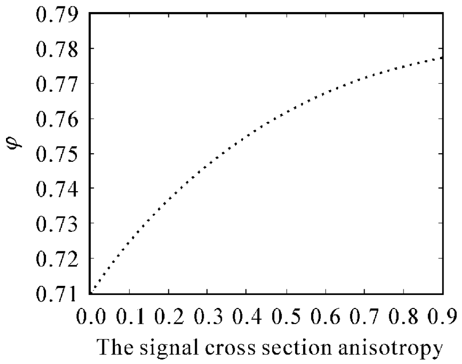

Fig. 7. φ changed with the signal cross section anisotropy.

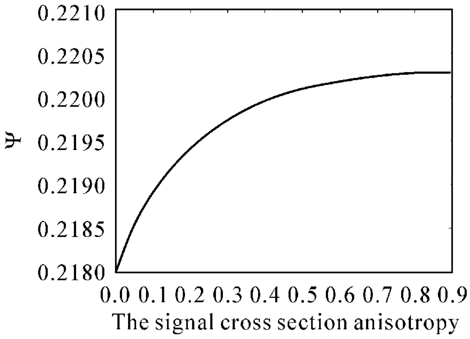

Fig. 8. Ψ changed with the signal cross section anisotropy.

In conclusion, we have numerically simulate the relative character of PDG and SOP of the output signal light in Yb^{3+}-doped fiber amplifiers, and make a relative discuss. It will be helpful to study the Yb^{3+}-doped fiber amplifiers.

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