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Group velocity control in Dy^{3+}-doped fiber Bragg grating

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ABSTRACT

In this paper, we propose to use a pump to decrease or increase the group velocity of a probing pulse in fiber Bragg gratings (FBG) with different grating parameters written into an Dy^{3+} doped optical fiber based on the facts of the observations that pump-induced changes on the refractive index and dispersion associated with the $^6H_{15/2}$–$^6F_{11/2}$ transition in Dy^{3+} doped optical fiber. We discuss the effects of pump power, fiber grating length and doping concentration on the group velocity control.

1. Introduction

Slow and fast light (SFL) is becoming a wide research field driven by an extensive effort to implement this new technology in real applications [1]. Potential applications include all optical communication networks [2], and optical sensing [3,4]. A range of techniques developed in the past decade have made possible to reduce the group velocity of a wavepacket to a few meters per second, and at the same time to obtain group velocities greater than c, or even negative, in a controllable way. The techniques to slow down the light speed include electromagnetic induced transparency (EIT) [5,6], stimulated Brillouin scattering (SBS) [7], stimulated Raman scattering (SRS) [8], wavelength conversion and dispersion [9], and coherent population oscillations (CPO) [10,11]. To propagate the superluminal pulses of light ($v_g > c$), one needs to prepare a medium in which the refractive index changes rapidly in anomalous dispersive regions [12,13]. Some media with a barrier, such as waveguides and fiber Bragg grating (FBG), are just suit for being chosen as the media to perform experiments on superluminal tunneling [14–16].

In Ref. [16], Longhi et al. introduced fiber Bragg grating as a medium exhibiting superluminal group velocities, where the relatively large ratio between the thickness of the barrier (2 cm) and the wavelength of probing optical pulses ensured the direct measurements for the superluminal tunneling in the optical region. A tunneling with the group velocity equal to 1.97 times the speed of light in vacuum is observed. However, the value of group velocity they observed is limited by the peak power reflectivity R at the barrier center. Although the group velocity tends to infinity as R approaches unity, the approximate zero transmission ($T = 1 - R$) will lead to the light pulse strongly absorbed or distorted. Here we propose to use a pump in a FBG written into a Dy^{3+} doped optical fiber to increase the group velocity of a probing pulse instead of enlarging the peak power reflectivity since there are experiments indicating that pump-induced changes the refractive index and dispersion associated with the $^6H_{15/2}$–$^6F_{11/2}$ transition in Dy^{3+} doped optical fiber [17].

2. Theory model

2.1. Pump-induced complex susceptibility of Dy^{3+} doped optical fiber

In the unsaturated regime, the imaginary part of the complex susceptibility of Dy^{3+} originating from optical transitions between $^6H_{15/2}$ states and $^6F_{11/2}$ states can be derived as follows [17,18]:

$$\chi''(\lambda, z) = -n\frac{\lambda}{\pi}[N_2(z)\sigma_e(\lambda) - N_1(z)\sigma_a(\lambda)] \tag{1}$$

where n is the refractive index of the material, $\sigma_e(\lambda)$ and $\sigma_a(\lambda)$ are the emission cross section and absorption cross section at room temperature, which are function of wavelength λ, according to Ladenburg–Fuchtbauer [11], $N_1(z)$ and $N_2(z)$ are the average populations of the energy level $^6H_{15/2}$ and $^6F_{11/2}$ energy level at the position z [17,19]:

$$N_1(z) = \frac{N}{1 + ((P_{\rm pump}(z))/P_{\rm th})} \tag{2}$$

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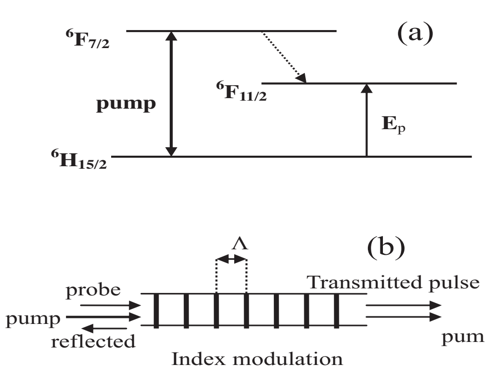

Fig. 1. (a) A simplified three-level system corresponding to Dy^{3+} ions doped in a fiber, Dy^{3+}-ions are pumped at a wavelength of 1240 nm, and the $^6F_{11/2}$ state is populated via a fast decay from $^6F_{7/2}$ state. A probe field E_p at a wavelength in the range 1300–1320 nm interacts with the $^6H_{15/2}$–$^6F_{11/2}$ transitions. (b) A FBG written into an Dy^{3+} doped fiber and its refractive index is modulated periodically.

$$N_2(z) = \frac{P_{\text{pump}}(z)}{P_{\text{th}}} \frac{N}{1 + ((P_{\text{pump}}(z))/P_{\text{th}})} \tag{3}$$

where N is the doping concentration, $P_{\text{pump}}(z)$ is the pump power at z, and P_{th} is a threshold pump power.

The real part of the complex susceptibility induced by pumps expresses as:

$$\begin{aligned} \chi'(\lambda, z) &= [N_2(z) - N_1(z)] \frac{\lambda^3}{16\pi^2 n \tau_2} g_{12}(\nu - \nu_{12}) g_{12}(\nu - \nu_{12}) \\ &= \frac{1}{\pi} \frac{\nu - \nu_{12}}{(\Gamma_{12}/2) + (\nu - \nu_{12})^2} \end{aligned} \tag{4}$$

where Γ_{12} is the full width half maximum of the transition.

2.2. *Group delay of the tunneling pulse in Dy^{3+}-doped fiber Bragg grating controlled by pump*

We consider a simplified three-level system corresponding to Dy^{3+} ions doped in a fiber shown as Fig. 1(a). In this system, Dy^{3+} ions are pumped at a wavelength of 1240 nm, and the $^6F_{11/2}$ state is populated via a fast decay from $^6F_{7/2}$ state. A probe field E_p at a wavelength in the range 1300–1320 nm interacts with the $^6H_{15/2}$–$^6F_{11/2}$ transition. To the uniform Dy^{3+} doped fibers, the complex susceptibility $\chi = \chi' + i\chi''$ for the medium can be derived as discussed in part A. Here Dy^{3+} doped fiber is written into a FBG as shown in Fig. 1(b) and its modulated periodically as:

$$n(z) = n_0 \left[1 + 2h \cos\left(\frac{2\pi z}{\Lambda + \varphi} \right) \right], \quad 0 < z < L$$

where z is the propagation axis, L is the grating length, n_0 is the average refractive index of the structure, Λ is Bragg modulation period, and $h \ll <1$, φ are the slowly-varying amplitude and phase of the refractive index modulation. This three-level system is similar to Ref. [20]. Therefore, we get the spectral transmission coefficient t of the grating and the group delay τ_g of the grating expresses as:

$$t = \frac{1}{\cosh(\gamma L) - i(g/r)\sinh(\gamma L)} \tag{5}$$

$$\tau_g = \frac{n_0 L}{c_0} \frac{|q|^2}{\gamma^2 + g^2 \tanh^2(\gamma L)} \left[\frac{g^2}{|q|^2} \tanh^2(\gamma L) + \frac{1}{\gamma L} \tanh(\gamma L) - \frac{g^2}{|q|^2} \right] \tag{6}$$

where $\gamma = \sqrt{|q|^2 - g^2}$, $q = k_B h e^{i\varphi}$, $g = (\delta + g_r) + i g_i$, $g_r = (\omega_p^2 / 2 k_B c^2)\chi'$, $g_i = (\omega_p^2 / 2 k_B c^2)\chi''$, $\delta = k_p - k_B = n_0(\omega_p - \omega_B)/c$, $k_p = \omega_p n_0 / c$, $c = (\mu_0 \varepsilon_0)^{-1/2}$, ε_0 and μ_0 are the permittivity and the permeability of free space, respectively. k_p and ω_p are the wave number and the frequency of the probe field. $\omega_B = c\pi/(n_0 \Lambda)$ is the Bragg frequency. A group velocity is given by $v_g = L/\tau_g$.

Table 1
Parameters used for slow and fast light propagation in system as show in Fig.1.

Parameter	Value
Pump wavelength, λ_{pump}	1240 nm
Probe wavelength, λ_{probe}	1300 nm
Refractive index of the medium, n	1.452
Peak value of the emission cross section, σ_e	1.7×10^{-24}
Peak value of the absorption cross section, σ_a	2.8×10^{-24}
Threshold pump power, P_{th}	50 mW
$^4I_{13/2}$ lifetime, τ_2	2000 μs
Transition angular frequency, ω_{21}	1.438×10^{15} Hz
Doped concentration, N_d	3.2×10^{25}
Pump power, P_{pump}	100.0 mW
BFG frequency, ω_B	$2\pi \times 172.3$ THz
Amplitude of refractive index moderation, h	1.5×10^{-4}
The length of BFG, L	2 cm

3. Results and discussion

In the following, we analyze the effects of doped concentration, fiber grating length, and pump power on group velocity of the tunneling pulse in the system. Where the parameters of Dy^{3+} doped fiber in Table 1 are chosen as Ref. [17].

3.1. *Fast light propagation*

The numerically calculated spectral dependences of effective v_g are presented in Fig. 2(a) for the FBG with $h = 1.5 \times 10^{-4}$, $N_d = 4.8 \times 10^{25}$, for $L = 1.5, 2.5, 3.5$ cm, the other parameters are used as shown in Table 1. The numerically calculated spectral dependences of the transmission coefficient T are given in Fig. 2(b) for the FBG with the same parameters. The gain saturation effects within the FBG stop-band wavelength range are expected to be less pronounced due to reduction of light-to-matter interaction, which is caused by higher group velocity at these wavelengths. As it follows from Fig. 2(a) and (b), for $L = 1.5$, 2.5 and 3.5 cm, the effective v_g exceeds the speed of light in vacuum at the center of FBG stop-band, while the transmission exceeds or is equal to unity. The strong rise of v_g near the edges of FBG transmission dip (stop band) was observed exactly at the positions of maximum amplification of the signal $L = 3.5$ cm.

Fig. 3(a) is the numerically calculated spectral dependences of effective v_g for the FBG with $h = 1.5 \times 10^{-4}$, $L = 3.5$ cm for $N_d = 1.6$, 3.2, 4.8×10^{25}, the other parameters are used as shown in Table 1. The numerically calculated spectral dependences of the transmission coefficient T are given in Fig. 3(b) for the FBG with the same parameters.

The group velocity increases with the Dy^{3+} doped concentration enlarging. When $N_d = 4.8 \times 10^{25}$ emerge two other peaks of the group velocity at both sides of the gap, which becomes higher for larger concentration and they must be the result of the resonant absorption, while the transmission exceeds or is equal to unity.

Fig. 4(a) shows the group velocity v_g versus frequency detuning for the FBG with $h = 1.5 \times 10^{-4}$ for three different pump power $P_{\text{pump}} = 50$ mW, 100 mW, 150 mW; the other parameters are used as shown in Table 1. The numerically calculated spectral dependences of the transmission coefficient T are given in Fig. 4(b) for the FBG with the same parameters. Large pump power little aids to get large group velocity for the tunneling pulse in the medium.