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Enhanced refractive index without absorption in optical fibers via an indirect incoherent pump field

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ABSTRACT

We demonstrate a scheme for realizing the refractive index with zero absorption in an Er^{3+}-doped ZrF_4–BaF_2–LaF_3–AlF_3–NaF optical fiber. It is found that the refraction index of the probe laser can be easily controlled via adjusting properly the parameters of the corresponding system. Our scheme may provide some new possibilities for technological applications in optical-fiber communication.

1. Introduction

It is well known that quantum coherence and interference can give rise to some interesting phenomena [1–6], such as electromagnetically induced transparency (EIT), four-wave mixing, ultraslow optical solitons and so on. Based on atomic coherence and quantum interference, many schemes have been proposed for refractive index enhancement without absorption in atomic media. For example, in 1991, Scully showed that one can use quantum interference to engineer enhanced indices of refraction with simultaneously vanishing absorption in a three-level system [7]. Harris proposed how to reduce the refractive index of a probe beam to unity in a far-off resonant system in an EIT-like manner [8], and later Scully and colleagues presented a proof-of-principle experiment demonstrating a resonant enhancement of the index of refraction accompanied by vanishing absorption in a cell containing a coherently prepared Rb vapor [9]. The results are in good agreement with detailed theoretical predictions [10,11]. In a recent paper, Yavuz demonstrated a scheme where a laser beam which is very far detuned from an atomic resonance experiences a large index of refraction with vanishing absorption [12]. Quite recently, he and his coworkers experimentally investigated an index-enhancement scheme in a two-photon Raman configuration in an atomic vapor, by utilizing the interference of two Raman

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resonances, they found that the refractive index of a laser beam that is very far detuned from an electronic resonance can be enhanced while maintaining vanishing absorption [13].

In this paper, we investigate the refractive index of a weak probe field in an Er^{3+}-doped ZrF_4–BaF_2–LaF_3–AlF_3–NaF optical fiber. Our work and system are mainly based on the Refs. [7–17], however our scheme is different from those works. First, the rare-earth-ion-dope optical-fiber system is much more practical than its atomic counterpart due to its flexible design and the wide adjustable parameters. Second, we only utilize a three-level system instead of a four-level system proposed by Wang et al. [16]. Therefore, our scheme is convenient for experimental realization. Third, index of refraction with vanishing absorption can be achieved by controlling the indirect incoherent pump field, and the switching from positive to negative refraction index with vanishing absorption can be achieved simply by adjusting the detuning of coherent field.

2. Model and equations

We consider a three-level Er^{3+} ionic system in an Er^{3+}-doped ZrF_4–BaF_2–LaF_3–AlF_3–NaF optical fiber as shown in Fig. 1. The experimental system for this scheme can be realized by the Er^{3+} ion with $|^4I_{15/2}\rangle$, $|^4I_{13/2}\rangle$, and $|^4I_{9/2}\rangle$ behaving the $|1\rangle, |2\rangle$, and $|3\rangle$ state labels, respectively. The transition $|3\rangle \leftrightarrow |2\rangle$ is mediated by a coherent coupling field E_c (frequency ω_c), while a incoherent pumping field (rate 2Λ) and a probe field E_p (frequency ω_p) are applied to the transitions $|3\rangle \leftrightarrow |1\rangle$ and $|2\rangle \leftrightarrow |1\rangle$, respectively. If we take the level $|1\rangle$ as the energy origin and choose $H_0 = (\omega_c + \omega_p)|3\rangle\langle 3| + \omega_p|2\rangle\langle 2|$, in the interaction picture and under the rotating-wave approximation, the interaction Hamiltonian of this system is given as follow

$$H_{int} = \Delta_p|2\rangle\langle 2| + (\Delta_c + \Delta_p)|3\rangle\langle 3| - (\Omega_c|3\rangle\langle 2| + \Omega_p|2\rangle\langle 1| + H.c.), \tag{1}$$

where $H.c.$ means Hermitian conjugation, $\Delta_p = \omega_{21} - \omega_p$ and $\Delta_c = \omega_{32} - \omega_c$ are the detunings of the probe field and coherent coupling field, respectively; $\Omega_c = \mu_{32}E_c/2\hbar$ and $\Omega_p = \mu_{21}E_p/2\hbar$ are the one-half Rabi frequencies for the respective transitions, respectively; ω_{21} and ω_{32} are resonant frequencies which associates with the corresponding optical transitions $|2\rangle \leftrightarrow |1\rangle$ and $|3\rangle \leftrightarrow |2\rangle$, respectively.

By adopting the standard approach, the density-matrix equations of motion in dipole and rotating-wave approximations for this system can be written as follows

$$\frac{\partial\rho_{22}}{\partial t} = i\Omega_c\rho_{32} - i\Omega_c\rho_{23} + i\Omega_p\rho_{12} - i\Omega_p\rho_{21} - \gamma_{21}\rho_{22} + \gamma_{32}\rho_{33},$$
$$\frac{\partial\rho_{33}}{\partial t} = i\Omega_c\rho_{23} - i\Omega_c\rho_{32} - (\gamma_{31} + \gamma_{32})\rho_{33} + 2\Lambda\rho_{11},$$

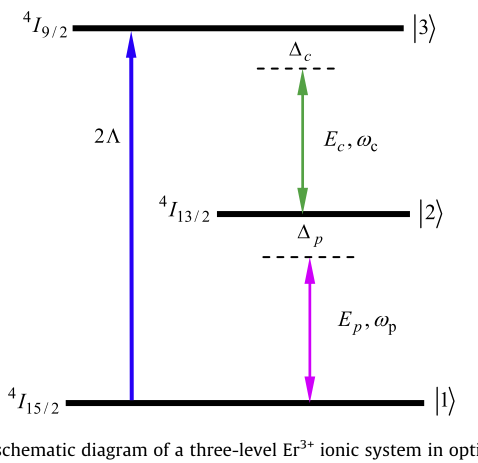

Fig. 1. A schematic diagram of a three-level Er^{3+} ionic system in optical fibers.