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High index of refraction via quantum interference in a three-level system of Er^{3+}-doped yttrium aluminium garnet crystal*

He Qiong-Yi(何琼毅)[b)c)], Wang Tie-Jun (王铁军)[b)c)], and Gao Jin-Yue(高锦岳)[a)b)c)†]

[a)] *CCAST (World Laboratory) Beijing*, 100080, *China*
[b)] *College of Physics, Jilin University, Changchun* 130023, *China*
[c)] *Key Laboratory of Coherent Light, Atomic and Molecular Spectroscopy, Educational Ministry of China, Changchun* 130023, *China*

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A simple three-level system is proposed to produce high index of refraction with zero absorption in an Er^{3+}-doped yttrium aluminium garnet (YAG) crystal, which is achieved for a probe field between the excited state $^4I_{13/2}$ and ground state $^4I_{15/2}$ by adjusting a strong coherent driving field between the upper excited state $^4I_{11/2}$ and $^4I_{15/2}$. It is found that the changes of the frequency of the coherent driving field and the concentration of Er^{3+} ions in the YAG crystal can maximize the index of refraction accompanied by vanishing absorption. This result could be useful for the dispersion compensation in fibre communication, laser particle acceleration, high precision magnetometry and so on.

Keywords: electromagnetically induced transparency, high index of refraction with zero absorption, Er^{3+}-doped yttrium aluminium garnet crystal
PACC: 4250, 4265, 3280

1. Introduction

It is well known that atomic coherence and quantum interference have led to many interesting optical phenomena, such as lasing without inversion (LWI)[1−6] and electromagnetically induced transparency (EIT)[7−15] and so on. The EIT is a modification to the absorption profile of an atomic transition when a strong laser field couples the upper or lower level coherently with a third one.

Under the appropriate circumstances, the absorption of a weak probe beam at a resonant frequency can then be substantially reduced. Recently, for an understanding of quantum coherence and interference in crystals and for various potential applications in device, the EIT in solid media has been studied extensively,[16−20] especially, an ultrahigh index of refraction with zero absorption induced by atomic coherence and quantum interference effects becomes more and more attractive.[21−26]

Recent observation of light amplification in rare-earth doped solids opens the door to practical applications in optical memories. Many researchers have studied the enhancement of the index of refraction accompanied by vanishing absorption in the Er^{3+}-doped YAG crystal, for example, Zhang *et al* [24,25] proposed a four-level system where a large index of refraction with zero absorption could be achieved by adjusting the incoherent pumping between levels $^4I_{11/2}$ and $^4I_{15/2}$, the coherent field between levels $^4I_{13/2}$ and $^4I_{9/2}$, as well as the concentration of Er^{3+} ions. Furthermore, the highest index of refraction can go up to $n = 9.93$, when the concentration of Er^{3+} ions in the crystal is 0.52 at%.

The purpose of the present paper is to give a simple three-level scheme in an Er^{3+}-doped YAG crystal. It is found that the absorption is completely cancelled and a high index of refraction can be achieved in the solid crystal by modifying the coherent field but not using the incoherent pump.

The maximum index of refraction can reach as high as $n = 15.23$ when the concentration of Er^{3+} ions in the crystal is 0.52 at%, which is the same as the concentration in the four-level system mentioned above. It is also found that the index of refraction with zero absorption can be raised up to a higher value under different detunings of coherent driving and probe fields, and different concentrations of the Er^{3+} ions in

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†Corresponding author. E-mail: jygao@mail.jlu.edu.cn

YAG crystals.

2. The model description

The simplified level of the Er^{3+}-doped YAG crystal is illustrated in Fig.1, where levels $|1\rangle$, $|2\rangle$, and $|3\rangle$ correspond to energy levels of $^4I_{15/2}$, $^4I_{13/2}$, and $^4I_{11/2}$ in Er^{3+} ions, respectively. The coherence in this system is established between levels $|3\rangle$ and $|1\rangle$ by a coherent driving field E_c with a Rabi frequency Ω_c. Simultaneously, level $|2\rangle$ is populated via fast phonon decay from level $|3\rangle$ to level $|2\rangle$, therefore the population inversion and the probe amplification between levels $|2\rangle$ and $|1\rangle$ can be realized. The probe field E_p with a Rabi frequency Ω_p interacts with the transition labelled by $|2\rangle \leftrightarrow |1\rangle$, which has a transition wavelength of 1550 nm. $\Gamma_3 = \Gamma_{31} + \Gamma_{32}$ is the spontaneous decay rate of level $|3\rangle$, and $\Gamma_2 = \Gamma_{21}$ is the spontaneous decay rate of level $|2\rangle$. When the Rabi frequency of the coherent driving field $\Omega_c = 0$, the system degenerates into a traditional two-level system, in which the absorption of the probe beam will be large when the index of refraction is large around the resonance.

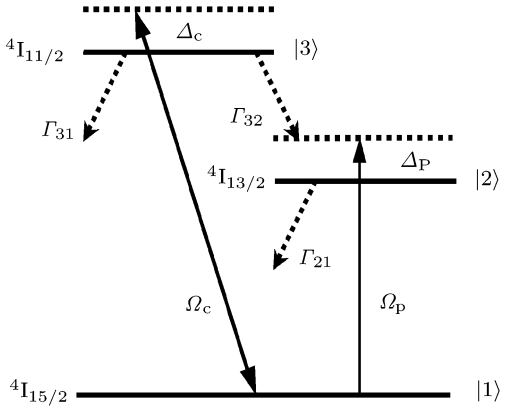


Fig.1. Schematic diagram of a three-level system where levels $|1\rangle$, $|2\rangle$ and $|3\rangle$ correspond to energy levels of Er^{3+} ions $^4I_{15/2}$, $^4I_{13/2}$, and $^4I_{11/2}$, respectively.

Based on the semiclassical theory, using the standard density matrix formalism in the dipole approximation and the rotating wave approximation, the interaction Hamiltonian H_I can be presented in the interaction picture by ($\hbar = 1$)

$$H_I = -\Delta_C|3\rangle\langle 3| - \Delta_P|2\rangle\langle 2| - (\Omega_C|3\rangle\langle 1| + \Omega_P|2\rangle\langle 1| + \text{c.c.}), \quad (1)$$

where

$$\Delta_p = \omega_p - \omega_{21},$$

and

$$\Delta_c = \omega_c - \omega_{31}$$

represent the detuning of the probe and the coherent fields, the Rabi frequencies Ω_p and Ω_c are defined as $\Omega_p = \mu_{21}E_p/2\,\hbar$, and $\Omega_c = \mu_{31}E_c/2\,\hbar$, respectively.

Then we obtain the density equations in the interaction picture on the assumption that $\Omega_p = \Omega_p^*$, and $\Omega_c = \Omega_c^*$

$$\begin{aligned}
\dot\rho_{11} &= \Gamma_{21}\rho_{22} + \Gamma_{31}\rho_{33} + \mathrm{i}\,\Omega_p(\rho_{21} - \rho_{12}) + \mathrm{i}\,\Omega_c(\rho_{31} - \rho_{13}),\\
\dot\rho_{22} &= -\Gamma_{21}\rho_{22} + \Gamma_{32}\rho_{33} + \mathrm{i}\,\Omega_p(\rho_{12} - \rho_{21}),\\
\dot\rho_{33} &= -\Gamma_{31}\rho_{33} - \Gamma_{32}\rho_{33} + \mathrm{i}\,\Omega_c(\rho_{13} - \rho_{31}),\\
\dot\rho_{12} &= (-\mathrm{i}\,\Delta_p - \gamma_{12})\rho_{12} + \mathrm{i}\,\Omega_p(\rho_{22} - \rho_{11}) + \mathrm{i}\,\Omega_c\rho_{32},\\
\dot\rho_{13} &= (-\mathrm{i}\,\Delta_c - \gamma_{13})\rho_{13} + \mathrm{i}\,\Omega_c(\rho_{33} - \rho_{11}) + \mathrm{i}\,\Omega_p\rho_{23},\\
\dot\rho_{23} &= (-\mathrm{i}\,\Delta_c + \mathrm{i}\,\Delta_p - \gamma_{23})\rho_{23} + \mathrm{i}\,\Omega_p\rho_{13} - \mathrm{i}\,\Omega_c\rho_{21},\\
\rho_{11} &+ \rho_{22} + \rho_{33} = 1,\\
\rho_{ij} &= \rho_{ji}^*, \qquad (2)
\end{aligned}$$

where Γ_{ij} is the population occupied spontaneously by damping from $|i\rangle$ to $|j\rangle$, while γ_{ij} refers to the coherence decay rate between $|i\rangle$ and $|j\rangle$ given by

$$\begin{aligned}
\gamma_{13} &= \gamma_{31} = \frac{1}{2}(\Gamma_{31} + \Gamma_{32} + \gamma_{31}^{\mathrm{dph}}),\\
\gamma_{23} &= \gamma_{32} = \frac{1}{2}(\Gamma_{31} + \Gamma_{32} + \Gamma_{21} + \gamma_{32}^{\mathrm{dph}}),\\
\gamma_{12} &= \gamma_{21} = \frac{1}{2}(\Gamma_{21} + \gamma_{21}^{\mathrm{dph}}), \qquad (3)
\end{aligned}$$

where $\gamma_{ij}^{\mathrm{dph}}$ is the dephasing rate of the quantum coherence of $|i\rangle \leftrightarrow |j\rangle$ transition. In contrast with many atomic schemes, $\gamma_{ij}^{\mathrm{dph}}$ determined by electron-electron, interface roughness, and phonon scattering processes, makes a dominant contribution to the γ_{ij} and the major obstacle to the observation of coherent effects such as EIT in solid materials.[20,24]

In order to evaluate the probe absorption spectrum, we write Eq.(2) in the form

$$\frac{\mathrm{d}\,\Psi}{\mathrm{d}t} = L\,\Psi + I, \qquad (4)$$

with

$$\psi = (\rho_{11}\,\rho_{12}\,\rho_{13}\,\rho_{21}\rho_{22}\,\rho_{23}\,\rho_{31}\,\rho_{32})^{\mathrm{T}}$$

and

$$I = (\Gamma_{31}\ \ 0\ \ \mathrm{i}\,\Omega_c\ \ 0\ \ \Gamma_{32}\ \ 0, -\mathrm{i}\,\Omega_c\ \ 0)^{\mathrm{T}}.$$

The matrix L has the form

$$L=\begin{pmatrix} -\Gamma_{31} & -\mathrm{i}\Omega_\mathrm{p} & -\mathrm{i}\Omega_\mathrm{c} & \mathrm{i}\Omega_\mathrm{p} & (\Gamma_{21}-\Gamma_{31}) & 0 & \mathrm{i}\Omega_\mathrm{c} & 0 \\ -\mathrm{i}\Omega_\mathrm{p} & L_{22} & 0 & 0 & \mathrm{i}\Omega_\mathrm{p} & 0 & 0 & \mathrm{i}\Omega_\mathrm{c} \\ -2\mathrm{i}\Omega_\mathrm{c} & 0 & L_{33} & 0 & -\mathrm{i}\Omega_\mathrm{c} & \mathrm{i}\Omega_\mathrm{p} & 0 & 0 \\ \mathrm{i}\Omega_\mathrm{p} & 0 & 0 & L_{44} & -\mathrm{i}\Omega_\mathrm{p} & -\mathrm{i}\Omega_\mathrm{c} & 0 & 0 \\ -\Gamma_{32} & \mathrm{i}\Omega_\mathrm{p} & 0 & -\mathrm{i}\Omega_\mathrm{p} & -(\Gamma_{31}+\Gamma_{21}) & 0 & 0 & 0 \\ 0 & 0 & \mathrm{i}\Omega_\mathrm{p} & -\mathrm{i}\Omega_\mathrm{c} & 0 & L_{66} & 0 & 0 \\ 2\mathrm{i}\Omega_\mathrm{c} & 0 & 0 & 0 & \Omega_\mathrm{c} & 0 & L_{77} & -\mathrm{i}\Omega_\mathrm{p} \\ 0 & \mathrm{i}\Omega_\mathrm{c} & 0 & 0 & 0 & 0 & -\mathrm{i}\Omega_\mathrm{p} & L_{88} \end{pmatrix}, \tag{5}$$

where $L_{22}=-(\mathrm{i}\Delta_\mathrm{p}+\gamma_{12})$, $L_{33}=-(\mathrm{i}\Delta_\mathrm{c}+\gamma_{13})$, $L_{44}=(\mathrm{i}\Delta_\mathrm{p}-\gamma_{13})$,

$$L_{66}=-(\mathrm{i}\Delta_\mathrm{c}-\mathrm{i}\Delta_\mathrm{p}+\gamma_{13}),\qquad L_{77}=(\mathrm{i}\Delta_\mathrm{c}-\gamma_{13}),\quad \text{and}\quad L_{88}=(\mathrm{i}\Delta_\mathrm{c}-\mathrm{i}\Delta_\mathrm{p}-\gamma_{13}).$$

Under the steady-state condition, the solutions of Eq.(2) for ρ_{12} to the first order and for other ρ_{ij} to the zero order of the probe field are

$$\rho_{22}=\frac{\Gamma_{32}A}{\Gamma_{21}(\Gamma_{31}+\Gamma_{32}+A)}\rho_{11},\qquad \rho_{33}=\frac{A}{\Gamma_{31}+\Gamma_{32}+A}\rho_{11},$$

$$\rho_{12}=\rho_{21}^{*}=\frac{\mathrm{i}\Omega_\mathrm{p}(\rho_{22}-\rho_{11})-\dfrac{\mathrm{i}|\Omega_\mathrm{c}|^2\Omega_\mathrm{p}(\rho_{11}-\rho_{33})}{[\gamma_{23}+\mathrm{i}(\Delta_\mathrm{p}-\Delta_\mathrm{c})](\mathrm{i}\Delta_\mathrm{c}-\gamma_{13})}}{\gamma_{12}+\mathrm{i}\Delta_\mathrm{p}+\dfrac{|\Omega_\mathrm{c}|^2}{\gamma_{23}+\mathrm{i}(\Delta_\mathrm{p}-\Delta_\mathrm{c})}}, \tag{6}$$

where $A=2|\Omega_\mathrm{c}|^2\gamma_{13}/(\gamma_{13}^2+\Delta_\mathrm{c}^2)$.

The absorption and the index of refraction are governed by the imaginary and real parts of the complex susceptibility of the probe field, which can be described as

$$\chi''=\mathrm{Im}\Big(\frac{2N\mu_{21}\rho_{12}}{\varepsilon_0 E_\mathrm{p}}\Big)=\mathrm{Im}\Big(\frac{N\mu_{21}^2\rho_{12}}{\varepsilon_0\Omega_\mathrm{p}\hbar}\Big),$$

$$\chi'=\mathrm{Re}\Big(\frac{2N\mu_{21}\rho_{12}}{\varepsilon_0 E_\mathrm{p}}\Big)=\mathrm{Re}\Big(\frac{N\mu_{21}^2\rho_{12}}{\varepsilon_0\Omega_\mathrm{p}\hbar}\Big), \tag{7}$$

where N is the number of Er^{3+}-doped ions per unit volume and μ_{ij} is the electric dipole matrix element between levels $|i\rangle$ and $|j\rangle$ in the Er^{3+}-doped YAG crystal. Finally, the dressed dielectric function experienced by the probe field can be written as

$$\varepsilon(\omega)=n^2=1+4\pi\chi,\quad n=\sqrt{1+4\pi(\chi'+\mathrm{i}\chi'')}\,, \tag{8}$$

when the absorption is zero, i.e. $\chi''=0$, we can obtain the index of refraction as

$$n=\sqrt{1+\chi'}\,. \tag{9}$$

3. Analyses of the solutions

As can be seen immediately from Eq.(7), the susceptibility is associated with the electric dipole moment μ_{21}, the number of doped ions per unit volume N and the density ρ_{12} when the intensity of the probe is kept constant for all concentrations of doped ions. There are many possible combinations of these parameters, which can lead to zero χ'' and nonzero χ'. We have written the steady-state solution of ρ_{12} as shown in Eq.(6), from which we see that ρ_{12} depends on detunings of the probe field and the coherent driving field, coherence relaxation rate γ_{ij} as well as the Rabi frequencies Ω_p and Ω_c. There exist two terms that can make contributions to ρ_{12}. They are the population difference $(\rho_{22}-\rho_{11})$ and the atomic coherence term $[-|\Omega_\mathrm{c}|^2(\rho_{11}-\rho_{33})]$. When the contribution from population difference is identical with that of atomic coherence, the high index of refraction with zero absorption can be obtained under the steady-state condition.

In the following, by numerical calculation, we discuss the effects of the Rabi frequency Ω_c, the detun-

ings Δ_p and Δ_c, and the concentration of Er^{3+} ions on the generation of high index of refraction with zero absorption.

3.1. Under the resonant condition ($\Delta_c = 0$)

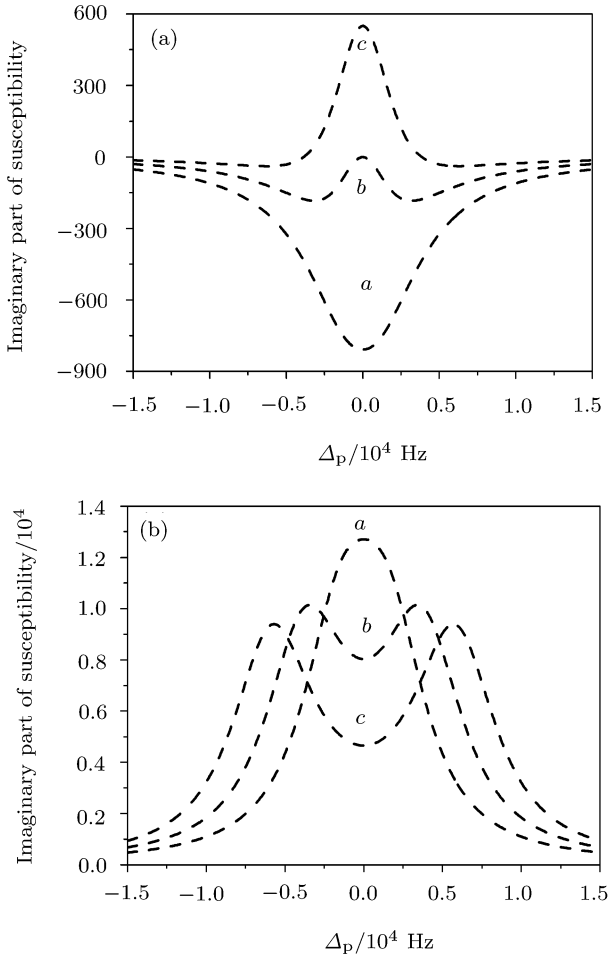


Fig.2. Absorptive part of susceptibility, χ'', versus the probe detuning Δ_p subject to Rabi frequency of the probe $\Omega_p = 60.0$ Hz, and $N = 0.52$ at%. (a) for $\Omega_c = 690.0$ Hz, 714.5 Hz, and 750.0 Hz, corresponding to curves a, b, and c, respectively. (b) for $\Omega_c = 2000.0$ Hz, 4000.0 Hz, and 6000.0 Hz, corresponding to curves a, b, and c, respectively.

We use the concentration of Er^{3+} ions 0.52 at% in YAG crystal, and $\Gamma_{21} = 239.1$ Hz, $\Gamma_{31} = 190.6$ Hz, $\Gamma_{32} = 2391$ Hz, $\mu_{21} = 3.106 \times 10^{-32}$ Cm that are based on Ref.[27], and $\gamma_{21}^{dph} = \gamma_{31}^{dph} = \gamma_{32}^{dph} = 20\Gamma_{21}$ that are based on Ref.[28]. Fixing the Rabi frequency of probe field $\Omega_p = 60.0$ Hz, the effect of Rabi frequency Ω_c on the imaginary part of the complex susceptibility is shown in Fig.2(a), which is related to the absorption. With the increase of Ω_c, probe beam absorption becomes smaller and smaller, and the EIT can be at resonance. When the Ω_c continues to increase, more populations are pumped to level $|2\rangle$ via the fast decay from level $|3\rangle$, then the population difference $(\rho_{22} - \rho_{11})$ will become larger than that of atomic coherence. It means that the system changes from absorbing the probe beam to amplifying it, at last, Ω_c becomes large enough and makes the dressed states split completely by the ac-Stark effect as shown in Fig.2(b).

From $\Omega_c = 714.5$ Hz to $\Omega_c = 750.0$ Hz, the absorption and gain exist at the same time. There certainly exists such a point that the absorption is zero but the index of refraction still has a certain value, which gives rise to the possibility of high index of refraction accompanied by vanishing absorption. For example, when $\Omega_c = 730.0$ Hz, we can obtain a very high index of refraction with zero absorption at this concentration, the index goes up to $n = 15.23$ as shown in Fig.3.

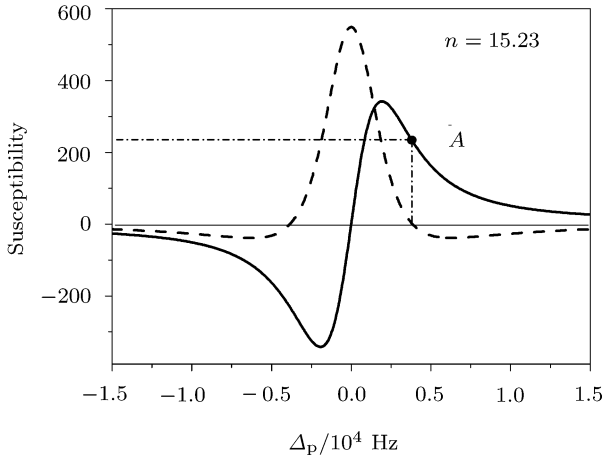


Fig.3. χ'' (dotted) and χ' (solid) parts of susceptibility versus the probe detuning Δ_p subject to Rabi frequencies: $\Omega_p = 60.0$ HZ and $\Omega_c = 730.0$ Hz, and $N = 0.52$ at%. At point A, the system has the highest index of refraction with zero absorption.

3.2. Effect of the detuning of coherent driving field ($\Delta_c \neq 0$)

In the above analyses we obtain a high index of refraction with zero absorption at an ion concentration of 0.52 at% when $\Omega_p = 60$ Hz, and $\Omega_c = 730$ Hz. Now we consider the case where the coherent field is not at resonance with the transition $|3\rangle \leftrightarrow |1\rangle$. Fixing $\Omega_p = 60$ Hz, and $\Omega_c = 730$ Hz but changing the detuning of coherent driving field Δ_c, we find that

the two peaks of χ' and χ'' both become lower than before. That is to say, the absorption and the index of refraction are lower than those under the condition of resonance at the same Rabi frequency of the coherent driving field Ω_c. So we combine the Rabi frequency of the coherent field Ω_c with the detuning of coherent driving field Δ_c together to realize the enhancement of the index of refraction accompanied by vanishing absorption. In Fig.4, at $\Delta_p = -1140.0$ Hz, $\Delta_c = -3000.0$ Hz, and $\Omega_c = 920.0$ Hz, we find that the index of refraction with zero absorption at point A becomes much higher than that in Fig.3, and the maximum index of refraction can reach as high as $n = 21.33$ when the concentration of Er^{3+} ions in the crystal is 0.52 at%. Therefore the detuning of coherent driving field Δ_c is an important factor to achieve a high index of refraction with zero absorption.

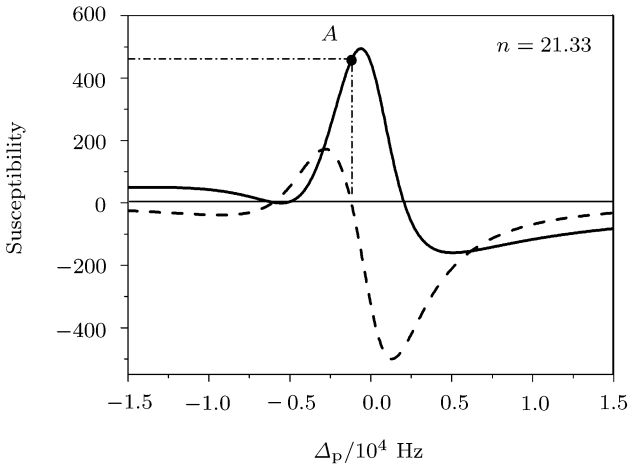


Fig.4. The same as Fig.3 expect for $\Omega_c = 920.0$ Hz, and $\Delta_c = -3000.0$ Hz.

3.3. Effect of Er^{3+} ion concentration

In a rare-earth doped crystal, the decay rate of population Γ_{ij} and the electric dipole moment μ_{21} vary as a function of the concentration due to the influence of some factors, such as phonon decay and the interaction among ions.[27,28] So the following work is to acquire an ultra high index of refraction with zero absorption by choosing an appropriate concentration of Er^{3+} ions and a Rabi frequency of the coherent driving field Ω_c. Based on Refs.[29] and [30], we can have populations with a spontaneous emission probability Γ_{ij}, and electric dipole moments μ_{21} at different concentrations 0.52 at%, 0.79 at%, 17.38 at%, and 20.57 at%, as shown in Table 1.

Fixing a Rabi frequency of probe field $\Omega_p = 60.0$ Hz, we calculate the susceptibility at different concentrations of Er^{3+} ions, and find that a high index of refraction accompanied by vanishing absorption cannot be realized at the same Rabi frequency of coherent driving field Ω_c for all concentrations of Er^{3+}-doped ions, which is mentioned by Zhang *et al.*[26] So we have to change Ω_c according to different concentrations of Er^{3+} ions. In Fig.5, the broken lines are for the light absorption, and the solid lines for the index of refraction. We can see that at different concentrations of Er^{3+} ions, the system can achieve different ultrahigh indices of refraction with zero absorption. When the concentrations of Er^{3+} ions in the crystal are 0.52 at%, 0.79 at%, 17.38 at%, and 20.57 at%, the highest indices of refraction with zero absorption can be obtained respectively at points A, B, C, and D as shown in Figs.5(a), (b), (c), and (d). The maximum indices of refraction with the same frequency of probe field but different frequencies of coherent driving field and different concentrations of the Er^{3+} ion under the resonant condition are shown in Table 2.

The above discussion shows clearly that the concentration of Er^{3+} ions in the crystal is also a critical factor to obtain a high index of refraction with zero absorption.

Table 1. Transition probabilities and electric dipole moments in Er^{3+}: YAG crystal containing different concentrations of the Er^{3+} ions.

concentration of Er^{3+} ions in crystal/at%	transition probability/Hz			electric dipole moment
	Γ_{21}	Γ_{31}	Γ_{32}	$\mu_{21}/10^{-32}$Cm
0.52	239.1	190.6	2391	3.106
0.79	258.8	216.4	2588	3.268
17.38	184.6	128.7	1846	2.393
20.57	187.8	129.4	1878	2.316

Table 2. The indices of refraction at the same frequency of probe field, different frequencies of coherent driving field, and different concentrations of the Er^{3+} ion under the resonant condition.

concentration of Er^{3+} ion in crystal/at%	Ω_p/Hz	Ω_c/Hz	Δ_p/Hz	Δ_c/ Hz	n
0.52	60.0	730.0	3990.0	0.0	15.23
0.79	60.0	790.0	3750.0	0.0	18.76
17.38	60.0	560.0	3060.0	0.0	75.14
20.57	60.0	570.0	3120.0	0.0	79.92

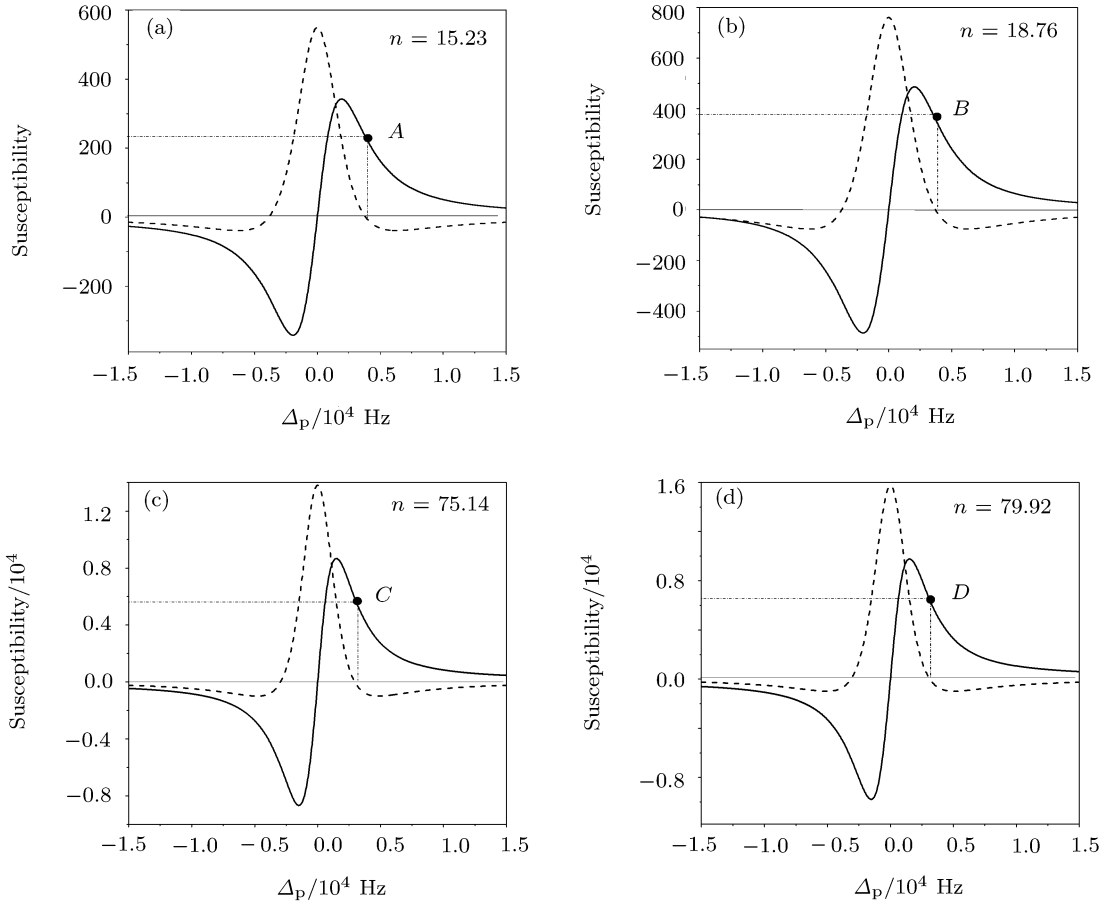


Fig.5. χ'' (dotted) and χ' (solid) parts of susceptibility versus the probe detuning Δ_p. With $\Omega_p = 60.0$ Hz fixed, one can observe the effect of the concentration of Er^{3+} ions in the crystal on the high index of refraction with zero absorption. At points A, B, C, and D, the system has the highest indices of refraction with zero absorption: (a) for $N = 0.52$ at%, and $\Omega_c = 730.0$ Hz. (b) for $N = 0.79$ at%, and $\Omega_c = 790.0$ Hz. (c) for $N = 17.38$ at%, and $\Omega_c = 560.0$ Hz. (d) for $N = 20.57$ at%, and $\Omega_c = 570.0$ Hz.

3.4. Effect of the detuning of coherent driving field at different concentrations of Er^{3+} ions

The effects of the coherent driving field and the concentration of Er^{3+} ions have been analysed in the above sections, separately. At last, we are interested in the result in which these two factors are changed

simultaneously, which is illustrated in Fig.6, where (a), (b), (c), and (d) correspond to the concentrations of Er^{3+} ions in the crystal 0.52 at%, 0.79 at%, 17.38 at%, and 20.57 at%, respectively. We can see that under non-resonant condition, the index of refraction with zero absorption is obviously enhanced at different concentrations of Er^{3+} ions and densities of coherent driving field as shown in Table 3.

Table 3. The indices of refraction at the same Rabi frequency of probe field but different Rabi frequencies of coherent driving field and concentrations of the Er^{3+} ion under non-resonant condition.

concentration of Er^{3+} ion in crystal/at%	Ω_p/Hz	Ω_c/Hz	Δ_p/Hz	Δ_c/Hz	n
0.52	60.0	920.0	–1140.0	–3000.0	21.33
0.79	60.0	980.0	–2010.0	–3000.0	25.31
17.38	60.0	800.0	–1050.0	–3000.0	113.71
20.57	60.0	800.0	–1320.0	–3000.0	122.68

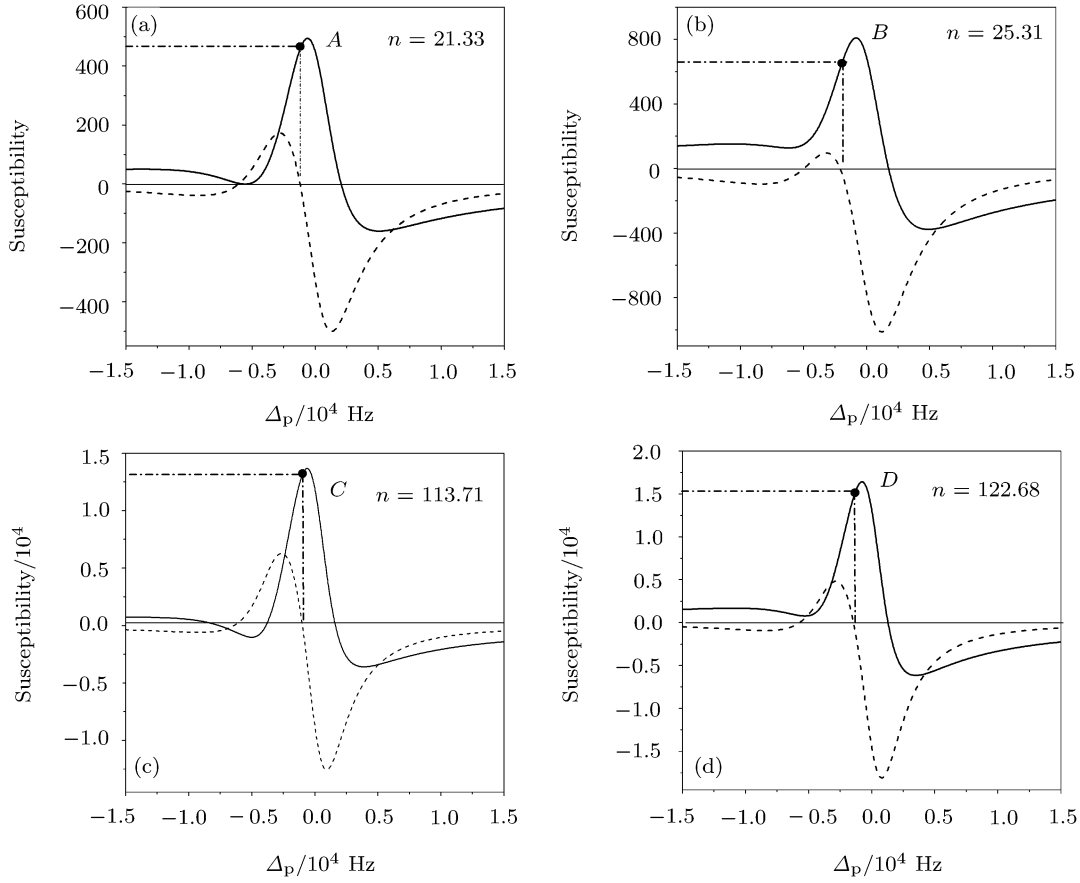


Fig.6. χ'' (dotted) and χ' (solid) parts of susceptibility versus the probe detuning Δ_p. With $\Omega_p = 60.0$ Hz, and $\Delta_c = -3000.0$ Hz fixed, one can observe the effects of both the coherent driving field and the concentration of Er^{3+} ions in the crystal on the high index of refraction with zero absorption. (a) for $N = 0.52$ at%, and $\Omega_p = 920.0$ Hz. At point A, $n = 21.33$. (b) for $N = 0.79$ at%, and $\Omega_c = 980.0$ Hz. At point B, $n = 25.31$. (c) for $N = 17.38$ at%, and $\Omega_p = 800.0$ Hz. At point C, $n = 113.71$. (d) for $N = 20.57$ at%, $\Omega_p = 800.0$ Hz. At point D, $n = 122.68$.

4. Conclusions

In the present paper, we have analysed the effects of the coherent driving field and concentration of Er^{3+} ions on the enhancement of the index of refraction accompanied by vanishing absorption in a simple three-level of Er^{3+}: YAG crystal, including the probe field

and the coherent driving field that not only establishes the coherence but also takes the role of pump field to contribute a small fraction of atoms to the excited state. It is found that the high index of refraction with zero absorption may be successfully achieved by adjusting the coherent field and the concentration of Er^{3+} ions in the crystal. The result may be useful in optical communications.

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