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Effect of concentration of Er^{3+} ions on ultra-large index of refraction via atomic coherence in Er^{3+}: YAG crystal*

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A four-level system is proposed to produce large index of refraction accompanied by vanishing absorption in the Er^{3+}-doped yttrium aluminium garnet (YAG) crystal. It is found that the high index of refraction with zero absorption can be provided by adjusting the incoherent pumping, the coherent field, as well as the concentration of Er^{3+} ions in the crystal. Furthermore, the value of the incoherent pump to achieve the high index of refraction with zero absorption is greatly changed with increasing the concentration of Er^{3+} ions in the crystal. This indicates that the effect of concentration on the high index of refraction with zero absorption cannot be neglected.

Keywords: electromagnetically induced transparency, concentration, high index of refraction with zero absorption

PACC: 4250, 4265, 3280

1. Introduction

There are a lot of theoretical[1−4] and experimental[5,6] results indicating that quantum interference can lead to lasing without inversion (LWI) and electromagnetically induced transparency (EIT) for resonant enhancement of nonlinear effects with a reduced absorption. Recently, it has been shown that atomic coherence and interference effects can lead to complete absorption cancellation and an ultrahigh index of refraction.[7,8] The experimental demonstration of enhanced index of refraction accompanied by a vanishing absorption via quantum coherence in Rb vapour also has been presented.[9] Interest in these phenomena is due, on one hand, to the fundamental nature of coherence effects and, on the other hand, to possible applications. For example, the dispersive properties of coherently prepared media have been studied with an eye toward the generation of pulses with very slow group velocity,[10] effective control of nonlinearities,[11] high precision magnetometry,[12] and laser acceleration of particles.

Many researchers have studied the basic physics of EIT phenomenon by using atomic gases,[13] impurity ion doped crystals,[14,15] and semiconductor quantum wells.[16,17] Recent observation of nonlinear optical processes based on EIT in rare-earth doped solids opens the door to practical applications of optical memories,[18] enhanced nonlinear optical processes,[19] optical switches,[20,21] and gain levelling in optical fibre[22], etc. However, all of these experiments in solid crystals were carried out under the same concentration of doped ions. Yttrium-aluminium-garnet (YAG) is an excellent host material and superior in hardness and thermal conductivity. The Er^{3+}-doped YAG crystals are efficient active media for lasers operating in the 1.5μm region, coinciding with the telecommunication band. The theoretical study of EIT in Er^{3+}: YAG when the concentration of doped Er^{3+} ions changes has been also reported.[23]

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In this paper, we investigate a four-level system in an Er^{3+}-doped YAG crystal. It is found that the enhancement of the index of refraction with zero absorption can be achieved in solid crystals by modifying the incoherent pump and the coherent field. It is also found that the index of refraction with vanishing absorption can be changed under different concentration of the Er^{3+} ions in YAG crystals. In the rare-earth doped crystal, the decay rate of population and the electric dipole moment vary as functions of the concentration due to the influence of some factors, such as phonon decay and the interaction among ions.[24,25] The purpose of this paper is to acquire ultra high index of refraction with zero absorption by choosing appropriate concentration of Er^{3+} ions, the incoherent pumping rate, the Rabi frequency of the coherent field.

2. Equations and solutions

We consider a closed four-level system shown in Fig.1. The energy-level scheme is relevant to the Er^{3+} ions in the Er^{3+}: YAG crystal, where levels $|1\rangle$, $|2\rangle$, $|3\rangle$ and $|4\rangle$ correspond to energy levels of Er^{3+} ions $^4I_{15/2}$, $^4I_{13/2}$, $^4I_{11/2}$, and $^4I_{9/2}$, respectively. In this system, via a fast decay from $|3\rangle$, level $|2\rangle$ is populated by an incoherent pump process Λ interacting with the transition $|1\rangle \leftrightarrow |3\rangle$. A coherent driving field E_c with Rabi frequency G_c drives the $|2\rangle \leftrightarrow |4\rangle$ atomic transition, and a probe field E_p with Rabi frequency G_p interacts with the transition labelled $|1\rangle \leftrightarrow |2\rangle$. $\Gamma_4 = \Gamma_{41} + \Gamma_{42} + \Gamma_{43}$ is the spontaneous decay rate of level $|4\rangle$, $\Gamma_3 = \Gamma_{31} + \Gamma_{32}$ is the spontaneous decay rate of level $|3\rangle$, and $\Gamma_2 = \Gamma_{21}$ is the spontaneous decay rate of level $|2\rangle$.

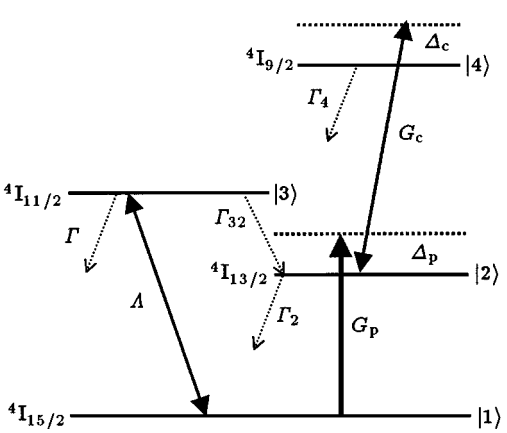


Fig.1. Schematic diagram of a four-level system, with levels $|1\rangle$, $|2\rangle$, $|3\rangle$ and $|4\rangle$ corresponding to energy levels of Er^{3+} ions in the Er^{3+}:YAG crystal $^4I_{15/2}$, $^4I_{13/2}$, $^4I_{11/2}$, and $^4I_{9/2}$, respectively.

Within the framework of the semiclassical theory, by the standard density-matrix formalism under the dipole approximation and the rotating wave approximation, the interaction Hamiltonian H_I can be represented in the interaction picture by

$$H_I = -\Delta_p|2\rangle\langle 2| - (\Delta_p + \Delta_c)|4\rangle\langle 4| - (G_p|2\rangle\langle 1| + G_c|4\rangle\langle 2| + \text{c.c.}), \quad (1)$$

where the detunings of the probe and the coherent field are defined as: $\Delta_p = \omega_p - (\omega_2 - \omega_1)$, $\Delta_c = \omega_c - (\omega_4 - \omega_2)$, respectively; the Rabi frequencies G_c and G_p are defined as: $G_c = \mu_{42} \cdot E_c/2\hbar$, $G_p = \mu_{21} \cdot E_p/2\hbar$, respectively.

Assuming $\hbar$=1 for simplicity, the master equation of motion for the density operator in an arbitrary multi-level atomic system in the interaction picture can be written as

$$\frac{\partial \rho}{\partial t} = -\mathrm{i}[H_I, \rho] + \Lambda'\rho. \quad (2)$$

By expanding Eq.(2), we can easily arrive at the equations of motion

$$\begin{aligned}
\dot\rho_{11} =& \Lambda(\rho_{33} - \rho_{11}) + \Gamma_{21}\rho_{22} + \Gamma_{31}\rho_{33} \\
&+ \Gamma_{41}\rho_{44} + \mathrm{i}G_p^*\rho_{21} - \mathrm{i}G_p\rho_{12}, \\
\dot\rho_{22} =& -\Gamma_{21}\rho_{22} + \Gamma_{32}\rho_{33} + \Gamma_{42}\rho_{44} \\
&+ \mathrm{i}G_p\rho_{12} - \mathrm{i}G_p^*\rho_{21} + \mathrm{i}G_c^*\rho_{42} - \mathrm{i}G_c\rho_{24}, \\
\dot\rho_{33} =& -\Lambda(\rho_{33} - \rho_{11}) - \Gamma_{31}\rho_{33} - \Gamma_{32}\rho_{33} + \Gamma_{43}\rho_{44}, \\
\dot\rho_{41} =& -[\gamma_{41} - \mathrm{i}(\Delta_p + \Delta_c)]\rho_{41} + \mathrm{i}G_c\rho_{21} - \mathrm{i}G_p\rho_{42}, \\
\dot\rho_{42} =& -(\gamma_{42} - \mathrm{i}\Delta_c)\rho_{42} + \mathrm{i}G_c(\rho_{22} - \rho_{44}) - \mathrm{i}G_p^*\rho_{41}, \\
\dot\rho_{43} =& -[\gamma_{43} - \mathrm{i}(\Delta_p + \Delta_c)]\rho_{43} + \mathrm{i}G_c\rho_{23}, \quad (3) \\
\dot\rho_{32} =& -(\gamma_{32} + \mathrm{i}\Delta_p)\rho_{32} - \mathrm{i}G_p^*\rho_{31} - \mathrm{i}G_c\rho_{34}, \\
\rho_{31} =& -\gamma_{31}\rho_{31} - \mathrm{i}G_p\rho_{32}, \\
\dot\rho_{21} =& -(\gamma_{21} - \mathrm{i}\Delta_p)\rho_{21} + \mathrm{i}G_p(\rho_{11} - \rho_{22}) + \mathrm{i}G_c^*\rho_{41}, \\
\rho_{11} + \rho_{22} + \rho_{33} + \rho_{44} =& 1, \\
\rho_{ij} =& \rho_{ji}^*,
\end{aligned}$$

where Γ_{ij} designates the population spontaneous damping from $|i\rangle$ to $|j\rangle$, while γ_{ij} are total coherence relaxation rates between $|i\rangle$ and $|j\rangle$, given by[17]

$$\begin{aligned}
\gamma_{41} &= (\Gamma_{41} + \Gamma_{42} + \Gamma_{43} + \Lambda + \gamma_{41}^{\mathrm{dph}})/2, \\
\gamma_{42} &= (\Gamma_{41} + \Gamma_{42} + \Gamma_{43} + \Gamma_{21} + \gamma_{42}^{\mathrm{dph}})/2, \\
\gamma_{43} &= (\Gamma_{41} + \Gamma_{42} + \Gamma_{43} + \Gamma_{31} + \Gamma_{32} + \Lambda + \gamma_{43}^{\mathrm{dph}})/2, \quad (4)
\end{aligned}$$

$$\gamma_{32} = (\Gamma_{32} + \Gamma_{31} + \Gamma_{21} + \Lambda + \gamma_{32}^{\rm dph})/2,$$
$$\gamma_{31} = (\Gamma_{32} + \Gamma_{31} + \Lambda + \Lambda + \gamma_{31}^{\rm dph})/2,$$
$$\gamma_{21} = (\Gamma_{21} + \Lambda + \gamma_{21}^{\rm dph})/2,$$

where $\gamma_{ij}^{\rm dph}$ is the dephasing decay rate of the quantum coherence of the $|i\rangle \leftrightarrow |j\rangle$ transition. In contrast to many atomic schemes, the $\gamma_{ij}^{\rm dph}$, determined by electron–electron, interface roughness and phonon scattering processes, are the dominant contributions to the γ_{ij} and the major obstacle to the observation of coherent effects such as EIT in solid materials.

In the limit of a weak probe, under the steady-state condition, the solutions of Eq.(1) for ρ_{21} to the first order of the probe field and for other ρ_{ij} to the zero order of the probe field are

$$\rho_{22} = \frac{\Lambda\Gamma_{32}/(\Lambda + \Gamma_{31} + \Gamma_{32})}{\left[\Gamma_{21} + (\Gamma_{41} + \Gamma_{43}(\Lambda + \Gamma_{31})/(\Lambda + \Gamma_{31} + \Gamma_{32}))\frac{D_2}{D_1}\right]}\rho_{11},$$
$$\rho_{33} = \left[\Gamma_{21} + (\Gamma_{41} + \Gamma_{43})\frac{D_2}{D_1}\right]\frac{\rho_{22}}{\Gamma_{32}}, \tag{5}$$
$$\rho_{44} = \frac{D_2}{D_1}\rho_{22}, \qquad \rho_{42} = \frac{{\rm i}G_{\rm c}(\rho_{22} - \rho_{44})}{\gamma_{42} - {\rm i}\Delta_{\rm c}},$$

and

$$\rho_{12} = \rho_{21}^* = \frac{{\rm i}G_{\rm p}(\rho_{22} - \rho_{11}) - \dfrac{{\rm i}|G_{\rm c}|^2 G_{\rm p}(\rho_{22} - \rho_{44})}{(\gamma_{41} + {\rm i}(\Delta_{\rm p} + \Delta_{\rm c}))(\gamma_{42} + {\rm i}\Delta_{\rm c})}}{\gamma_{21} + {\rm i}\Delta_{\rm p} + \dfrac{|G_{\rm c}|^2}{\gamma_{41} + {\rm i}(\Delta_{\rm p} + \Delta_{\rm c})}}, \tag{6}$$

where $D_1 = \Gamma_{41} + \Gamma_{42} + \Gamma_{43} + \dfrac{2|G_{\rm c}|^2\gamma_{42}}{\gamma_{42}^2 + \Delta_{\rm c}^2}$, $D_2 = \dfrac{2|G_{\rm c}|^2\gamma_{42}}{\gamma_{42}^2 + \Delta_{\rm c}^2}$.

The complex polarizability of the probe field can be described as[26]

$$\begin{cases} \chi'' = {\rm Im}\left(\dfrac{2N\mu_{21}\rho_{12}}{\varepsilon_0 E_{\rm p}}\right) = {\rm Im}\left(\dfrac{N\mu_{21}^2\rho_{12}}{\varepsilon_0 G_{\rm p}\hbar}\right), \\ \chi' = {\rm Re}\left(\dfrac{2N\mu_{21}\rho_{12}}{\varepsilon_0 E_{\rm p}}\right) = {\rm Re}\left(\dfrac{N\mu_{21}^2\rho_{12}}{\varepsilon_0 G_{\rm p}\hbar}\right), \end{cases} \tag{7}$$

where N is the number of doped ions per unit volume and is proportional to the concentration of Er^{3+} ions, μ_{ij} is the electric dipole matrix element between level $|i\rangle$ and level $|j\rangle$ of Er^{3+} ions, which is given by[27,28]

$$\mu_{21}^2 = e^2|\langle\psi|r|\psi'\rangle|^2$$
$$= e^2\frac{2}{(2J+1)}\frac{2}{(2J'+1)} \times \sum_{t=2,4,6}\Omega_t|\langle 4f^N(\alpha SL)J||U^t||4f^N(\alpha' S'L')J'\rangle|^2, \tag{8}$$

where Ω_t (t=2, 4, 6) is the phenomenological intensity parameter, J and J' are the quantum numbers of angular momentum of the level $|i\rangle$, $|j\rangle$, respectively. The factors 2 in Eq.(8) arise from the Kramers degenerate of the Stark levels of Er^{3+} ions. The reduced matrix element U^t can be obtained from Ref.[29] and the spectral intensity parameters can be described by an empirical formula[24]

$$\Omega_t(10^{-20}) = 1.25X^{1/4}\exp[-0.4(X - A)^{2/3}] + B, \tag{9}$$

where X is the concentration of doped ions. A and B are empirical parameters: A=1.0, B=0.33 for Ω_2; A=1.1, B=0.72 for Ω_4; and A=1.4, B=0.59 for Ω_6.

3. Results and discussion

The indices of refraction and absorption are governed by the real and imaginary parts of the complex polarizability, i.e. by χ' and χ''. From Eq.(7), we see that χ' and χ'' depend on the electric dipole moment μ_{21}, the number of doped ions per unit volume N, the Rabi frequency of the probe field $G_{\rm p}$, as well as ρ_{12} etc. ρ_{12} is the main factor to obtain the high index of refraction with zero absorption. We have written the steady-state solution of ρ_{12} as in Eq.(6), from which we see that ρ_{12} depends on detunings, coherence relaxation rates and the incoherent pumping rate Λ as well as the Rabi frequencies $G_{\rm p}$ and $G_{\rm c}$. ρ_{12} is contributed by two terms, the population difference term which is proportional to $(\rho_{22} - \rho_{11})$ and the atomic coherence term which is proportional to $-|G_{\rm c}|^2(\rho_{22} - \rho_{44})$. When the contribution from population difference equals to

that of atomic coherence, the high dispersion with zero absorption can be obtained in the steady-state condition. At the same time, ρ_{12} is relevant to the concentration of doped ions because the population spontaneous damping is changed along with the concentration of doped ions. From Eqs.(8) and (9), the electric dipole moment μ_{21} is also closely related to the concentration of doped ions. So it is obvious that the concentration of doped ions can affect the generation of the high index of refraction with zero absorption.

In the following, by numerical calculation, we discuss how to combine the incoherent pump and the coherent field to realize the enhancement of the index of refraction accompanied by vanishing absorption under different concentrations of Er^{3+} ions.

Based on Refs.[24] and [29], we can have population spontaneous emission probabilities Γ_{ij}, spectral intensity parameters of the Er^{3+} ions in Er^{3+}:YAG crystals under different concentrations 0.52at%, 0.79at%, 17.38at%, 20.57at%, 29.06at%. The electrical dipole moments under different concentrations have been calculated using Eq.(8), and listed in Table 1. The population spontaneous emission probabilities Γ_{ij} under different concentrations are listed in Table 2, which is based on Ref.[24]. In Ref.[30], we found the dephasing time $T_2 = 75\mu$s for Er^{3+}:YAG crystals with an Er^{3+} concentration of 0.1% on the $^4I_{15/2} \leftrightarrow {}^4I_{13/2}$ transition of Er^{3+} at 1526.97nm, the homogeneous line width Γ_h=4.246kHz. Therefore, it is reasonable to estimate the dephasing decay rate as $\gamma_{21}^{dph} = \gamma_{31}^{dph} = \gamma_{32}^{dph} = \gamma_{41}^{dph} = \gamma_{42}^{dph} = \gamma_{43}^{dph} = 20\Gamma_{21}$.

Table 1. Spectral intensity parameters, electrical dipole moments and population decay rates in Er^{3+}:YAG crystals containing different concentrations of the Er^{3+} ion.

Concentration of Er^{3+} ion in crystal /at%	Spectral intensity parameters/10^{-20}cm^2[24]			Electric dipole moments/10^{-32}Cm
	Ω_2	Ω_4	Ω_6	μ_{21}
0.52	1.16	1.52	1.33	3.106
0.79	1.35	1.70	1.47	3.268
17.38	0.52	0.92	0.79	2.393
20.57	0.47	0.87	0.74	2.316
29.06	0.40	0.79	0.66	2.189

Table 2. Radiative transition probabilities of the Er^{3+}:YAG crystals containing different Er^{3+} ion concentrations.[24]

Concentration of Er^{3+} ion in crystal/at%	Transition probabilities/s^{-1}					
	Γ_{21}	Γ_{31}	Γ_{32}	Γ_{41}	Γ_{42}	Γ_{43}
0.52	239.1	190.6	2391	206.5	68.3	10.3
0.79	258.8	216.4	2588	211	76.6	16.3
17.38	184.6	128.7	1846	127.4	46.7	7.6
20.57	187.8	129.4	1878	152.4	48.0	7.9
29.06	175.4	122.3	1754	85.0	44.6	7.6

In order to explore the effects of concentration on complete cancellation of absorption and the ultrahigh index of refraction, we depict the variation of the polarizability (relative value) of the probe field versus the detuning of the probe in Figs 2–5. In Ref.[31], we have reported the high index of refraction with zero absorption under the same concentration of doped ions. In this case, the polarization is governed by the real and imaginary parts of ρ_{12} because the polarization is proportional to ρ_{12}. According to Eq.(7), we find that the polarizability is associated with the concentration N, electrical dipole moment μ_{21} and ρ_{12} when the intensity of the probe is kept constant for all concentrations of doped ions. At first, we study the effect of concentration of Er^{3+} ions on the imaginary part of the complex polarizability χ'' shown in Fig.2, which is related to light amplification and absorption. When the Rabi frequency of the coherent field G_c equals zero, this system is a pure three-level light amplification system. From Eqs.(5) and (6), the probe can be amplified when the population inversion between levels $|2\rangle$ and $|1\rangle$ is established at the incoherent pumping rate $\Lambda > \Gamma_{21}(\Gamma_{31} + \Gamma_{32})/(\Gamma_{32} - \Gamma_{21})$. With fixed G_p=180.0Hz and the incoherent pumping rate Λ=250.0Hz, we can see that the system undergoes an absorption when the concentrations of Er^{3+} ions are 0.52at% and 0.79 at%, and undergoes a gain when the concentrations of Er^{3+} ions are 17.38 at%, 20.57

at%, and 29.06 at% because the population spontaneous emission probabilities Γ_{ij} vary with the concentrations of doped ions. When the incoherent pump Λ equals zero, this system is an EIT ladder-type. With fixed G_p=180.0Hz and the Rabi frequency of the resonant coherent field G_c=5000.0Hz, we calculate the absorption under different concentrations of Er^{3+} ions in Fig.3. It is found that the absorption near the region Δ_p=0.0 changes dramatically with the concentration of Er^{3+} ions. The absorption for 0.52at% and 0.79at% Er^{3+} ions approaches zero. At the same time, the two absorption peaks also vary remarkably under different concentrations of Er^{3+} ions. We can see from Fig.3, that the concentration of 17.38 at% is better than others when the EIT phenomenon is considered. It is found that the variation of the polarizability is not linear with increasing the concentration of Er^{3+} ions because the relations between Γ_{ij}, μ_{21} and the concentration of doped ions are complicated.

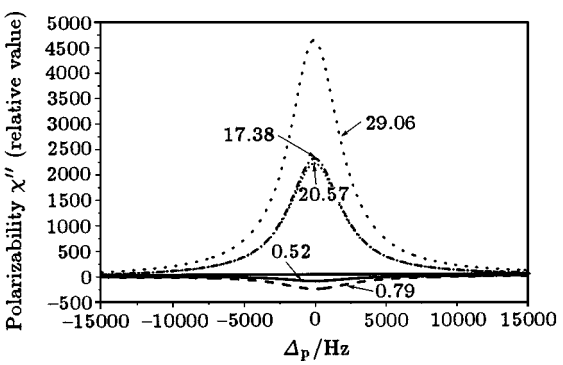


Fig.2. Configurations of absorptive χ'' parts of polarizability versus the probe detuning Δ_p. With fixed incoherent pump Λ=250Hz, the probe G_p=180.0Hz, one can observe the effect of concentration of Er^{3+} ions in the crystal on light amplification when the Rabi frequency of the coherent field G_c equals zero.

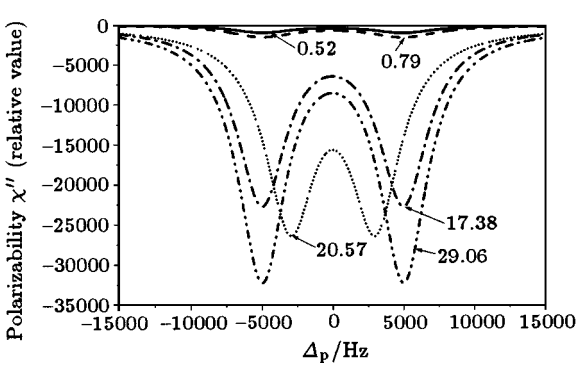


Fig.3. Configurations of absorptive χ'' parts of polarizability versus the probe detuning Δ_p. With fixed Rabi frequency of the coherent field G_c=5000.0Hz, the probe G_p=180.0Hz, one can observe the effect of concentration of Er^{3+} ions in the crystal on EIT when the incoherent pump Λ equals zero.

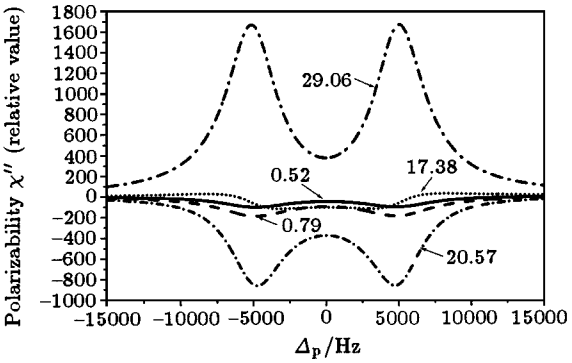


Fig.4. Configurations of absorptive χ'' parts of polarizability versus the probe detuning Δ_p. With fixed Rabi frequency of the coherent field G_c=5000.0Hz, the incoherent pump Λ=400Hz, and the probe G_p=180.0Hz, one can observe the probe absorption or gain under different concentrations of Er^{3+} ions.

The high index of refraction with zero absorption can be accomplished when the resonant coherent field and the incoherent pump are in action. At first, we fix the incoherent pump rate Λ=400.0Hz, the Rabi frequency of the resonant coherent field G_c=5000.0Hz, and the probe G_p=180.0Hz, and observe the probe absorption or gain under different concentrations of Er^{3+} ions in Fig.4. We find that zero absorption can be obtained when the concentration of Er^{3+} ions in the crystal is 17.38at%; the system exhibits an absorption when the concentrations of Er^{3+} ions in the crystal are 0.52at%, 0.79at%, and 20.57 at%; the system shows a gain when the concentration of Er^{3+} ions in the crystal is 29.06at%. These indicates that the high index of refraction with zero absorption cannot be realized for all concentrations of doped ions under the same Rabi frequency of the coherent field G_c and the incoherent pump Λ. Next, we discuss how to achieve the high index of refraction with zero absorption under the different concentrations of Er^{3+} ions in Fig.5 when we fix the probe G_p=180.0Hz, the Rabi frequency of the resonant coherent field G_c=5000.0Hz. When the concentration of Er^{3+} ions in the crystal is 0.52at%, a high index of refraction with zero absorption at point A (Δ_p=−4409.0Hz) can be obtained under the incoherent pumping rate Λ=600.0Hz, as shown in Fig.5 (a). Next, we consider the case in which the concentration of Er^{3+} ions in the crystal is 0.79at%. The high index of refraction with zero absorption can be obtained at point B (Δ_p=−3567.0Hz) when the incoherent pumping rate increases, i.e. Λ=640.0Hz, as shown in Fig.5(b). When the concentration of Er^{3+} ions in the crystal is 17.38at%, the index of refraction with zero absorption becomes much higher at

point C in Fig.5(c) (Δ_p=−4874.0Hz) than at point A in Fig.5 (a) when the incoherent pumping rate Λ=405.0Hz. When the concentration of Er^{3+} ions in the crystal is 20.57at%, the incoherent pump increases to Λ=460.0Hz for gaining the high index of refraction with zero absorption at point D (Δ_p=−4162.0Hz), as shown in Fig.5(d). Finally, we consider the case in which the concentration of Er^{3+} ions in the crystal is 29.06at%, the high index of refraction with zero absorption can be seen at point E (Δ_p=−4930.0Hz) when Λ=330.0Hz, as shown in Fig.5(e). From Ref.[23], we know that EIT may disappear when the concentration of Er^{3+} ions is 100at%, thus the high index of refraction with zero absorption may not be reached for large concentration of Er^{3+} ions because the contribution from population difference $(\rho_{22}-\rho_{11})$ may become far exceeding that of atomic coherence $(\propto -|G_c|^2(\rho_{22}-\rho_{44}))$.

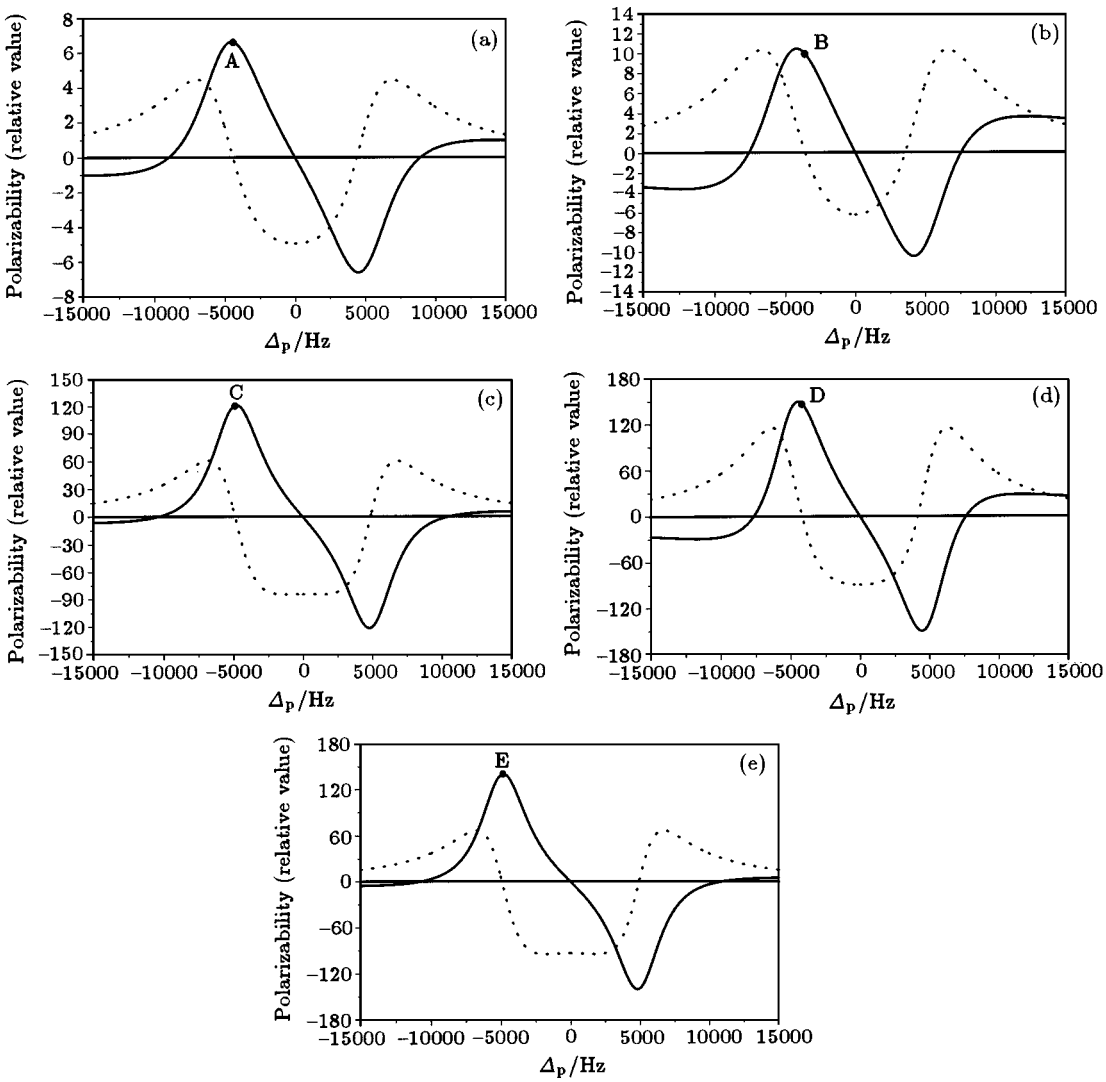


Fig.5. Configurations of absorptive χ'' (dotted) and dispersive χ' parts of polarizability versus the probe detuning Δ_p. With fixed Rabi frequency of the coherent field G_c=5000.0Hz, the probe G_p=180.0Hz, one can observe the effect of concentration of Er^{3+} ions in the crystal on the high index of refraction with zero absorption. (a) N=0.52at%, Λ=600.0Hz, at point A the system has zero χ'' and nonzero χ'. (b) N=0.79at%, Λ=640.0Hz, at point B the system has zero χ'' and nonzero χ'. (c) N=17.38at%, Λ=405.0Hz, at point C the system has zero χ'' and nonzero χ'. (d) N=20.57at%, Λ=460.0Hz, at point D the system has zero χ'' and nonzero χ'. (e) N=29.06at%, Λ=330.0Hz, at point E the system has zero χ'' and nonzero χ'.

The above discussion shows clearly that the concentration of Er^{3+} ions in the crystal is also a critical factor to obtain the high index of refraction with zero absorption. It is seen that the value of the incoherent pump for the high index of refraction with zero absorption is very different under the same Rabi frequency of the coherent field when the concentration of Er^{3+} ions changes. The index of refraction is also changed greatly when the concentration of Er^{3+} ions varies from 0.79at% to 17.38at%, and then changes little when the concentration continues to increase. Finally, we find that the concentration of doped ions can dramatically affect the index of refraction with zero absorption because the index of refraction depends on a lot of parameters, at the same time, many of the parameters vary as a function of the concentration. So, in order to realize the high index of refraction with zero absorption, we have to select the optimal concentration region, the proper incoherent pump and the coherent field.

4. Conclusions

In the present paper, we have analysed the concentration effect of Er^{3+} ions on the enhancement of the index of refraction with zero absorption in a four-level system in an Er^{3+}-doped YAG crystal. It is found that the high index of refraction with zero absorption can be provided by adjusting the incoherent pumping, the coherent field, as well as the concentration of Er^{3+} ions in the crystal. Furthermore, the value of the incoherent pump to achieve the high index of refraction with zero absorption is greatly changed with increasing the concentration of Er^{3+} ions in the crystal under the same coherent field. The value of index of refraction with zero absorption is also changed for different concentration of Er^{3+} ions. This indicates that the effect of concentration on the high index of refraction with zero absorption cannot be neglected.

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