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Goos–Hänchen shift via refractive index control of four-level quantum dot nanostructure

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In this paper, we will discuss the Goos–Hänchen shifts properties of reflected and transmitted light beams from the cavity with four-level InGaN/GaN quantum dots nanostructure. We find that the Goos–Hänchen shifts properties of reflected and transmitted light beams can be controlled via adjusting the refractive index of four-level quantum dot nanostructure. Here, we show that by tunable infrared laser field the negative refraction index can be possible at certain values of probe frequency. Therefore, the large Goos–Hänchen shifts for reflected and transmitted light beams are possible for negative refractive index condition.

Keywords: quantum dot nanostructure, Goos–Hänchen shift, negative refractive index.

1. Introduction

Quantum coherence and interference in quantum nonlinear optics can lead to many unforeseen phenomena which cannot be seen in usual systems [1–7]. For example, electromagnetically induced transparency (EIT) [5] is one of the most important phenomenon which has been studied in many theoretical and experimental works [8–14]. EIT is responsible for many interesting phenomena such as lasing without inversion (LWI) [15], enhancement of refractive index [16, 17], optical bistability (OB) [18–23], Goos–Hänchen (GH) shifts [24–29] and so on [30–33]. The GH shifts refer to the displacement between incident and totally reflected light beams at a dielectric interface [34]. The properties of GH shifts due to potential applications in optical sensing devices [35, 36], have been studied in many structures such as photonic crystals, negative refractive medium, plasmonic and others [37–45]. The negative lateral shift of the reflected beam from a metal surface at 826 nm has been studied experimentally [46]. The properties of GH shifts have been discussed by changing in geometry and thickness of the proposed structures. Therefore, it cannot be favorable for future all-optical based technologies. The properties of GH shifts in fixed structures have been studied by Li-Gang Wang *et al.* [47]. In fact, the GH shifts of the cavity can be adjusted by controlling the susceptibility of the intracavity medium. Therefore, the lateral shifts of reflected and transmitted light beams can be possible without changing the structure of the cavity. Many models have been suggested for controlling the GH shifts in reflected and transmitted light beams [24–26, 28, 29, 48–52]. WEN-XING YANG *et al*. studied the tunneling induced giant GH shifts in a quantum well semiconductor by using the external control field. They realized that for a suitable condition of quantum well structure, the maximum negative shift of 2.62 mm and the positive shift of 0.56 mm are possible [27]. In another study, polarized dependence of GH shifts through a cavity with a single-layer graphene nanostructure has been discussed [29]. It is realized that the GH shifts in reflected and transmitted light beams can occur in the infrared and terahertz region.

It can be found that by controlling the refractive index of the intracavity medium, the GH shifts in reflected and transmitted light beams can be possible. Therefore, in this study we proposed a model based on negative refraction of intracavity medium for studying the GH shifts in reflected and transmitted light beams. The intracavity medium consists of four-level InGaN/GaN quantum dot (QD) nanostructure where its permittivity and permeability can become negative simultaneously. Due to the negative refraction and negative permittivity and permeability, these structures are called left -handed materials (LHMs). Naturally, these types of materials are not available. Therefore, several approaches have been proposed for realizing LHMs such as artificial composite materials [53], photonic crystal structures [54] and others [55–57]. Based on quantum coherence and interference theories, the LHM has been investigated in multilevel atomic systems [58–63]. For example, AI-PING FANG *et al*. [63] studied the negative refraction without absorption based on quantum coherence in a cascade-type four-level atom. The negative refraction in double QDs have also been discussed by SHUN-CAI ZHAO *et al*. [64]. They realized that by applying a bias voltage and a pulsed laser, the negative refractive index can be possible. Coherent optical properties of quantum well and quantum dot nanostructures based on quantum coherence and interference have been discussed by different mechanisms [52, 65–69]. For example, ASADPOUR *et al*. discussed the optical bistability properties of a weak probe light in a unidirectional ring cavity doped with multiple quantum well nanostructure based on spin coherence. In another study, by ASADPOUR, the switching mechanism between optical bistability and optical multistability in a InGaN/GaN QD nanostructure which was doped in a unidirectional ring cavity has been investigated.

In this paper, we first discuss the features of permeability and permittivity of the four-level QD nanostructure and identify the negative refraction band. Second, we will study the GH shifts of reflected and transmitted light beams for negative refraction of intracavity medium.

2. Model and equations

In our proposed structure, we consider a four-level InGaN/GaN QD nanostructure which interacts with three optical fields, *i.e*. the coupling beam, probe light and signal field as shown in Fig. 1. Via the same method, which has been studied in [70], we can

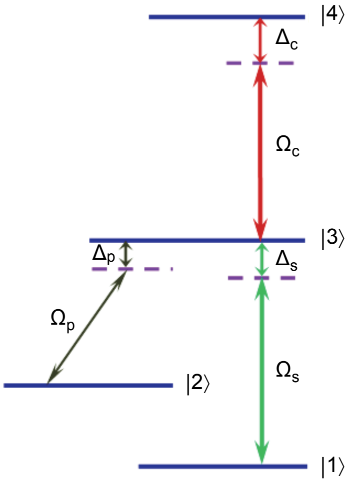

Fig. 1. Schematic diagram of four-level InGaN/GaN QD nanostructure with radius 3.5 nm and thickness of the barrier 3 nm which interacted with a weak probe light, a coherent coupling and pumping fields and a cycling field. The wave function and other parameters can be found in [70].

obtain the wave functions of corresponding energy levels of QD nanostructure by appropriate choosing of some controllable parameters. Therefore, one can obtain the properties of the laser fields for interactions with the four-level QD nanostructure [70]. A coupling field E_c with frequency ω_c and phase φ_c interacts with transition $|3\rangle \leftrightarrow |4\rangle$. The transitions $|3\rangle \leftrightarrow |2\rangle$ and $|2\rangle \leftrightarrow |1\rangle$ are coupled with electric and magnetic parts of weak probe field E_p with frequency ω_p. Moreover, transition $|1\rangle \leftrightarrow |3\rangle$ interacts with a weak signal field E_s with frequency ω_s, respectively. The corresponding Rabi frequencies of applied fields are shown by Ω_c, Ω_p and Ω_s, respectively. Moreover, detunings of applied fields are also denoted by Δ_c, Δ_p and Δ_s, respectively. The decay rates of the corresponding energy levels are shown by γ_2, γ_3 and γ_4, respectively. The non-radiative relaxation of the level $|2\rangle$ is denoted by γ_1. Here, we assume that the two states of $|3\rangle$ and $|2\rangle$ have opposite parity with $\mathbf{d}_{23} = \langle 2|\hat{\mathbf{d}}|3\rangle \neq 0$, while the levels $|2\rangle$ and $|1\rangle$ have the same parity and so $\boldsymbol{\mu}_{12} = \langle 1|\hat{\boldsymbol{\mu}}|2\rangle \neq 0$; $\hat{\boldsymbol{\mu}}$ and $\hat{\mathbf{d}}$ are the electric dipole and magnetic dipole operators, respectively. The corresponding Hamiltonian of the quantum system under the dipole and rotating-wave approximation (RWA) can be given as follows:

$$\hat{H} = \Delta_p|2\rangle\langle 2| + \Delta_s|1\rangle\langle 1| + \Delta_c|4\rangle\langle 4| + \left[\Omega_p|3\rangle\langle 2| + \Omega_s|3\rangle\langle 1| + \Omega_c|3\rangle\langle 4| + \text{H.c.}\right] \tag{1}$$

The quantum mechanical density matrix equations can be obtained under the rotating-wave and dipole approximations via $\dot{\rho} = -(i/\hbar)[H, \rho]$:

$$\dot{\rho}_{11} = 2\gamma_1\rho_{22} + 2\gamma_3\rho_{33} + i\Omega_s(\rho_{13} - \rho_{31}) \tag{2a}$$

$$\dot{\rho}_{22} = -2\gamma_1\rho_{22} + 2\gamma_2\rho_{33} + i\Omega_p(\rho_{23} - \rho_{32}) \tag{2b}$$

$$\dot{\rho}_{33} = -2(\gamma_2+\gamma_3)\rho_{33} + 2\gamma_4\rho_{44} - i\Omega_s(\rho_{13}-\rho_{31}) - i\Omega_p(\rho_{23}-\rho_{32}) + i\Omega_c(\rho_{34}-\rho_{43}) \tag{2c}$$

$$\dot{\rho}_{44} = -2\gamma_4\rho_{44} - i\Omega_c(\rho_{34}-\rho_{43}) \tag{2d}$$

$$\dot{\rho}_{12} = -\left[\gamma_1 - i(\Delta_s-\Delta_p)\right]\rho_{12} + i\Omega_p\rho_{13} - i\Omega_s\rho_{32} \tag{2e}$$

$$\dot{\rho}_{13} = -(\gamma_2+\gamma_3-i\Delta_s)\rho_{13} + i\Omega_p\rho_{12} + i\Omega_c\rho_{14} + i\Omega_s(\rho_{11}-\rho_{33}) \tag{2f}$$

$$\dot{\rho}_{14} = -\left[\gamma_4 - i(\Delta_s+\Delta_c)\right]\rho_{14} + i\Omega_c\rho_{13} - i\Omega_s\rho_{34} \tag{2g}$$

$$\dot{\rho}_{23} = -(\gamma_2+\gamma_3-i\Delta_p)\rho_{23} + i\Omega_s\rho_{21} + i\Omega_c\rho_{24} + i\Omega_p(\rho_{22}-\rho_{33}) \tag{2h}$$

$$\dot{\rho}_{24} = -\left[\gamma_1+\gamma_4 - i(\Delta_c+\Delta_p)\right]\rho_{24} + i\Omega_c\rho_{23} - i\Omega_p\rho_{34} \tag{2i}$$

$$\dot{\rho}_{34} = -(\gamma_2+\gamma_3+\gamma_4-i\Delta_c)\rho_{34} - i\Omega_s\rho_{14} - i\Omega_p\rho_{24} + i\Omega_c(\rho_{33}-\rho_{44}) \tag{2j}$$

The above density matrix elements additionally obey the normalization and Hermitian condition $\sum_{i=0}^{2}\rho_{ii} = 1$ and $\rho_{ij} = \rho_{ji}^*$. The electric and magnetic response of the medium to the probe light can be obtained by the same method which is well presented in [64]. The induced complex electric dipole moment of the system is given by:

$$\mathbf{P}(\omega_p) = \mathrm{Tr}\{\hat{\rho}\mathbf{d}\} = \mathbf{d}_{23}\rho_{32} + \text{c.c.} \tag{3}$$

By solving the equation $\mathbf{P}(\omega_p) = \varepsilon_0\alpha_e(\omega_p)\mathbf{E}(\omega_p)$, one can obtain the complex polarizability tensor α_e as follows [64]:

$$\alpha_e = \frac{\mathbf{d}_{23}\rho_{32}}{\varepsilon_0\mathbf{E}_p} = \frac{|d_{23}|^2\rho_{32}}{\varepsilon_0\hbar\Omega_p} \tag{4}$$

Similarly, the magnetic response of the medium to the probe field is related to the coherent term ρ_{21} and given as follows [64]:

$$\alpha_m = \frac{\mu_0 c\,\boldsymbol{\mu}_{12}\rho_{21}}{\eta\mathbf{E}_p} = \frac{\mu_0 c\,\mu_{12}d_{23}\rho_{21}}{\hbar\eta\Omega_p} \tag{5}$$

Thus, the coherence ρ_{21} drives a magnetic dipole, while the coherence ρ_{32} drives an electric dipole. Here μ_0 is the permeability of vacuum, c is the speed of light in vacuum and η is a unitary complex number depending on the polarization of the probe field $\mathbf{E}_p$. The relative permittivity and relative permeability based on the Clausius –Mossotti relations and local effect can be given by [64]:

$$\varepsilon_r = \frac{1 + \frac{2}{3} N\alpha_e}{1 - \frac{1}{3} N\alpha_e} \tag{6}$$

$$\mu_r = \frac{1 + \frac{2}{3} N\alpha_m}{1 - \frac{1}{3} N\alpha_m} \tag{7}$$

By using the expression $n = -\sqrt{\varepsilon_r \mu_r}$, the refractive index of the four-level QD nanostructure can be studied.

In the next step, we describ the structure of the cavity which consists of four-level QD nanostructure for analyzing the GH shifts of the reflected and transmitted light beams. And then discussed the properties of the GH shifts of reflected and transmitted light beams by adjusting the refractive index of intracavity medium. The proposed cavity consists of three layers of materials: two nonmagnetic dielectric slabs ε_1 with the same thickness d_1 and an intracavity medium ε_2 with thickness d_2, as shown in Fig. 2. A probe beam E_p with angular frequency ω_p and angle θ is incident on one side of the cavity which is in the vacuum with permittivity $\varepsilon = 1$. The permittivities of the

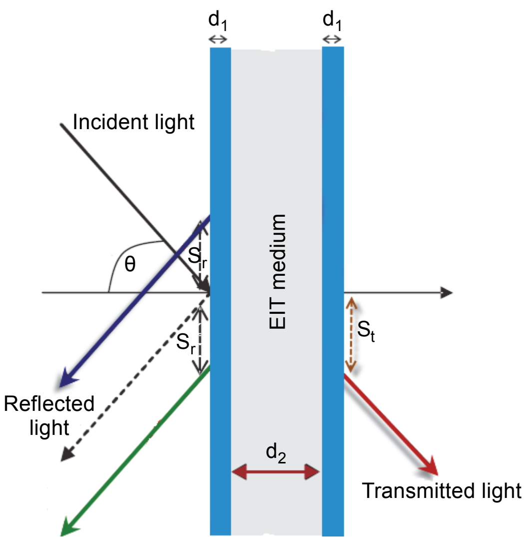

Fig. 2. Schematic diagram of the GH shifts of the reflected and transmitted light beams in a fixed cavity; S_r and S_t denote the GH shifts of reflected and transmitted probe beams, respectively.

layers 1 and 3 are assumed to be constant, while the permittivity ε_2 of the intracavity medium is not constant and given by relation [29]:

$$\varepsilon_2 = 1 + \chi \tag{8}$$

where χ is the susceptibility of the four-level QD nanostructure with positive or negative refraction index.

For the incident probe light to the cavity structure, the GH shifts of both the reflected and transmitted light beams can be obtained by using a stationary phase theory [29]:

$$S_\mathrm{r} = -\frac{\lambda}{2\pi}\frac{1}{|r|^2}\left\{\mathrm{Re}(r)\frac{\mathrm{d}}{\mathrm{d}\theta}\mathrm{Im}(r) - \mathrm{Im}(r)\frac{\mathrm{d}}{\mathrm{d}\theta}\mathrm{Re}(r)\right\} \tag{9a}$$

$$S_\mathrm{t} = -\frac{\lambda}{2\pi}\frac{1}{|t|^2}\left\{\mathrm{Re}(t)\frac{\mathrm{d}}{\mathrm{d}\theta}\mathrm{Im}(t) - \mathrm{Im}(t)\frac{\mathrm{d}}{\mathrm{d}\theta}\mathrm{Re}(t)\right\} \tag{9b}$$

where r and t are the reflection and transmission coefficients, respectively. For finding the GH shifts of reflected and transmitted light beams, one can calculate the reflection, transmission and permittivity of the intracavity medium first. The more mathematical and physical interpretations about finding these coefficients can be realized in details in [47, 71]. In the next section, we will first study the refraction index of the intracavity medium and discuss about the positive and negative refraction index and then will study the properties of GH shifts in both reflected and transmitted light beams for both positive and negative refraction index.

3. Results and discussion

Now we discuss in details the effects of quantum interference on the refractive index of intracavity medium and then study the GH shifts of the transmitted and reflected probe beams for positive and negative value of it. It is known that the thickness of intracavity medium can affect the GH shifts of reflected and transmitted light beams [29], but here we consider a fixed cavity structure and manipulate the GH shifts of reflected and transmitted light beams only by adjusting the refractive index of the intracavity medium. By solving the density-matrix Eq. (2) we explore the sign property of both electric permittivity and magnetic permeability of four-level QD nanostructure. Moreover, we will use these results for analyzing the GH shifts of the transmitted and reflected probe beams in the cavity with the negative refractive index. In our numerical calculation, all of the parameters are scaled by the spontaneous emission rate which is in order $\gamma = 10^9$ Hz. The values of decay rates are chosen as $\gamma_1 = 0.2\gamma$, and $\gamma_2 = \gamma_3 = \gamma_4 = 0.1\gamma$. Moreover, we assume $\Delta_\mathrm{s} = \Delta_\mathrm{c} = 0.01\gamma$ and $\Delta_2 = 0.1\gamma$ which are the detunings of applied fields. The atomic density is also chosen as $N = 8 \times 10^{21}\ \mathrm{m}^{-3}$.

In the following part, we discuss the property of both electric permittivity and magnetic permeability through the numerical calculations. For determining the frequency

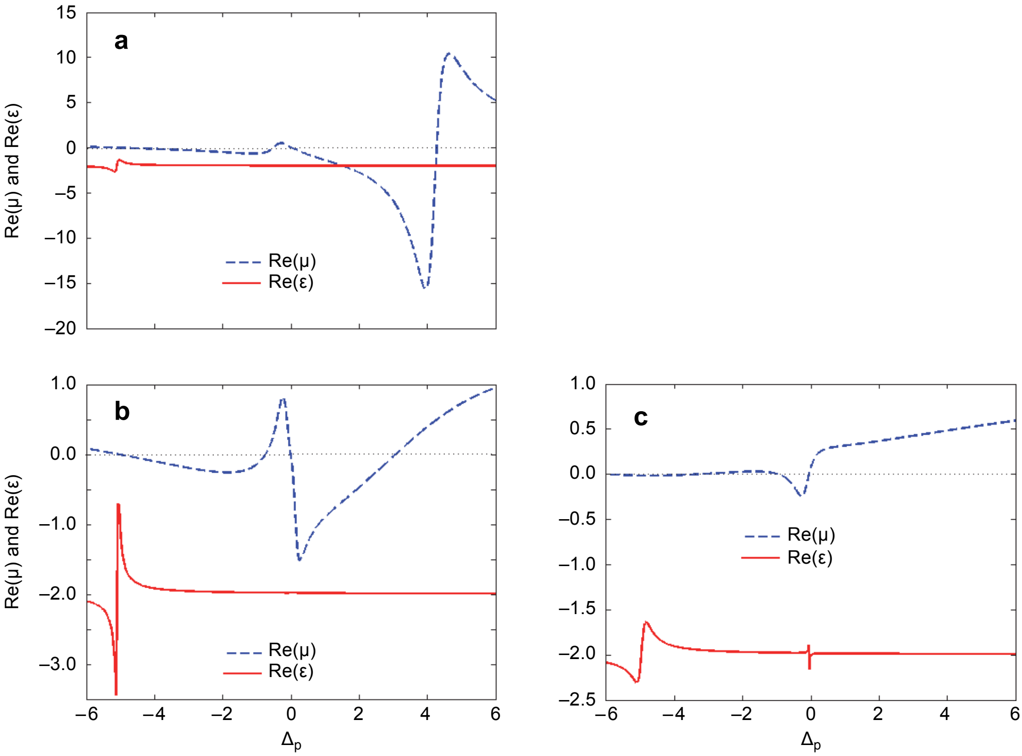

Fig. 3. Real parts of the permittivity ε_2 (solid line) and permeability μ_2 (dashed lines) as a function of the fields detuning Δ_p with relative phase $\Phi = 0$ (**a**), $\Phi = \pi/6$ (**b**), and $\Phi = 3\pi/2$ (**c**). The selected parameters are $\Omega_c = 3.5\gamma$, $\Omega_s = 5.5\gamma$, $d_1 = 20$ nm and $d_2 = 80$ nm.

bands of negative refraction index, we will present the real parts of the relative electric permittivity ε_2 and magnetic permeability μ_2 *vs.* probe light detuning in Fig. 3. We know that in the presence of magnetic field, the medium becomes phased dependent. Therefore, we can consider the impact of relative phase Φ on refractive index of the four-level QD nanostructure. It is found that for the some frequencies, the real part of permittivity and permeability can be simultaneously negative when we assume $\Phi = 0$, $\pi/6$, and $3\pi/2$. In these frequencies bands, the four-level quantum system becomes a left-handed medium. In Fig. 4, we consider the influence of Rabi frequencies Ω_s (**a**) and Ω_p (**b**) on the real parts of electric permittivity ε_2 and magnetic permeability μ_2, respectively. The obtained results show that the real part of relative electric permittivity in any frequencies of probe light becomes negative, while the real part of the magnetic permeability in some frequencies of probe light becomes negative and in other frequencies has positive values. In these conditions, we find that the QD nanostructure behaves as left-handedness medium with both negative permittivity and permeability.

In Fig. 5, we discuss the GH shifts properties of reflected and transmitted light beams for two cases. In case one, we assume that the refractive index of doped QD nano-

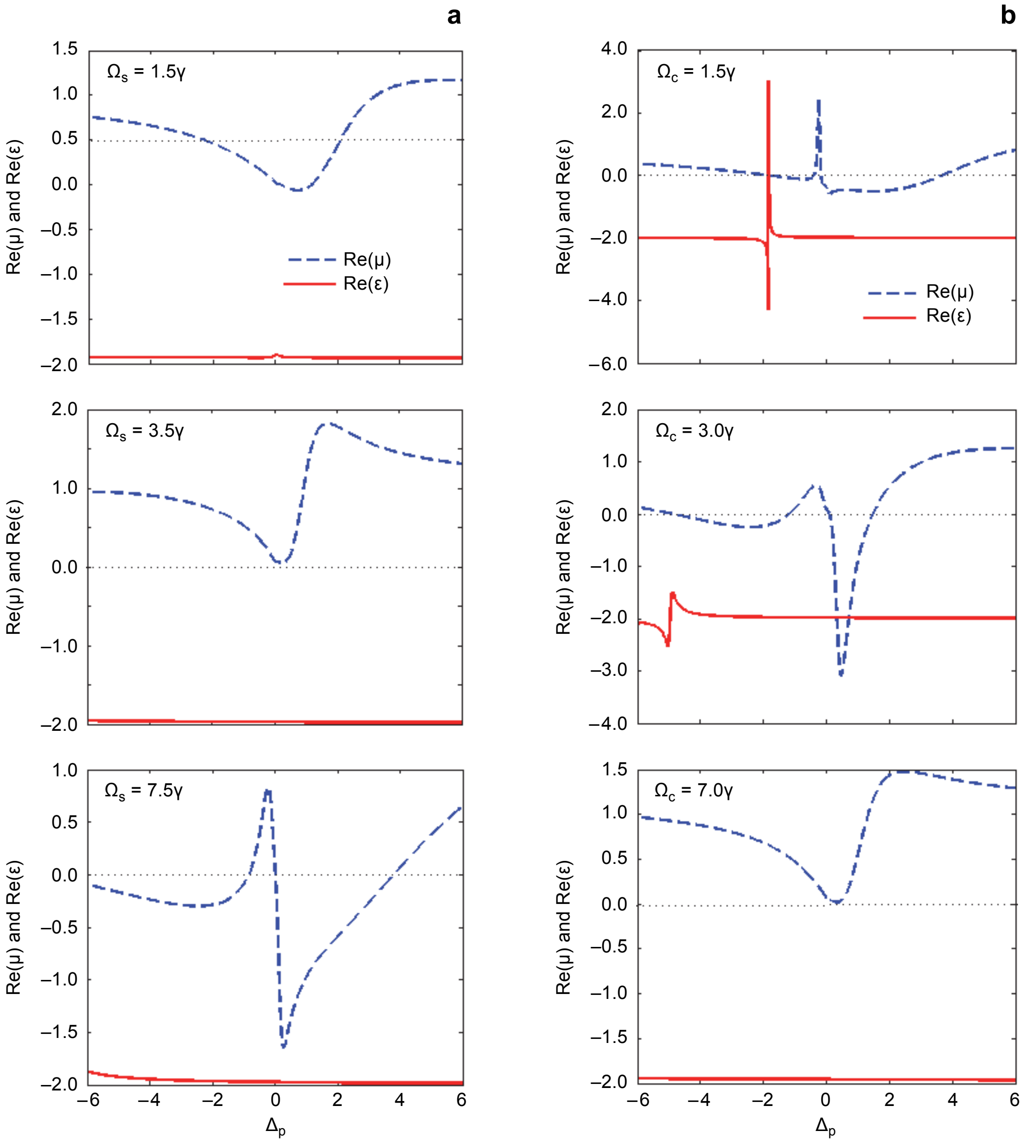

Fig. 4. Real parts of the permittivity ε_2 (solid line) and permeability μ_2 (dashed lines) as a function of the fields detuning Δ_p at the varied Rabi frequencies of signal field $\Omega_s = 1.5\gamma$, 3.5γ, 7.5γ and $\Omega_c = 5\gamma$ (**a**), and at the varied Rabi frequencies of coupling field $\Omega_c = 1.5\gamma$, 3γ, 7γ and $\Omega_s = 4\gamma$ (**b**). The selected parameter is $\Phi = \pi/6$ and the other parameters are the same as in Fig. 3.

structure becomes positive and in case two we suppose the refractive index of doped material becomes negative. Here, we find that the GH shifts behaviors of reflected and transmitted light beams are the same for both values of refractive index. However,

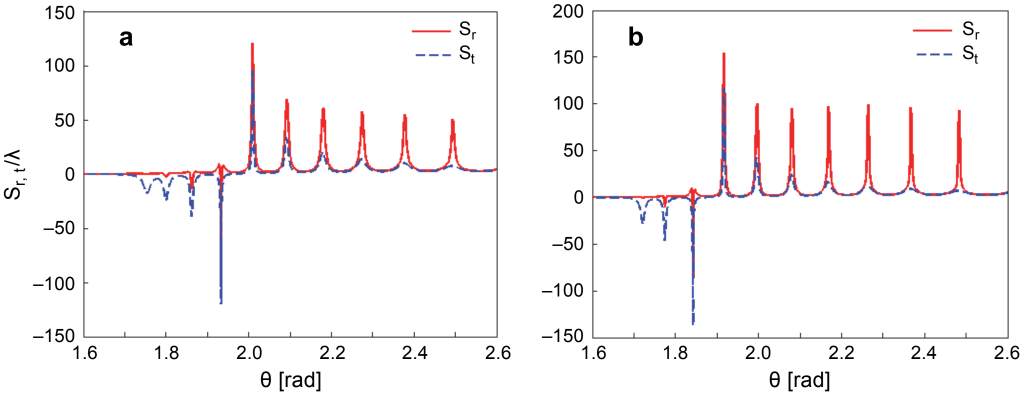

Fig. 5. The phase dependence of both S_t (dashed line) and S_r (solid line) on the incident angle of probe light beam for positive refractive medium (**a**), and $\Delta_p = 1.5\gamma$ in negative refractive medium (**b**). The selected parameter is $\Phi = 0$ and the other parameters are the same as in Fig. 3.

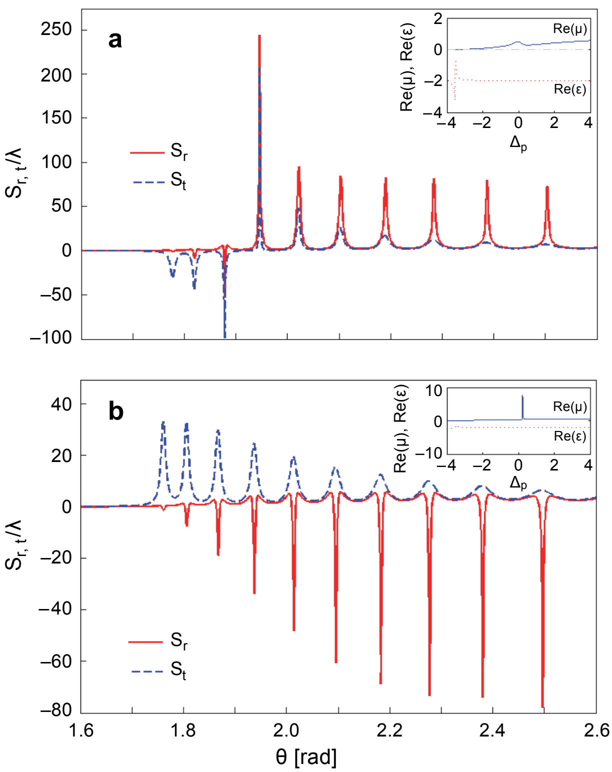

Fig. 6. The phase dependence of both S_t (dashed line) and S_r (solid line) on the incident angle of probe light beam for positive refraction index of intracavity medium: $\Phi = \pi/2$ (**a**), and $\Phi = \pi$ (**b**). The selected parameters are $\Omega_s = 4\gamma$ and $\Omega_c = 2.5\gamma$, and the other parameters are the same as in Fig. 3.

when we assume the refractive index becomes negative, the values of GH shifts enhance dramatically with respect to the positive refractive index.

The effects of relative phase of applied fields on GH shifts of reflected and transmitted probe beams in positive (Fig. 5**a**) and negative (Fig. 5**b**) refractive medium are presented in Fig. 6. It can be seen that for $\Phi = \pi/2$ and $\Phi = \pi$ at $\Delta_p = 2.5\gamma$, the refractive index of intracavity medium becomes positive. In this condition, the GH shifts for the reflected and transmitted probe beams can be altered by changing the relative phase Φ. It is observed that for $\Phi = \pi/2$ (Fig. 6**a**) both values of S_r and S_t can be increased and they simultaneously become positive or negative at specific angles. However, for $\Phi = \pi$, the GH shift of the reflected probe beam becomes highly negative at the resonant angle, while the GH shift of the transmitted probe beam becomes positive in the same angles (Fig. 6**b**). In this case, the lateral shifts of the reflected and transmitted light beams are very small. The phase dependence of GH shifts for reflected and transmitted light beams for the negative refraction index of intracavity medium are presented in Fig. 7. We realize that for the negative refractive index of intracavity medium, the GH shifts of reflected and transmitted light beams simultaneously become positive or negative

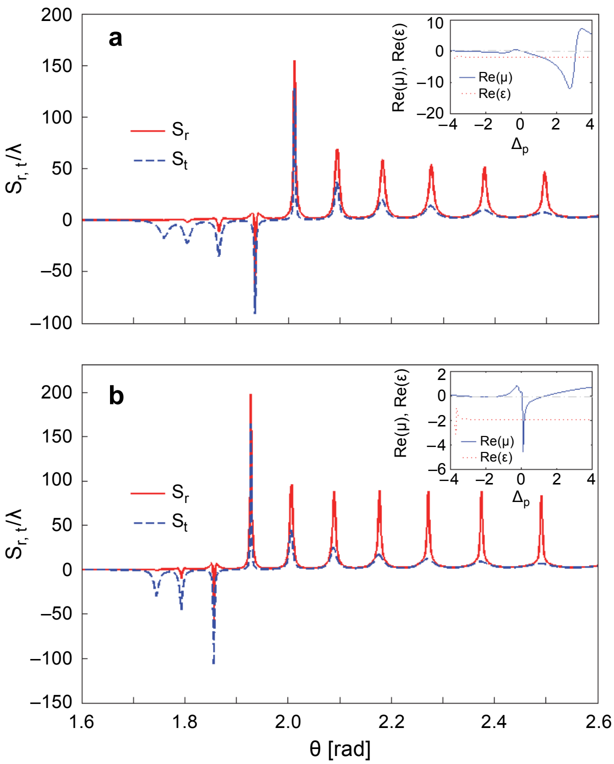

Fig. 7. The phase dependence of both S_t (dashed line) and S_r (solid line) on the incident angle of probe light beam for negative refraction index of intracavity medium: $\Phi = 0$ (**a**), and $\Phi = \pi/4$ (**b**). The selected parameters are $\Omega_s = 4\gamma$ and $\Omega_c = 2.5\gamma$, and the other parameters are the same as in Fig.3.

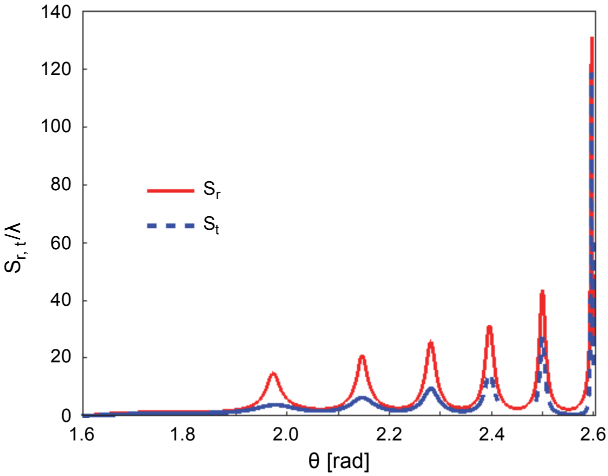

Fig. 8. The dependence of both S_t (dashed line) and S_r (solid line) on the incident angle of probe light beam for negative refraction index of intracavity medium for $d_2 = 60$ nm. The other selected parameters are same as in Fig. 7.

in certain angels of incident light. In the other word, by controlling the relative phase of applied fields, probe field detuning, Rabi frequencies of coupling and magnetic fields and under the certain conditions, the large GH shifts of the reflected and transmitted probe beam can be both positive and negative in the negative refractive index of defect slab doped QD nanostructure. Before ending this paper, we will discuss the thickness effect of intracavity medium on GH shifts of reflected and transmitted light beams. The thickness effect of intracavity medium has been well studied in [29]. In Fig. 8, we will discuss the thickness of intracavity medium for $d_2 = 60$ nm. It can be seen that for this thickness of the intracavity medium, the GH shifts in reflected and transmitted light beams have similar behaviors and positive value. This is a very interesting result which has not been reported yet.

4. Conclusion

In conclusion, we have analyzed the behavior of the GH shifts in the reflected and transmitted probe light beams in the cavity containing a four-level InGaN/GaN QD nanostructure driven by tunable infrared laser pulses and magnetic fields. We find that under certain conditions by controlling the relative phase of applied fields, Rabi frequencies of coupling and magnetic fields, the large GH shifts of the reflected and transmitted probe beam can be both positive and negative in the negative refractive index of defect slab doped QD nanostructure. Our obtained results illustrate the potential to utilize tunneling-induced interference for optimizing the GH shifts within negative refraction medium, as well as guidance in the design of optical devices in sensors and information processing.

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