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Goos–Hänchen shifts of partially coherent light beams from a cavity with a four-level Raman gain medium

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ABSTRACT

We theoretically investigate spatial and angular Goos–Hänchen (GH) shifts (both negative and positive) in the reflected light for a partial coherent light incident on a cavity. A four-level Raman gain atomic medium is considered in a cavity. The effects of spatial coherence, beam width, and mode index of partial coherent light fields on spatial and angular GH shifts are studied. Our results reveal that a large magnitude of negative and positive GH shifts in the reflected light is achievable with the introduction of partial coherent light fields. Furthermore, the amplitude of spatial (negative and positive) GH shifts are sharply affected by the partial coherent light beam as compared to angular (negative and positive) GH shifts in the reflected light.

1. Introduction

The spatial Goos–Hänchen (GH) shift means the lateral displacement of a light beam from its expected geometrical optics path. The existence of this shift was first observed experimentally by Goos and Hänchen in 1947 [1] in the phenomenon of total internal reflection from the interface of two different media. Since then, a lot of attention has been emerged to study the spatial GH shift (positive) using different systems [2–5]. In addition to positive GH shifts, several media also give negative GH shifts, such as negative permittivity media [6], negative refractive media [7,8] and absorptive media [9]. Furthermore, due to the fundamental nature of the lateral shift, there are also interesting application to measure various quantities such as beam angle, refractive index, displacement, temperature, and film thickness [10]. The phenomenon of spatial GH shift can also be used for the characterization of the permeability and permittivity of materials [11] and in the development of near-field optical microscopy and lithography [12].

In addition to spatial GH shifts due to the total reflection of light beam, angular GH shift also occurs due to the partial reflection [13,14]. The angular GH shift is a small deviation from the law of reflection i.e., $\theta_{Inc} = \theta_{Ref}$ [14,15] and has been investigated experimentally in optical and microwave regimes [16,17]. Even though, it is common thinking that the spatial and angular GH shifts are two different phenomena and do not depend on each other, the dual nature of angular and spatial GH shifts in the reflected light has been studied [18].

To have a coherent control on the GH shifts in the reflected light (both for spatial and angular shifts), several schemes are proposed by using different atomic media in a cavity [19–21]. In these investigations, a coherent light beam is considered for the investigations on the negative and positive GH shifts in the reflected light without changing the structure of the medium, which shows that the coherence plays an important role to study the GH shift.

Now a debate raises whether the GH shift is influenced by the partial coherent light beam or not. Simon and Tamir were the first to consider a partially coherent light beam incident on a multilayer structure and reported that the spatial GH shift could not be affected by spatial coherence [22]. Similarly, a theory of GH shift has reported for partially coherent light beams, revealing that the spatial coherence has no effect on spatial GH shift [23]. Later, the influence of spatial coherence on spatial GH shift has been studied experimentally, and concluded that the spatial coherence has no effect on the GH shift [24,25]. However, in some other studies

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[26,27], the spatial GH shift in the reflected light depends on the spatial coherence.

This challenge has been solved thoroughly by Wang and coworkers for the first time [28], then by Ziauddin and coworkers in considering a partial coherent light incident on cavity having three-level Raman gain medium [29]. In our previous article [29], we concentrated the effect of partial coherent light field on negative and positive GH shifts in the reflected light. Even though control of negative and positive GH shifts was demonstrated with the corresponding probe field detuning, it is a difficult task experimentally to realize such a proposal. Therefore, it is constructive to revisit the problem on spatial and angular GH shifts (negative and positive) via external control field for a partial coherent light field. In this work, we consider a partial coherent light field incident on a cavity embedded with a four-level Raman gain atomic medium. We report the control of negative and positive GH shifts in the reflected light via external control field Ω_2. The spatial and angular GH shifts in the reflected light are studied, for different spatial coherence, beam widths, and mode indexes of partial coherent light beams. The current study of the GH shift in the reflected light has an advantage over the previous investigation [19], because giant spatial GH shift in the reflected light is investigated. Besides, we also investigate that the angular GH shifts in the reflected light are less affected via spatial coherence, beam width and mode index of partial light beam as compared to spatial GH shift. In contrary to the coherent counterpart, a completely different scenario for spatial and angular GH shifts in the reflected light happens with partial coherent light fields.

2. Model

We consider a TE-polarized partial coherent light field incident on a cavity, which contains an atomic vapor cell. The incident partial coherent light beam makes an angle θ with z-direction. Inside the cavity, each atom follows a N-type atomic configuration and the atom-field system behaves as a Raman gain process. The cavity consists of three-layers, labeled as 1, 2 and 3, see Fig. 1(a). The layers 1 and 2 are the walls of the cavity with thickness d_1 and permittivity ϵ_1; while the layer 3 is the intracavity medium with thickness d_2 and permittivity ϵ_2. The permittivity ϵ_2 of the intracavity medium is directly related to the susceptibility of the medium via the relation $\epsilon_2 = 1 + \chi$.

We follow the same approach as reported previously [28,29] and use Marcer's mode expansion. The mth-order mode of electric fields in a partial coherent light field at $z=0$ can be written as

$$E^i_m(z, y) = \frac{1}{\sqrt{2\pi}} \int E_m(k_y - k_{y0}) e^{i(k_z z + k_y y)}\, dk_y, \tag{1}$$

where

$$E_m\left(k_y - k_{y0}\right) = \frac{1}{(2c\pi)^{1/4}} \times \frac{(-i)^m}{\sqrt{2^m m!}} \times e^{\frac{(k_y - k_{y0})^2}{4c}} \times H_m\left(\frac{\left(k_y - k_{y0}\right)}{\sqrt{2c}}\right), \tag{2}$$

is the angular spectrum that can be calculated using a Gaussian Schell model (GSM) beam. For the normalized eigen-function in GSM light beams, one has [30]

$$E_m(y) = (2c/\pi)^{1/4} \times \frac{1}{\sqrt{2^m m!}} H_m[y\sqrt{2c}\,] e^{-cy^2}. \tag{3}$$

One can calculate the corresponding angular spectrum $E_m(k_y)$ by taking Fourier transform of Eq. (3). Here, $E_m(k_y)$ is replaced by $E_m(k_y - k_{y0})$, and k_y is the y-component of the wave vector k, $k_{y0} = k \sin\theta$, and θ is the incident angle. In Eqs. (2)–(3), H_m is the Hermite polynomials and $c = [a^2 + 2ab]^{1/2}$, which can be calculated using the eigenvalues $\beta_m = A^2[\pi/(a + b + c)]^{1/2}[b/(a + b + c)]^m$ of GSM beams with $a = (4w_s^2)^{-1}$, $b = (2w_g^2)^{-1}$. Furthermore, w_g and w_s are the spectral coherence and beam width of partial coherent light, respectively. We have the expression for $c = (q^2 + 4)^{1/2}/(4qw_s^2 \sec^2\theta)$ with $w_s \to w_s \sec\theta$ and $w_g \to w_g \sec\theta$. To describe a partially coherent light field, the parameter $q = w_g/w_s$ measures the degree of the coherence in a GSM beam, which is also denoted as the spatial coherence.

For the reflected partial coherent light in mth-order mode, we have [28,29]

$$E^r_m(y) = \frac{1}{\sqrt{2\pi}} \int r\left(k_y\right) E_m\left(k_y - k_{y0}\right) e^{ik_y y}\, dk_y, \tag{4}$$

where $r(k_y)$ is the reflection coefficient of the proposed cavity, which can be calculated using the characteristic matrix [20] as

$$m_j\left(k_y, \omega_p, d_j\right) = \begin{pmatrix} \cos(k^z_j d_j) & i\,\sin(k^z_j d_j)/q_j \\ iq_j\,\sin(k^z_j d_j) & \cos(k^z_j d_j) \end{pmatrix},$$

where $k^z_j = k\sqrt{\epsilon_j - \sin^2\theta}$ is the wave number of three-layer structure, $k = \omega/c$ in vacuum, c is the speed of light, $q_j = k^z_j/k$, d_j is the thickness of jth layer. Our system consists of three layers, therefore, the total transfer matrix for the system can be written as,

$$Q(k_y, \omega_p) = m_1(k_y, \omega_p, d_1) m_2(k_y, \omega_p, d_2) m_1(k_y, \omega_p, d_1),$$

and finally the reflection coefficient can therefore be calculated as,

$$r(k_y, \omega_p) = \frac{q_0(Q_{22} - Q_{11}) - (q_0^2 Q_{12} - Q_{21})}{q_0(Q_{22} + Q_{11}) - (q_0^2 Q_{12} + Q_{21})}, \tag{5}$$

where Q_{ij} be the elements of total transfer matrix $Q(k_y, \omega_p)$ and $q_0 = \sqrt{\epsilon_0 - \sin^2\theta}$ and $r(k_y, \omega_p) = |r(k_y, \omega_p)| e^{i\phi_r}$, where ϕ_r is phase

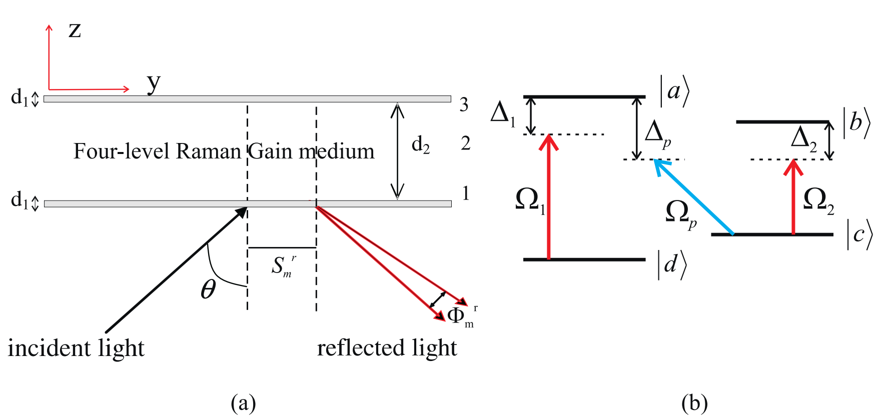

Fig. 1. (a) Schematics of the partial coherent light field incident on a cavity; (b) the energy-level configuration of a four-level Raman gain medium.