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Tunable lateral shift in a prism-waveguide system with biaxially anisotropic metamaterial

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ABSTRACT

We construct a prism-waveguide system with electro-optical (EO) crystal and biaxially anisotropic metamaterial (BAM) as the prism and guiding layer, respectively. Stationary-phase approach is employed to explore the modulation of EO material on the phase, reflectivity and lateral shift, different thicknesses of air and BAM are also considered. Simulation results show that the refractive index change of EO material does not change the maximum value of lateral shift and a configuration with larger phase maximum value, smaller reflectivity minimum and sharper angle-reflectivity curve generates a larger value of absolute value of lateral shift. These results give us a guidance for the design of EO-modulated sensors based on tunable lateral shift.

1. Introduction

Metamaterial with negative permeability and/or permittivity is a type of artificial composite [1] with a large number of unusual electromagnetic properties, such as negative refractive index, anti-parallel group and phase velocities [2]. It has significant applications in perfect lens, flat lens imaging and optical information storage for amplifying evanescent waves. Metamaterial can be artificially fabricated by metal strips and split ring resonators, and they are intrinsically anisotropic on account of the orientations of the rings and rod in space [3] with permittivity and permeability tensors. When the diagonal parameters are different with each other, the metamterial can be termed as biaxially anisotropic metamaterial (BAM).

Goos-Hänchen (GH) shift is a lateral shift of the reflected light beam occurs from the position predicted by geometrical optics when a light beam is totally reflected at a dielectric interface [4,5], which is of the order of the wavelength in an ordinary case. Recently the enhancement of GH shift has attracted much attention of researchers and large lateral shift has been realized in different structures [6] for its potential applications in integrated optics, optical storage and optical sensors, such as a Krestschmann configuration with long-range surface plasmon resonance and a prism-waveguide system with gold layer. As tunable giant lateral shift is significant for further applications in flexible optical beam steering and optical devices in information processing [7], the modulation of giant GH shift was realized by two-dimensional photonic crystals or electro-optic nanostructures in 2008 [8,9]. Recently Wang et al. reported an electrical controllable giant GH shift in a Kretschmann configuration consists of electro-optic (EO) crystal and gold film with an applied electric field [7]. In this structure, surface plasmon resonance (SPR) was excited at the interface of gold film and EO crystal, and the giant GH shift can be adjustable by the change of applied electric field.

In this paper, we introduce EO crystal and BAM into the prism-waveguide system as the prism and guiding layer, respectively. We make use of stationary-phase approach to explore the modulation of EO material on the phase, reflectivity and GH shift, and with different thicknesses of air and BAM layers, the lateral shift can be adjusted flexibly.

2. Model and theory analysis

We adopt a classic prism-waveguide system [3] as shown in Fig. 1, where the relative permittivity of the EO prism, air layer, BAM and dielectric are denoted by ε_1, ε_2, ε_3 and ε_4, respectively, and the relative permeabilities are denoted by μ_1, μ_2, μ_3 and μ_4, here we assume ε_1, ε_2 and ε_4 are positive real numbers, and $\mu_1 = \mu_2 = \mu_4 = 1$.

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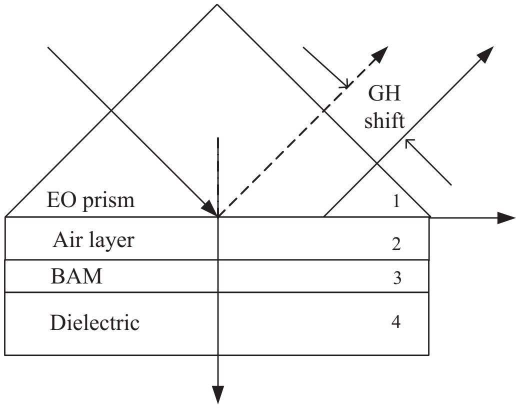

Fig. 1. Schematic diagram of prism-waveguide system.

In our configuration, ε_3 and μ_3 are biaxially anisotropic tensors with

$$\varepsilon_3 = \varepsilon_0 \begin{pmatrix} \varepsilon_x & & \\ & \varepsilon_y & \\ & & \varepsilon_z \end{pmatrix} \quad \text{and} \quad \mu_3 = \mu_0 \begin{pmatrix} \mu_x & & \\ & \mu_y & \\ & & \mu_z \end{pmatrix}$$

where, $\varepsilon_j = \varepsilon_{jr} + i\varepsilon_{ji}$ and $\mu_j = \mu_{jr} + i\mu_{ji}$ $(j = x, y, z)$.

The reflection coefficient of the four-layer optical system can be written as:

$$r_{1234} = \frac{r_{12} + r_{12}r_{23}r_{34}\exp(2ik_{3z}d_3) + [r_{23} + r_{34}\exp(2ik_{3z}d_3)]\exp(2ik_{2z}d_2)}{1 + r_{23}r_{34}\exp(2ik_{3z}d_3) + r_{12}[r_{23} + r_{34}\exp(2ik_{3z}d_3)]\exp(2ik_{2z}d_2)} \tag{1}$$

with

$$r_{ij} = \begin{cases} \dfrac{k_{iz}/\varepsilon_i - k_{jz}/\varepsilon_j}{k_{iz}/\varepsilon_i + k_{jz}/\varepsilon_j} & \text{TM wave} \\ \dfrac{k_{iz} - k_{jz}}{k_{iz} + k_{jz}} & \text{TE wave} \end{cases} \tag{2}$$

where r_{ij} is the Fresnel reflection coefficient and k_{iz} are the normal components of the wave vectors in each medium. In layers 1, 2 and 4, $k_{iz} = k_0\sqrt{\varepsilon_i\mu_i - k_x^2}$, while in layer 3 with BAM, $k_{iz} = k_0\sqrt{\varepsilon_x\mu_y - (\varepsilon_x/\varepsilon_z)k_x^2}$ for $\varepsilon_x > 0$ and $k_{iz} = -k_0\sqrt{\varepsilon_x\mu_y - (\varepsilon_x/\varepsilon_z)k_x^2}$ for $\varepsilon_x < 0$.

The reflection coefficient of the four-layer optical system can be approximated by a Lorentzian-type relation around the resonance angle and written as:

$$r_{1234} = r_{12}\frac{k_x - \mathrm{Re}(\beta^0) - \mathrm{Re}(\beta^{\mathrm{rad}}) - i\left[\mathrm{Im}(\beta^0) - \mathrm{Im}(\beta^{\mathrm{rad}})\right]}{k_x - \mathrm{Re}(\beta^0) - \mathrm{Re}(\beta^{\mathrm{rad}}) - i\left[Im(\beta^0) + \mathrm{Im}(\beta^{\mathrm{rad}})\right]} \tag{3}$$

where r_{12} is the Fresnel reflection coefficient from prism to coupling layer, β^0 is the eigenpropagation constant of a guided mode for the three layer waveguide (layer2, layer 3 and layer4) in which the thickness of layer 2 is semi-infinite and β^{rad} is the difference between the eigenpropagation constants of the three-layer waveguide and the prism-waveguide system.

We assume, $W = k_x - Re(\beta^0) - Re(\beta^{rad})$, and the reflectivity of the prism-coupling waveguide system can be obtained as:

$$R = |r_{12}|^2\left(1 - \frac{4\mathrm{Im}(\beta^0)\,\mathrm{Im}(\beta^{\mathrm{rad}})}{W^2 + \left(\mathrm{Im}(\beta^0)^2 + \mathrm{Im}(\beta^{\mathrm{rad}})^2\right)}\right) \tag{4}$$

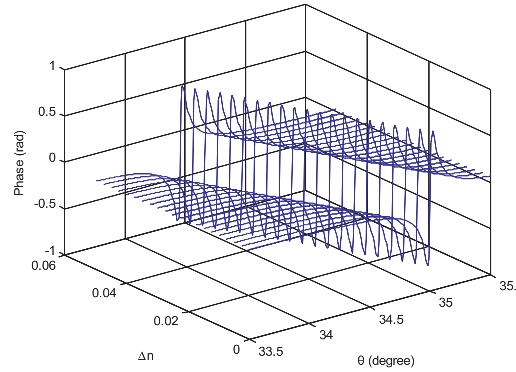

Fig. 2. The dependencies of the phase difference on Δn.

When $W = 0$, the phase-matching condition $k_x = Re(\beta^0) + Re(\beta^{\mathrm{rad}})$ is satisfied, and in this case the reflectivity reaches the minimal value and the GH shift reaches the maximum value. Here we use θ_r to denote the incident angle under the phase-matching condition, and the following simulations are focus on the modulation of EO material on the reflectivity and lateral shift around this incident angle.

According to the stationary-phase approach, the lateral beam shift is given by

$$L = -\frac{1}{k} \times \frac{d\phi}{d\theta} \tag{5}$$

where $\phi = a\tan\left(\mathrm{Im}(ND^*)/\mathrm{Re}(ND^*)\right)$, N and D^* represent the numerator and the complex conjugate of denominator of r_{1234}. The phase shift ϕ is composed of two terms, we use ϕ_1 and ϕ_2 to denote the phase shift induced by r_{12} and the second term, respectively. Then the GH shift can be also written as:

$$L = -\frac{1}{k_0 n_1} \times \frac{d\phi}{d\theta} = -\frac{1}{k_0 n_1}\left(\frac{d\phi_1}{d\theta} + \frac{d\phi_2}{d\theta}\right) \tag{6}$$

Calculations show that, $(d\phi_1/d\theta) \ll (d\phi_2/d\theta)$, therefore $d\phi_1/d\theta$ can be ignored. The GH shift can be rewritten as:

$$L = -\frac{1}{k_0 n_1} \times \frac{d\phi_2}{d\theta} \tag{7}$$

where $\phi_2 = \arctan\left(\left(2WIm(\Delta\beta^{\mathrm{rad}})\right) / \left(W^2 + \left[\mathrm{Im}(\Delta\beta^0)^2 - \mathrm{Im}(\Delta\beta^{\mathrm{rad}})^2\right]\right)\right)$.

3. Simulation results and discussion

A TM polarized light is injected into the interface of prism and cladding layer with a incident angle θ, and k_0 is the wave number of the incident light in the vacuum. Here, we choose $\lambda = 0.98$ µm, $\varepsilon_1 = 6$, $\varepsilon_2 = 1$, $\varepsilon_x = -3 + 0.001i$, $\varepsilon_y = 2.5 + 0.001i$, $\varepsilon_z = -2 + 0.001i$, $\mu_x = 1$, $\mu_y = -1$, $\mu_z = 1.5$, $\varepsilon_4 = 2.5$, $d_2 = 0.1$ µm and $d_3 = 2.6$ µm.

Fig. 2 shows the dependence of the phase difference of the reflected beam on Δn. When the phase-matching condition is satisfied, the phase difference experiences a distinct sharp variation around the resonance angle θ_r. And we can also find θ_r has a shift to smaller incident angle with the increase of Δn. For $\Delta n = 0$, the phase changes from 0.7241 rad to −0.7233 as the incident angle changes from 34.98 degree to 35.02 degree, while for $\Delta n = 0.05$, the phase changes from 0.7241 rad to −0.7233 rad as the incident angle changes from 34.18 degree to 34.22 degree. We can get a conclusion that with the increase of Δn, the phase difference between the maximum and minimum values becomes larger and the incident angles corresponding to these two values are almost unchanged. In Fig. 3, we give the reflectivity of incident