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Large positive and negative lateral shift in prism-waveguide system with left-handed material of weak absorption

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ABSTRACT

We study the mechanism of large positive and negative lateral shift in a prism-waveguide coupling system where the guiding layer is composed of left-handed material with weak absorption. As the giant lateral shift is always dramatically decreased by the loss of guiding layer, we introduce lossy cladding layer and substrate to realize large lateral shift in the above system, theoretical expression of lateral shift is derived and simulation results illustrate the appearance of large lateral shift.

1. Introduction

Goos–Hänchen (GH) shift was firstly demonstrated by Goos and Hänchen in 1947, in which a lateral shift of the reflected light beam occurs from the position predicted by geometrical optics when totally reflected [1,2]. In an ordinary case, the GH shift is of the order of the wavelength which impedes its direct observation in a single reflection. Recently the enhancement of GH shift has attracted much attention of researchers and large lateral shift has been realized in different structures for its potential applications in integrated optics, optical storage and optical sensors. One of such structure is the prism-waveguide system, in which the positive and negative lateral shift was studied, and this effect can be widely used in the detection of surface irregularities, roughness because of its high sensitivity [3]. In this kind of system, we notice that if the guide layer is lossy, the generation of large lateral shift will be significantly influenced, including its location and peak value [3]. In addition Chen reported their observation of large positive and negative lateral shifts on a symmetrical metal-cladding waveguide in their experiment [4,5]. And the experimental results help to realize it applications in precise processing and sensors.

Left-handed material (LHM) is a kind of metamaterial with negative refractive index which is first introduced and analyzed by Veselago [6,7], in which the electric field, the magnetic field, and the wave vector of an electromagnetic wave propagating in it obeys the left-handed rule. For its property of amplifying evanescent waves, LHM shows strong coupling capability in plane waveguides and brings more flexibility in the design of slab waveguide devices [7,8]. In addition, large positive or negative lateral shift in plane waveguides with LHM also attracts much attention due to its potential applications and rich physics [9–12].

In this paper, we study the mechanism of large positive and negative lateral shift in a prism-waveguide coupling system where the guiding layer is composed of left-handed material with weak absorption. As the giant lateral shift is always dramatically decreased by the loss of guiding layer, we introduce a method to realize large lateral shift in the above system by the compensation effect of lossy cladding layer and substrate.

2. Theoretical analysis

We adopt a classic prism-waveguide system [3] as shown in Fig. 1, where the relative permittivity of the prism, cladding layer, LHM and substrate are ε_1, ε_2, ε_3 and ε_4, respectively, and the relative permeability is $\mu_1 = \mu_2 = \mu_4 = 1$ and $\mu_3 = -1$. Here we assume $\varepsilon_2 = \varepsilon_4 = \varepsilon_{2r} + i\varepsilon_{2i}$ and $\varepsilon_3 = \varepsilon_{3r} + i\varepsilon_{3i}$ for the lossy material.

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. According to the stationary-phase approach, the lateral beam shift is given by [3]

$$L = \frac{2Im(\beta_1)\cdot(Im(\beta_0)^2 - Im(\beta_1)^2 - W^2)}{\left(Im(\beta_0)^2 - Im(\beta_1)^2 + W^2\right)^2 + 4W^2 Im(\beta_1)^2}\cos\theta \tag{1}$$

where $W = k_x - \mathrm{Re}(\beta_0) - \mathrm{Re}(\beta_1)$, $k_x = \sqrt{\varepsilon_1}k_0 \sin\theta$, β_0 is the eigen propagation constant of a guided mode for the three layer waveguide (layer 2, layer 3 and layer 4) in which the thickness of

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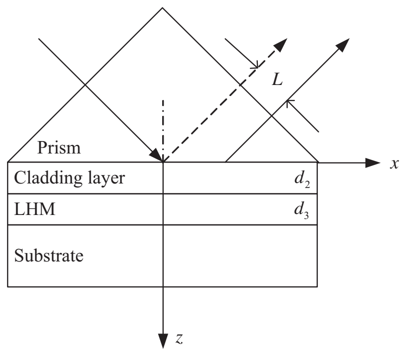

Fig. 1. Schematic diagram of prism-waveguide system.

layer 2 is semi-infinite and β_1 is the difference between the eigen propagation constants of the three-layer waveguide and the prism-waveguide system. Im(β_1) and Im(β_0) can be deduced on the basis of Ref. [13] in the case of ε_2 and ε_4 are complex ($\varepsilon_{2i} \neq 0$). We first define

$$k_{\rm j} = \sqrt{(\beta_0)^2 - k_0^2 \varepsilon_{\rm j}} \quad ({\rm j} = 2, 3, 4) \tag{2}$$

when $\varepsilon_{\rm j}$ is complex and $|\varepsilon_{\rm jr}| \gg \varepsilon_{\rm ji}$, we can obtain

$$k_{\rm j} = \sqrt{(\beta_0)^2 - k_0^2 \varepsilon_{\rm j}} \approx k_{\rm jr} + ik_{\rm ji} \quad ({\rm j} = 2, 3, 4) \tag{3}$$

where

$$k_{\rm jr} = \sqrt{(\beta_0)^2 - k_0^2 \varepsilon_{\rm jr}} \quad ({\rm j} = 2, 3, 4) \tag{4}$$

$$k_{\rm ji} = -\frac{k_0^2 \varepsilon_{\rm ji}}{2k_{\rm jr}} \quad ({\rm j} = 2, 3, 4) \tag{5}$$

Here we introduce a phase-matching condition of $W(\theta_{\rm r}) = 0$, and when the incident angle equals θ_r, an extreme value of lateral shift appears. In order to realize large lateral shift we must make sure the extreme value is rather large. In what following we deduce the sufficient conditions for the appearance of large positive or negative lateral shift from Eq. (1), respectively.

To get a large positive lateral shift, the sufficient condition is

$$0 < (Im(\beta_0)^2 - Im(\beta_1)^2) \ll -Im(\beta_1) \quad \text{or}$$
$$0 < |Im(\beta_0)| \ll Im(\beta_1) \ll 1 \tag{6}$$

To get a negative positive lateral shift, the sufficient condition is

$$0 < (Im(\beta_0)^2 - Im(\beta_1)^2) \ll Im(\beta_1) \quad \text{or}$$
$$0 < |Im(\beta_0)| \ll -Im(\beta_1) \ll 1 \tag{7}$$

Once the above conditions are satisfied, large lateral shift can be generated when $\varepsilon_{2i} \neq 0$ and $\varepsilon_{3i} \neq 0$. Based on the above analysis, we find that even if LHM is lossy, giant lateral shift can still be realized by the use of lossy cladding layer and substrate (2 and 4).

3. Simulation results and discussion

Based on the theoretical analysis in Section 2, we illustrate some simulation results in this section. Here we choose $\lambda = 0.808$ μm, $d_3 = 1.0$ μm, $d_2 = 1.0$ μm, $\varepsilon_1 = 6$, $\varepsilon_2 = \varepsilon_4 = 2.15 + \varepsilon_{2i}$i, $\varepsilon_3 = -4 + \varepsilon_{3i}$i, $\mu_3 = -1$, and $\mu_{\rm j} = 1$ (j = 1, 2, 4). When layers 2, 3 and 4 are all lossless, the lateral shift is shown in Fig. 2. Obviously there is a negative lateral shift of 356.4 μm at $\theta_r = 28.82°$. When the LHM is weakly lossy ($\varepsilon_{3i} = 0.05$), there is no lateral shift peak at a larger range of incident angle around $\theta = 29°$ as shown in Fig. 3. This phenomenon shows a lossy guiding layer can exactly prevent the appearance of large lateral shifts. Then if we introduce a loss compensation of layer 2 and 4, the large lateral shift may appear again. In order to find its exact location, we draw a three dimensional figure about the imaginary part of ε_2 and ε_4 when $\varepsilon_{3i} = 0.05$ as shown in Fig. 4. In these curves we can find two lateral shift peaks generated when $\varepsilon_{2i} \neq 0$. Further study shows that when $\theta_r = 29.08°$, a positive lateral shift of $L = 1634$ μm and negative lateral shift of $L = -1033$ μm appear respectively when $\varepsilon_{2i} = 0.0435$ and $\varepsilon_{2i} = 0.0440$. The peak values of these two lateral shifts both exceed the peak value when LHM is lossless. Here we notice that when ε_{2i} is different, the corresponding θ_r remains 29.08°. This is not because the change of ε_{2i} has no effect on θ_r, but because the change is too small and results in a negligible change of θ_r. We can find that as the increase of ε_{2i} the critical angle θ_r at which the largest lateral shift appears decreases slightly. A detail analysis about strongly lossy cladding and substrate layers will be shown in detail in our other paper. In addition, we must emphasize that certain coupler structure having fixed layer sizes and constants indicates the only shift peak, positive or negative, and the sign of the shift depends on the layer's constants. The reason for the appearance of more than one lateral shift peaks in our figure is due to different ε_{2i} at different peaks. And this is not con-

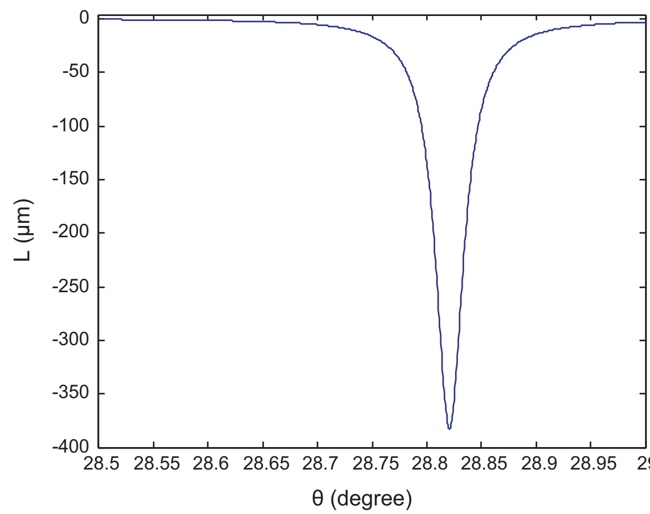

Fig. 2. Calculated lateral shift when $\varepsilon_{3i} = 0$ and $\varepsilon_{2i} = 0$.

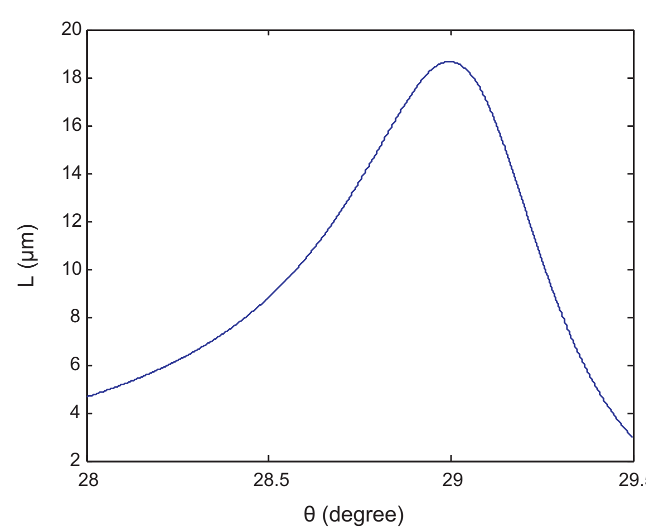

Fig. 3. Calculated lateral shift when $\varepsilon_{3i} = 0.05$, $\varepsilon_{2i} = 0$.