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Lateral shift assisted by guided modes on a metal cladding planar waveguide of micrometer scale

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ABSTRACT

We investigate the lateral shifts of both the reflected and transmitted beams when a Gaussian beam is incident on a symmetrical metal cladding planar waveguide of micrometer scale. Different from the other schemes, the shifts are greatly enhanced when the guided modes are excited and cannot be attributed to the Fabry–Perot like resonance. Owing to the absorption of the metal films, the lateral shifts corresponding to the reflected and transmitted beams are not the same. The displacement of the transmitted beam can be negative, by suitable adjustment of the parameters of the structure, such as the incident angle, wavelength, and etc. Near the resonance dip of the reflection spectrum, the reflected beams undergone significant distortion and may split into two parts with positive and negative shifts, respectively.

1. Introduction

It is highly desirable to efficiently control the lateral shift (Goos–Hänchen effect) of the electromagnetic (EM) waves for its potential applications in fields such as integrated optics, chemical and biological sensing and various devices such as modulator, switch and etc. Different schemes using dispersive materials or structural resonances have been proposed to investigate this effect. For example, giant lateral displacement is possible of both the reflected and transmitted beams on a 1-D photonic crystal containing a defect layer due to the localization of the electromagnetic wave [1]. The metal/dielectric or a dielectric/LHM (left-handed media) interface [2–6] is even demonstrated to be able to generate a negative lateral shift, which is of particular interest. Later it was proposed that the negative shift can also be achieved via a simple slab of optically denser medium [7]. On the other side, many efforts have been devoted to enhance such displacement for the practical purpose. The prism-waveguide coupling system is studied, and the related theory shows that the larger displacement appears when the radiative damping is close to the intrinsic damping [8]. This is demonstrated when Goos–Hänchen shift of hundreds of micrometers is observed in a prism coupled symmetrical metal-cladding optical waveguide structure [9]. Meanwhile, some groups suggest that the lateral shift is proportional to the penetration depth of the light [10], so it seems difficult to achieve a large displacement while reducing its size.

In this paper, we show that it is possible to enhance such effect in a metal cladding planar waveguide structure even of sub-micrometer scale, given that a leaky guided mode can be excited. Both the reflected and transmitted beams are reconstructed as the energy of guided mode leaking into the free space, and large lateral shifts can be achieved. This effect cannot be simply explained by the Fabry–Perot (FP) like resonance, which is resulted from the interference of the multiply reflected waves. The metal film with complex dielectric constant plays a crucial role, namely, its introduced loss can alter the intrinsic damping of the waveguide and thus the magnitude of the lateral shift. However, the shifted light beams are usually broadened or even seriously distorted. This work may lead to interesting applications in optical devices and integrated optics. This paper is organized as follows. In Section 2, we introduce the structure and verify the existence of the guide modes by presenting the dispersion equation and the calculation of reflection spectrum. Numerical results for the planar waveguide with or without metal substrate are shown in Section 3. Our conclusions are summarized in Section 4.

2. Structure and theory

The schematic structure of the metal cladding planar waveguide with metal substrate is illustrated in Fig. 1, where no transmission beam exists due to the attenuation in the substrate. If

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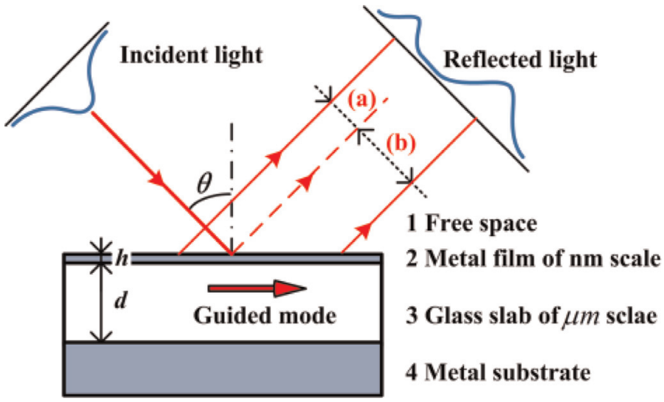

Fig. 1. The reflection of an incident Gauss beam on the metal cladding planar waveguide with metal substrate. As the guided modes are excited, the reflected beam may split into two humps with (a) negative lateral shift and (b) positive shift, respectively.

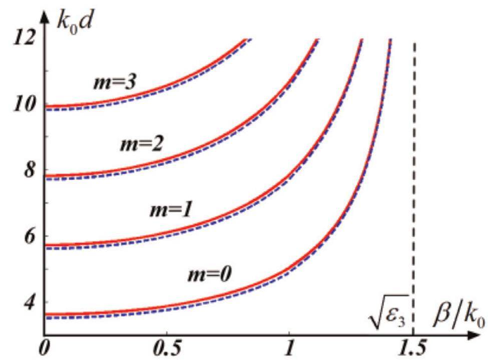

Fig. 2. Dispersion characteristics of the waveguide structure with metal substrate (solid line) and double metal cladding waveguide (dash line). The thickness of the silver film is taken as 15 nm. The wavelength is assumed to be 600 nm and the dielectric constant of silver is calculated by Eq. (1).

we replace the metal substrate with another metal cladding layer of nm scale, both reflection and transmission of the incident beam can be observed. Later, we will refer to the second structure as double metal cladding waveguide. For simplicity, the guiding layer of both structures are assumed to be a quartz glass slab ($\varepsilon_3 = 2.25$) of micrometer or sub-micrometer scale. The metal are assumed to be silver and its dielectric constant is given by

$$\varepsilon_{Ag} = 1 - \omega_p^2/(\omega^2 + i\gamma\omega), \tag{1}$$

where ω is the circular frequency of light, $\omega_p = 1.37036 \times 10^{16}$ Hz is the plasma frequency, and $\gamma = 2\pi \times 0.27332 \times 10^{14}$ Hz. In the following, we restrict ourselves to the TE-polarized waves, while results for the TM-polarized waves could be obtained similarly. Let us begin with the dispersion equation of the leaky modes in the structure in Fig. 1.

$$\kappa_3 d = m\pi + \arctan(\alpha/\kappa_3) + \arctan(p/\kappa_3), \quad (m = 0, 1, 2, 3\cdots), \tag{2}$$

where

$$\begin{cases} \kappa_1 = (k_0^2\varepsilon_1 - \beta^2)^{1/2} \\ \kappa_3 = (k_0^2\varepsilon_3 - \beta^2)^{1/2} \\ \alpha = (\beta^2 - k_0^2\varepsilon_{Ag})^{1/2} \\ p = \alpha\dfrac{\tanh(\alpha h) - i\kappa_1/\alpha}{1 - i\kappa_1 \cdot \tanh(\alpha h)/\alpha} \end{cases},$$

with $\beta = k_0 n_1 \sin\theta$ denotes the propagation constant, θ is the incident angle, $k_0 = 2\pi/\lambda$ is the wave number of vacuum, λ is the wavelength of light and m is the mode order. If we consider the double metal cladding waveguide structure, then Eq. (2) should be replaced by

$$\kappa_3 d = m\pi + 2\arctan(p/\kappa_3), \quad (m = 1, 2, 3\cdots). \tag{3}$$

From Fig. 2, it is clear that the dispersion characteristics of the two structures given by Eqs. (2) and (3) are close to each other, since the transmission probability is relatively small in the double metal cladding waveguide. The propagation constant β can approach zero, which means that the energy can be directly coupled into the waveguide from the free space without applying the prism-coupling method [11], and the guided modes can be excited with a very small incident angle. Furthermore, the guided mode can be excited if the thickness of the guiding layer exceeds a threshold. For $\lambda = 600$ nm, the $m = 0$ mode can be excited if $d > 343$ nm. When the phase match condition of the guide mode is satisfied, energy is lost from the reflected beam to the guided mode and a resonance dip is formed in the reflection spectrum. Fig. 3 plots the reflection probability of the double metal cladding

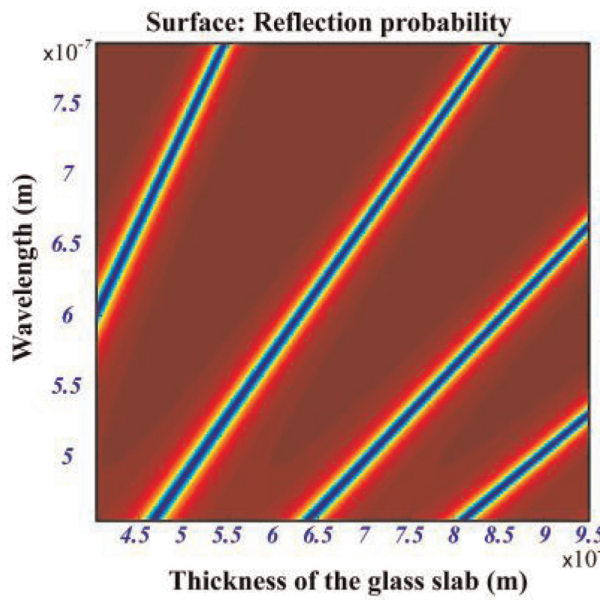

Fig. 3. The reflection probability as a function of both the wavelength and the thickness of the guiding layer. The silver film is of 15 nm thick.

waveguide, which is calculated via the transfer matrix method [12].

3. Enhanced lateral shifts

For a good comparison with the double metal cladding waveguide structure, let us consider a simple Fabry–Perot (FP) cavity with two lossless mirrors of reflectivity R spaced by a distance d [13]. This simple model can also be applied to understand the transmission of electromagnetic waves through successive photonic band gap structure [14] or a planar waveguide below cutoff frequency [15]. Since there is no loss in FP cavity, the lateral shifts of the reflected and transmitted beams should be equal [16]. So let us focus on the lateral shift of the transmitted beam, which according to the stationary-phase approach [17] is presented by

$$S_t = -\frac{\lambda}{2\pi n\cos\theta}\left(\frac{\partial\phi_t}{\partial\theta}\right)\Bigg|_{\omega}, \tag{4}$$

where n is the refractive index of the medium between the mirrors, and the phase shift of the transmission coefficient is