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Physical origin of large positive and negative lateral optical beam shifts in prism–waveguide coupling system

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ABSTRACT

Large lateral beam shift in prism–waveguide coupling system is theoretically analyzed from the viewpoint of interference between multiple reflected beam constituents. It is shown that the reflected beam is a result of interference between two beams: the beam directly reflected from the prism and the total leaky beam coming from guided mode. The thickness of coupling layer determines the amplitude of the total leaky beam, and further determines the sign (positive or negative) of the reflected beam shift. Because of interference between two beams, intrinsic damping itself plays an important role in deciding the distortion of the reflected beam.

1. Introduction

When a beam of light undergoes total internal reflection (TIR) upon an interface between two dielectric media, there exists a lateral shift between the reflected light beam and the incident light beam at the interface. This lateral shift is known as Goos–Hänchen (GH) shift which was first demonstrated [1,2] by Goos and Hänchen, and was theoretically explained by Artmann's stationary phase method [3] and Renard's energy flux method [4]. The GH shift has attracted much attention and has been studied in both theoretical and experimental aspects [3–11]. For TIR of a beam upon an interface between two media, the GH shift is usually of the order of wavelength, but large lateral shift can be obtained by using structural resonances, for example, multilayer structures [12,13], a dielectric slab [14–16] and surface plasmon resonance [17].

It has been reported that abnormally large positive and negative lateral shifts can be achieved in prism–waveguide coupling system (PWCS) [18,19]. Optical sensors based on the large lateral shifts in PWCS have been demonstrated [20,21]. Why does the sign (positive or negative) of lateral beam shift in PWCS depends on the thickness of the coupling layer? This problem can be easily resolved by using stationary phase theory (see Fig. 3 in Ref. [18]), but this explanation lacks physical meaning. In terms of energy flux model [4], the GH shift is believed to be associated with evanescent wave along the interface, and negative GH shift is usually caused by backward propagation of the evanescent wave [5]. Considering the reflection of a plane wave upon a PWCS where all the media have positive permittivity, there is no evanescent wave propagating in the backward direction along the interface in PWCS. So the negative lateral shift cannot be explained from the viewpoint of energy flux. In this work, we investigate the physical origin of the large lateral shift in PWCS. It is shown that with a Gaussian beam illumination, the large lateral shift of the whole reflected beam is caused by superposition of the successively reflected beam constituents. Although all the reflected beam constituents undergo positive lateral shifts, there is an opportunity for the whole reflected beam to reshape by interference between multiple reflected beam constituents to give a negative lateral shift. Because of interference between two beams, the intrinsic damping itself also plays an important role in deciding the distortion of the reflected beam.

2. Lateral shifts in PWCS based on stationary phase theory

The schematic diagram of PWCS is shown in Fig. 1. The guiding layer on the substrate is separated from the high-index prism by a coupling layer (air gap). A TE- or TM-polarized plane wave is incident upon the base of the prism with a resonant angle θ. When $\beta = k_0 n_1 \sin\theta$ where k_0 is the wavenumber in vacuum and β is the propagation constant of guided mode, guided mode is excited in the waveguide, and the intensity of the reflected wave decreases sharply due to the energy transfer from the incident wave into the guided mode. For polarized plane wave incidence with incident

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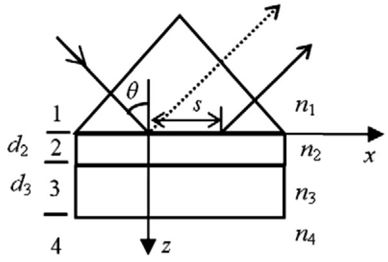

Fig. 1. Schematic diagram of PWCS: (1) prism, (2) coupling layer, (3) guiding layer, and (4) substrate.

angle of θ, as is shown in Fig. 1, the reflection coefficient of the PWCS is written as

$$r = |r|e^{i\varphi} = \frac{r_{12}[1 + r_{23}r_{34}\exp(2i\kappa_3 d_3)] + [r_{23} + r_{34}\exp(2i\kappa_3 d_3)]\exp(2i\kappa_2 d_2)}{1 + r_{23}r_{34}\exp(2i\kappa_3 d_3) + r_{12}[r_{23} + r_{34}\exp(2i\kappa_3 d_3)]\exp(2i\kappa_2 d_2)} \tag{1}$$

with

$$r_{ij} = \begin{cases} \dfrac{\kappa_i/\varepsilon_i - \kappa_j/\varepsilon_j}{\kappa_i/\varepsilon_i + \kappa_j/\varepsilon_j} & \text{for TM wave} \\ \dfrac{\kappa_i - \kappa_j}{\kappa_i + \kappa_j} & \text{for TE wave} \end{cases} \tag{2}$$

where φ is the phase shift, r_{ij} is the Fresnel reflection coefficient, $\varepsilon_i = n_i^2$ is the dielectric constant, d_2 and d_3 are the thicknesses of coupling layer and guiding layer respectively, and $\kappa_i = k_0\sqrt{n_i^2 - n_1^2\sin^2\theta}$ is the normal component of wave vector at medium i. The subscripts i, $j = 1$–4 refer to the prism, the coupling layer, the guiding layer, and the substrate, respectively. Based on stationary phase theory, the lateral beam shift upon PWCS around the angle of resonance is given by $s = -[1/(k_1\cos\theta)]\cdot(\mathrm{d}\varphi/\mathrm{d}\theta)$ with $k_1 = k_0 n_1$, and can be written as [18]

$$s = -\frac{2\mathrm{Im}\left(\Delta\beta^{rad}\right)}{\mathrm{Im}(\Delta\beta^0)^2 - \mathrm{Im}(\Delta\beta^{rad})^2}, \tag{3}$$

where β^0 is the propagation constant of the three-layer waveguide where the thickness of the coupling layer is semi-infinite, and $\Delta\beta^{\mathrm{rad}}$ is caused by the finite thickness of the coupling layer and represents the difference of the propagation constants between three-layer waveguide and the PWCS. So the imaginary part of β^0 (intrinsic damping) represents the absorption of the guided mode in guiding layer, and the imaginary part of $\Delta\beta^{\mathrm{rad}}$ (radiative damping) represents the additional attenuation arising from the outcoupling component through the prism. Since the radiative damping is inversely proportional to the exponential function of the thickness of the coupling layer [22], large positive and negative lateral shifts can be obtained by changing the thickness of coupling layer. Although Eq. (3) is simple, it lacks physical meaning, and the lateral shift can be infinite on the condition that intrinsic damping is equal to radiative damping. More importantly, it cannot explain the negative lateral shift in PWCS from physics, because no wave propagates in backward direction ($-x$ direction) along the interface at the condition that all the media satisfy $\varepsilon_i \geq 1$.

3. The physical origin of lateral shifts in PWCS

For simplicity, a two-dimensional variation ($\partial/\partial y = 0$) is employed. A linearly polarized Gaussian beam is incident upon the base of the prism, and the center of the beam waist is located at ($x = 0$, $z = 0$). The electric (or magnetic) field of the TE (or TM) polarized Gaussian beam at the interface $z = 0$ is approximated by [23] $\psi_i(x, z = 0) = \exp(-x^2/2w_x^2)\exp(ik_{x0}x)$ where $w_x = w_0\sec\theta_0$ with w_0 the width of the beam at waist, $k_{x0} = k_0 n_1\sin\theta_0$ with θ_0 the incident angle of the beam axis, and the time dependence $\exp(-i\omega t)$ is implied and suppressed. The field of the incident beam at the interface $z = 0$ can be expressed by

$$\psi_i(x, z = 0) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} A(k_x)\exp[i(k_x x + k_z z)]dk_x, \tag{4}$$

where $k_x = k_0 n_1\sin\theta$, $k_z = k_0 n_1\cos\theta$, $A(k_x) = w_x\exp[-(w_x^2/2)(k_x - k_{x0})^2]$ is the angular spectral distribution of the incident beam. The field of the reflected beam at the interface $z = 0$ is given by

$$\psi_r(x, z = 0) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} r(k_x)A(k_x)\exp[i(k_x x - k_z z)]dk_x, \tag{5}$$

and the beam shift can be obtained by finding the location where $|\psi_r|_{z=0}$ is maximal. In order to explain the negative and positive lateral shifts, we will divide the reflected field $\psi_r(x, z = 0)$ into a series of reflected field constituents, and investigate interference between those reflected constituents.

Based on the Tien's model [24,25], the fields in PWCS can be divided into groups of waves, as is demonstrated in Fig. 2. A polarized plane wave is incident upon the base of the prism. For simplicity, we only draw one optical ray A_1 at x_n. In fact, the incident wave is uniformly distributed at the base of the prism. In the distance between x_{n-1} and x_n (called propagation period of guided wave), as is shown in Fig. 2(a), the wave (or the ray) $(A_3)_{n-1}$ in the guiding layer is reflected into B_3 wave at the interface between media n_3 and n_4, and B_3 wave is reflected as A_3' wave at the interface between media n_2, and n_3, and is transmitted as B_1' wave (or leaky wave). The waves B_3, B_1', and A_3' form a self-consistent set in the vicinity of $x = x_n$, and their amplitudes are

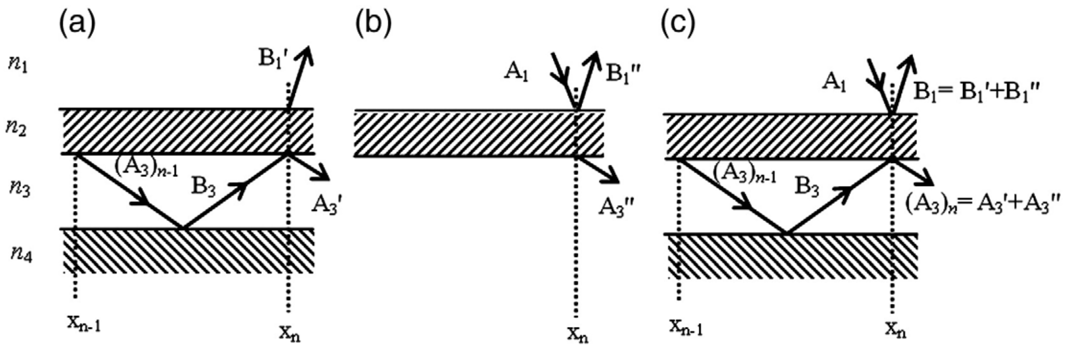

Fig. 2. The waves in PWCS: (a) guided mode coupled to a semi-infinite medium n_1 (the prism) through the coupling layer n_2, (b) two semi-infinite media n_1 and n_3 coupled through the coupling layer n_2, and (c) combination of multiple waves in a PWCS.