Large positive and negative lateral optical beam shift in prism-waveguide coupling system

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In this paper, the lateral beam shift in a prism-waveguide coupling system at wavelengths ranging from visible to near infrared is theoretically examined. A simple theoretical formula is derived to analyze the behavior of the beam shift. We demonstrate that large positive and negative lateral optical beam shifts can be obtained when guided modes are excited. It is also found that the magnitude of the beam shift is closely related to the intrinsic and radiative damping. When the intrinsic damping is larger than the radiative damping, negative lateral beam shift occurs. Numerical calculations confirm the theoretical analysis and show that a beam shift of the order of millimeters is possible.

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I. INTRODUCTION

Since the Goos-Hänchen (GH) shift was first demonstrated experimentally by Goos and Hänchen in 1947 [1], it has been the subject of many theoretical and experimental investigations [2–14]. It refers to the lateral shift of a totally reflected beam from the position predicted by geometrical optics. Artmann explained the effect by expanding the incident beam into its plane wave components, each with a slightly different transverse wave vector. Then each plane wave component undergoes a slightly different phase change after total internal reflection so that the sum of all the reflected plane waves, which forms the reflected beam, results in a lateral shift of the intensity peak [2].

At a single dielectric interface, the GH shift is of the order of the wavelength. The smallness of the shift for optical wavelengths impeded its direct observation in a single reflection until Bretenaker *et al.* proposed a new experimental method based on the sensitivity of laser eigenstates to small perturbations [3]. Large lateral shifts under different conditions were analyzed in many papers [4–11]. Tamir *et al.* have demonstrated the relation between the lateral beam shift and leaky waves and shown that the beam shift in multilayered structures could be of the order of the beam width [4]. Schreier *et al.* reported large positive beam displacement in a waveguide structure, which could reach the millimeter scale at the optical wavelength [6]. Meanwhile, a negative lateral beam shift was found in the reflection from layered structures with left-handed metamaterials [7,10], weakly absorbing media [13,14], negatively refractive media [15,16], resonant artificial structures [17]. Recently, Yin *et al.* reported the observation of abnormally large positive and negative lateral optical beam shifts when the surface plasmon resonance (SPR) is excited. They also found that the optimal metal thickness for minimal reflection in the SPR configuration was identified as the critical thickness above which a negative beam displacement was observed [8].

In this paper, we examine theoretically the lateral beam shift in a prism-waveguide coupling system at wavelengths ranging from visible to near infrared. A simple theoretical formula has been obtained to analyze the behavior of the beam shift. Our calculations show that large positive and negative lateral optical beam shifts can be obtained. It is also found that the lateral beam shift depends on the intrinsic and radiative damping. Negative lateral beam shift can be obtained when the intrinsic damping is larger than the radiative damping. The positive lateral shift corresponds to the reverse case. Numerical simulations demonstrate the validity of the theoretical analysis and show that a lateral beam shift of the order of millimeters is possible.

II. PRINCIPLE

According to the stationary-phase approach, the lateral beam shift is given by [2]

$$S = -\frac{1}{k}\frac{d\phi}{d\theta} \tag{1}$$

where k is the wave vector in the medium of incidence, θ is the incident angle, and ϕ is the phase difference between the reflected and incident waves.

The schematic diagram of the prism-waveguide coupling system is shown in Fig. 1. The guiding film on the substrate is separated from the high-index prism by an air gap. As a polarized laser beam is incident upon the prism base with a synchronous angle which is always larger than the critical angle of total reflection, the intensity of the reflected light decreases sharply due to the energy transfer from the incident light into the guided mode. The reflection coefficient of the four-layer optical system can be written as

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

with

$$r_{ij}=\begin{cases}\dfrac{k_{iz}/\varepsilon_i-k_{jz}/\varepsilon_j}{k_{iz}/\varepsilon_i+k_{jz}/\varepsilon_j} & \text{for TM polarization,}\\[2ex] \dfrac{k_{iz}-k_{jz}}{k_{iz}+k_{jz}} & \text{for TE polarization,}\end{cases} \tag{3}$$

where r_{ij} is the Fresnel reflection coefficient, k_{iz} are the normal components of the wave vectors in each medium, and $\varepsilon_i=n_i^2$ are the dielectric constants. The subscripts $i,j=1-4$ refer to the prism, the air gap, the guiding film, and the substrate, respectively. Here it is assumed that the guiding layer is a weakly absorbing medium and the substrate is lossless. When guided modes are excited, the electromagnetic fields in the air gap and the substrate are evanescent, that is, k_{2z} and k_{4z} are purely imaginary. In order to calculate the lateral beam shift, both the numerator and denominator in Eq. (2) are multiplied by the complex conjugate of the denominator. Then the phase difference ϕ can be defined by

$$\tan\phi=\frac{\mathrm{Im}(ND^*)}{\mathrm{Re}(ND^*)} \tag{4}$$

where N and D^* represent the numerator and the complex conjugate of the denominator in Eq. (2). From Eqs. (1)–(4), the lateral shift of the reflected beam can be obtained.

Under the conditions $|\exp(2ik_{2z}d_2)|\ll 1$, the reflection coefficient of Eq. (2) can be approximated by a Lorentzian-type relation around the resonance angle of a guided mode and may be cast in the form [18]

$$r_{1234}=r_{12}\frac{k_x-[\mathrm{Re}(\beta^0)+\mathrm{Re}(\Delta\beta^{rad})]-i[\mathrm{Im}(\beta^0)-\mathrm{Im}(\Delta\beta^{rad})]}{k_x-[\mathrm{Re}(\beta^0)+\mathrm{Re}(\Delta\beta^{rad})]-i[\mathrm{Im}(\beta^0)+\mathrm{Im}(\Delta\beta^{rad})]} \tag{5}$$

where k_x is the parallel component of the wave vector, and β^0 is the eigenpropagation constant of a guided mode for the three-layer waveguide in which the thickness of the second medium for the proposed configuration is semi-infinite. $\Delta\beta^{rad}$, which arises from the presence of the coupling prism, represents the difference between the eigenpropagation constants of the three-layer waveguide and the prism-waveguide coupling system. It is approximately given by [18]

$$\begin{aligned}\Delta\beta^{rad}=&\{k_{3z}^0r_{12}[r_{23}^0+r_{34}^0\exp(2ik_{3z}^0d_3)]\exp(2ik_{2z}d_2)/2\beta^0\}\\ &\times\left(\frac{\varepsilon_2\varepsilon_3(k_{2z}^{0\,2}-k_{3z}^{0\,2})}{k_{2z}^0(k_{2z}^{0\,2}\varepsilon_3^2-k_{3z}^{0\,2}\varepsilon_2^2)}\right.\\ &\left.+\frac{\varepsilon_3\varepsilon_4(k_{3z}^{0\,2}-k_{4z}^{0\,2})}{k_{4z}^0(k_{3z}^{0\,2}\varepsilon_4^2-k_{4z}^{0\,2}\varepsilon_3^2)}-id_3\right)^{-1}\end{aligned} \tag{6}$$

for TM modes and

$$\Delta\beta^{rad}=\frac{k_{3z}^0r_{12}[r_{23}^0+r_{34}^0\exp(2ik_{3z}^0d_3)]\exp(2ik_{2z}d_2)}{2\beta^0\left(\dfrac{1}{k_{2z}^0}+\dfrac{1}{k_{4z}^0}-id_3\right)} \tag{7}$$

for TE modes, where the superscript 0 denotes the function's value at $k_x=\beta^0$. The imaginary parts of β^0 and $\Delta\beta^{rad}$ are called the intrinsic and radiative dampings, respectively. The former results from $\mathrm{Im}(\varepsilon_3)$ and represents absorption loss of the guided wave due to the materials. The latter represents the leakage loss of the guided mode back into the prism and is inversely proportional to the exponential function of d_2. Calculation shows these two dampings can be roughly approximated by [19]

$$\mathrm{Im}(\beta^0)\cong c_1n_{3i}/d_3 \tag{8}$$

and

$$\mathrm{Im}(\Delta\beta^{rad})\cong\frac{c_2\exp(2ik_{2z}d_2)}{\mathrm{Re}(\beta^0)d_3}, \tag{9}$$

where c_1,c_2 are constants, and n_{3i} is the imaginary part of the refractive index of the guiding layer.

From Eq. (5), the reflectivity of the multilayer system can be written as [18]

$$R=|r_{12}|^2\left(1-\frac{4\,\mathrm{Im}(\beta^0)\mathrm{Im}(\Delta\beta^{rad})}{\{k_x-[\mathrm{Re}(\beta^0)+\mathrm{Re}(\Delta\beta^{rad})]\}^2+[\mathrm{Im}(\beta^0)+\mathrm{Im}(\Delta\beta^{rad})]^2}\right). \tag{10}$$

When the phase-matching condition $k_x=\mathrm{Re}(\beta^0)+\mathrm{Re}(\Delta\beta^{rad})$ is satisfied, the reflectivity reaches the minimal value

$$R_{\min}=|r_{12}|^2\left(1-\frac{4\,\mathrm{Im}(\beta^0)\mathrm{Im}(\Delta\beta^{rad})}{[\mathrm{Im}(\beta^0)+\mathrm{Im}(\Delta\beta^{rad})]^2}\right) \tag{11}$$

and the lateral beam shift at the resonance can be simplified as (see the Appendix)

$$S=-\frac{2\,\mathrm{Im}(\Delta\beta^{rad})}{\mathrm{Im}(\beta^0)^2-\mathrm{Im}(\Delta\beta^{rad})^2}\cos\theta_r \tag{12}$$

where θ_r is the incident angle under the phase-matching condition. Equation (11) shows that the minimal reflectivity of the system becomes zero when the intrinsic damping is equal to the radiative damping, that is to say,

$$\mathrm{Im}(\beta^0)=\mathrm{Im}(\Delta\beta^{rad}). \tag{13}$$

From Eq. (12), it is clear that the sign of the lateral beam shift is determined by the intrinsic and radiative dampings.

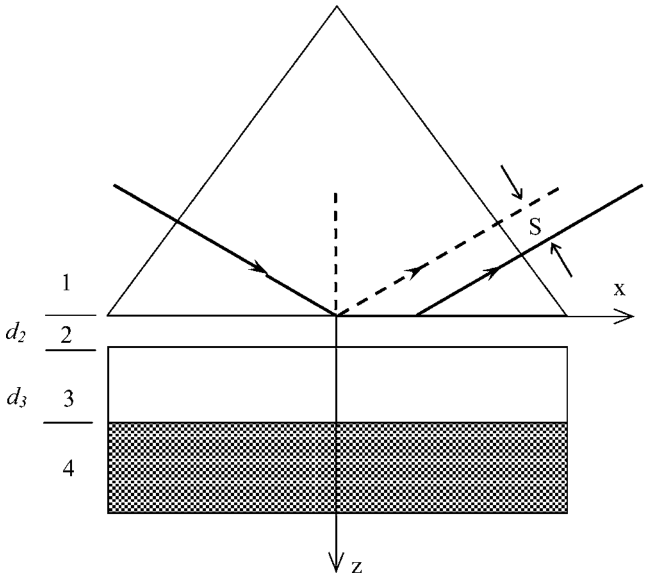

FIG. 1. Schematic diagram of prism-waveguide coupling system: (1) the prism, (2) the air gap, (3) the guiding film, (4) the substrate. $\varepsilon_1=3.23$, $\varepsilon_2=1.0$, $\varepsilon_3=2.8+0.001i$, $\varepsilon_4=2.25$.

When the intrinsic damping is larger than the radiative damping, a negative lateral beam shift can be obtained. The positive lateral shift corresponds to the reverse case.

III. RESULT AND DISCUSSION

From Eqs. (1)–(4), the calculated dependence of the lateral beam shift on incident angle with various thickness of the air gap d_2 is shown in Fig. 2. The incident light is assumed to be a TM-polarized He-Ne laser at the wavelength of 632.8 nm. The parameters are taken as follows: a high-index prism (ZF7, $\varepsilon_1=3.23$), air ($\varepsilon_2=1.0$), a polymer layer ($\varepsilon_3=2.8+0.001i$), glass substrate ($\varepsilon_4=2.25$), and $d_3=1.0$ μm. Without loss of any generality, the TM1 mode is employed as an example. The reflectivity and phase difference ϕ as functions of incident angle with various thickness of the air gap d_2 are plotted in Figs. 3(a) and 3(b). With the parameter set above, $|\exp(2ik_{2z}d_2)|\approx 0.068$, which satisfy the requirement of the derivation of Eq. (5), and the calculated optimal thickness of the air gap for zero reflection is 110 nm. As discussed above, zero reflection means the intrinsic damping is equal to the radiative damping.

Figure 2 shows that the lateral shift S is greatly enhanced owing to the resonance of guided mode. It is shown in Fig. 3 that around the resonance angle of the guided mode, the phase difference experiences a distinct sharp variation. As a result, Artmann's formula Eq. (1) leads to a large lateral beam shift, which can be of the order of millimeter. Figure 3 also shows that the phase difference exhibits different features for different thickness of air gap. The behavior of the lateral shift with the variation of d_2 can be easily explained by use of the intrinsic and radiative dampings in Eq. (12). As mentioned above, the intrinsic damping is independent of the thickness of the air gap d_2 and the radiative damping is inversely proportional to the exponential function of d_2. When $d_2<110$ nm, which means the radiative damping is larger than the intrinsic damping, the phase difference is a monotonically decreasing function of incident angle and the positive lateral beam shift can be obtained. As the thickness of the air gap approaches the optimal value, the lateral shift becomes larger and larger and would approach to an approximated δ function near the optimal thickness 110 nm. In this case, the reflectivity becomes zero and the radiative damping equals the intrinsic damping. Thus the phase difference ϕ suffers an abrupt change and the shift S is infinity. However, ϕ has no physical meaning in this case [9,11]. When the

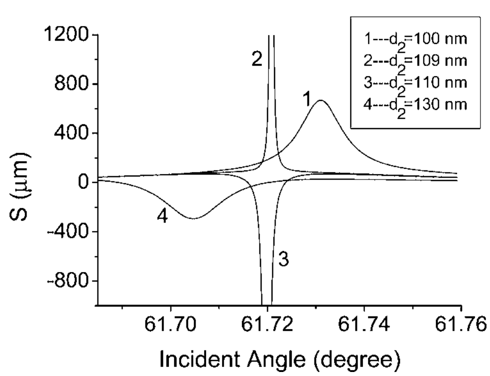

FIG. 2. Calculated dependence of the lateral beam shift on incident angle with various thicknesses of the air gap, d_2. The dielectric constants are the same as shown in Fig. 1. $d_3=1.0$ μm. The incident beam is assumed to be a TM-polarized He-Ne laser at 632.8 nm.

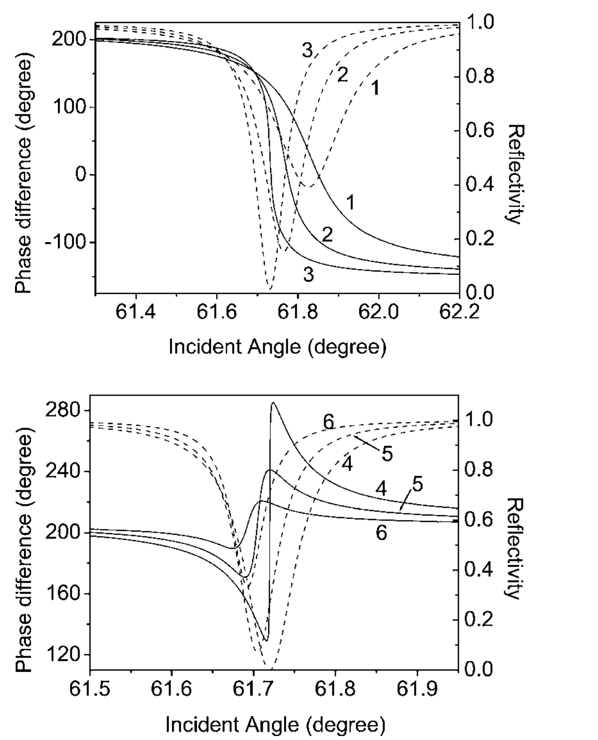

FIG. 3. Calculated reflectivity and phase difference as functions of incident angle with various thickness of the air gap, d_2. The solid lines are phase curves, the dashed lines correspond to reflectivity curves. The numbers in the panels represent different thickness of the air gap: d_2= (1) 60; (2) 80; (3) 100; (4) 110; (5) 130; (6) 160 nm.

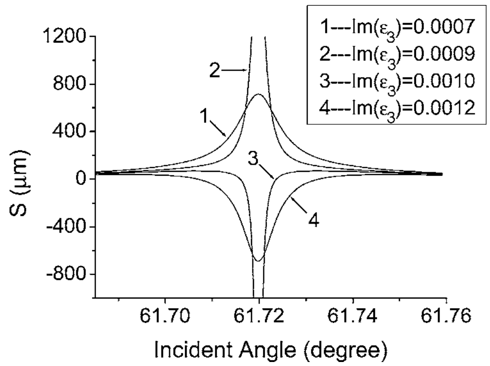

FIG. 4. The calculated lateral beam shift as a function of incident angle with various $\mathrm{Im}(\varepsilon_3)$. $d_2 = 110$ nm. Other parameters are the same as in Fig. 2.

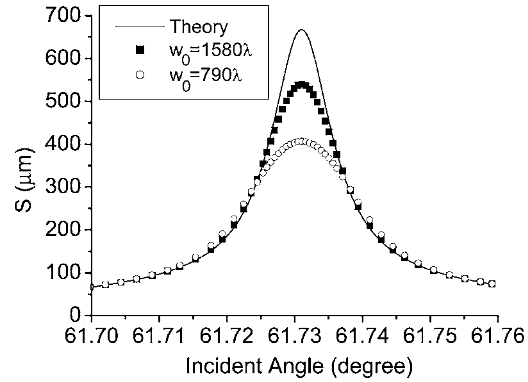

FIG. 5. Dependence of the lateral beam shift on the incident angle. $d_2 = 100$ nm. Other parameters are the same as in Fig. 2. The theoretical result is shown by the solid curve; the numerical results are shown by solid squares (for $w_0 = 1580\lambda$) and open circles (for $w_0 = 790\lambda$).

thickness d_2 exceeds the optimal value, which means the radiative damping is smaller than the intrinsic damping, large negative shift occurs.

Figure 4 shows the calculated lateral beam shift as a function of incident angle with various $\mathrm{Im}(\varepsilon_3)$. d_2 is assumed to be 110 nm. Other parameters are the same as in Fig. 2. The optimal value of $\mathrm{Im}(\varepsilon_3)$ of zero reflection is about 0.001. According to Eq. (8), $\mathrm{Im}(\varepsilon_3)$ is directly proportional to the intrinsic damping. Calculation shows the variation of the radiative damping with $\mathrm{Im}(\varepsilon_3)$ is so small that $\mathrm{Im}(\Delta\beta^{rad})$ can be nearly regarded as a constant. From Fig. 4, it is clear that, above the optimal value of $\mathrm{Im}(\varepsilon_3)$ of zero reflection, which means $\mathrm{Im}(\beta^0) > \mathrm{Im}(\Delta\beta^{rad})$, negative beam shifts occurs. Consequently, both the results in Figs. 2 and 4 are in good agreement with Eq. (12). In addition, we examined the lateral beam shift for TE polarization (not shown here) and the results are fundamentally same as those for TM polarization.

In order to demonstrate the validity of the above analysis, numerical calculations have been performed. Considering an incident beam of Gaussian shape, $\psi_i(x,z=0) = \exp(-x^2/2w_x^2 + ik_{x0}x)$, which can be represented by the Fourier integral

$$\psi_i(x,z=0) = \frac{1}{\sqrt{2\pi}} \int A(k_x)\exp(ik_x x)dk_x \qquad (14)$$

where $w_x = w_0 \sec\theta_0$, w_0 is the beam width at the waist, and $A(k_x) = w_x \exp[-(w_x^2/2)(k_x - k_{x0})^2]$ is the Fourier spectrum of the incident beam, the field of the reflected beam is given by

$$\psi_r(x,z=0) = \frac{1}{\sqrt{2\pi}} \int r_{1234}(k_x)A(k_x)\exp(ik_x x)dk_x. \qquad (15)$$

The integration above is extended over the interval $(-k_p, k_p)$ and k_p is the wave vector in the prism. The calculated beam shift can be obtained by finding the location where $|\psi_r|_{z=0}$ is maximal [11,12].

As an example, Fig. 5 shows the numerical calculation results of curve 1 in Fig. 2, i.e., $d_2 = 100$ nm. The incident beam width is chosen to be $w_0 = 1580\lambda \approx 1$ mm and $w_0 = 790\lambda \approx 0.5$ mm. For comparison, both the numerical and theoretical results are shown in Fig. 5. The peaks of the numerical shifts are about 539 μm for $w_0 = 1580\lambda$ and 407 μm for $w_0 = 790\lambda$, and the peak of the theoretical shift is about 668 μm. As indicated by Shadrivov *et al.* [10], Eq. (1) is accurate if the phase difference ϕ is a linear function of the incident angle across the spectral width of the beam, i.e., the incident beam is a wide beam. If the incident beam is narrow, the reflected beam will be distorted, which results in a discrepancy between the theoretical and numerical results. The narrower the incident beam is, the larger the discrepancy is [9,11]. Because the absorption loss of the guiding layer is very weak, the reflection resonance dip of the TM1 mode is narrow (its full width at half maximum is only about 0.085°), which requires the incident beam to be sufficiently wide to keep the profile of the reflected beam almost undistorted. Calculation results show that when w_0 is smaller than 0.2 mm, the reflected beam is seriously distorted and cannot be described in terms of a shifted beam.

We also numerically calculated the lateral beam shift under Gaussian beam illumination with various d_2. Other parameters are the same as in Fig. 2. The beam width is chosen to be $w_0 = 1580\lambda$. It is found that when $108 \leq d_2 \leq 111$ nm, which means d_2 is near the optimal thickness of zero reflection, the reflected beam is very weak and its profile is distorted so severely that the beam shift concept loses its physical meaning [9–11]. When d_2 is equal to 107 and 112 nm, the maximum reachable shifts are 920 and −723 μm, respectively. It shows that lateral beam shifts of the order of a millimeter are possible and confirms the conclusions drawn above by the stationary-phase method.

IV. CONCLUSION

In conclusion, the lateral beam shift in a prism-waveguide coupling system is examined. We have shown that large positive and negative lateral optical beam shifts can be obtained when guided modes are excited. It is also found that the lateral beam shift depends on the intrinsic and radiative dampings of the system. When the intrinsic damping is larger than the radiative damping, negative lateral beam shift occurs. A positive lateral shift occurs in the reverse case. It should be pointed out that the conclusion holds not only for guided modes in an air gap prism coupler, but also for SPR [8] and guided modes in other prism-waveguide coupling systems, for example, where the second medium is a metal layer. Numerical simulations confirm the theoretical analysis and show that a lateral beam shift of the order of a millimeter is possible. Because the prism-waveguide coupling technique is widely used, the predicted effects may have potential applications in the detection of surface irregularities, roughness, or variation of material absorption owing to its high sensitivity to the thickness of the second medium and absorption loss of the waveguide.

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APPENDIX

In order to calculate the lateral beam shift, Eq. (5) can be rewritten as

$$r_{1234} = r_{12}\frac{W^2 + [\mathrm{Im}(\beta^0)^2 - \mathrm{Im}(\Delta\beta^{rad})^2] + 2iW\,\mathrm{Im}(\Delta\beta^{rad})}{W^2 + [\mathrm{Im}(\beta^0) + \mathrm{Im}(\Delta\beta^{rad})]^2} \tag{A1}$$

with

$$W = k_x - [\mathrm{Re}(\beta^0) + \mathrm{Re}(\Delta\beta^{rad})].$$

Equation (A1) shows that the phase difference ϕ of the reflection coefficient r_{1234} is composed of two terms, which are the phase of r_{12} and that of the second term. We use ϕ_1 and ϕ_2 to denote them. Therefore the lateral beam shift is given by

$$S = -\frac{1}{k_0 n_1}\frac{d\phi}{d\theta} = -\frac{1}{k_0 n_1}\left(\frac{d\phi_1}{d\theta} + \frac{d\phi_2}{d\theta}\right) \tag{A2}$$

with

$$\phi_2 = \arctan\left(\frac{2W\,\mathrm{Im}(\Delta\beta^{rad})}{W^2 + [\mathrm{Im}(\beta^0)^2 - \mathrm{Im}(\Delta\beta^{rad})^2]}\right) \tag{A3}$$

where n_1 is the refractive index of the prism. Calculations show that $d\phi_1/d\theta \ll d\phi_2/d\theta$. Therefore $d\phi_1/d\theta$ can be ignored. After some calculations, we obtain

$$\begin{aligned}\frac{d\phi_2}{dk_x} = \Bigg(&2\,\mathrm{Im}(\Delta\beta^{rad})[\mathrm{Im}(\beta^0)^2 - \mathrm{Im}(\Delta\beta^{rad})^2 - W^2]\frac{dW}{dk_x} \\ &- 4W\,\mathrm{Im}(\beta^0)\mathrm{Im}(\Delta\beta^{rad})\frac{d(\mathrm{Im}(\beta^0))}{dk_x} + 2W[\mathrm{Im}(\beta^0)^2 \\ &+ \mathrm{Im}(\Delta\beta^{rad})^2 + W^2]\frac{d(\mathrm{Im}(\Delta\beta^{rad}))}{dk_x}\Bigg)\{[\mathrm{Im}(\beta^0)^2 \\ &- \mathrm{Im}(\Delta\beta^{rad})^2 + W^2]^2 + 4W^2\,\mathrm{Im}(\Delta\beta^{rad})^2\}^{-1}.\end{aligned} \tag{A4}$$

When the phase-matching condition is satisfied, that is, $W=0$, the reflectivity reaches the minimal value and Eq. (A4) may be cast in the form

$$\frac{d\phi_2}{dk_x} = \frac{2\,\mathrm{Im}(\Delta\beta^{rad})}{[\mathrm{Im}(\beta^0)^2 - \mathrm{Im}(\Delta\beta^{rad})^2]}\frac{dW}{dk_x}. \tag{A5}$$

It is noted that β^0 is the eigenpropagation constant of a guided mode and $\Delta\beta^{rad}$ is the difference between the eigenpropagation constants of the three-layer waveguide and the prism-waveguide coupling system. Both of them are independent of the parallel component of the wave vector k_x, which means

$$\frac{dW}{dk_x} = 1. \tag{A6}$$

Substituting Eqs. (A5) and (A6) into Eq. (A2), we get

$$S = -\frac{1}{k_0 n_1}\frac{d\phi_2}{dk_x}\frac{dk_x}{d\theta} = -\frac{2\,\mathrm{Im}(\Delta\beta^{rad})}{\mathrm{Im}(\beta^0)^2 - \mathrm{Im}(\Delta\beta^{rad})^2}\cos\theta_r \tag{A7}$$

where θ_r is the incident angle under the phase-matching condition.

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