Progress In Electromagnetics Research, PIER 82, 351–366, 2008

LATERAL DISPLACEMENT OF AN ELECTROMAGNETIC BEAM REFLECTED FROM A GROUNDED INDEFINITE UNIAXIAL SLAB

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Abstract—A theoretical analysis of the lateral shift for an electromagnetic beam reflected from an uniaxial anisotropic slab coated with perfect conductor is presented. The analytic expression for the lateral shift is derived by using the stationary-phase approach, and the conditions for negative and positive lateral shifts are discussed. It is shown that the lateral shift depends not only on the slab thickness and the incident angle, but also on the constitutive parameters of the uniaxial medium. Enhancement and suppression of lateral shift are observed and are attributed to the interference between the reflected

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waves from the two interfaces of the slab. By tuning the thickness of the slab and material parameters, large negative and positive shifts can be attained. In particular, when total reflection occurs at the upper interface, the lateral shift will saturate with increasing slab thickness.

1. INTRODUCTION

The Goos-Hänchen effect [1, 2], which usually refers to the lateral shift of a totally reflected beam displaced from the path of geometrical optics, has been widely analyzed both theoretically [3–5] and experimentally [6–9]. The concept of Goos-Hänchen lateral shift has been expanded to partial reflection at arbitrary incident angle [10–13]. In order to get a large or negative lateral shift, many attempts have been made with various materials and configurations, such as dielectric slabs [14–17], metal surfaces [18–20], dielectric-chiral surface [21], multilayered structures [22], metallic gratings [23], and photonic crystals [24]. Recently, left-handed metamaterial with negative permeability and permittivity has attracted a lot of attention due to their extraordinary electromagnetic characteristics [25–32], and negative lateral shift has been observed in left-handed materials [33–37]. In those works, the case for the isotropic left-handed material has been analyzed extensively. In practice, left-handed materials in experiments are intrinsically anisotropic. Furthermore, each component of the permittivity and permeability tensors of the metamaterial can have either a positive or negative real part. Hence, it is worthwhile to illustrate the relationship between material parameters and the corresponding lateral shift at the anisotropic interface. The lateral shift of the transmitted beam from an anisotropic slab has been discussed [38, 39], but little work has been done on the lateral shift of the reflected beam from a grounded anisotropic slab, which has the advantage that the reflected beam energy is always equal to the incident one at any incident angles no matter whether total reflection occurs or not. In this paper, we consider an electromagnetic beam reflecting from an indefinite uniaxial slab on the top of a perfect conductor. The analytic expression for the lateral shift as a function of the slab parameters is derived by the stationary-phase method and different conditions are discussed for both negative and positive lateral shifts. By tuning the thickness of the slab and material parameters, large negative or positive shift can be attained.

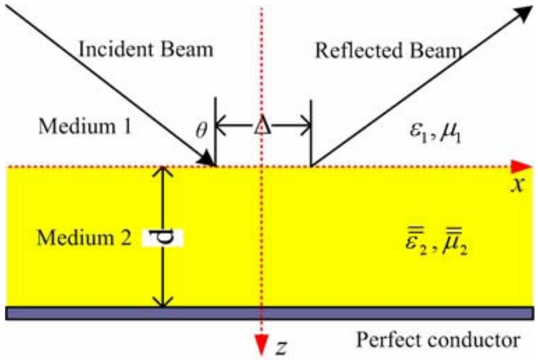


Figure 1. Configuration of an electromagnetic beam incident upon a grounded uniaxial slab. Medium 1 is isotropic, and medium 2 is uniaxial with its optical axis in the z-direction. The slab is backed by a perfect conductor.

2. LATERAL SHIFTS OF AN GROUNDED UNIAXIAL SLAB

The grounded uniaxial anisotropic slab is shown in Figure 1, in which medium 1 is isotropic and is characterized by the relative permittivity ε_1 and permeability μ_1. Medium 2 is uniaxial with its optical axis being normal to the interface, and the relative permittivity and permittivity tensors of medium 2 can be expressed in the following form:

$$\bar{\bar{\varepsilon}} = \begin{pmatrix} \varepsilon_t & 0 & 0 \\ 0 & \varepsilon_t & 0 \\ 0 & 0 & \varepsilon_z \end{pmatrix}, \quad \bar{\bar{\mu}} = \begin{pmatrix} \mu_t & 0 & 0 \\ 0 & \mu_t & 0 \\ 0 & 0 & \mu_z \end{pmatrix}. \tag{1}$$

When a TE polarized wave is incident from the isotropic medium into the uniaxial medium at an oblique angle θ with respect to the normal of the interface, the dispersion relations in the two media can be written as

$$k_{1z}^2 + k_x^2 = k_0^2 \varepsilon_1 \mu_1 \tag{2}$$
$$k_{2z}^2 + \sigma k_x^2 = k_0^2 \varepsilon_t \mu_t \tag{3}$$

where $\sigma = \mu_t/\mu_z$, k_0 is the wavenumber in the free space, $k_x = k_0\sqrt{\varepsilon_1\mu_1}\sin\theta$ is the wavenumber in the x-direction of the two media, and k_{1z} and k_{2z} are wavenumbers in the z-direction of the media 1 and 2 respectively. Here, we consider only TE polarized wave and the case for a TM polarized wave can also be discussed in the similar manner.

The reflection coefficient can be expressed as [40]

$$R = -\frac{k_{2z} + ipk_{1z}\tan(k_{2z}d)}{k_{2z} - ipk_{1z}\tan(k_{2z}d)} \tag{4}$$

where $p = \mu_t/\mu_1$, and d is the thickness of the slab.

From Eq. (4), we can get the amplitude and phase of the reflection coefficient as

$$|R| = 1 \tag{5}$$

$$\phi = 2\tan^{-1}(pk_{1z}\tan(k_{2z}d)/k_{2z}) + \pi \tag{6}$$

From Eq. (5), we can see that the amplitude of reflection coefficient is unity and is independent of the incident angle. This means that the reflected intensity of each plane wave component is always equal to the incident one no matter whether the total reflection occurs or not.

For a wide beam with a narrow angular spectrum, the lateral shift can be calculated by the stationary-phase method [41]:

$$\Delta = -\frac{1}{k_1\cos\theta}\frac{d\phi}{d\theta} \tag{7}$$

where $k_1 = k_0\sqrt{\varepsilon_1\mu_1}$.

Substituting Eq. (6) into Eq. (7), we can get the lateral shift as

$$\Delta = 2dp\tan\theta\frac{(k_{2z}^2 - \sigma k_{1z}^2)\sin(2k_{2z}d)/2k_{2z}d + \sigma k_{1z}^2}{k_{2z}^2\cos^2(k_{2z}d) + p^2k_{1z}^2\sin^2(k_{2z}d)} \tag{8}$$

Obviously, the denominator in Eq. (8) is positive, so the sign of lateral shift is determined by the numerator of Eq. (8).

In the limit $k_{2z}d \ll 1$, $\sin(2k_{2z}d) \approx 1$, Eq. (8) can be approximately written as

$$\Delta \approx 2dp\tan\theta \tag{9}$$

In the limit $k_{2z}d \gg 1$, the first term of Eq. (8) which is proportional to function $\sin(2k_{2z}d)/2k_{2z}d$ tends to vanish and the lateral shift is dominated by the second term of Eq. (8). Hence, Eq. (8) can be approximately expressed as

$$\Delta \approx 2dp\tan\theta\frac{\sigma k_{1z}^2}{k_{2z}^2\cos^2(k_{2z}d) + p^2k_{1z}^2\sin^2(k_{2z}d)} \tag{10}$$

From Eq. (10), we can see that the enhancement of lateral shift occurs if the $k_{2z}d$ satisfies the resonant conditions $k_{2z}d = m\pi$ for

$|k_{2z}| > |pk_{1z}|$ and $k_{2z}d = (m - 0.5)\pi$ for $|k_{2z}| < |pk_{1z}|$, where m is positive integer. In fact, the lateral shift enhancement results from the constructive interference of the reflected waves from the isotropic-uniaxial interface and uniaxial-conductor interface. When $k_{2z} = pk_{1z}$, the refection caused by the isotropic-uniaxial interface vanishes, and the corresponding Brewster angle can be calculated by $\theta_b = \sqrt{(\varepsilon_t\mu_t/\varepsilon_1\mu_1 - p^2)/(\sigma - p^2)}$. In such case, the enhancement of the lateral shift will be negated.

When total reflection occurs, according to Eq. (3), the inequality $\sigma k_x^2 > k_0^2\varepsilon_t\mu_t$ should be satisfied in order to keep k_{2z} imaginary. If we assume that $k_{2z} = i\alpha_{2z}$, then, the Eq. (8) can be rewritten as

$$\Delta = 2dp\tan\theta \frac{(\alpha_{2z}^2 + \sigma k_{1z}^2)\, sh(2\alpha_{2z}d)/2\alpha_{2z}d - \sigma k_{1z}^2}{\sigma_{2z}^2 ch^2(\alpha_{2z}d) + p^2k_{1z}^2 sh^2(\alpha_{2z}d)} \tag{11}$$

where $sh(\cdot)$ and $ch(\cdot)$ are hyperbolic sin and cos functions. In the limit $\alpha_{2z}d \ll 1$, Eq. (11) can be approximately written as

$$\Delta \approx 2dp\tan\theta \tag{12}$$

which is the same as Eq. (9).

In the limit $\alpha_{2z}d \gg 1$, Eq. (11) can be approximately written as

$$\Delta \approx \frac{2p\tan\theta}{\alpha_{2z}} \frac{\alpha_{2z}^2 + \sigma k_{1z}^2}{\alpha_{2z}^2 + p^2k_{1z}^2} \tag{13}$$

which is consistent with that of [28].

From the analysis above, we can conclude that the lateral shift from the grounded uniaxial slab can be positive as well as negative, which is related to the incident angle, the slab thickness, and the constitutive parameters of the uniaxial medium.

3. DISCUSSION AND RESULTS

In the following analysis, we assume that medium 1 is free space ($\varepsilon_1 = 1,\ \mu_1 = 1$) and the medium 2 is an indefinite uniaxial medium. Since the components of the permittivity and permeability tensors of the uniaxial medium may not have the same sign, the dispersion relation in the indefinite uniaxial medium will correspond to either an elliptic or hyperbolic equation depending on the combination of material parameters. Hence, the lateral shift from the grounded uniaxial slab is greatly influenced by the dispersion property of the uniaxial medium.

From Eqs. (2) and (3), the dispersion relation for the uniaxial medium can be rewritten as

$$k_{2z}^2 = k_0^2(\varepsilon_t\mu_t - (\mu_t/\mu_z)\varepsilon_1\mu_1 \sin^2\theta). \tag{14}$$

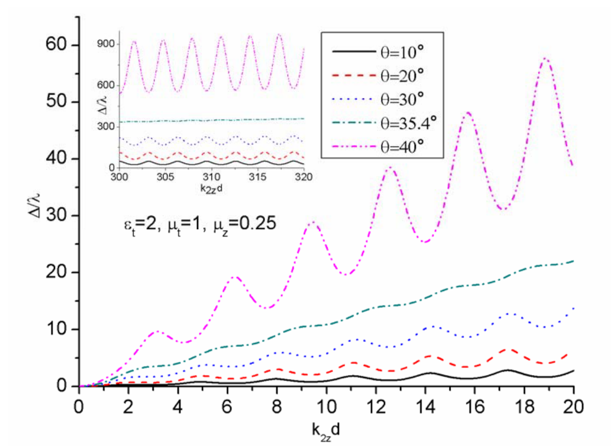
The sign of k_{2z}^2 can be used to distinguish the propagation property of an electromagnetic beam in the uniaxial medium. The cases with $k_{2z}^2 > 0$ and $k_{2z}^2 < 0$ correspond to solutions of waves with real k_{2z} and imaginary k_{2z} respectively. According to their spatial cutoff properties [42], the uniaxial media can be classified into four kinds: cutoff medium, anti-cutoff medium, never-cutoff medium, and always-cutoff medium. All the conditions for both real and imaginary k_{2z} solutions are considered and summarized in Table 1. Here, we focus on the discussion on the lateral shift for $\mu_t > 0$, and the result for $\mu_t < 0$ is opposite to that for $\mu_t > 0$. In addition, it should be noted that the critical angles for both the normal total reflection in the cutoff medium and the anomalous total reflection in the anti-cutoff medium can be calculated by $\theta_c = \sin^{-1}\sqrt{(\varepsilon_t\mu_z)/(\varepsilon_1\mu_1)}$.

Table 1. Conditions for the real and imaginary.

Uniaxial medium	$\varepsilon_t\mu_t$	μ_t/μ_z	$\varepsilon_t\mu_z$	θ	k_{2z}
			$0 < \varepsilon_t\mu_z < \varepsilon_1\mu_1$	$0 < \theta < \theta_c$	Real
Cutoff	$\varepsilon_t\mu_t > 0$	$\mu_t/\mu_z > 0$	$0 < \varepsilon_t\mu_z < \varepsilon_1\mu_1$	$\theta_c < \theta < \pi/2$	Imaginary
			$\varepsilon_t\mu_z > \varepsilon_1\mu_1$	$0 < \theta < \pi/2$	Imaginary
			$0 < \varepsilon_t\mu_z < \varepsilon_1\mu_1$	$0 < \theta < \theta_c$	Imaginary
Anti-cutoff	$\varepsilon_t\mu_t < 0$	$\mu_t/\mu_z < 0$	$0 < \varepsilon_t\mu_z < \varepsilon_1\mu_1$	$\theta_c < \theta < \pi/2$	Real
			$\varepsilon_t\mu_z > \varepsilon_1\mu_1$	$0 < \theta < \pi/2$	Real
Never-cutoff	$\varepsilon_t\mu_t > 0$	$\mu_t/\mu_z < 0$		$\theta_c < \theta < \pi/2$	Real
Always-cutoff	$\varepsilon_t\mu_t < 0$	$\mu_t/\mu_z > 0$		$\theta_c < \theta < \pi/2$	Imaginary

In order to illustrate the relationship between the lateral shifts and dispersion property of the grounded uniaxial slab, we starts with discussing the lateral shift for the solution with real k_{2z}. When k_{2z} is real, it means that the electromagnetic beam can propagate inside the uniaxial medium and is influenced by the reflection from the perfect conductor. In the limit $k_{2z}d \ll 1$, according to Eq. (9), the sign of lateral shift for the solution with real k_{2z} is determined by the sign of μ_t. In the limit $k_{2z}d \gg 1$, enhancement and suppression of lateral shifts occur, corresponding to constructive resonances and destructive resonances, respectively. In addition, according to Eq. (10), the sign of the lateral shift in the limit $k_{2z}d \gg 1$ is determined by the sign of μ_z. For a given incident angle, large negative or positive shift can be attained by tuning the slab thickness and material parameters. As an example, the dependence of lateral shifts on the slab thickness for the solution with real k_{2z} at different incident angles for different media is presented in Figure 2. The insets in Figure 2 show the lateral shift of a much thicker slab. It is shown that the lateral shift depends on not only the slab thickness and the incident angle, but also the material parameters. When the slab thickness is small, the lateral shift is always positive due to the assumed positive μ_t. As the slab thickness increases, fluctuation of lateral shift is observed due to the periodic occurrence of the constructive resonances and destructive resonances, as shown in the insets of Figure 2.

In the cut-off uniaxial slab, the solution with real k_{2z} can exist for



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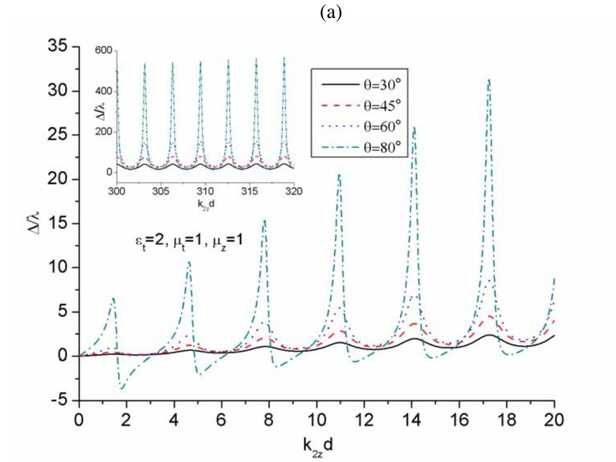

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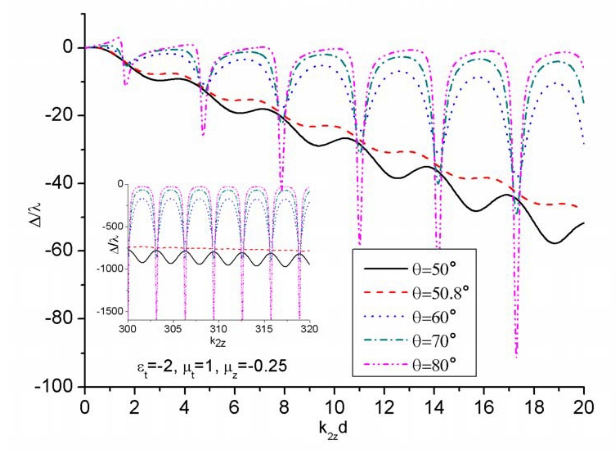

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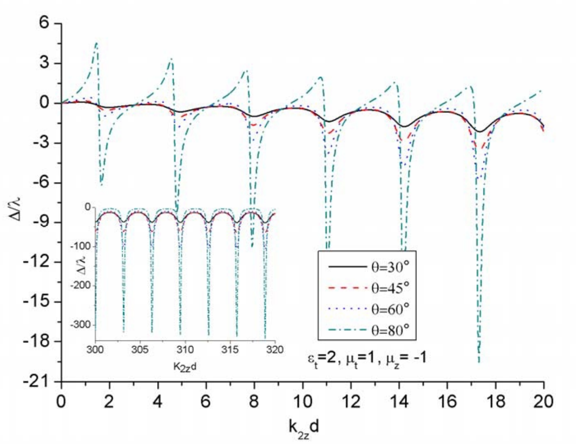

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Figure 2. Dependence of lateral shift on the thickness of a grounded uniaxial slab for different incident angles. (a) $\varepsilon_t = 2$, $\mu_t = 1$, and $\mu_z = 0.25$; (b) $\varepsilon_t = 2$, $\mu_t = 1$ and $\mu_z = 1$; (c) $\varepsilon_t = -2$, $\mu_z = 1$, and $\mu_z = -0.25$; and (d) $\varepsilon_t = 2$, $\mu_t = 1$, and $\mu_z = -1$. The insets show the lateral shifts as a function of the slab thickness for a much thicker slab.

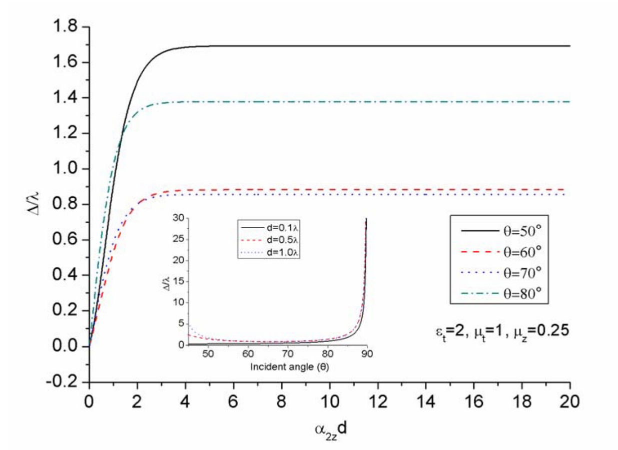
a small incident angle ($\theta < \theta_c$) in the case of $\varepsilon_t\mu_z < \varepsilon_1\mu_1$, or arbitrary incident angle in the case of $\varepsilon_t\mu_z > \varepsilon_1\mu_1$. The calculated lateral shifts for the two cases are shown in Figures 2a and 2b. In the first case ($\varepsilon_t = 2$, $\mu_t = 1$, and $\mu_z = 0.25$), when the incident angle is smaller than the critical angle ($\theta_c = 45°$), the lateral shift remains positive in spite of its fluctuation. However, in the second case ($\varepsilon_t = 2$, $\mu_t = 1$, and $\mu_z = 1$), the fluctuation of the lateral shift is so strong that both positive and negative lateral shift can be attained by choosing the proper thickness of the slab. Moreover, in the first case, when the incident angle is close to the Brewster angle of the isotropic-uniaxial interface ($\theta_b = 35.4°$), the fluctuation of lateral shift diminishes due to a lack of reflected wave from the isotropic-uniaxial interface, and since there is a phase shift of π upon the reflection in the isotropic-uniaxial interface of the slab, hence the large enhancement of lateral shift can occur near the resonances at $k_{2z}d = (m - 0.5)\pi$ for $\theta < \theta_b$, and $k_{2z}d = m\pi$ for $\theta > \theta_b$. In the second case, the large enhancement of lateral shift can occur near the resonances at $k_{2z}d = (m - 0.5)\pi$ for any incident angle. In addition, as the slab thickness increases, the lateral shifts for the two cases tend to be positive.

In the anti-cutoff uniaxial slab, the solution with real k_{2z} can only exist for an large incident angle ($\theta > \theta_c$), which is opposite to the cutoff uniaxial slab. Figure 2c shows the lateral shift as a function of the slab thickness with $\varepsilon_t = -2$, $\mu_t = 1$, and $\mu_z = -0.25$. The corresponding Brewster angle θ_b and critical angle θ_c are 50.77° and 45° respectively. When the slab thickness is smaller, the lateral shift is positive, but as the slab thickness increases, the lateral shift tends to be negative, which is different from that of the cutoff uniaxial slab. The large negative enhancement of lateral shift can occur near the resonances at $k_{2z}d = m\pi$ for $\theta < \theta_b$ and $k_{2z}d = (m - 0.5)\pi$ for $\theta > \theta_b$.

In the never-cutoff uniaxial slab, the incident wave can propagate inside the slab and is reflected from the perfect conductor. Hence, the solution with real k_{2z} can exist for any incident angle. The dependence of the lateral shift on the slab thickness is illustrated in Figure 2d, where $\varepsilon_t = 2$, $\mu_t = 1$, and $\mu_z = -1$. It can be observed that the lateral shift increases with the increasing of the incident angle, and tends to be negative as the slab thickness increases. The large negative enhancement of lateral shift can occur near the resonances $k_{2z}d = (m - 0.5)\pi$ for any incident angle. Moreover, when the incident angle increases, the fluctuation of the lateral shift with the slab thickness becomes more obvious.

Now, we turn to discuss the lateral shift for the solution with imaginary $k_{2z}\,(k_{2z} = i\alpha_{2z})$. In such case, the electromagnetic beam will become evanescent in the uniaxial medium and total reflection phenomenon occurs. In the limit $\alpha_{2z}d \ll 1$, according to Eq. (12), the sign of lateral shift is determined by the sign of μ_t and is positive under the present condition. The property of lateral shift for the solution with imaginary k_{2z} in the uniaxial grounded slab is shown in Figure 3. The insets in Figure 3 show the relationship between the lateral shift and the incident angle in the grounded slab. We can see that the lateral shift for the thin slab is positive, which is identical to the real k_{2z} case. However, as the slab thickness increases, the lateral shift approaches to a saturated value, which is different from the real k_{2z} case. Moreover, the lateral shift for the thick slab in the present case depends on the incident angle more than the slab thickness.

In the cut-off uniaxial slab, the solution with imaginary k_{2z} can exist for a large incident angle ($\theta > \theta_c$) in the case of $\varepsilon_t\mu_z < \varepsilon_1\mu_1$. The calculated lateral shift is shown in Figure 3a, where the material parameters are the same as Figure 2a. It is shown that, as the increase of the slab thickness, the lateral shifts will increase quickly, and then gradually approach to an asymptotic positive value. The



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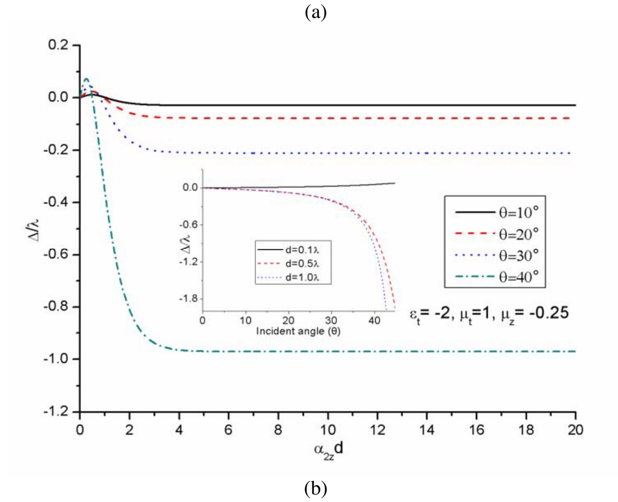

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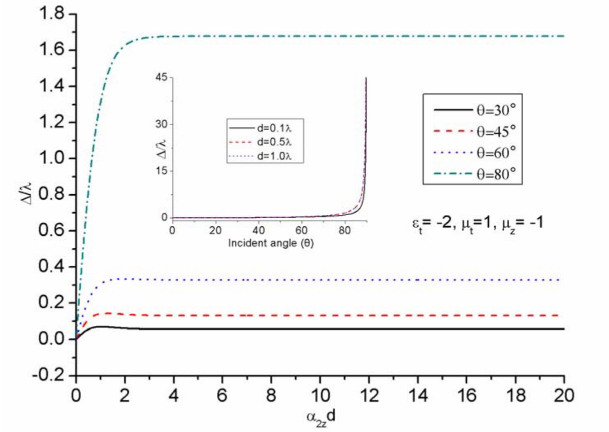

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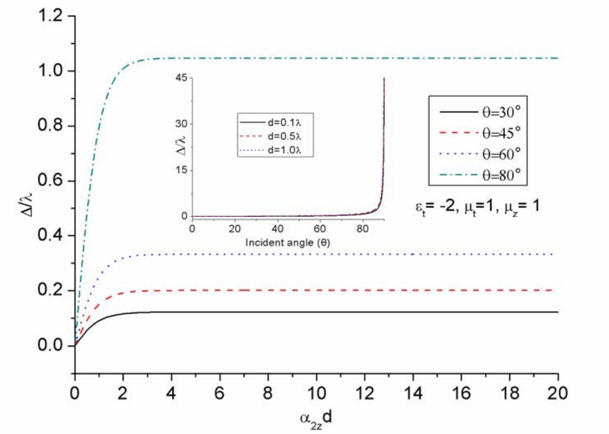

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Figure 3. Dependence of lateral shift on the thickness of a grounded uniaxial slab for different incident angles. (a) $\varepsilon_t = 2,\ \mu_t = 1$, and $\mu_z = 0.25$; (b) $\varepsilon_t = -2,\ \mu_t = 1$ and $\mu_z = -0.25$; (c) $\varepsilon_t = -2,\ \mu_z = 1$, and $\mu_z = -1$; and (d) $\varepsilon_t = -2,\ \mu_t = 1$, and $\mu_z = 1$. The insets show the lateral shifts as a function of the slab thickness for a much thicker slab.

inset in Figure 3a shows the relation between the lateral shift and the incident angle when the slab thickness is $d = 0.1\lambda, 0.5\lambda$, and 1λ. It is straightforward to see that the lateral shift increases with the increasing of incident angle in the thin slab, while in the thick slab the lateral shift decreases, reaches a minimum, and then increases with the increasing incident angle.

In the anti-cutoff uniaxial slab, the solution with imaginary k_{2z} can exist for an small incident angle ($\theta < \theta_c$) in the case of $\varepsilon_t\mu_z < \varepsilon_1\mu_1$, or any incident angle in the case of $\varepsilon_t\mu_z > \varepsilon_1\mu_1$. The calculated lateral shifts for the two cases are shown in Figures 3b and 3c, in which, $\varepsilon_t = -2,\ \mu_t = 1$, and $\mu_z = -0.25$ and $\varepsilon_t = -2,\ \mu_t = 1$, and $\mu_z = -1$, respectively. From Figures 3b and 3c, we can see that the signs of lateral shift for the two cases are positive when the slab thickness is smaller. However, as the slab thickness increases, the lateral shift for the first case tends to be negative while the lateral shift for the second case tends to be positive. Moreover, the lateral shifts for a given slab thickness in the two cases increases with the increasing of incident angle, which is different from that of the cutoff uniaxial slab.

In the always-cutoff uniaxial slab, any incident wave will become evanescent and the total reflection occurs at all times. Hence, the solution with imaginary k_{2z} can exist for any incident angle. The dependence of the lateral shift on the slab thickness with $\varepsilon_t = -2,\ \mu_t = 1$, and $\mu_z = 1$ is shown in Figure 3d. The result indicates that the lateral shift is always positive when $\mu_t > 0$. Besides, as shown in the inset of Figure 3d, the lateral shift increases with the increasing of the incident angle, this is obviously different from that of the cut-off uniaxial slab.

4. SUMMARY

In summary, an investigation on the lateral shift for a grounded indefinite uniaxial slab has been done by using the stationary-phase approach. The result shows that the lateral shift is related to the slab thickness, the incident angle, and the material parameters of the uniaxial medium. By changing the material parameters of the uniaxial medium, we can get real or imaginary k_{2z}. In the case of real k_{2z}, the fluctuation of lateral shift can be observed due to the interference between the reflected waves from the two interfaces of the slab. By tuning the thickness of the dielectric slab and material parameters, large negative and positive shift can be attained. In the case of imaginary k_{2z}, the lateral shift due to the total reflection at the isotropic-uniaxial interface will be saturated with the increasing of slab thickness.

ACKNOWLEDGMENT

This work is sponsored in part by the Office of Naval Research under Contract N00014-01-1-0713, the Department of the Air Force under Air

Force Contract F19628-00-C-0002, the Chinese National Foundation under Contracts 60531020 and 60701007, the Chinese 973 Project under Contract 2007CB613200, the Key Project of Chinese Ministry of Education under Contract 105101, and Natural Science Foundation of Shandong Province under Contract Y2005G19.

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