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Arbitrary positive and negative lateral shift of Gaussian beam reflected from an anisotropic grounded slab

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ABSTRACT

Both positive and negative lateral shifts are demonstrated in this paper for a Gaussian beam reflected from an anisotropic grounded slab, whose constructive parameters are determined by the optical transformation approach. The incident wave is modeled as a tapered wave with a spatial Gaussian shape. Layered structures with alternating isotropic materials are applied to model the parameters of such an anisotropic grounded slab and good agreements are obtained when the positive lateral shifts caused by ideal anisotropic slab are compared with those of the equivalent isotropic layered slab.

1. Introduction

When an electromagnetic beam is reflected from a grounded slab, which is backed by a perfect electrical conductor (PEC), it will usually experience a lateral shift at the interface predicted by geometrical optics. The well-known Goos–Hänchen (GH) effect can lead to a small lateral shift [1,2], which is usually proportional to the penetration depth at the order of a wavelength. In order to get large positive or negative lateral shifts, many attempts have been made with various materials and configurations, such as metal surfaces [3,4], dielectric slabs [5–7], multilayered structures [8–10], photonic crystals [11,12], surface plasmon resonance [13], lossy medium [14–17] and some other metamaterial structures [18–21]. The lateral shift has potential applications in various optical and microwave fields, such as waveguide switches [22] and optical temperature sensors [23]. Based on the geometrical optics, the lateral shift of the light beam reflected from a dielectric slab backed by a metal is related to the slab thickness, the incident angle and the material parameters [6,24,25]. For a grounded slab with a given thickness and the incoming wave incident angle, it is worthwhile to illustrate the relationship between material parameters and the corresponding lateral shift at the slab interface.

In this paper, we consider an electromagnetic beam reflected from an anisotropic grounded slab, where the lateral shift at the interface can be arbitrarily designed. The parameters of the grounded slab with a given thickness are determined by transformation optics (TO) [26,27], which has been widely applied to control the microwave or light wave propagation along an expected path [28–40]. In the following section, the parameters of the uniaxial anisotropic slab for the case of causing arbitrary positive lateral shift is demonstrated by alternating layers of isotropic dielectrics based on the effective medium theory (EMT) [41], thus leading to an ease of practical fabrication.

2. Parameter design of the grounded slab

For the sake of simplicity, we consider the grounded slab on the top of a metal substrate as schematically shown in Fig. 1. Let us consider the grounded slab with a given thickness of d. The coordinate origin is located on the interface of the grounded slab and the whole grounded slab is in the space between $y = 0$ and $y = -d$. Suppose a Gaussian beam or optical ray impinging upon the slab, the lateral displacement reflected from the grounded slab could be arbitrary designed by utilizing the framework of coordinate transformation [26]. Let us first consider that the grounded slab is empty space without coordinate transformation as shown in Fig. 1a. Based on geometrical optics, the lateral displacement on the interface of the "empty space slab" should be $L1 = 2d\tan\theta$, in which θ is the incident angle of the Gaussian beam. The ray tracing is illustrated in Fig. 1a. What follows, in order to change the lateral displacement, we should construct a "virtual space", supposing the virtual metal substrate boundary is at $y' = -k$, and the up interface boundary keeps unchanged, which means the "virtual space" is between $y' = 0$

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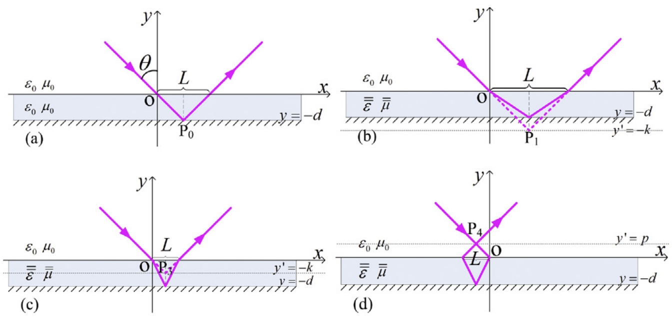

Fig. 1. Ray tracing diagram. (a) A ray incident upon an air slab; (b) and (c) a ray incident upon an anisotropic grounded slab with positive constructive parameters; (d) a ray incident upon an anisotropic grounded slab with negative constructive parameters.

and $y' = -k$. Now we transform the "virtual space" into physical space of the real grounded slab.

$$x = x', \quad y = \frac{d}{k}y', \quad z = z' \tag{1}$$

For a given coordinate transformation, the homogeneous Maxwell equations retain their form unchanged, but the constructive parameters change together with the field value. The transformed permittivity and permeability are given as

$$\gamma = \det(J)^{-1} J * J^T = \begin{bmatrix} \frac{k}{d} & 0 & 0 \\ 0 & \frac{d}{k} & 0 \\ 0 & 0 & \frac{k}{d} \end{bmatrix} \tag{2}$$

where, γ represent both permittivity tensor and permeability tensor, J is the Jacobian of the transformation and all the constructive parameters are positive.

The lateral displacement of the incident ray or beam caused by the transformation slab still with thickness of d has become $L = 2k\tan\theta$. So the lateral displacement of the reflected beam is dependent on the geometrical parameter k in the "virtual space". If the virtual substrate interface is under the real metal substrate interface of the grounded slab ($-k < -d$), the lateral shift will be enlarged compared with that of the "empty space slab" and the ray tracing is plotted in Fig. 1b. If the virtual reflection point is above the real substrate plane of the given grounded slab ($-k > -d$), the lateral displacement will be shortened, which is depicted in Fig. 1c. So, in order to get a desired positive lateral shift at the interface of the grounded slab, the constructive parameters could be determined by coordinate transformation from a proper "virtual space" into the real space of the grounded slab.

However, if we construct a lateral displacement with arbitrary negative value, a special coordinate transformation should be done. A negatively shifted reflection beam must cross with the incident beam and if we suppose that the cross point is at the plane $y' = p$. Then, we can map the virtual plane $y' = p$ into the real metal substrate plane $y = -d$ of the grounded slab by coordinate transformation of folding.

$$x = x', \quad y = -\frac{d}{p}y', \quad z = z' \tag{3}$$

By using the Jacobian of the transformation, we can get the constructive parameters of the grounded slab as follows:

$$\bar{\bar{\gamma}} = \det(J)^{-1} J * J^T = \begin{bmatrix} -\frac{p}{d} & 0 & 0 \\ 0 & -\frac{d}{p} & 0 \\ 0 & 0 & -\frac{p}{d} \end{bmatrix} \tag{4}$$

in which all the constructive parameters are negative. The negative lateral shift at the slab interface could be given as $L = -2p\tan\theta$ and the ray tracing is illustrated in Fig. 1d. So the negative lateral displacement for a given incident wave could be arbitrarily designed by properly selecting the geometrical parameter p with a given incident angle θ.

To firstly demonstrate arbitrary positive lateral shift we discussed above, we construct a TM Gaussian beam incident upon the given grounded slab backed by a metal substrate and provide the numerical simulations by full EM simulations using a commercial finite element-based EM solver (COMSOL MULTIPHYSICS©). Take the incident angle θ = 40° and incident point at the coordinate origin. The thickness of the grounded slab set to be d = 0.5 m. The transverse magnetic fields and time-average power density both inside and outside the grounded slab are calculated for three cases: the "empty space slab" [it means no slab on the metal substrate and see Fig. 2a] which causes a conventional positive lateral displacement of $L1$ = 1.0 m; the transformed grounded slab by space squeezing with virtual substrate boundary at $y' = -k = -1.0$ m, which causes a positive lateral displacement of $L2 = 2.0$ m [see Fig. 2b]; the transformed grounded slab by space expanding with virtual substrate boundary at $y' = -k = -0.25$ m, which causes a positive lateral displacement of $L3 = 0.5$ m [see Fig. 2c]. In the simulations, the time average power density for TM wave can be expressed as

$$\left| < \bar{S} > \right| = 0.5\sqrt{[Re(H_z E_x^*)]^2 + \left[Re\left(H_z E_y^*\right)\right]^2} \tag{5}$$

and the tapered incident wave with a Gaussian spectrum gives as

$$H_z = H_0 \exp\left((x - x_0)^2/\tau^2\right) \cdot \exp\left(-j\left(k_x x + k_y y\right)\right) \tag{6}$$

where $k_y = k\cos\theta$, $k_x = k\sin\theta$ (k is the wave number of the Gaussian beam and we take wavelength as $\lambda = 0.15$ m[$f = 2$ GHz] in all the simulations) and $\tau = 0.6$ represents the width of the Gaussian beam.

In addition, the lateral displacements of the three cases are still verified by simulating total average power outflow ($\left| < \bar{S} > \right| \vec{k}$) at the interface of the grounded slab as illustrated in Fig. 3. The total average power outflow patterns in Fig. 3 show that the reflection wave peaks have moved to a positive distance from the origin (incident wave peak with a Gaussian spectrum), and the three distances of the positive peaks represent the lateral shifts caused by the

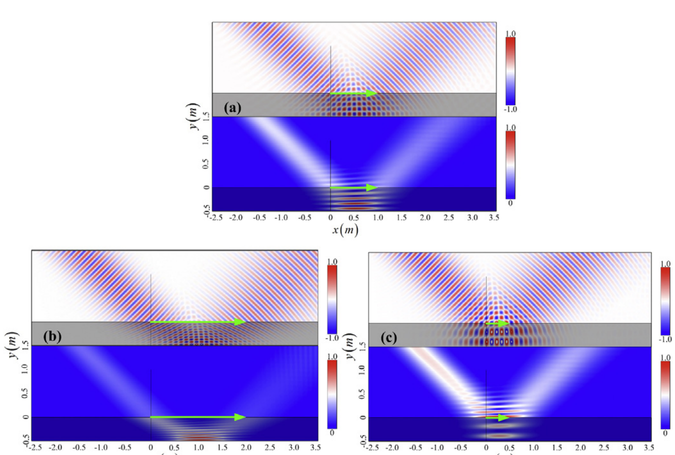

Fig. 2. Magnetic field distribution and time average power density of a Gaussian beam incident upon (a) the "empty space slab"; (b) the squeezed slab; and (c) the expanded slab with incident angle of $\varphi = 45°$.