A micromechanical beam-steering device for terahertz systems

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ABSTRACT

Beam-steering techniques are required to fully exploit terahertz imaging systems. We propose and model a device employing artificial dielectric techniques to provide a variable phase-control medium. The device consists of two interlocking artificial dielectric surfaces that are initially aligned parallel to each other. By mechanically introducing a relative tilt between the plates, a transmitted wave is subjected to a graded phase delay and thus the beam is steered away from the normal. Continuous and large steering angles are possible. We predict a practical device constructed from a silicon substrate could steer TE beams by up to 4.6 degrees.

Keywords: beam steering, artificial dielectrics, array factor, effective medium theory, terahertz

1. INTRODUCTION

Beam steering techniques are required to fully exploit the benefits of present and future terahertz imaging systems, particularly for applications such as security imaging where a longer operating range is required, the field of view is larger and targets may be moving. Existing techniques for visible and infra-red beam steering are usually based on nematic liquid crystals, ferroelectric liquid crystals, ferroelectric electrooptic materials[1] or arrays of microactuated mirrors.[2] However, at the longer terahertz wavelengths, alternative approaches are required to overcome difficulties that analogues of these techniques may suffer. Additionally, electronic techniques that are typical at microwave frequencies, such as phased array antennas,[3] are impractical because of the difficulty of scaling the in-circuit phase shifters to operate at the higher terahertz frequencies. Hence new approaches are required. In this paper, we propose a novel transmission-mode mechanical beam steering device that uses interlocking artificial dielectric grooves as the phase control medium. An example of the device is pictured in Fig 1.

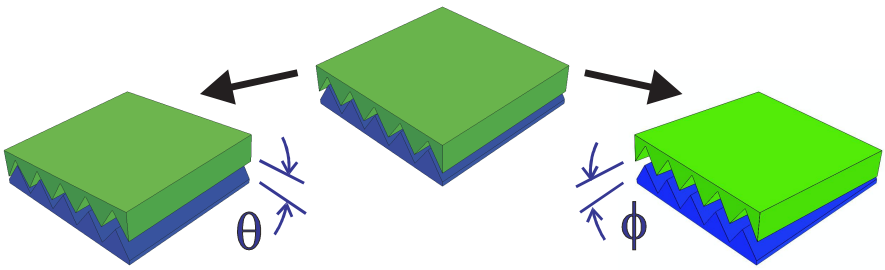

Figure 1. Diagram of a beam steering device with interlocking V-grooves that allow tilt both parallel and perpendicular to the gratings.

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2. THEORY OF OPERATION

The beam steerer comprises a pair of dielectric plates with interlocking grooves, as shown in Fig. 2, with a cross section in Fig. 2(a) and a side view in Fig. 2(b). Linearly polarised plane wave illumination of wavelength λ_0 is normally incident on one side of the device, propagating in the z-direction. The transverse electric (TE) and transverse magnetic (TM) electric field directions are defined with respect to the grating vector $\mathbf{k}$. The phase delay experienced by the transmitted beam is varied along the x-direction of the device by the adjustable phase control medium, that is formed by tilting interlocking artificial dielectric grooves. After transmission through the device, the beam is deviated by an angle $0 < \theta < \theta_{max}$ from the z-direction. We assume that there is no tilt, and therefore no phase gradient, in the y-direction. The interlocking artificial dielectric grooves have a grating vector $\mathbf{k}$ that is parallel to the y axis and a period Λ that is smaller than $\lambda_0/4$, similar to that used in a device for polarisation control.[4] The polarisation control device had a V-groove profile that was obtained by wet anisotropic etching of (100)-silicon in an aqueous solution of KOH. The rectangular grooves that we have shown in Fig. 2(a) can be produced by deep reactive etching. We have already developed a silicon batch microfabrication process for the production of double-sided woodpile-like photonic crystal filter plates,[5] that can be adapted to produce these beam steering plates. The dry etch process allows grooves to be produced with a higher aspect ratio, improving device performance. The analysis of the rectangular grooved plates is slightly simpler, and is presented here.

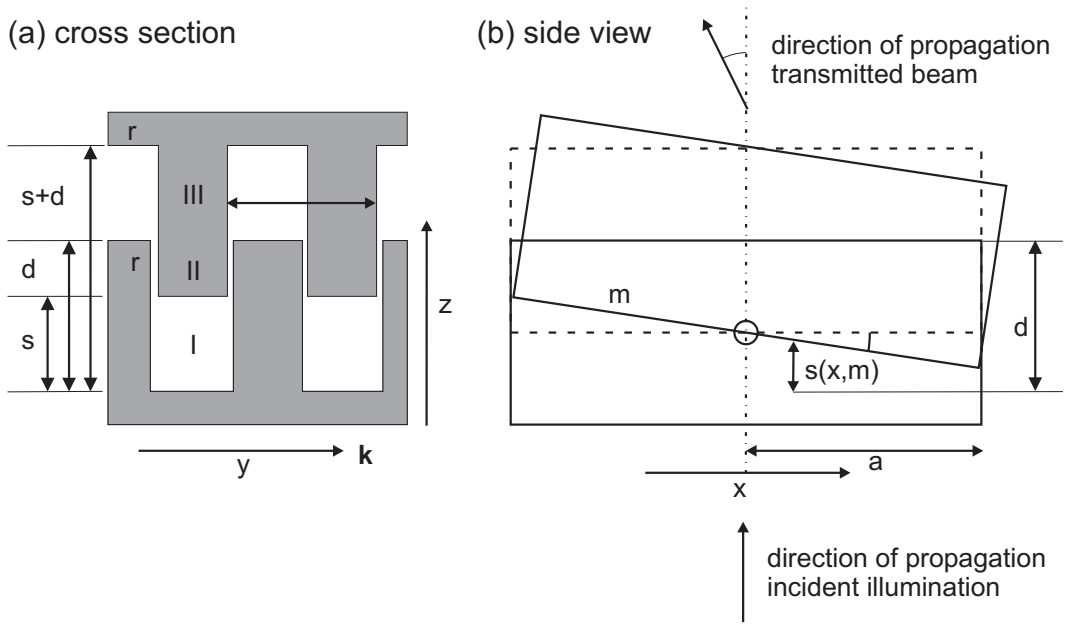

Figure 2. Schematic diagram of the rectangular-groove beam steering device; (a) cross section through the two interlocking plates and (b) side view of the tilted orientation between the plates that permits beam steering. The groove depth is d, the plate width $2a$, the plate separation s and the gradient of the tilted plate m.

The plate separation may be varied from its minimum at perfect interlock ($s = 0$), to its maximum at the grating depth ($s = d$). The larger the separation distance, the lower the net effective dielectric constant in the grooved region of the device. We have labelled the three distinct areas in this region as I, II and III, as shown in Fig. 2(a). The averaged propagation constant that is used to determine the device's phase shift in each region is

$$k_{u,v} = \frac{k_0}{v-u}\int_u^v n(z)dz, \tag{1}$$

where v and u define the boundaries of the portion of the artificial dielectric concerned, k_0 is propagation constant of free space and $n(z)$ is the effective refractive index in that region. The effective overall propagation constant

for the full extent of the interlocking region with thickness v can be calculated from

$$k_{eff} = \frac{k_0}{v}\int_0^v n(z)dz = \frac{k_0}{s+d}\left[\int_0^s n_1 dz + \int_s^d n_2 dz + \int_d^{s+d} n_3 dz\right] \tag{2}$$

where n_1 is the effective refractive index in region I, etc.[6] We choose the grating to have a mark-space ration of 50% and assume that the gap between the interlocking gratings is negligible. Zeroth order effective medium theory can then be used to approximate the effective refractive index in each of the regions as follows:

For TM polarisation ($E\|\mathbf{k}$)

$$n_1^{TM} = n_3^{TM} = \sqrt{\varepsilon_1^{TM}} \tag{3a}$$

$$\varepsilon_1^{TM} = 2\left[\frac{1}{\varepsilon_r} + 1\right]^{-1} \tag{3b}$$

$$n_2^{TM} = \sqrt{\varepsilon_r} \tag{3c}$$

For TE polarisation ($E\perp\mathbf{k}$)

$$n_1^{TE} = n_3^{TE} = \sqrt{\varepsilon_1^{TE}} \tag{3d}$$

$$\varepsilon_1^{TE} = \frac{1}{2}\left(\varepsilon_r + 1\right) \tag{3e}$$

$$n_2^{TE} = \sqrt{\varepsilon_r} \tag{3f}$$

where ε_r is the dielectric constant of the plate material, the surrounding medium is assumed to be air or vacuum and ε_1 is the effective dielectric constant in regions I and III. By combining Eq. 2 and Eq. 3, the effective propagation overall propagation constant becomes

$$k_{eff} = \frac{k_0}{s+d}\left(s\left(2n_1 - n2\right) + n_2 d\right) \tag{4}$$

for both TE and TM polarisations.

We use the array factor method to model the beam steering performance of the device. This method is typically used to model the effect of a finite array of sources, such a phased array antenna. For the present device we instead have a plane wave illuminating a plate with graded refractive index. However, the method is still applicable to the present situation because Huygen's principle states that a wavefront can be modelled as an array of infinitesimally small secondary waves originating from isotropic point sources positioned along a line of constant phase in the primary wave. An example of the method is depicted in the diagram of Fig. 3, where there is shown a section of a line of theoretical point sources arrayed along the x-direction between $-a < x < a$. If we set each point source to have identical unity magnitude but allow the phase take such values that the radiated wave propagates at an arbitrary angle θ to the x direction, then the radiated electric field may be described by the array factor (AF) as

$$AF = \int_{-a}^{a} e^{jk_0 x\cos\theta} dx \tag{5}$$

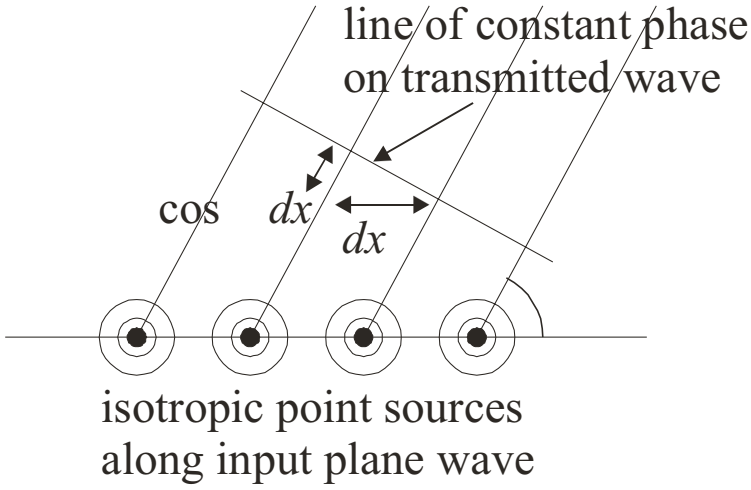

Figure 3. Schematic diagram of the method used to calculate the array factor of the beam steering device

In order to steer the beam, a phase modification $\alpha(x)$ is introduced

$$AF = \int_{-a}^{a} e^{j(k_0 x \cos\theta + \alpha(x))} dx \tag{6}$$

The phase modification produced by the present beam steering device is the product of the k_{eff} and the thickness of the artificial dielectric regions of the device ($v = s + d$), therefore

$$\alpha(x) = k_0 \left(s(x,m)(2n_1 - n_2) + n_2 d\right) \tag{7}$$

where the plate separation $s(x,m)$ is a function of the gradient of the tilt m and the position along the x-axis

$$s(x,m) = mx + \frac{d}{2} \tag{8}$$

where $-d/2a \leq m \leq d/2a$.

Substituting Eq. 8 into Eq. 7 and then substituting Eq. 7 into Eq. 6 gives

$$AF = \int_{-a}^{a} e^{j(k_0 x \cos\theta + A(x) + B)} dx \tag{9a}$$

where

$$A = m(2n_1 - n_2) \tag{9b}$$

$$B = d\frac{2n_1 - n_2}{2 + n_2 d}. \tag{9c}$$

Integrating Eq 9a gives the array factor as

$$AF = -2e^{jk_0 B} \frac{\sin(k_0(\cos\theta - A)a)}{k_0(\cos\theta - A)} \tag{10}$$

Substituting for A and normalising gives

$$AF = \frac{\sin(k_0(\cos\theta - m(2n_1 - n_2))a)}{k_0(\cos\theta - m(2n_1 - n2))} \tag{11}$$

This is a diffraction pattern that exhibits a beam steering angle θ_m. θ_m is calculated by setting the denominator of Eq. 11 to zero, giving

$$\theta_m = \cos^{-1}(m(2n_1 - n_2)) \tag{12}$$

The beam shape of transmitted beam can be plotted by using Eq. 3 and Eq. 11, and the parameters listed in Tab. 1. Note that the values in Tab. 1 assume that the silicon is lossless and has a dielectric constant of $\varepsilon_r = 12$. For practical operation of the device, we impose a limit on the maximum plate separation of $s \leq d$. Thus the length of the device ($2a$) limits the maximum possible gradient to $m = d/a$. The larger a, the smaller the maximum possible steering angle. Figure 4 shows a plot of the beam shape for a device with $d = \lambda_0$ and $a = 2.5\lambda_0$.

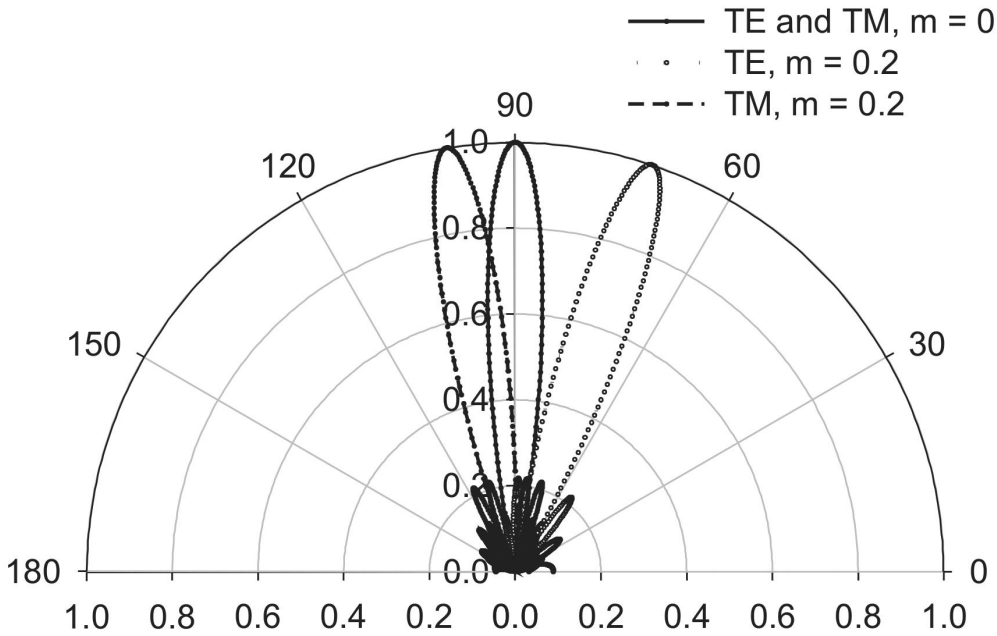

Figure 4. Plot of the transmitted beam shape predicted by the analytical array factor model.

A more practical device would have $2a \gg d$ but it is still possible to obtain significant beam-steering angles. For example, we consider the performance of a device with $2a = 20\lambda_0$. Figure 5 plots the TE and TM beam steering angle as a function of the plate tilt. The maximum tilt angle is 2.86° ($m = 0.05$). The TE beam is steered by up to 4.6° while the TM beam is steered by up to 1.9°. The TM beam is steered in the opposite direction because it has a negative gradient of refractive index (see Tab. 1).

Table 1. Typical values for n_1 and n_2. The refractive index gradient is negative for TM radiation.

	n_1	n_2	$2n_1 - n_2$
TE	2.5	3.4	1.6
TM	1.4	3.4	-0.6

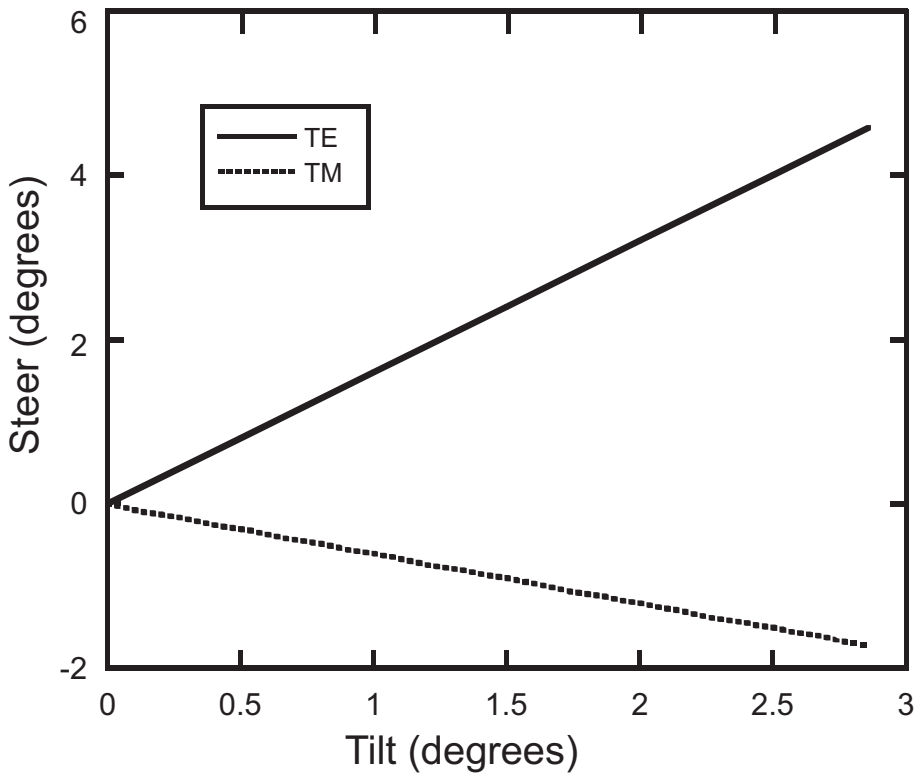

Figure 5. Plot of the beam steering angle as a function of the plate tilt angle for a device with $0 < m < 0.05$.

3. CONCLUSION

We propose a novel micro-electro-mechanical device that can be used as a transmission mode beam steering device in terahertz frequency systems. The device comprises two dielectric plates with interlocking artificial dielectric grooves. Tilting the plates relative to each other produces a linear phase gradient across the device that permits the transmitted beam to be steered. We predict the device performance using an analytical array factor (AF) calculation. Using readily manufacturable parameters, beam steering angles of up to 4.6° can be obtained for relative plate tilts of $< 2.9°$.

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