Parallel-plate leaky waveguides in the terahertz range

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***Abstract*—We describe a leaky-wave antenna based on a parallel-plate metal waveguide, suitable for use in the terahertz range. The emission from the antenna is highly directional. It can be controlled by shaping the waveguide plates, for engineering of terahertz wave fronts.**

I. INTRODUCTION

THE idea of using radiation in the 0.1-1.0 terahertz (THz) range as carrier waves for free-space wireless communications has attracted growing interest in recent years, due to the promise of the large available bandwidth [1]. Recent research has focused on system demonstrations [2], as well as the exploration of new components for modulation [3] and beam steering [4]. However, the multiplexing and demultiplexing of terahertz signals remains an unaddressed challenge, despite the importance of such capabilities for broadband networks. One promising approach involves the use of leaky-wave devices. Leaky-wave antennas have been used as directional antennas in the microwave and RF ranges since the 1940's [5]. In a leaky-wave antenna, a traveling wave is guided along a waveguiding structure and radiates outward azimuthally from the propagation axis. Often, the guide is a rectangular waveguide, for which the travelling wave is a fast wave with a phase velocity greater than the vacuum speed of light. The guided wave leaks into free space through an opening (a slot) in one of the waveguide walls. Although this mechanism can also work in the THz range, direct scaling of a rectangular waveguide from microwave to THz is challenging due to the increasing metallic losses and fabrication tolerance. Here, we investigate the use of a metal parallel-plate waveguide (PPWG) as a practical implementation of a leaky-wave structure in the terahertz range.

II. RESULTS

Our leaky wave antenna consists of a metal PPWG with a slot opened in one of the metal plates, parallel to the propagation axis (Fig. 1). This slot permits coupling between the guided wave and free space. Different frequencies couple to different propagation angles due to a phase matching condition. We employ the TE_1 mode of the waveguide, which is a fast wave. The effective refractive index of the TE_1 mode in a PPWG is determined by the frequency-dependent phase velocity [6], as

$$n_{eff} = \frac{c}{v_{phase}} = \sqrt{1-\left(\frac{c}{2bf}\right)^2}\,, \tag{1}$$

where b is the plate separation, f is the frequency, and c is the vacuum light speed. The angle of radiation emitted from the slot is determined by the phase-matching condition which is equivalent to Snell's law:

$$\sin\theta = n_{eff}\,, \tag{2}$$

where θ is the angle measured relative to the broadside orientation (perpendicular to the waveguide axis). As seen from Eqs. (1) and (2), the launch angle depends on the frequency f and the plate separation b. Fig. 1 shows measurements of the frequency-dependent angle of emission, for several different values of plate separation. The solid curves demonstrate excellent agreement between the measured values and the predictions from Eq. (2).

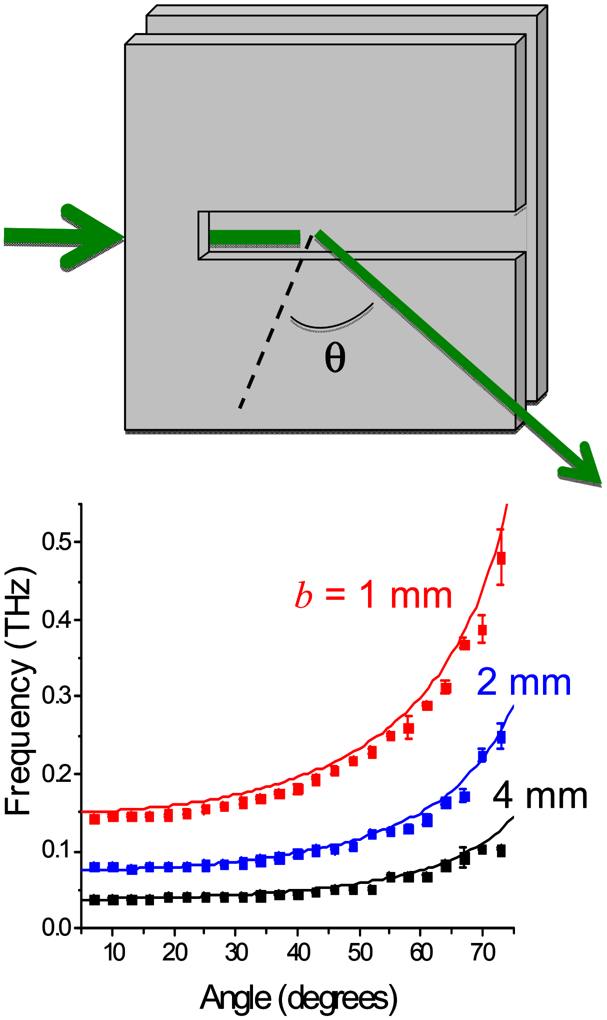

Fig. 1. (top) An illustration of the leaky-wave parallel-plate waveguide, with the emission angle θ defined relative to the surface normal, as shown. (bottom) Measured frequency-dependence of the angle of emission, for three different values of the plate separation b. The solid curves show the predictions from Eqs. (1) and (2).

We can exploit the fact that the angle of emission depends on the plate separation, by using a non-uniform plate separation along the waveguide axis. We have previously shown that a PPWG operating in the TE_1 mode remains single-mode as long as the variation in the plate separation is slow with respect to the wavelength [7]. Thus, we can vary the separation b along the propagation direction (so that b is a function of the propagation coordinate x) without sacrificing the single-mode nature of the guided wave. In a leaky-wave device, this freedom permits us to manipulate the wavefront of the emitted wave.

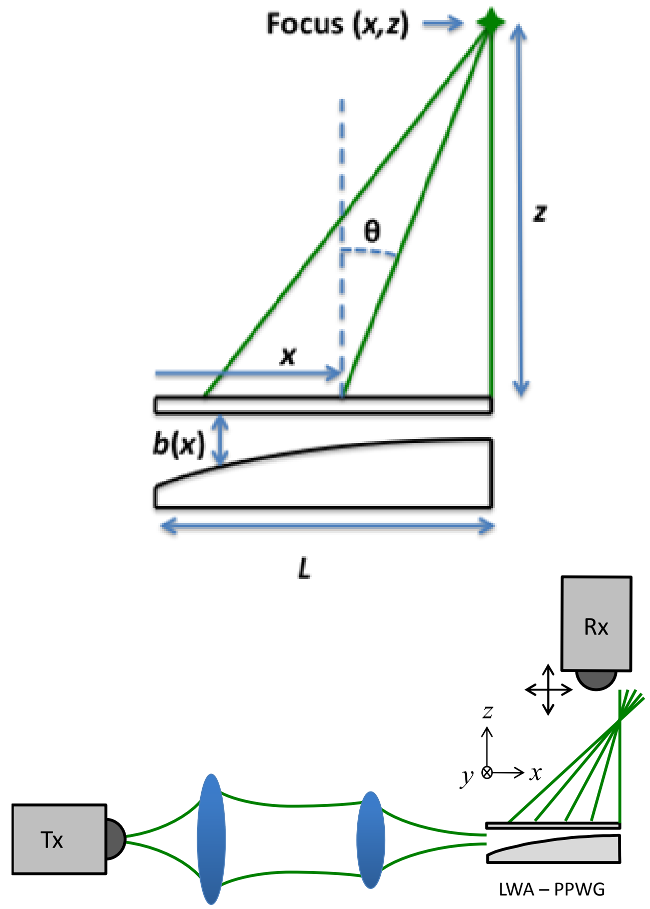

Fig. 2. (top) a schematic of the nonuniform PPWG, defining the (x,z) coordinate system as discussed in the text. (bottom) a schematic of the experimental setup. The receiver Rx is scanned in the x-z plane to characterize the field distribution in two dimensions, in the vicinity of the focal spot.

As an example, we demonstrate focusing of the wave emitted from the slot in the waveguide. We define an x-z coordinate system with respect to the upper waveguide plate (the one with the slot), as shown in Fig. 2(a). Using the phase-matching constraint, one can analytically solve for the plate separation $b(x)$ that would be needed to create a focal point at a given location (x_0,z_0). The result is

$$b(x) = \frac{c}{2f}\sqrt{1+\left(\frac{x_0 - x}{z_0}\right)^2} \quad . \qquad (3)$$

It should be mentioned that the plate separation becomes a minimum at $x = x_0$, and that this separation corresponds to the cut-off condition of the TE_1 mode. Therefore, it is preferable to define the focal point so that x_0 is no less than L, where L is the length of the waveguide as defined in Fig. 2.

Using Eq. (3), we construct several THz leaky-wave antennas designed to produce a focused beam at a specified location outside the waveguide. For each, the top plate is a solid flat aluminum plate (50 mm by 50 mm by 1 mm) with a slit (3 mm width and 42 mm length) cut along the middle. The bottom plate, for which a curved top surface is needed, is fabricated using 3D printing in the shape determined by Eq. (3), and then coated with a metallic layer so that it behaves as a solid metal object [8]. The two plates were held in place with the appropriate separation by spacers at the four corners. For the experiments, the leaky-wave antenna parallel-plate waveguide (LWA-PPWG) is excited using a broadband terahertz pulse from a fiber-coupled photoconductive antenna. The receiver, also a fiber-coupled photoconductive antenna, is scanned in two dimensions in the vicinity of the anticipated focal point. We extract spectral information at the target operating frequency by Fourier transform of the measured time-domain waveforms at each receiver location, and plot these values as field amplitudes as a function of receiver (x,z) position.

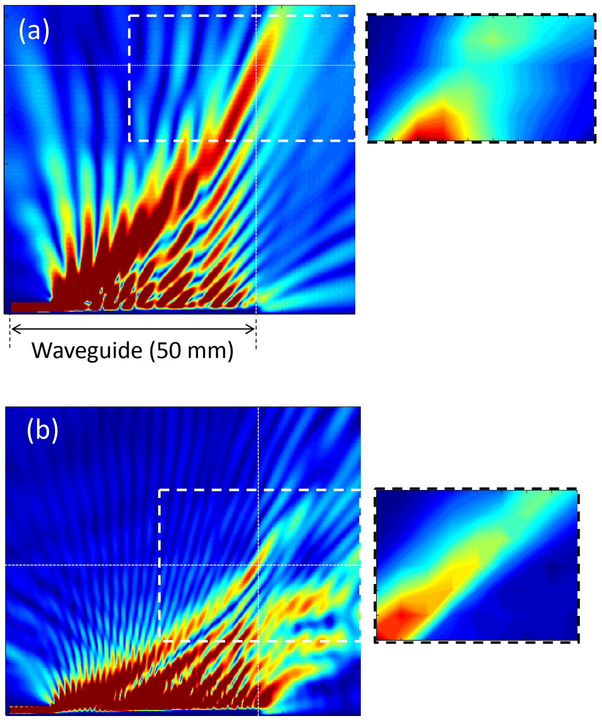

Fig. 3. Simulated and experimental result of leaky-wave focusing. The calculated (left) and measured (right) field amplitude in the x-z plane above the upper waveguide plate is presented for two waveguide designs. (a) Designed to focus 100 GHz radiation at (x_0, z_0) = (50 mm, 50mm) (b) Designed to focus 170 GHz radiation at (x_0, z_0) = (50 mm, 30 mm) at 170 GHz. In both cases, the rectangular area (white broken line) in the simulation indicates the scanned area in the experiments.

Fig. 3 illustrates simulated and experimentally measured field patterns in the x-z plane, for waveguides fabricated for two different design frequencies. For the first waveguide, designed to operate at 100 GHz, the focal point was chosen to be at (x_0, z_0) = (50 mm, 50 mm) – that is, above the end of the waveguide as illustrated in Fig. 2. For the second, with a design frequency of 170 GHz, the focal point was chosen at (50 mm, 30 mm), closer to the upper plate. In both cases, the measured beam focus is close to that anticipated from the design process.

III. SUMMARY

In conclusion, we describe a study of leaky-wave antennas in the terahertz range, using parallel-plate metal waveguides operating in the TE_1 mode. We demonstrate that moderate variations in the plate separation, along the waveguide propagation axis, can be used to engineer the wavefront of the wave emerging from the leaky-wave output port. Given the wide freedom in specifying the functional form for the waveguide plate separation function $b(x)$, this device architecture offers great promise for use in future applications involving terahertz wireless communications.

IV. ACKNOWLEDGEMENTS

This work was funded in part by the W. M. Keck Foundation.

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