A Steerable Leaky-Wave Antenna Using a Tunable Impedance Ground Plane

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***Abstract*—A steerable leaky-wave antenna is built using a mechanically tunable impedance surface. A horizontally polarized antenna couples energy into leaky transverse electric waves on a tunable textured ground plane. By tuning the resonance frequency of the surface, the band structure is shifted in frequency, which changes the tangential wave vector of the leaky waves for a fixed frequency. This steers the elevation angle of the resulting radiated beam. This steerable leaky-wave antenna can scan over a range of 45° using a mechanical movement of about 1/500 wavelength.**

***Index Terms*—Conformal antennas, electromagnetic surface waves, leaky wave antennas, scanning antennas.**

I. INTRODUCTION

A variety of surface textures are known to alter the electromagnetic properties of a metal ground plane. Some well-known surface textures are the soft and hard surfaces, in which quarter-wavelength corrugations provide a high impedance boundary condition for one polarization, but low impedance for the other [1]. These structures are used in various applications, such as manipulating the radiation patterns of horn antennas or controlling the edge diffraction of reflectors. A related structure known as a high-impedance surface, or artificial magnetic conductor, provides high effective surface impedance for both polarizations [2].

These textures can also be used to control the propagation of surface waves. For example, a flat metal ground plane supports transverse magnetic (TM) waves, but forbids transverse electric (TE) waves. Conversely, a high-impedance surface, or artificial magnetic conductor, forbids TM waves but allows TE waves in the form of leaky waves, which radiate energy into the surrounding space as they travel across the surface. Soft and hard surfaces can be considered as hybrids of the electric and magnetic conductors, as the hard surface allows both TM and TE polarizations, while the soft surface forbids both.

These various textured surfaces generally involve periodic resonant structures, which transform a conductive ground plane into a high-impedance boundary for one or both polarizations. For the soft and hard surfaces, the resonant structures are typically quarter-wavelength corrugations. For the high-impedance surfaces, they can be modeled as small resonant circuits. By adjusting the resonance frequency, the surface impedance and the surface wave propagation characteristics can be tuned. These tunable surfaces are the basis of our steerable leaky-wave antenna. By tuning the resonance frequency, we can manipulate the tangential wave vector of the leaky TE waves and steer the angle at which they radiate. This steerable leaky-wave antenna has an advantage compared to reflective beam steering methods using these surfaces [3], [4] because the feed lies adjacent to the surface, so the entire antenna is planar rather than requiring illumination by a separate feed.

II. TUNABLE IMPEDANCE SURFACES

A high-impedance surface is typically constructed as a two-dimensional (2-D) lattice of small metal plates that are shorted to a ground plane by vertical metal vias. It can be modeled as a lattice of resonant LC circuits, where the capacitance C is determined by the geometry of the neighboring metal plates and the inductance L is controlled by the thickness. The reflection phase varies from π at low frequencies to $-\pi$ at high frequencies, and crosses through zero at the LC resonance frequency given by

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{1}$$

where the surface behaves as an artificial magnetic conductor. A surface wave bandgap is centered about the resonance frequency and separates a lower TM band from an upper TE band. Within the gap, the material does not support bound surface waves of either polarization, however, leaky TE waves are supported.

The resonance frequency of these textured surfaces can be adjusted by tuning the capacitance in each unit cell. An example of a mechanically tunable surface is shown in Fig. 1. A layer of movable plates is shifted with respect to a stationary textured surface, to adjust the overlap area between the plates, and change the capacitance between neighboring cells. This tunes the resonance frequency, and also tunes the reflection phase for a fixed frequency. The reflection phase can be programmed as a function of position across the surface to produce a tunable phase gradient, so the surface can be used as a steerable reflector [3]. Electrically tuned structures can also be built using varactor diodes, [4] which can provide a low-cost alternative to traditional phased arrays. These same tunable surfaces can also be used to build a steerable leaky-wave antenna, which is the subject of the present discussion. Because many applications cannot tolerate the size required for a free-space feed, a steerable leaky-wave antenna is an attractive solution where conformal antennas are needed.

Manuscript received October 24, 2002; revised December 5, 2002. This work was supported in part by DARPA Contract N6601-99-C-8635.

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Digital Object Identifier 10.1109/LAWP.2002.807788

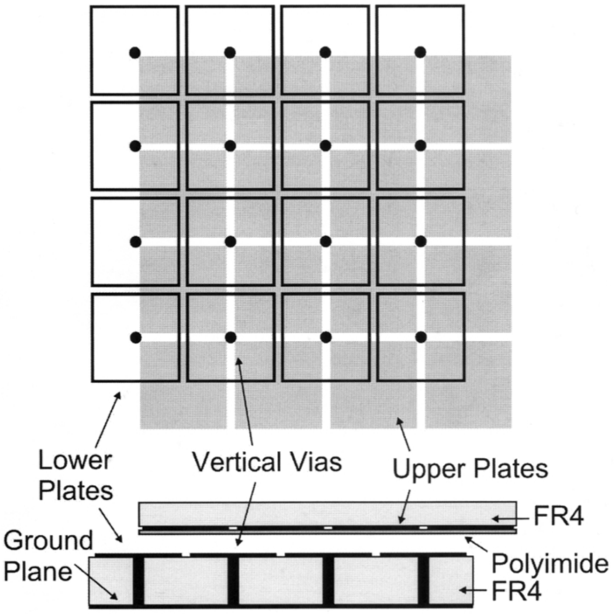


Fig. 1. The mechanically tunable impedance surface consists of two printed circuit boards: a high-impedance ground plane, and a separate tuning layer. The tuning layer is moved across the stationary high-impedance surface to vary the capacitance between the overlapping plates and tune the resonance frequency of the surface.

III. LEAKY-WAVE BEAM STEERING

Leaky-wave antennas are typically waveguide-like structures that posses a mode having a complex propagation constant, so that it radiates some of its energy into free space as it travels along the waveguide. One advantage of this type of antenna is that a large effective aperture can be addressed with a single feed, which is usually coplanar with the radiating part of the antenna. They are built in a wide variety of different geometries such as either longitudinal [5], [6] or transverse metal strips [7], [8] or the inverse structures such as longitudinal [9] or transverse slots [10]. Two-dimensional periodic structures have also been built using arrays of patches [11] or apertures [12]. Other kinds of leaky-wave antennas are built using dielectric waveguides [13], [14]. Like these various other structures, high-impedance surfaces also support a mode with a complex propagation constant—the leaky TE wave [2]. By tuning the resonance frequency of the surface, we can vary the propagation constant of the leaky TE wave and steer the radiated beam.

The behavior of leaky waves on a high-impedance surface is best understood by examining the surface wave band diagram shown in Fig. 2, which has been derived elsewhere [2]. The TM band begins at $\omega = 0$ and, for low frequencies, the TM modes are loosely bound to the surface. Initially, the TM band follows the light line, which corresponds to free-space propagation, and is indicated in Fig. 2 with the function $\omega = ck$. For frequencies approaching the resonance condition, the TM band bends below the light line, indicating a slow wave. In other words, the tangential wave vector $k_{||}$ is longer than the free-space wave vector for the same frequency, so $\omega/k_{||} < c$. Waves in this part of the TM band are closely bound to the surface. At the Brillouin zone boundary, the group velocity is zero, and a standing wave occurs.

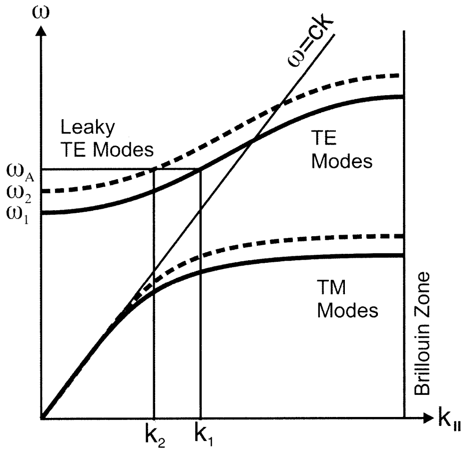


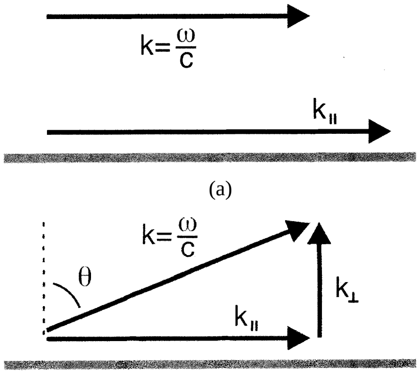
Fig. 2. The dispersion diagram of the tunable impedance surface. As the resonance frequency is tuned from ω_1 to ω_2 the band structure is shifted vertically from the solid curves to the dashed curves. For an applied wave at frequency ω_A the tangential component of the wave vector is changed from k_1 to k_2. Modes that lie above the light line represent leaky waves, which radiate at an angle governed by phase matching at the surface. By tuning the resonance frequency, the beam is steered in the elevation plane.

The TE band begins at the resonance frequency, where the mode at $k_{||} = 0$ represents a standing wave of uniform oscillating current. Because the tangential component of the wave vector is zero, radiation from this oscillating current is in the direction normal to the surface. As the frequency is increased, the TE band curves upward, and radiation occurs at an angle given by

$$\theta = \sin^{-1}\left(\frac{ck_{||}}{\omega}\right) \tag{2}$$

as illustrated in Fig. 3. Modes that lie above the light line correspond to fast waves, because the phase velocity $\omega/k_{||} > c$ and these are the leaky TE waves that are used in our steerable leaky-wave antenna. Of course, the group velocity is always slower than the speed of light, $\partial\omega/\partial k_{||} < c$. The point where the TE band crosses the light line represents a wave traveling parallel to the surface, not bound to it, but also not radiating from it. At higher frequencies the TE waves are slow waves, and are bound to the surface. Thus, traversing the TE band from the resonance frequency up to the light line, the leaky TE waves radiate at an angle that varies from normal to grazing. It has already been shown that beam steering can be accomplished with these surfaces by tuning the excitation frequency [6]. Conversely, the radiation angle can be scanned for a fixed frequency by tuning the resonance frequency.

The mechanism of leaky-wave beam steering is illustrated in Fig. 2 by solid and dashed lines, which correspond to the allowed surface wave bands for two different resonance frequencies ω_1 and ω_2. When the resonance frequency is ω_1, a leaky wave excited at ω_A will have a tangential wave vector of k_1, and will radiate at an angle of θ_1 given by (2). As the resonance frequency is tuned to ω_2, the tangential wave vector is shifted to k_2 and the leaky wave radiates at a different angle θ_2. In principle, the beam can be steered from nearly normal to nearly grazing by tuning the tangential wave vector from 0 to ω/c.



(a)

(b)

Fig. 3. (a) Phase matching between a surface wave and a free-space wave is impossible when the tangential wave vector is greater than the free space wave vector, so the wave is bound to the surface. (b) When the tangential wave vector is less than the free space wave vector, the surface wave can leak energy into free space at an angle determined by phase matching at the surface. This occurs for modes that lie above the light line on the surface wave-band diagram.

IV. MEASUREMENTS

The mechanically tunable impedance surface shown in Fig. 1 was used for the leaky-wave beam steering measurements. For our experimental structure, the square metal plates on both boards measured 6.10 mm and they were distributed on a 6.35-mm lattice. The fixed board was 6.35 mm thick and the conducting vias were 0.5 mm in diameter, centered on the square metal plates. The movable board was 1.57 mm thick, and the polyimide insulator that covered the tuning plates was 0.05 mm thick. The surface measured 25.4 cm on each edge. To ensure uniform, intimate contact between the two matching surfaces, a vacuum pump was attached to the back of the fixed board. This evacuated the space between the boards by way of the hollow vias and forced the two together. This structure is described in greater detail in a previous publication [3].

A leaky wave was launched across the surface using a horizontally polarized flared notch antenna as shown in Fig. 4, which lies flush with the superstrate of the tuning layer. This method of excitation was chosen because the flared notch antenna provides horizontally polarized, end-fire radiation, which couples into the leaky TE modes of the tunable impedance surface. The surface was tuned by moving the tuning layer with respect to the fixed lower layer in the direction transverse to the surface wave propagation, which changes the surface capacitance and adjusts the resonance frequency. The leaky waves radiate into free space at an angle that is determined by phase matching at the surface, which depends on the resonance frequency with respect to the excitation frequency. The angle of the main beam is determined by (2), with the tangential wave vector given by the dispersion relation shown in Fig. 2. By changing the tangential wave vector, we change the elevation angle of the resultant wave vector, as illustrated in Fig. 3, and steer the radiated beam.

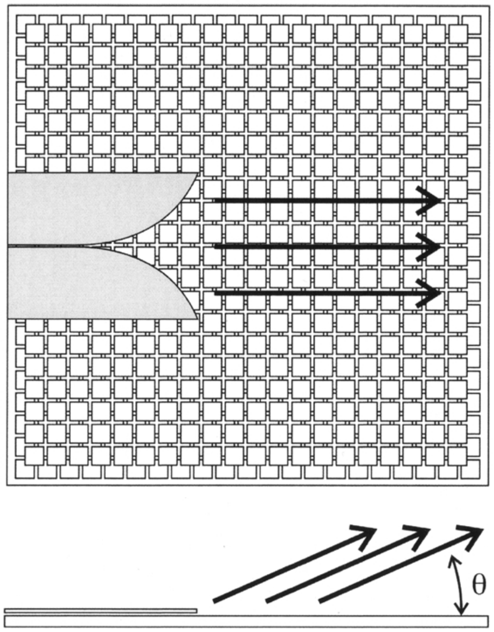


Fig. 4. A horizontally polarized antenna couples energy into leaky modes on the tunable impedance surface. The waves propagate across the surface and radiate at an angle governed by the surface resonance frequency with respect to the excitation frequency. By tuning the surface resonance frequency, the beam is steered in the elevation plane.

Fig. 5 shows several radiation patterns at 2.5 GHz as the tuning layer is moved in increments of 63.5 μm. For Fig. 5(a), the flared notch antenna excites a mode near the resonance frequency, so the tangential wave vector is nearly zero, and the wave is radiated almost normal to the surface. For Fig. 5(e) the flared notch antenna excites a mode that is closer to the light line, so the beam is radiated closer to a grazing angle from the surface. By mechanically tuning the surface, the beam can be steered in an analog fashion over a range from about 5° to about 50°. To steer the beam over this range, only 254 μm, or about 1/500 wavelength of motion was required. One could expect similar results with the electrically tunable impedance surfaces that have recently been developed [4].

Because this antenna relies on dispersion for beam steering, it also has limited instantaneous bandwidth, because the beam angle varies with frequency for a fixed position of the tuning plates. For the surface we studied, this frequency steering effect was found to be about 0.1°/MHz. This results in significant beam squint for broadband signals, so the antenna is most suited to narrowband or swept-frequency applications. The beam squint could likely be reduced, and the usable instantaneous bandwidth improved, by increasing the thickness of the textured surface. By using a thicker structure, the leaky waves would have higher average group velocity over the usable part of the dispersion curve, so the beam angle would vary less with frequency for a given position of the tuning plates.

The antenna typically maintained a return loss below -10 dB over the scan range shown. However, the measured average gain was about 10 dBi, which is lower than the expected gain for an aperture having the size of the tunable surface. This is because the single flared notch used in our experiments launches a localized leaky wave that occupies only a fraction of the available surface area. Ideally, the antenna would be fed by launching a broad, flat surface wave, which would reduce the beam width in the nonscanning plane and use more of the available surface area. We can estimate the antenna efficiency by integrating the plots in Fig. 5, and assuming an E-plane 3-dB beamwidth of

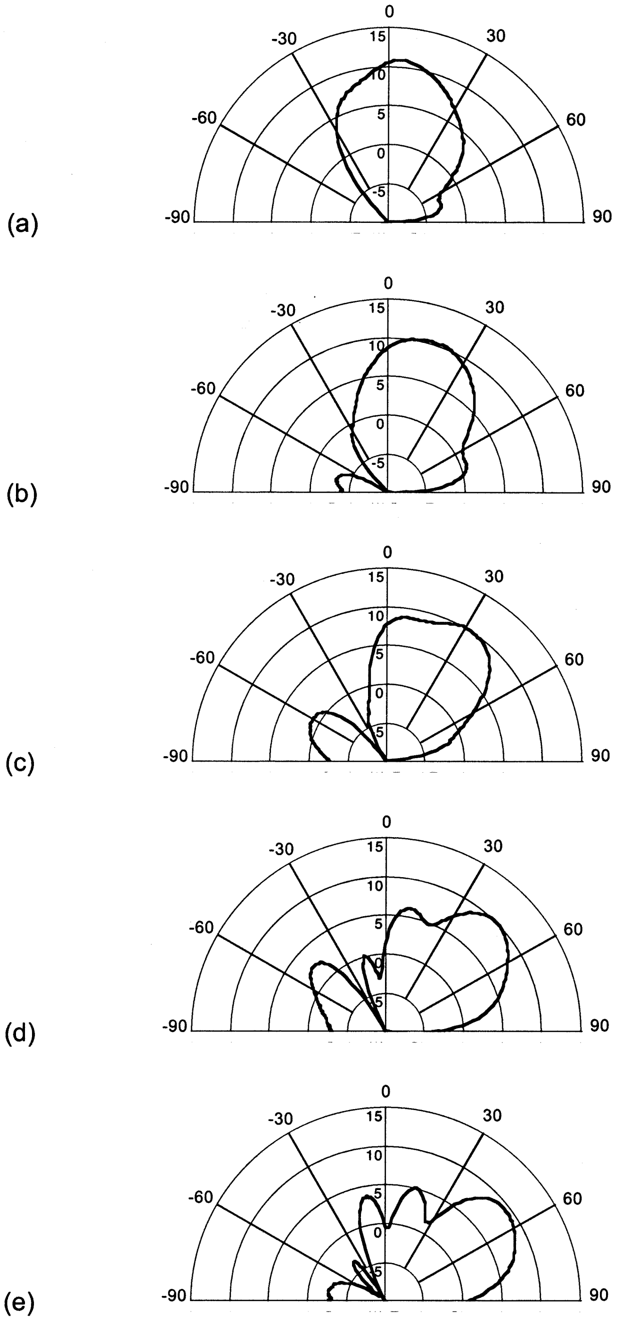


Fig. 5. (a–e) The radiation patterns for five different positions of the tuning plate, at a frequency of 2.5 GHz. Each successive plot represents a change in the relative position of the tuning plate by 63.5 μm. The angle of the leaky-wave radiation can be mechanically steered over a 45° range by moving the tuning layer only 254 μm or less than 1/500 wavelength.

about 60°, which is typical for this geometry. The antenna efficiency is calculated to be close to unity for the plots shown, indicating that the antenna is not losing a large fraction of the incoming power to dielectric or conductive losses. However, this estimate is of limited accuracy because it is strongly dependent on the overall radiation pattern, and because of additional measurement errors due to reflections within our anechoic chamber. In general, the efficiency depends primarily on the materials and tuning method used.

V. CONCLUSION

We have demonstrated a steerable leaky-wave antenna using a tunable impedance surface. By tuning the resonance frequency of the surface, we shift the surface wave dispersion curve and, thus, vary the tangential wave vector for a fixed frequency, to steer the radiated beam in the elevation plane. We have built a mechanically tuned antenna can be steered over a range of 5° to 50° using only 1/500 wavelength of motion. The radiation pattern is as expected for a single-flared notch feed and the efficiency is not significantly degraded by material losses. While this concept has been demonstrated using a mechanically tuned surface, it is expected that similar results can be obtained using electronically tunable impedance surfaces, such as those based on varactor diodes. Furthermore, 2-D scanning may be possible using a linear phased array to feed the surface. This tunable leaky-wave antenna can serve as a low-cost alternative to traditional phased arrays in applications that require planar or conformal antennas.

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