HORN IMAGE GUIDE LEAKY-WAVE ANTENNA

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ABSTRACT

A novel approach for designing a frequency-scanning millimeter-wave antenna is described. The antenna is constructed by using an image guide leaky-wave antenna embedded in a long trough with metal flares along both sides. The optimum flare angle for achieving maximum gain is theoretically predicted. The design of the leaky-wave antenna, which is comprised of metallic-strip perturbations on top of a dielectric guide, is also discussed.

Introduction

Recent trends toward the use of low-cost, high-resolution antennas for short-range communications have encouraged the design and development of different millimeter-wave antennas.[1-3] The leaky-wave antenna structure is well-suited for these applications due to its low-cost, light weight and compatibility with the dielectric-based millimeter-wave integrated circuits. Another major advantage of this structure is the ability to electronically scan the beam, simply by varying the operating frequency. Most of the antenna structures mentioned above consist of a dielectric rectangular rod or an image guide with periodic perturbations on top. These antennas provide good radiation characteristics in the E-plane, which is the plane containing the longitudinal axis of the antenna. However, the radiation patterns of these antennas are usually too wide for many applications in the plane transverse to the axis.

To reduce the beamwidth in the transverse plane, we propose a new structure in which the dielectric guide with periodic perturbations on top is embedded in a rectangular trough with a metal flare along both sides. With this arrangement, the antenna behaves like a linear array in the longitudinal (or E-) plane while the radiation pattern resembles that of a horn in the transverse (or H-) plane.

Design Criteria

Perturbation Strips

The key factors that influence the radiation characteristics of a leaky-wave antenna structure in the E-plane are the guide wavelength and the geometry of the perturbating strips on the top surface of the dielectric guide (see Figure 1). For uniform strip spacing, the angular direction θ_n' of the leaky-wave beam, measured by the y-z plane, is given by[4]

$$\theta_n' = \sin^{-1}\left(\frac{\lambda_o}{\lambda_g} + n\,\frac{\lambda_o}{d}\right), \left|\frac{\lambda_o}{\lambda_g} + n\,\frac{\lambda_o}{d}\right| \leq 1 \qquad (1)$$

where λ_o = free-space wavelength, λ_g = guide wavelength, d = perturbation spacing between the centers of two adjacent strips, and n = index of the space harmonic (0, $\pm$ 1, $\pm$2,...) and is most likely to be -1. The above formula is valid for a guide with a dielectric medium whose relative permittivity is not too large.

For very narrow strip widths, the radiation from each strip element is so small that a very long antenna has to be constructed in order to radiate off the energy in an efficient manner. Experiments have confirmed that, for a uniformly spaced array, there is always a noticeable amount of residual energy in the endfire direction if the strip width is less than 0.2 λ_g, even if 50 strips are used. This indicates that not all the traveling wave energy launched in the guide has been radiated by the metal strips.

On the other hand, if the metal strips are too wide ($>0.5\lambda_g$), the bulk of the radiated energy of radiation is produced by the first few strips and, consequently, the effective aperture is very small. Also, for large strip widths, the side lobes are very high, due probably to the large mismatch at the first strip. A parameter study of the E-plane gain characteristics of the antenna revealed that the optimum strip width was approximately $0.4\lambda_g$ for uniform strips.

The study also revealed that the radiation characteristics in the E-plane are much improved when the strip width is continuously tapered.[5] By linearly tapering the strip width (see Figure 1), the effective aperture of the antenna is considerably enlarged and the beamwidth is narrowed. The larger strips at the end of the antenna radiate efficiently and assures that only negligible power is left in the endfire (axial) direction. The near field power distribution plots for a leaky-wave antenna with tapered strip width show that little or no radiation is produced by the first few strips, and their role appears to be limited to providing an impedance match in the transition region[6] and lowering the side-lobe levels of the antennna. The width of the n-th strip is found from the following empirical relation

$$w_n = \begin{Bmatrix} 0.15 + 0.015\ (n-1), & n \leq 18 \\ 0.4 & , n > 18 \end{Bmatrix} \lambda_g \qquad (2)$$

where λ_g is the guide wavelength (see Appendix A).

Several other linear tapered distributions for the strip width were investigated. However, the relation in (2) provided the most satisfactory results. More exotic distribution functions for the strip width, e.g., exponential, were not investigated in this study.

Trough with Metal Flares Attached

It is well-known that the beamwidth in the H-plane of the conventional leaky-wave antennas is extremely wide; for instance, the null-to-null beamwidth of these antennas is almost 180 degrees. To narrow the beam down, the dielectric guide with metal strip perturbations described in a previous section was embedded in a trough with a rectangular cross-section and with metal flares attached to each

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side. The resulting configuration is shown in Figure 2.

The width of the trough was chosen such that it can easily interface with the waveguide, which is used to feed the antenna structure. For an E-band waveguide, the trough width was chosen to be 3.4 mm and a slight taper was introduced near the feed end. The dielectric guide was designed to fit snugly against the side walls of the metal trough thus eliminating the need for adhesive materials which were used to bond the dielectric guide to the ground plane. The height of the trough is such that the propagation constant of the dielectric-loaded trough guides can be calculated. The height of the dielectric guide is then chosen to provide a single-mode operation.

With these guidelines and constaints in mind, a dielectric waveguide of dimensions 3.4 x 1.4 mm was constructed. The trough height was chosen to be 3.4 mm to simplify the constructions. At 81.5 GHz, the guide wavelength was calculated to be 2.70 mm.

The flare angle α was chosen to maximize the directive gain. Since the radiation in the E-plane is fixed by the distribution of the silver strips, the overall gain of the antenna depends only on the radiation pattern in the H-plane which is a function of the flare angle and the length of the tapered metal flare. Under the assumption that the structure is infinitely long in the z-direction and that E_z is the principal component of the electric field, the metal flare can be modeled as an H-plane sectoral horn.[7,8] Figure 3 shows the remarkable similarity between the measured directive gain of the test antenna and that of an H-plane sectoral horn. The length of the tapered metal flare was chosen to be 4 cm in this design.

For the strip-width distribution chosen according to Equation (2) and the flare angle selected from Figure 3 for maximum gain, the radiation patterns in both E- and H-planes of the horn image guide leaky-wave antenna were measured and are plotted in Figure 4. The overall gain of the antenna is a product of the gains in the E- and H-planes and was measured to be 26 dB. The side lobes are at least 25 dB below the main lobe. Note that the return loss at the feed was slightly less than 15 dB. The half-power beamwidths (HPBW) in the E- and H-planes are 3.2 and 12.4 degrees, respectively. There were 32 silver strips on top of the dielectric guide. The antenna was designed for broadside radiation. However, the experimental beam angle deviated slightly from the normal direction.

Conclusions

A horn image guide leaky-wave antenna structure has been described. Both the E- and H-plane beamwidths achieved were much narrower than for a conventional image guide design. Optimum designs of the perturbation strips on top of the dielectric waveguide and the flare angles of the horn have been determined.

References

(1) Y. Shiau, "Dielectric rod antennas for millimeter-wave integrated circuits," IEEE Trans. Microwave Theory Tech., vol. MTT-24, pp. 869-872, Nov. 1976.

(2) K. L. Klohn, R. E. Horn, H. Jacobs and E. Freibergs, "Silicon waveguide frequency scanning linear array antenna," IEEE Trans. Microwave Theory Tech., vol. MTT-26, pp. 764-773, Oct. 1978.

(3) R. E. Horn, H. Jacobs, E. Freibergs, and K. L. Klohn, "Electronic modulated beam-steerable silicon waveguide array antenna," IEEE Trans. Microwave Theory Tech., vol. MTT-28, pp. 647-653, June 1980.

(4) F. J. Zucker, "Surface- and leaky-wave antennas," in Antenna Engineering Handbook, Jasik, Ed. New York: McGraw-Hill, 1961, ch. 16.

(5) S. Ray, Master's Thesis, University of Illinois at Urbana-Champaign, to appear.

(6) E. E. Malecki and H. Jacobs, "Design, fabrication and evaluation of low cost diode oscillators for millimeter-waves," R & D Technical Report DELET-TR-80-8, U.S. Army Elec. Command, Fort Monmouth, New Jersey, April 1980.

(7) W. L. Weeks, Antenna Engineering, New York: McGraw-Hill, 1968, ch. 6.

(8) S. A. Schelkunoff and H. T. Frus, Antennas: Theory and Practice, New York: Wiley, 1952, ch. 16.

Appendix A

Calculations of the Propagation Constants

It is advantageous to keep the dielectric waveguide in contact with the metallic side walls of the trough in order to ease the supporting problems, and to eliminate the need for adhesive materials which were used to bond the dielectric guide to the ground plane. This study was primarily conducted using this configuration, and, therefore, only the propagation constants for this structure are presented.

The field's variation in the x-direction must satisfy the boundary conditions at the metal side walls resulting in

$$k_x = \frac{n\pi}{a}, \; n = 1, 2, \ldots \qquad \text{(A-1)}$$

where a is the large dimension of the dielectric guide and n = 1 for the fundamental mode.

Matching the field distributions at the dielectric-air interface yields the following eigenvalue equation for k_y

$$k_y b = \frac{m\pi}{2} - \tan^{-1}\left(\frac{\eta k_y}{\varepsilon_r}\right), \; m = 1, 2, \ldots \qquad \text{(A-2)}$$

where $$\eta = [(\varepsilon_r - 1)\, k_o^2 - k_y^2]^{-1/2} \qquad \text{(A-3)}$$

and η is the field decay coefficient outside of the dielectric, k_o is the wave number of free space, b is the height of the dielectric guide, and m = 1 for the fundamental mode.

The longitudinal propagation constant is obtained as follows

$$k_z = \frac{2\pi}{\lambda_g} = (\varepsilon_r k_0^2 - k_x^2 - k_y^2)^{+1/2} \qquad \text{(A-4)}$$

where λ_g is the guide wavelength.

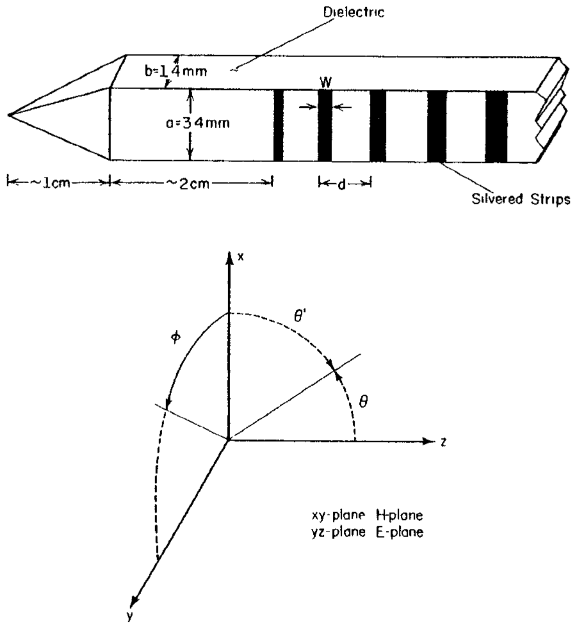

Figure 1. Leaky-wave antenna and the co-ordinate system.

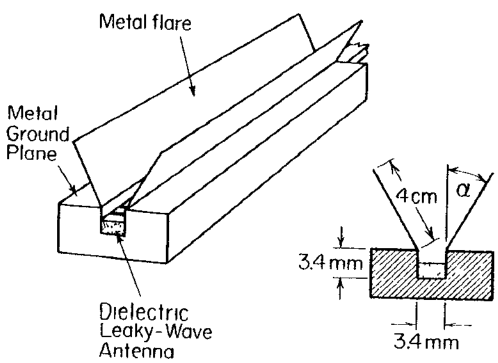

Figure 2. Horn image guide leaky-wave antenna.

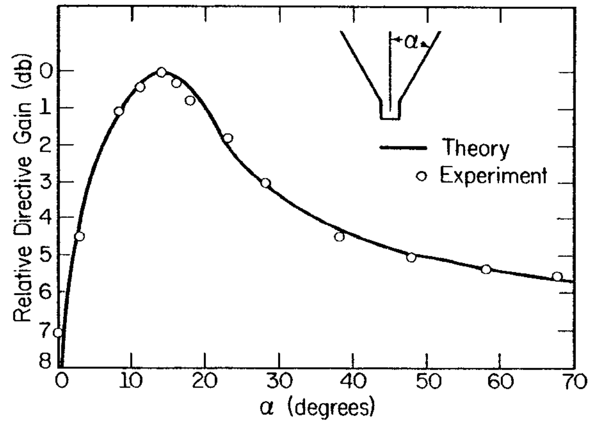

Figure 3. Relative gains of the test antenna and an H-plane sectoral horn vs. flair angle.

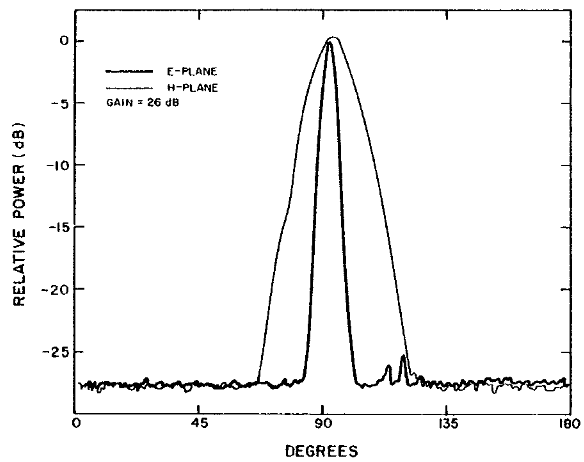

Figure 4. E- and H- plane radiation patterns of the constructed antenna.