A Novel Millimeter-Wave Beam-Steering Technique Using a Dielectric-Image-Line-Fed Grating Film

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***Abstract* — This paper introduces a novel, broad-band, low-cost technique for beam steering at millimeter-wave frequencies using a moveable grating film fed by dielectric image line. An excellent radiation pattern is maintained across the measured scanning ranges at 30, 35, and 40 GHz, with up to 53° scanning reported at 35 GHz. Theoretical calculations closely predict the observed scan angle across the entire range of measurement.**

I. Introduction

Current interest in developing broadband, low-cost methods of beam control at millimeter-wave frequencies has been the inspiration for much recent research. Early [1]-[6] and recent [7]-[8] beam steering studies using array-effect antennas fed by integrated dielectric guides have offered alternatives to solid-state and ferrite phase shifters, which typically display either narrow bandwidth, significant insertion loss, or low phase shift at millimeter wave frequencies. The patch antenna array fed by dielectric image line with reflector plate (DILWRP) [7]-[8] is already finding application in commercial systems requiring low-cost, high-performance beam scanning.

This paper presents a new technique for millimeter-wave beam steering that uses a dielectric image line perturbed by a thin, moveable grating film. Although leaky-wave antennas of the grating type are well described in literature, the concept and implementation reported here are unique and demonstrate a simple means of scanning a highly directive beam over a wide angle at frequencies across the Ka-band.

II. Concept & Design

A general class of leaky-wave antenna may be constructed by placing dielectric or conducting strips periodically along a dielectric waveguide. These strips form a grating that perturbs the energy traveling along the guide, exciting leaky modes above the surface that determine the nature of the far-field pattern [6]. The radiated beam is fan-shaped, being highly directive in the array-effect dimension. Assuming the grating strips themselves have a negligible effect on the propagation constant along the perturbed guide, the angle of radiation in the direction forward from broadside can be calculated at any given frequency of excitation as a simple function of the guide wavelength λ_g and strip spacing d:

$$\theta_n = \arcsin\left(\frac{\lambda_o}{\lambda_g} + \frac{n\lambda_o}{d}\right), \qquad \left|\frac{\lambda_o}{\lambda_g} + \frac{n\lambda_o}{d}\right| \le 1 \qquad (1)$$

where λ_o is the free space wavelength and n, the space harmonic (0, ±1, ±2, ···), is conventionally chosen as –1 for single beam operation [1]. Previous beam-scanning studies using this class of antenna have focused on scanning θ_n by varying the operating frequency or by finding a means to modulate the guide wavelength. The approach taken in this investigation is to alter the grating spacing d along the guide while leaving the guiding structure itself intact.

Figure 1 illustrates the configuration of the new scanning antenna. A thin, moveable dielectric film with metal gratings etched on its underside (but depicted as visible in the figure) is extended across a dielectric image line. The unused portions of the grating layer are fixed directly onto the ground plane on either side of the image line. By choosing a sufficiently wide image line and sufficiently thin grating film, the curvature of the grating strips above the image line may be minimized. The widths of the grating strips themselves are tapered according to an empirical guideline [9] in order to gradually perturb the electromagnetic signal traveling along the image line. The resulting radiation pattern of the leaky wave antenna is E-polarized in the x-direction. Shifting the grating layer in the $\pm y$-direction varies the spacing between grating elements, scanning the radiated beam along θ in the x-z plane.

The design featured in this study is optimized for operation from 30 to 40 GHz using an effective dielectric

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constant technique [10] to calculate the dispersion of the guide wavelength along the unperturbed image line. The dielectric image line is constructed to be 1.57 mm high, 6.10 mm wide, and 153 mm long. The moveable grating film is 0.13 mm thick and 368 mm long in the *y*-direction of Figure 1. Eighteen grating strips are used, with the spacing between elements decreasing linearly from d_{max} = 8.60 mm to d_{min} = 4.56 mm. Both the image line and dielectric film are fabricated using RT-Duroid 5880, with relative dielectric constant $\varepsilon_r = 2.2$.

III. Measured Performance

Figure 2 illustrates the measured and calculated main beam angle of the scanning antenna as the element-to-element spacing of the perturbing grating is varied along the image line. Over the entire range shown in Figure 2, maximum side-lobe levels are a minimum of 10 dB below the main beam. Using this conservative criterion to define the scanning range, we report 32° scanning at 30 GHz, 53° at 35 GHz, and 35° at 40 GHz. The typical maximum side-lobe level is 13 dB below the main beam. Cross-polarization levels at the main beam angle are greater than 25 dB down at all three frequencies for the 7.6-mm element-to-element spacing.

Figure 3 illustrates the *E*-plane radiation pattern of the antenna at 35 GHz as the beam steers from –6.5° to 46.5°. An excellent radiation pattern is maintained across the scanning range.

Figure 4 displays measured isotropic gain and input return loss as a function of element-to-element spacing for the 30, 35, and 40 GHz scans. Return loss is typically well below –15 dB across the scanning range. The grating structure itself, however, has a stopband effect at $d = \lambda_g$, [4], causing the return loss to exceed –10 dB and the gain to drop within ±1° of the broadside angle. Isotropic gains observed across the 30, 35, and 40 GHz scans are 17.7 ± 1.5 dB, 19.1 ± 1.7 dB, and 19.0 ± 1.2 dB, respectively. For applications requiring greater gain flatness across the scanning range, additional grating strips may be added as the spacing between elements narrows.

IV. Conclusions & Discussion

This paper has introduced a novel leaky-wave antenna design in which a moveable grating film extended across a stationary dielectric image line allowed wide-angle beam scanning at 30, 35, and 40 GHz. Measured and calculated results for the main-beam scan angle were in good agreement. The results should have many applications in broadband millimeter-wave beam-control techniques.

Acknowledgement

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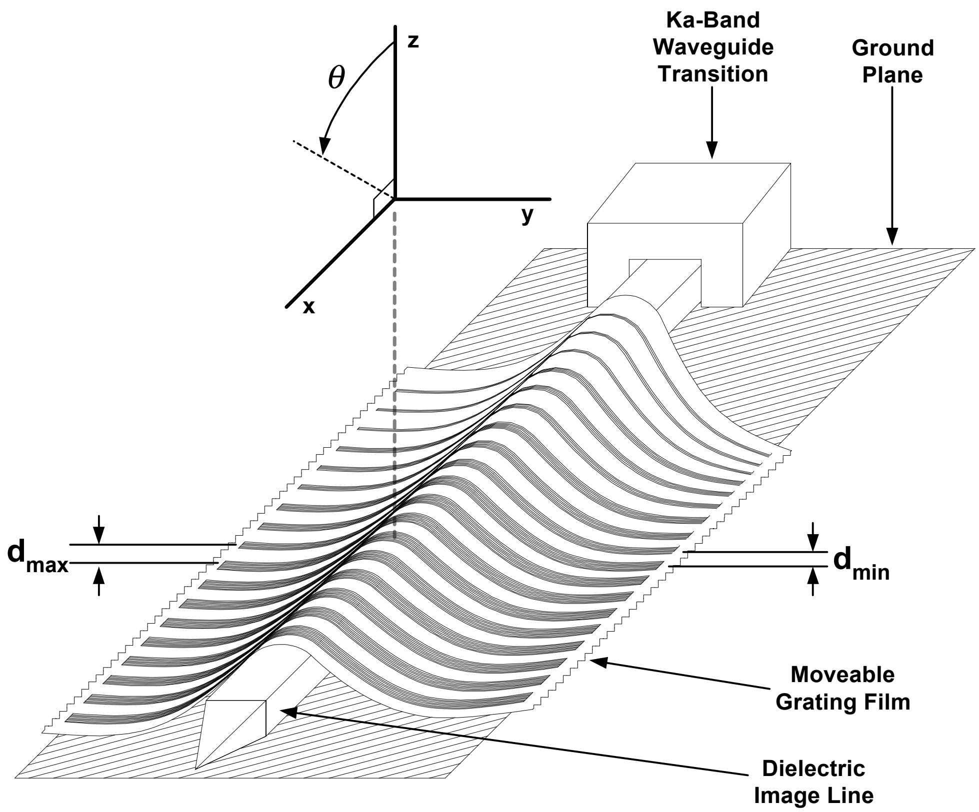

Figure 1 Scanning antenna configuration (not to scale).

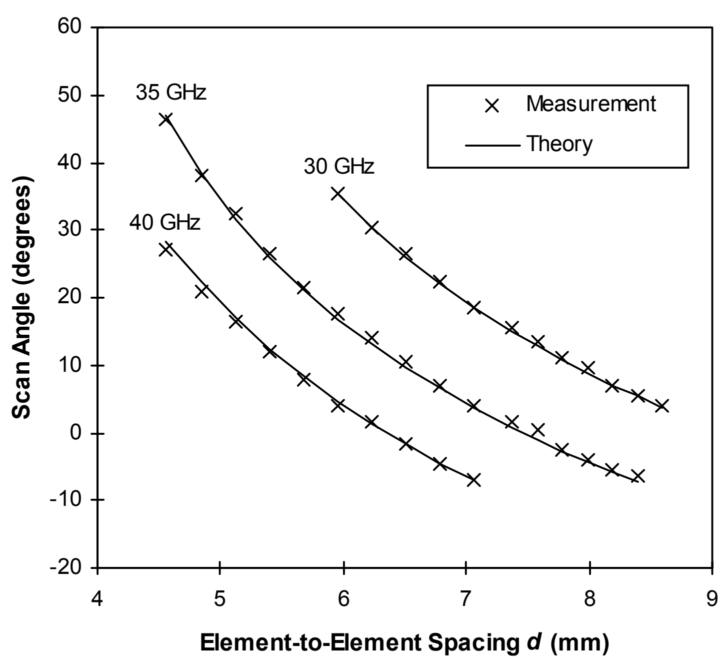

Figure 2 Measured and calculated beam scanning along the θ-direction at 30, 35, and 40 GHz.

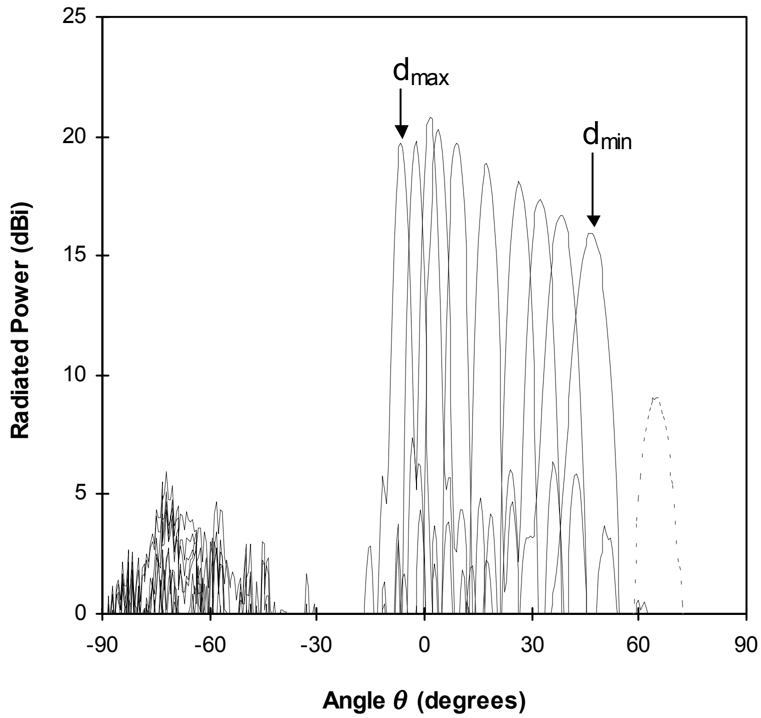

Figure 3 Measured *E*-plane radiation pattern as the beam scans from 46.5° to –6.5° at 35 GHz. The second space harmonic (dashed) is associated solely with the maximum reverse scan.

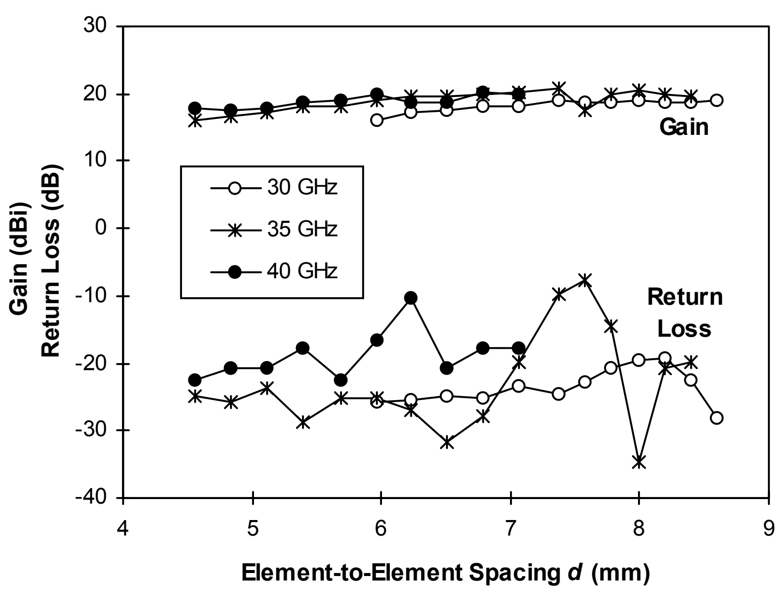

Figure 4 Isotropic gain and input return loss at 30, 35, and 40 GHz.