Electronic Modulated Beam-Steerable Silicon Waveguide Array Antenna

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Abstract—The design and experimental findings for a low-cost easily fabricated millimeter-wave line scanner is described. This antenna consists of a 1-mm×1-mm silicon dielectric rod with a metal grating (periodic structure) on the upper surface and p-i-n diodes mounted on the sidewall. A narrow 8° beam is radiated from the grated (perturbed) surface at an angle dependent on the guide and perturbation spacing. The beam angle is switched over a 10° angle by application of a dc forward current through the p-i-n diode modulators.

I. INTRODUCTION

RECENT DEMANDS for high-resolution radar for terminal homing and for surveillance and target acquisition have led to research work on electronic millimeter-wave beam steerable antennas. These devices would replace mechanical gimbals which are expensive and have too slow a scanning rate for many applications. This paper describes the design of a line scanning element which may lead to future beam steering devices with operation at a single frequency. This device, operating near 60 GHz, consists of a rectangular silicon rod with small metallic stripe perturbations on one surface (upper side) and distributed p-i-n diodes attached to the adjacent surface (sidewalls), as shown in Fig. 1. The angle of radiation of the fan-shaped beam is determined by the guide wavelength and the perturbation spacing. When the p-i-n diodes are in a nonconducting state (unbiased), the guide wavelength is a specific value which determines the angle of radiation. When the p-i-n diodes are biased in the forward direction, an effect is produced equivalent to moving a metal wall up to the side surface. The result is a longer guide wavelength in the dielectric and a change of the radiated angle of the fan-shaped beam. A shift in angle of about 10° was easily obtained corresponding to approximately a 6.7-percent change in guide wavelength or a phase shift of 24.3° per wavelength.

II. EXPERIMENT

A silicon waveguide, 0.1 cm wide, 0.1 cm high, and 13 cm long with 16 rectangular copper foil stripes (0.1 cm wide by 0.06 cm long) cemented across the upper silicon surface at a periodic spacing of 0.18 cm, provides a means of transforming the propagated energy in the dielectric guide to radiated energy from the periodic grated surface. The theoretical beamwidth was calculated as a function of the antenna aperture [1] as

\[ \theta_w \approx \frac{\lambda_0}{D} = \frac{\lambda_0}{d(m-1)} \]  

(1)

where \( \lambda_0 \) = free-space wavelength, \( D \) = length of the aperture, \( d \) = periodic grating spacing, and \( m \) = number of per-
turbations. If a beamwidth of $10^\circ$ (0.18 radians) is desired at 61 GHz, with $d=0.18$ cm, then $m$ is determined from (1) as 16. This assumes that the total angle at the half-power points. Subsequent experiments gave beamwidths of approximately 8°. The beam direction in the $r, \Theta$ plane is determined by the following equation [2], [3]:

$$\Theta_n = \sin^{-1}\left(\frac{\lambda_0}{\lambda_r} + \frac{n \lambda_0}{d}\right), \quad \left|\frac{\lambda_0}{\lambda_r} + \frac{n \lambda_0}{d}\right| < 1 \tag{2}$$

where $\Theta_n$ = the beam angle from the normal, $\lambda_r$ = the silicon guide wavelength in the direction of propagation, $n$ = the spatial harmonic ($0, 1, 2, \cdots$), and $d$ = periodic grating spacing. With $n = -1$, and from the experiment, $\lambda_r$ can be calculated from measured and known data using (2). At $f_s=68$ GHz, $\lambda_0=0.44$ cm; with a grating spacing of $d=0.18$ cm, assume an angle of $\Theta$ near 0° is desired. Then from (2) it is obvious that $\lambda_r = d=0.18$ cm. For frequencies below 68 GHz, $\lambda_r$ increases as a function of $\lambda_0$, and with $d$ held fixed, $\Theta<0^\circ$. Thus for any source frequency, $\lambda_r$ can be calculated from (2) by measuring the angle of radiation $\Theta$. The perturbation spacing of 0.18 cm was chosen to provide a radiation angle from $-8^\circ$ to $-42^\circ$ over the range of the frequencies desired. The width of the perturbation stripes determines the power radiated but does not markedly change the angle of radiation if power is transferred through the entire aperture length. The aperture distribution is exponential.

From equations developed by Marcatili [4], Toulios [5], and Schwering [6], theoretical calculations of $\lambda_r$ can also be made as a check on the experimental value of $\lambda_r$ calculated by (2). From the Marcatili equations

$$k_z = \sqrt{k_x^2 - k_y^2 - k_z^2} \tag{3}$$

$$\lambda_r = \frac{2 \pi}{k_x}, \lambda_x = \frac{2 \pi}{k_x}, k_x = \frac{2 \pi n_1}{\lambda_0} \tag{4}$$

and if air surrounds the dielectric waveguide on all sides to infinity, then

$$k_x a = \pi - \tan^{-1}(k_y \xi_3) - \tan^{-1}(k_y \xi_4) \tag{5}$$

$$k_y b = \pi - \tan^{-1}\left(\frac{k_y \eta_2}{\epsilon_1}\right) - \tan^{-1}\left(\frac{k_y \eta_4}{\epsilon_1}\right) \tag{6}$$

where $a$ = the $x$ dimension (width) and $b = y$ dimension (height) of the silicon guide. The distances the fields penetrate the surrounding media (media 2 and 4, above and below: media 3 and 5, left and right) are given by

$$\xi_{3,5} = \frac{1}{\sqrt{\left(\frac{\pi}{A_{3,5}}\right)^2 - k_z^2}} \tag{7}$$

$$\eta_{2,4} = \frac{1}{\sqrt{\left(\frac{\pi}{A_{2,4}}\right)^2 - k_z^2}} \tag{8}$$

where

$$A_{2,3,4,5} = \lambda_0/2\sqrt{n_1^2 - n_{2,3,4,5}^2} \tag{9}$$

and $n_1$ = the index of refraction of silicon; $n_{2,3,4,5}$ = index of refraction of surrounding media (in this case, air).

If the p-i-n diodes are mounted on the sidewall of the silicon guide as in Fig. 1, then (5) must be modified to account for the finite distance of the surrounding medium. Conducting diodes (like a metal wall) will set $E_y=0$ at the diode surface reducing $\lambda_x$ and thus from (4) increasing $\lambda_r$ causing more negative radiation angle $\Theta$. A detailed example is described in Appendix A. In these experiments, a metal plate was placed on the bottom of the silicon guide separated by an insulating layer 0.024 cm thick. The purpose of the bottom plate was to assure that all power would be radiated from the top side. Without the bottom plate, an equal amount of power would be radiated from the bottom surface as is radiated from the upper surface [7]. The bottom metal plate redirects the power which would have been radiated from the bottom surface back up and out the upper surface at exactly the same angle as the radiation from the upper surface. The thickness of the insulating tape between the bottom of the silicon guide and the metal tape was experimentally increased to obtain the largest change in $\Theta$ with a change in conductivity of the p-i-n diodes. Beyond this thickness, no further improvement was noted.

### III. p-i-n Diode Modulators

The physical arrangement for the guide and diodes [8] is shown in Fig. 1. The diodes are attached to the guide sidewall adjacent to the perturbed upper surface with an insulating tape layer 0.016 cm thick so that the diodes are not directly on the sidewall. Due to the long carrier lifetime characteristics of p-i-n diodes in the intrinsic region under forward biased conditions, the free carriers act as a metal sheath across the intrinsic region as would a permanent metal surface (Fig. 2). With the diodes forward biased (100 mA per diode), the sidewall of the silicon acts as a metallic surface which increases the propagation constant ($k_x$). This reduces $\lambda_r$ and hence increases $\lambda_r$ and results in a shift of the radiated beam in a negative direction as indicated in (2). The effect on wavelength due to unbiased and biased diodes is shown in Figs. 2 and 3.

The semiconductor modulating p-i-n diodes were constructed as follows: the dimensions of the trapezoidal diodes were 1.2 cm long (bottom side), 0.1 cm high, 0.05 cm wide, and 0.9 cm long (upper side). A trapezoidal diode configuration was chosen (Fig. 1) to provide a gradual transition in the direction of propagation to assure an impedance match for minimum reflection from the diode discontinuity and hence reduce the possibility of radiation from the diode edges. The i region was made with high resistivity 20,000 $\Omega$-cm silicon. The p and n regions were coated with a 200-A layer of chromium and then overcoated with gold. Measured lifetimes were greater than 40 $\mu$s after all processing was completed.1

1The p-i-n diode wafers (from which the trapezoidal diodes were cut) were obtained from Martin–Marietta Aerospace Company, Orlando, FL.
IV. DATA

The test setup for this study is shown in Fig. 4. RF power was applied from a 55- to 75-GHz source (square-wave modulated at 100 Hz) through a calibrated attenuator, frequency meter, E-H tuner, and two 10-dB directional couplers and detectors (for forward and reflected power measurements). The silicon waveguide under test was placed in a test fixture calibrated for accurate radiation angle measurements. Most of the incident propagated power was transformed into radiated power; the remainder (not transformed) was measured using another 10-dB directional coupler and detector. The silicon waveguide was tapered on both ends, (Fig. 1) to assure the best impedance match and the highest power transfer from metal waveguide (TE$_{10}$ mode) to silicon waveguide (E$_{11}$ mode). The relative radiated power was measured with a horn waveguide and the modulation detected using a square-law diode detector placed at a distance of 20 cm above the perturbed surface. This was checked with the far field pattern at a distance greater than 100 cm with approximately the same results. The test setup provided a means of measuring radiation angle $\Theta$, relative radiated power, incident propagated power ($P_f$), reflected power ($P_R$), and transmitted power ($P_0$). The power levels $P_f$, $P_R$, and $P_0$ provided VSWR and loss measurements. Both $P_R$ and $P_0$ were 30 dB less than $P_f$.

Measurements of insertion loss on the silicon waveguide without metal perturbations but with the diode mounted on the side wall showed an overall worst case insertion loss of 2.1 dB. This accounts for power losses due to: diode absorption, metal-to-silicon waveguide transitions (extraneous radiation and reflection), and silicon guide dissipation. With this knowledge of the system losses, the silicon guide with perturbations added was installed in the test setup and radiation tests performed. Experimentally, the forward power $P_f$ was maintained at 20 mW. Reflected power $P_R$ was approximately 20 $\mu$W. With a 2.1-dB system loss, the power loss was 7 mW which accounts for 38 percent of the input power with a remaining power of 13 mW which was converted to radiated power. This assumed negligible loss in the metal perturbations.

Although small, radiation leakage at the metal-to-silicon guide transitions was inhibited by use of end absorbers (carbon compound material) positioned directly over each transition. The radiation angle $\Theta$ was then measured as a function of frequency. The data plotted in Fig. 5 shows the peak radiation angle $\Theta$ as a function of frequency with the p-i-n diodes unbiased (upper curve) and biased (lower curve). The experimental data was obtained by setting the source frequency at 61 GHz, and then adjusting the position of the silicon waveguide for the highest level of radiated power. The angle of peak radiation was noted. Diode bias current was then applied and again the angle of peak radiation observed. This procedure was continued over a range of frequencies from 61 to 66 GHz. The plot shows a consistent shift of about 8° between the biased and unbiased states over the frequency range examined. From the data shown, $\lambda_c$ can be calculated from (2) using both curves A (upper) and B (lower). The calculations show that at 61 GHz, $\lambda_c = 0.2278$ cm, $\lambda_B = 0.2399$ cm, and $\Delta \lambda_c = \lambda_B - \lambda_c = 0.012$ cm. A change in $\lambda_c$ of 0.012 cm due to the p-i-n modulators, results in a radiation angle change of 8°.

A radiation pattern plot of power level $|V|$ as a function of radiation angle at a frequency of 63.06 GHz for both unbiased and biased diodes is shown in Fig. 6. The radiation angle shifted from $-22.5^\circ$ with no bias to $-32^\circ$ with a bias 100 mA on each of the three diodes. A polar
plot of this data is shown in Fig. 7. The two beams were identical in amplitude and shape but displaced from each other by 9.5°.

Intermediate bias current levels were used (Fig. 6) to determine if a continuous change of Θ as a function of bias current could be realized. Test data showed that intermediate current levels greater than zero and up to 18 mA caused an increase of attenuation of the radiated beam. For bias current levels greater than 18 mA, the radiated power again increased with a more negative angle. A continuous change of Θ with bias current changes may be possible, although not readily apparent from this data due to the high intermediate power loss. The reason for the attenuation of power at intermediate current levels was thought to be as follows. At zero bias, the intrinsic region of the p-i-n diode has a very high resistivity. The wave propagating down the dielectric waveguide experienced very little loss due to conduction processes. At low current levels (19 mA), the i region of the modulator became slightly conductive and the propagating wave diffracted into the modulator material thereby permitting a increased loss. At higher current
level (100 mA per diode) the density of excess electrons and holes in the intrinsic region increased to such an extent that the p-i-n diode behaved as a metal wall. This condition prevented the $E_y$ field from penetrating the bulk silicon material and in so doing, permitted a low-loss condition. In summary, high losses occur when the intrinsic region of the p-i-n diode is slightly conductive allowing the wave to enter the lossy medium. In all other condi-
tions the losses are relatively small. To minimize losses, insulator tape was inserted between silicon dielectric waveguide and the modulator diodes in order to decouple the dielectric guide from the modulator. This definitely decreased the loss, but also decreased the modulation and change in angle which occurred due to a change in diode current. This interpretation is related to Fig. 6. At 0 current, the power radiated is maximum and beamwidth being narrow indicates low loss and transmission down the entire length of perturbing elements. At 19 mA, the radiated power is low and the beam widens indicating the loss is higher and only a few of the perturbing elements contribute to the effective aperture diameter. At higher currents the i-region wall behaves like a metal. The result is low loss in transmission and an increase in $\lambda_2$ which increases the angle of radiation in a more negative direction. The beam is again narrow which is the result of low-loss transmission past the perturbations and a larger effective aperture diameter.

V. CONCLUSIONS

A line scanning antenna is proposed whereby electronic scanning can be carried out at a single frequency. High-resistivity silicon dielectric rectangular rods were used with metal stripes placed on the upper surface to form periodic perturbations causing radiation to be emitted. Grating structures incorporated in dielectric integrated circuits are covered in a paper by Itoh [9] and another paper by Song and Itoh [10]. The radiation angle $\Theta$ measured from the normal was found to be a function of periodic distance of the perturbations and the wavelength $\lambda_2$ in the dielectric rod. This wavelength could be changed by appending long, distributed p-i-n diodes to the sidewall. By making the i region of the diodes conductive, an effect similar to placing a metal wall on the side of the dielectric rod was observed and the guide wavelength increased resulting in a shifting of the beam to a larger negative angle. The beam angle was found to shift 8° – 10° with some cases showing a $\Delta \Theta$ of as much as 13° in the region of frequency near 60 GHz. The observed line scanning, so far, is not yet continuous as a function of modulating current. A narrow beam is found with no current and a shifted narrow beam is found at high currents. At intermediate currents attenuation and wide beamwidth occurs.

In order to obtain continuous scanning as a function of modulating current (analog scanning) new geometrical arrangements of the p-i-n diode modulators are being investigated.

APPENDIX A

CALCULATION OF PROPAGATION CONSTANTS, WAVELENGTHS, AND RADIATION ANGLES

Calculations using (A-1)–(A-9) and (2) were made for a comparison with experimental results. Exact equations were used in all calculations, with the same known physical parameters (Table I) as used in the experiment. Results of this comparison are in Table II.

If air surrounds the dielectric waveguide on all sides to finite distances $h_3$, $h_5$, $t_2$, and $t_4$ and terminated by metal boundaries (Fig. 3), (A-1) and (A-2) may be used to calculate $k_x$ and $k_y$ in terms of $k_{x3}$ and $k_{y2,4}$ as

$$k_x = \pi - \tan^{-1} \left( \frac{k_x}{k_{x3}} \right) - \tan^{-1} \left( \frac{k_x}{k_{x5}} \right)$$

$$k_y = \pi - \tan^{-1} \left( \frac{k_y}{k_{y2}} \right) - \tan^{-1} \left( \frac{k_y}{k_{y4}} \right)$$

(terms defined in Table I). If all the metal boundaries are extended to infinity (Fig. 3(a)), then $t_2$, $t_4$, $h_3$, and $h_5$ are all infinite, and (A-1) and (A-2) reduce to

$$k_x = \pi - \tan^{-1} \left( \frac{k_x}{k_{x3}} \right)$$

$$k_y = \pi - \tan^{-1} \left( \frac{k_y}{k_{y2}} \right)$$

The attenuation constants in the surrounding air media (2, 3, 4, and 5) are calculated by

$$\eta_{2,4} = \left( \frac{\pi}{A_{2,4}} \right)^2 - k_y^2 \left( \frac{\pi}{A_{2,4}} \right)^2 = \frac{1}{k_y}$$

$$\xi_{3,5} = \left( \frac{\pi}{A_{3,5}} \right)^2 - k_x^2 \left( \frac{\pi}{A_{3,5}} \right)^2 = \frac{1}{k_{x3}}$$

$$A_{2,3,4,5} = \frac{\lambda_0}{2\sqrt{\epsilon_1 - \epsilon_{2,3,4,5}}}.$$ 

The waveguide wavelength in the direction of propagation is

$$\lambda_2 = \frac{1}{k_x} \left( k_x^2 - k_y^2 - k_0^2 \right)^{-1/2}$$

where

$$k_0 = \frac{2\pi \sqrt{\epsilon_1}}{\lambda_0}. \quad (A-9)$$

Calculations for three configurations of the silicon guide were made (Figs. 2 and 3). Results are in Table II. It can be shown that $k_{y2,4}$ changes very little with changes in $k_y$. This is because $(\pi/A_{2,4})^2 > k_y^2$ so that small variations in $k_y$ produce negligible changes in $k_{y2,4}$ or $\eta_{2,4}$. If (A-5) and (A-2) are solved simultaneously, $k_y$ can be obtained as indicated in Table II, column B. Similarly,
TABLE I
TEST PARAMETERS

<table>
<thead>
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<th>Symbol</th>
<th>Description</th>
<th>Dimension</th>
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<tbody>
<tr>
<td>a</td>
<td>Silicon guide width</td>
<td>0.097 cm</td>
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<tr>
<td>b</td>
<td>Silicon guide height</td>
<td>0.107 cm</td>
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<tr>
<td>f₀</td>
<td>Frequency of source</td>
<td>61 GHz</td>
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<tr>
<td>λ₀</td>
<td>Wavelength of source</td>
<td>0.4918 cm</td>
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<td>k</td>
<td>2π/λ₀ (Free-space propagation constant)</td>
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<td>e₁</td>
<td>Silicon (medium 1) relative dielectric constant</td>
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<tr>
<td>η₂,₃,₄,₅</td>
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<td>h₃</td>
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<tr>
<td>h₅</td>
<td>Air dielectric thickness in medium 5</td>
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<td>t₂</td>
<td>Air dielectric thickness in medium 2</td>
<td>∞</td>
</tr>
<tr>
<td>t₄</td>
<td>Air dielectric thickness in medium 4</td>
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<tr>
<td>m</td>
<td>Number of perturbations</td>
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<tr>
<td>d</td>
<td>Spacing of perturbations (leading edge to leading edge)</td>
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<tr>
<td>k₁</td>
<td>Propagation constant in medium 1 (silicon)</td>
<td>44.256 cm⁻¹</td>
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TABLE II
THEORETICAL AND EXPERIMENTAL RESULTS AT 61 GHz

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<th>Configuration</th>
<th>k₁ cm⁻¹</th>
<th>k₂ cm⁻¹</th>
<th>h₂,₃,₄,₅ cm</th>
<th>λ₂,₃,₄,₅ cm</th>
<th>Calculated Θ</th>
<th>Experimental* From Fig. 5</th>
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<tr>
<td>A. Open Guide (Fig. 2(a))</td>
<td>21.45</td>
<td>28.00</td>
<td>26.73</td>
<td>0.02740</td>
<td>0.03144</td>
<td>0.2351</td>
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<tr>
<td>B. Guide With Metal Near Bottom, t₄ = 0.024 cm (Fig. 2(b))</td>
<td>21.45</td>
<td>27.65</td>
<td>27.21</td>
<td>0.02740</td>
<td>0.03114</td>
<td>0.2319</td>
</tr>
<tr>
<td>C. Guide With Metal Near Bottom And Sidewall (Fig. 2(c))</td>
<td>23.11</td>
<td>27.65</td>
<td>25.69</td>
<td>0.02816</td>
<td>0.03114</td>
<td>0.2446</td>
</tr>
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*Experimental values were measured using p-i-n diodes while theoretical values were obtained using metal wall concepts as shown in Fig. 3. λ₂ is calculated from experimental Θ using (2). The calculated and experimental values of radiation angle Θ and guide wavelengths λ₂ in close agreement. This shows that the experimental results can be predicted prior to measurement and hence parameters such as guide size and boundary wall locations can be determined.

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