Metal Walls in Close Proximity to a Dielectric Waveguide Antenna

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Abstract—The effect of placing metal walls in close proximity to a dielectric antenna has been examined theoretically. When these walls are less than one millimeter away from a silicon dielectric waveguide operating nominally at 60 GHz, they affect the wavelength of the electromagnetic radiation within the guide. As the guide wavelength changes, the angle of radiated energy emanating from the metal stripe perturbations on the upper surface of the dielectric guide also changes. A line scanning antenna can be realized by varying the change in guide wavelength in a controlled manner. Theoretical calculations were made to determine the physical parameters such as waveguide size, spacing of metal stripe perturbations and location of metal walls with respect to the silicon waveguide which can produce a large angular scan. Design curves are presented which can be used to examine tradeoffs between the initial radiation angle and range of angular scan as a function of frequency and perturbation spacing. A means of electronically controlling the simulated absence or presence of metal walls by current biasing distributed p-i-n diodes attached to the side of the dielectric guide from a nonconducting state into a high conductivity state is discussed.

I. Introduction

DIELECTRIC WAVEGUIDES are currently being designed and developed as a low cost approach for an electrically scanned antenna which could be placed on a missile or projectile as part of a high resolution radar for terminal homing [1]–[4]. The antenna consists of a rectangular dielectric rod with periodic perturbations on one surface from which electromagnetic radiation would emanate. The initial angle of radiation is a function of frequency, physical size and relative dielectric constant of the dielectric rod, and the spacing of the perturbations. This radiation angle can be shifted by changing the wavelength within the guide. A change in wavelength can be effected by either bringing metal walls in close proximity to the waveguide or simulating the appearance of metal walls by current biasing nonconducting distributed p-i-n diodes which are attached to the waveguide, into a high conductivity state.

This paper will discuss the effects on radiation angle, when metal walls or their equivalent are brought in close proximity to a dielectric waveguide antenna and the various design tradeoffs which can be made to achieve a large shift in radiation angle while maintaining an initial, near broadside radiation angle of -10 to -20 degrees.

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II. Design Criteria

When metal walls are brought in close proximity to a dielectric waveguide as shown in Fig. 1, the propagation constants k_x, k_y, and k_z will be affected in accordance with the following equations [5]:

$$ak_x = p\pi - \tan^{-1}\left[k_x\xi_3 \tanh(h_3/\xi_3)\right] - \tan^{-1}\left[k_x\xi_5 \tanh(h_5/\xi_5)\right] \quad (1)$$

$$bk_y = q\pi - \tan^{-1}\left[\frac{n_2^2}{n_1^2}k_y\eta_2 \coth(t_2/\eta_2)\right] - \tan^{-1}\left[\frac{n_4^2}{n_1^2}k_y\eta_4 \coth(t_2/\eta_4)\right] \quad (2)$$

$$k_z = \sqrt{k_1^2 - \left(k_x^2 + k_y^2\right)} \quad (3)$$

where

- a is x dimension of waveguide (width);
- b is y dimension of waveguide (height);
- p is number of electric field extrema in x dimension;
- q is number of electric field extrema in y dimension;
- $\xi_{3,5}$ and $\eta_{2,4}$ is distance electric field penetrates the respective surrounding medium until the field amplitude has decayed to $1/e$ of its maximum in that medium;
- $h_{3,5}$ and $t_{2,4}$ is distance from waveguide to metal walls in the respective surrounding medium;
- $n_{1,2,4}$ is index of refraction in media 1, 2, 4, respectively;
- k_1 is propagation constant in the dielectric waveguide.

The derivation of (1) and (2) is based on Marcatili's derivations [6] using Maxwell's equations and introducing an additional term to account for field reflection from the metal walls, applying a technique similar to Toulios and Knox as described in [7].

As k_x or k_y changes, the guide wavelength also changes since

$$\lambda_g \equiv \lambda_z = 2\pi/k_z. \quad (4)$$

This change in λ_g will, in turn, cause a shift in the angle of radiation

$$\theta_m = \sin^{-1}\left[\frac{\lambda_0}{\lambda_g} + \frac{\lambda_0}{d}m\right], \qquad m = -1 \quad (5)$$

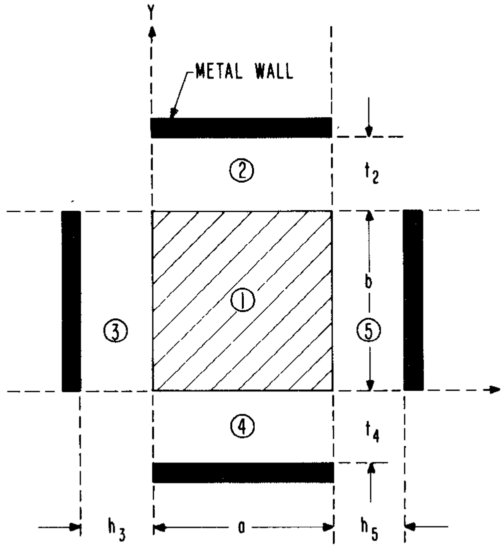

Fig. 1. Dielectric waveguide (medium 1) with metal walls in media 2, 3, 4, 5.

where

$$\left|\frac{\lambda_0}{\lambda_g}+\frac{\lambda_0}{d}m\right|\leq 1$$

θ_m is radiation angle from broadside (normal);
λ_0 is free space wavelength;
d is perturbation spacing;
m is space harmonic; $0, \pm 1, \pm 2, \cdots$.

If the metal walls are infinitely far away from the dielectric waveguide ($h_{3,5}$ and $t_{2,4}=\infty$), (1) and (2) will reduce to the equations for no metal walls [6]

$$ak_x = p\pi - \tan^{-1}[k_x\xi_3] - \tan^{-1}[k_x\xi_5] \tag{6}$$

$$bk_y = q\pi - \tan^{-1}\left[\frac{n_2^2}{n_1^2}k_y\eta_2\right] - \tan^{-1}\left[\frac{n_4^2}{n_1^2}k_y\eta_4\right]. \tag{7}$$

III. Calculations

A plot of the change in calculated radiation angle from normal as a metal wall was brought from an infinite distance in medium 5 (air) to zero (metal in contact with dielectric waveguide) is illustrated in Fig. 2. In this specific case, the waveguide was silicon ($\epsilon_r = 12$), operating frequency was 61 GHz, the a and b dimensions of the waveguide were 0.97 and 1.07 mm, respectively, t_4 was 0.24 mm and the perturbation spacing was 1.8 mm. No metal was placed in media 2 or 3, therefore t_2 and h_3 were infinite. Fig. 2 shows that the radiation angle is essentially constant once the metal in medium 5 is more than 1.0 mm from the guide and we can, therefore, assume that $h_5 > 1.0$ mm represents an infinite distance or no metal in the medium. The calculated radiation angle at $h_5 = 1.0$ mm was -37.6 degrees from normal. As the metal wall was brought closer to the guide, the radiation angle shifted more negatively since λ_g increased due to an increase of k_x. When the metal wall was in direct contact with the guide, $h_5 = 0$ mm,

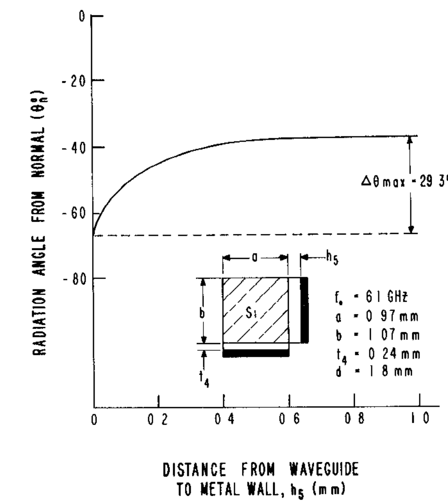

Fig. 2. Radiation angle as a function of distance from metal wall in medium 5 to dielectric antenna.

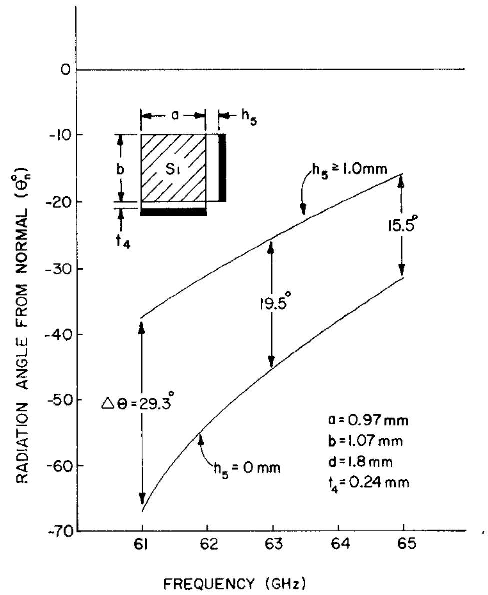

Fig. 3. Maximum angular shift as a function of frequency.

the calculated radiation angle was -66.9 degrees. Thus the maximum angular shift caused by bringing a metal wall from a position greater than 1.0 mm away from the guide to a position directly on the guide was approximately 29 degrees.

The maximum angular shift caused by changing h_5 from a distance ≥ 1.0 mm to 0.0 mm as a function of frequency (all other parameters held constant) is indicated in Fig. 3. This plot shows that the amount of maximum shift decreases from 29 degrees at 61 GHz to 15 degrees at 65 GHz. At the same time, the initial angle of radiation (when $h_5 \geq 1.0$ mm) decreased from approximately -38 degrees at 61 GHz to -15 degrees at 65 GHz. This was due to the fact that a change in frequency alters both λ_0 and λ_g, both of which influence the radiation angle in accordance with (5).

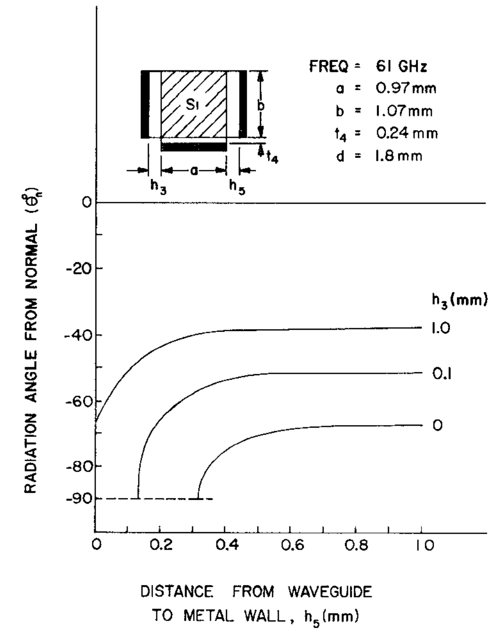

Fig. 4. Radiation angle for various values of h_3 and h_5.

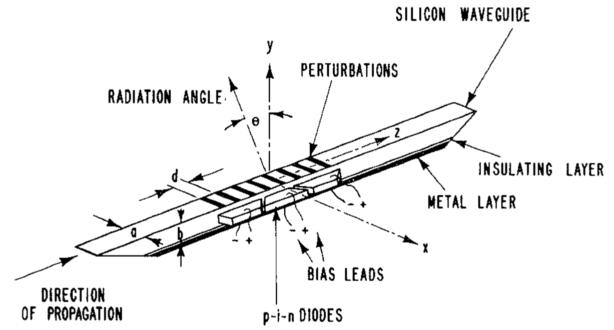

Fig. 5. Line scanning antenna with distributed p-i-n diodes attached.

TABLE I
EFFECT OF t_4 ON RADIATION ANGLE

t_2 (mm)	t_4 (mm)	h_3 (mm)	h_5 (mm)	k_x (mm^{-1})	k_y (mm^{-1})	k_z (mm^{-1})	λ_g (mm)	Θ_{-1} (deg)
10	0.24	0.1	1.0	2.389	2.766	2.500	2.514	-50.9
10	0.50	0.1	1.0	2.389	2.794	2.469	2.545	-53.1
10	1.00	0.1	1.0	2.389	2.799	2.463	2.551	-53.5
10	10.00	0.1	1.0	2.389	2.799	2.463	2.551	-53.5

TABLE II
EFFECT OF h_3 ON INITIAL RADIATION ANGLE

h_3 (mm)	h_5 (mm)	t_2 (mm)	t_4 (mm)	λ_g (mm)	Θ_{-1} (deg)
1.0	1.0	10	0.24	2.317	-38
0.1	1.0	10	0.24	2.514	-51
0.0	1.0	10	0.24	2.564	-67

TABLE III
ANGULAR SHIFT DUE TO CHANGE IN h_5 FOR VARIOUS VALUES OF h_3

h_3 (mm)	min h_5 (mm)	$\Theta_{initial}$* (deg)	Θ_{final} (deg)	$\Delta\Theta$ (deg)
1.0	0	-38	-67	29
0.1	0.13	-51	-90	39
0.0	0.32	-67	-90	23

* from Table II

A metal surface placed on the bottom of the guide (medium 4) reflects the power radiated out of the bottom (an amount approximately equal to the power radiated from the upper surface) which would normally be lost, back up and out of the upper surface to reinforce and essentially double the total power output. If the metal is placed directly on the guide ($t_4 = 0$ mm), an image guide is formed and the height of the guide (b-dimension) would be effectively doubled. This situation could result in the propagation of the E_{12}^y mode unless the effective height is less than the maximum allowed for single E_{11}^y mode propagation [8]. Placing an intervening dielectric between the metal and the guide avoids this problem. Such a structure is referred to as an insular dielectric waveguide. As t_4 increases (all other conditions held constant), the radiation angle will shift more negatively. However, the effect is much less severe than placing metal walls in media 3 or 5. Data is tabulated in Table I.

Another variation investigated theoretically, consisted of three metal walls. One at a fixed distance in medium 4, one at three different distances in medium 3, and the third at varying distances in medium 5. The results are plotted in Fig. 4. As the metal wall in medium 3 was moved from 1.0 mm to 0.1 mm to 0 mm from the silicon dielectric guide, the initial radiation angle, corresponding to $h_5 = 1.0$ mm, became more negative; data is summarized in Table II.

As h_5 was varied from 1.0 mm down toward 0.0 mm for each of the three values of h_3, the radiation angle shifted more negatively. When $h_3 = 1.0$ mm, the angle of radiation shifted to -67 degrees as h_5 was reduced to 0.0 mm; a $\Delta\theta$ of 29 degrees. For the two cases, $h_3 = 0.1$ mm and $h_3 = 0$ mm, the radiation angle shifted to -90 degrees before the metal wall in medium 5 reached the surface of the waveguide ($h_5 = 0$ mm). Thus the amount of angular scan reached a maximum and began to decrease as indicated by the data summarized in Table III.

IV. APPLICATION

A more practical realization of moving metal walls has been experimentally achieved by using distributed p-i-n diodes mounted on the side of the guide, as indicated in Fig. 5 [4]. These diodes will simulate a metal wall whenever they are biased "on," i.e., into a high conductivity state. When the diodes are "off" (in a nonconducting state) they are assumed to be nonexistant ($h_5 \geqslant 1.0$ mm); simulating a condition in which no metal is present. Initial measurements made with distributed p-i-n diodes mounted on the side of the Si guide in medium 5 with an intervening dielectric insulator 0.16 mm thick, give a consistent shift of about 8 degrees between the biased and unbiased states. These results are in good agreement with the theoretical predictions.

V. Discussion

In general, the design of a line scanning antenna should enable it to scan through a large angle with an initial radiation angle of -10 to -20 degrees from normal. This angular scan could be achieved by moving external metal plates in close to the dielectric guide.

Fig. 6 represents a set of typical curves which can be used to achieve a desired amount of angular scan $\Delta\theta$ at a specific initial radiation angle by adjusting the operating frequency and/or the perturbation spacing. These curves have been calculated for the specific physical situation in which silicon was used as the dielectric waveguide with a and b dimensions of 0.97 mm and 1.07 mm, respectively, a metal wall in medium 3 was 1.0 mm or more away from the guide (effectively no metal present), a second metal wall was 0.24 mm from the guide in medium 4, and a third metal wall was in medium 5 which could be moved from 1.0 mm to within 0.16 mm of the Si guide.

As an example, if the dielectric waveguide antenna had a perturbation spacing of 2.0 mm and was operated at 61 GHz, the initial angle of radiation (when $h_5 \geq 1.0$ mm) would be -20 degrees from broadside (normal). If h_5 is then reduced to 0.16 mm, the radiation angle would shift by approximately 6.6 to -26.6 degrees. If the frequency would be reduced (everything else held constant) the $\Delta\theta$ would increase with an attendant shift in the initial radiation angle to a more negative position. For the specific example cited, a shift in frequency to 59 GHz would result in a $\Delta\theta$ of 9 degrees with an initial radiation angle slightly greater than -30 degrees. In order to maintain the initial -20 degrees radiation angle, the perturbation spacing would have to be increased to 2.15 mm. In making such a change, however, $\Delta\theta$ will also drop to approximately 8 degrees.

In Fig. 7 a comparison was made of the angular shift $\Delta\theta$ which could be obtained for the case in which there was effectively no metal wall in medium 3 ($h_3 \geq 1.0$) with the case in which $h_3 = 0$ mm, i.e., a metal placed directly on the side wall of the silicon guide. All other physical parameters were the same as in Fig. 6. The calculated curves indicate that, in the latter case, a substantial increase in $\Delta\theta$ would occur. To keep the initial radiation angle equal in both cases, a slight variation would have to be made in the perturbation spacing. In case 1 ($h_3 \geq 1.0$ mm, $d = 2.0$ mm) a scan of nearly 7 degrees could be achieved with an initial θ of -20 degrees. By reducing h_3 to 0.0 mm and increasing the perturbation spacing to 2.18 mm (case 2), a scan of nearly 12 degrees would be possible with the same initial θ of -20 degrees.

Curves such as those shown in Figs. 6 and 7 must be examined carefully since, under certain conditions, the radiation angle could shift to -90 degrees. In such a situation, no radiation could be found experimentally inasmuch as this would be a backfire condition and may not be of use in a practical situation. Examination of Fig. 7 shows that such a situation could exist for a perturbation spacing of 1.8 mm, when $h_3 = 0$. In this particular case the initial θ is approximately -55 degrees and will shift to -90 degrees when $h_5 = 0.16$ mm.

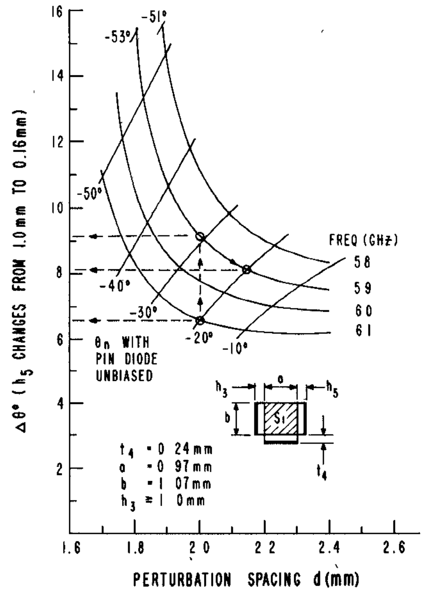

Fig. 6. Design curves for θ and $\Delta\theta$ as a function of frequency and perturbation spacing.

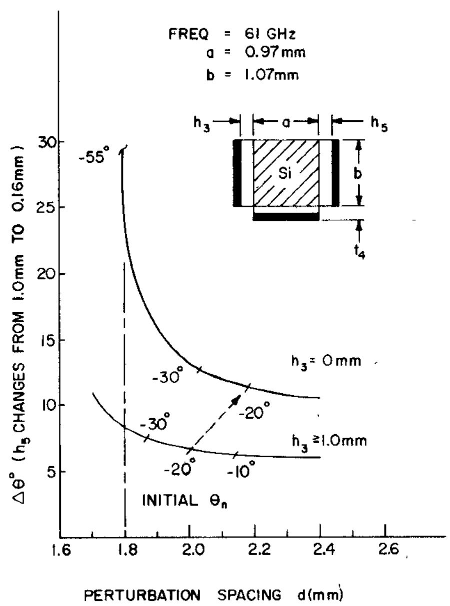

Fig. 7. Comparison of $\Delta\theta$ for an antenna with and without a metal wall in medium 3.

VI. Summary

A theoretical examination of the effects of metal walls or their equivalent, i.e., distributed p-i-n diodes biased into a high conductivity state, placed in close proximity to a dielectric waveguide antenna has been made. It showed that metal walls or their equivalent can influence the initial angle of radiation as well as the amount of angular shift if they are less than 1.0 mm from a silicon dielectric antenna, operating near 60 GHz. The closer they are, the more influence they will have. This is due to the fact that they will interact with more of the evanescent electric field.

For the specific case examined in this report (Si waveguide, $f_0=61$ GHz, $a=0.97$ mm, $b=1.07$ mm, $t_4=0.24$ mm, and $d=1.8$ mm) and angular shift of nearly 30 degrees could be achieved with an initial radiation angle of -38 degrees from normal if a metal wall was brought from infinity to a point directly on the sidewall of the dielectric waveguide antenna (Fig. 2). The initial angle can be made more normal to the antenna by either increasing the operating frequency or increasing the perturbation spacing (Figs. 3 and 6). In each situation, however, the total amount of angular scan is also decreased. Fig. 6 presents a set of design curves which can be used to examine possible tradeoffs between the initial radiation angle and $\Delta\theta$ as a function of frequency and perturbation spacing. Placing a third metal wall directly on the surface of the waveguide ($h_3=0$ mm) directly opposite the variable metal wall or distributed p-i-n diodes produces a substantial increase, approximately a factor of 2, in the maximum obtainable angular shift. This metal wall prevents any portion of the electric field from entering medium 3 and in effect, pushes the electric field such that it extends further into medium 5. Thus the metal wall in medium 5 interacts with a greater portion of the electric field and this causes a greater angular shift to occur when the wall is moved.

The theoretical study presented in this paper clearly indicated that a beam of electromagnetic energy radiating from the surface of a dielectric waveguide antenna having periodic perturbations can be shifted by as much as 12 degrees. Various design curves are presented to indicate the necessary physical and electrical parameters required to achieve these results.

Such an inexpensive antenna, which could be electronically controlled to scan over this much angle, would find substantial potential use in precisely guiding projectiles to home-in on targets in adverse battlefield environments.

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