SIMULATION STUDY OF ELECTRONICALLY SCANNABLE ANTENNAS AND TUNABLE FILTERS INTEGRATED IN A QUASI-PLANAR DIELECTRIC WAVEGUIDE*

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ABSTRACT

Preliminary studies on electronically scannable leaky-wave antennas integrated in a dielectric waveguide are reported. Electronic scan is simulated by a small mechanical motion from which the relation between the scan angle and the necessary change in dielectric constant can be derived. The work is also applicable to electronically tunable band-stop filters.

Introduction

This paper presents an economical method useful as a preliminary study for the design of electronically scannable antennas and tunable filters in dielectric millimeter-wave integrated circuits. The results obtained by the present study can be helpful in establishing the requirement to the material in which the dielectric constant can be varied electronically.

A number of dielectric waveguides have been proposed for developing new types of millimeter-wave integrated circuits[1,2,3] which resemble optical integrated circuits. Recently, grating structures created in the dielectric waveguides have been used as leaky-wave antennas and band-stop filters.[4] The main beam direction and the stop-band are determined from the electrical length of the unit cell of gratings. In the leaky-wave antenna in Ref. 4, the beam was steered by changing the operating frequency. However, in actual application, often one would like to keep the frequency fixed and still needs to steer the beam. Also, in the filter in Ref. 4, the stop-band cannot be altered once the gratings are fabricated.

These problems may be overcome by incorporating an electronic phase shifter in the structure, which changes the electrical length for a fixed frequency. Recently, the use of a PIN layer incorporated in a submillimeter-wave dielectric waveguide was suggested as an electronic phase shifter.[5] It is important, however, to study how much scan is obtainable for a given amount of change in dielectric constant. The purpose of this paper is to investigate the relation of the scan angle and the shift of the stop-band versus the change in dielectric constant provided by a phase shifter. To this end, we introduce a mechanically tunable phase shifter in the leaky-wave antenna and the filter. A small mechanical motion creates a change in effective dielectric constant of the waveguide, thus simulating the electronic change of dielectric constant.

Analysis

Although the method in this paper is applicable to other types of dielectric waveguides, we selected an inverted strip (IS) dielectric waveguide which has a quasi-planar structure (Fig. 1(a)). In the cross section most of the energy propagates in that portion of ε_2 layer immediately above the ε_1 strip. When a PIN layer is created in the waveguide (Fig. 1(b)) and the applied bias voltage is varied, the dielectric constant in the PIN portion changes. Hence, the field distribution and the propagation constant in the waveguide will change. This situation is simulated by structures shown in Fig. 1(c) or (d) in which an additional dielectric layer (ε_4) is moved up and down.

Hence, the field distribution and the propagation constant β are functions of the gap spacing δ. The dispersion characteristics of the composite structure are obtainable by applying the effective dielectric constant technique.[3] We will use the structure in Fig. 1(c) for analysis as it corresponds to a more general case in which the PIN structure is wider than W. The effective dielectric constant in Region I in Fig. 1(c) is obtained by solving the eigenvalue equation derived from the following assumed field distributions for the E^y modes which have principal field components of E_y, H_x, E_z and H_z.

$$H_x = \begin{cases} \cosh \eta_1 y & 0 < y < h_1 \\ A_2 \cos k_y y + B_2 \sin k_y y & h_1 < y < h_1 + h_2 \\ A_3 \cosh \eta_3 y + B_3 \sinh \eta_3 y & h_1 + h_2 < y < h_1 + h_2 + \delta \\ A_4 \cos \bar{k}_y y + B_4 \sin \bar{k}_y y & h_1 + h_2 + \delta < y < h_1 + h_2 + \delta + t \\ A_5 \exp(-\eta_5 y) & y > h_1 + h_2 + \delta + t \end{cases} \tag{1}$$

where

$$\varepsilon_1 k_o^2 + \eta_1^2 = \varepsilon_2 k_o^2 - k_y^2 = \varepsilon_3 k_o^2 + \eta_3^2 = \varepsilon_4 k_o^2 - \bar{k}_y^2 = \varepsilon_5 k_o^2 + \eta_5^2$$

In the present case $\varepsilon_3 = \varepsilon_5 = 1$ (air). By matching H_x and E_z field at each interface, we can eliminate all

*This work was in part supported by a US Army Research Grant DAAG29-77-G-0220.

CH1355-7/78/0000-0030$00.75

the A_i's and B_i's and obtain an eigenvalue equation which is to be solved for k_y. The effective dielectric constant defined by

$$\varepsilon_{eI} = \varepsilon_2 - \frac{k_y^2}{k_o^2} \quad (2)$$

is a function of frequency and a gap δ. Similarly we obtain the effective dielectric constant ε_{eII} in Region II. Having obtained $\varepsilon_{eI}(\delta)$ and $\varepsilon_{eII}(\delta)$, we can compute the propagation constant $\beta(\delta)$ by first replacing Regions I and II by hypothetical vertical slabs having dielectric constants ε_{eI} and ε_{eII} and solving the eigenvalue equation for such a hypothetical structure. Note that for a given frequency β can be adjusted by changing δ as ε_{eI} and ε_{eII} can be altered by δ.

When grooves are created periodically in the strip (ε_1), we obtain a grating section in the composite waveguide structure (Fig. 2). The grating section supports a leaky wave if one of space harmonics satisfy

$$|\beta_m/k_o| < 1 \quad (3)$$

where

$$\beta_m = \beta + \frac{2m\pi}{d}, \quad m = 0, \pm 1, \pm 2, \cdots \quad (4)$$

Here d is the period of the grooves and m = -1 is chosen in most practice. The direction of radiation is determined by $\theta_m = \sin^{-1}(\beta_m/k_o)$ and is also function of the gap size δ. Hence, by changing δ, we can steer the direction of radiation without changing the frequency.

Let us turn our attention to the filter. When the period d is chosen such that

$$\beta d = \pi \quad (5)$$

the grating exhibits a stop-band phenomenon at the frequency satisfying (5). If, therefore, δ is changed, the frequency corresponding to the stop-band changes. Thus we can tune the center frequency of the band-stop filter by changing δ.

Results

Figure 3 shows dispersion characteristics of the structure in Fig. 1(c) without any gratings. The results are plotted for a number of gap size parameters δ. These curves are used as the fundamental information for investigating scanning properties of grating structures.

The design of the grating structures has been carried out for 60 GHz operation and subsequently all the dimensions have been scaled four times to permit experiments at the 15 GHz range. This scaling is only for convenience of measurement as we do not have any high frequency equipment. As the output frequency of our Ku band source was 15.25 GHz, we studied the variations of ε_{eI} and ε_{eII} versus the gap size from the information at 61 GHz in Fig. 3. The results are shown in Fig. 4 in which all the dimensions including δ are four times of those in Fig. 3.

In Fig. 5, we plotted the main beam direction versus the gap δ when the grating period of the antenna operated at 15.25 GHz was 10.16mm. Agreement between computed and measured data is seen to be excellent. Information contained in Figures 4 and 5 are useful in studying the requirement for the PIN structure. We can obtain curves similar to those in Fig. 4 except that the effective dielectric constants are now function of applied bias voltage. Hence, such information allows us to determine required bias change for a given scan angle. More extensive investigation will be carried out on such relations in the paper.

The grating period was chosen to be d = 6.25mm for tunable filter applications. All other structural parameters were kept identical to those for the antenna. Computed center frequencies of the stop-band were 13.55, 15.00 and 15.26 GHz for δ = 0, 2 and ∞ (mm). Center frequencies were measured at δ = 0 and ∞, and the results were 13.79 and 15.75 GHz. These values are considered reasonable when computational and experimental errors are taken into consideration.

Conclusions

In this paper, we studied the basic characteristics of the futuristic electronic scan of a leaky-wave antenna and the tuning of a grating dielectric waveguide filter. The electronic change of dielectric constants has been simulated by an infinitesimal up-and-down movement of an additional dielectric layer. It was found that a considerable amount of scanning can be obtained from the setup. The center frequency of the stop-band of the grating filter was found to be adjustable by mechanically varying the effective dielectric constants in the structure. Agreement between theoretical and experimental data has been reasonable throughout this work.

References

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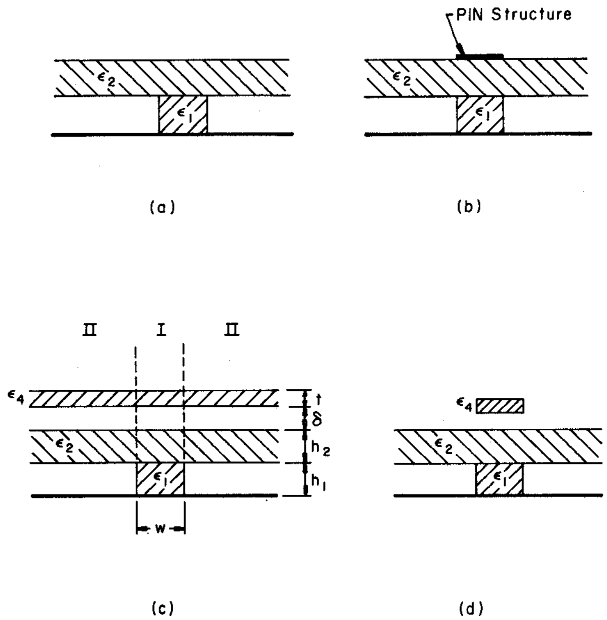

Fig. 1. Cross sections of dielectric waveguides

(a) Original structure (b) With a PIN structure

(c) Modified structure (d) Modified structure

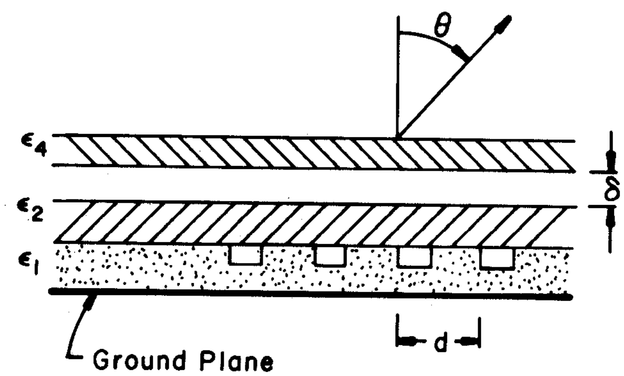

Fig. 2. Side view of the grating section for a mechanical scan antenna and a tunable filter

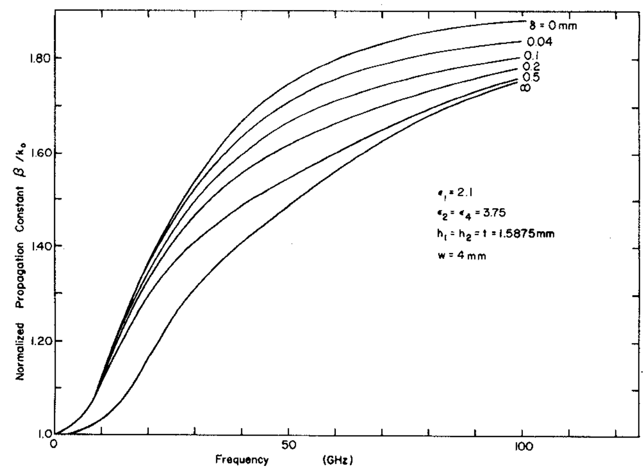

Fig. 3. Normalized propagation constant versus frequency for a number of gap dimensions

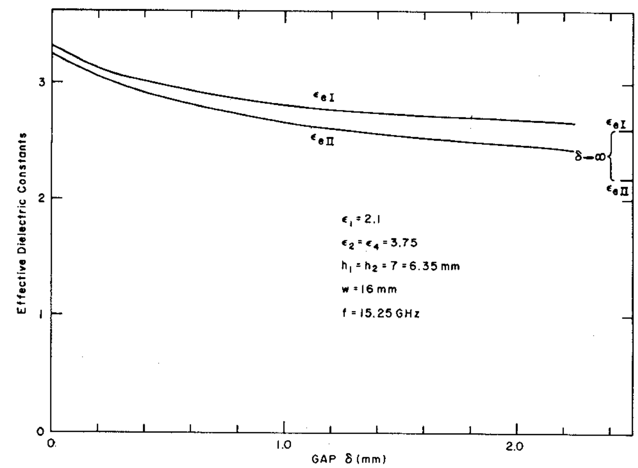

Fig. 4. Effective dielectric constants versus the gap size

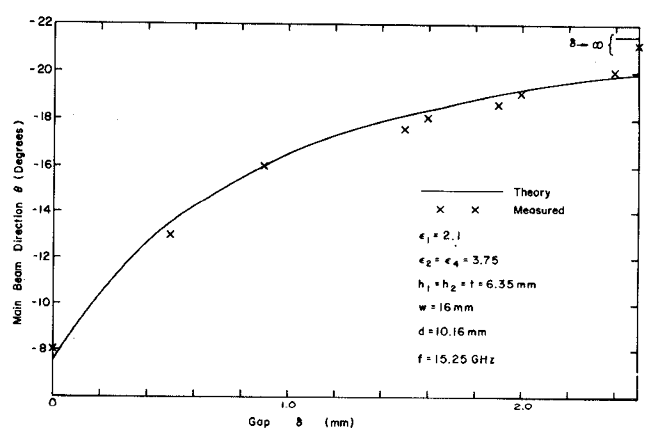

Fig. 5. Main beam direction versus the gap size for a grating antenna