LEAKAGE FROM A GAP IN NRD GUIDE

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ABSTRACT

Results are presented for the effect of an air gap between the top metal plate and the dielectric strip in nonradiative dielectric (NRD) guide, a promising candidate for millimeter wave integrated circuits. The leakage from small gaps can cause crosstalk between components, and that from larger gaps can furnish a new type of leaky wave antenna.

1. Introduction

Nonradiative dielectric (NRD) guide is one of the newer waveguides for millimeter wave use, and it shows great promise for application to millimeter-wave integrated circuits. It is basically a modification of H guide where the plate separation is reduced to less than half of a free-space wavelength; because of this change, discontinuity structures that maintain the symmetry of the waveguide become purely reactive, and components can be built readily and connected together in integrated circuit fashion. Yoneyama and Nishida, who first proposed [1] the NRD guide, have also designed and measured many components for this guide type [2,3], and have demonstrated its attractiveness. The basic NRD guide (together with the primary orientation of the electric field) is shown in Fig. 1(a).

In fabricating the waveguide, which consists of a dielectric strip between parallel metal plates, a small air gap may be present between the upper plate and the dielectric strip. Due to gravity, the lower plate will be in contact with the dielectric strip, but the upper plate may not be if it is slightly bowed, for example. An exaggerated example of such a gap is shown in Fig. 1(b). It is also possible to glue the strip to the plate, but then, unless the glue's dielectric constant matches that of the strip, we must also be concerned with what effects may be produced by the thickness of the glue, which introduces a problem qualitatively similar to that of an air gap, but quantitatively less significant.

The questions examined in this study are:

1. What are the physical effects produced by such an air gap?

2. What gap size is permissible before any noticeable effect is introduced?

It is shown in the next section that the effects introduced by the gap are two-fold. First, there is a small shift in the phase constant β, or equivalently, in the guide wavelength λ_g. Second, leakage is produced in the form of a TEM wave that propagates away at an angle from the dielectric strip on both sides. The leakage effect is certainly the more interesting of these two effects because such leakage can produce cross talk between neighboring components. The third section, below, presents some quantitative numerical results for these effects as a function of gap size. The leakage, which is expressed in terms of an attenuation constant, is also compared with the attenuation produced by dielectric and wall losses in NRD guide.

When the gap size is large, we find that the leakage is so strong that this structure becomes of interest as a new type of leaky wave antenna for millimeter waves. The strong leakage permits substantial flexibility in the choice of beam width, and the antenna is one that can be fed directly from an NRD guide integrated circuit. The analysis in this study also yields information of direct relevance to the design of such line source antennas.

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2. Effects Due to the Gap: Theory

Let us examine what occurs qualitatively when a gap is present. In the presence of the gap, propagation along the guide can be viewed in terms of a pair of surface waves that propagate at an angle to the axis of the guide and are successively reflected by the sides of the dielectric strip. Because of the polarization of the electric field, as seen in Fig. 1(b), these surface waves are TE waves. When these surface waves strike the sides of the strip, TE-TM mode coupling is introduced [4,5] and a net vertical electric field is produced. Within the strip region, this coupling creates two TM above-cutoff waves that bounce back and forth between the sides of the strip. For small air gaps, the lower of these two modes is the lowest TM surface wave, which is nearly TEM in nature, and the other mode is the first higher TM mode, which is degenerate with the lowest TE mode (but not excited) when the air gap is zero. In the parallel plate regions on both sides of the strip, a TEM mode is produced that leaks away at an angle. As seen in Fig. 1(b), however, the polarizations of the TEM waves on the two sides are reversed from each other.

This leakage of energy makes the propagation constant complex, with an attenuation constant α being a measure of the leakage, and with a change $\Delta\beta$ in the phase constant. A quantitative analysis of the changes in the propagation constant as a function of gap width was conducted using a mode-matching procedure [4], and a computer program was devised for obtaining the numerical values.

Quantitative curves for $(\beta/k_o)^2$ and α/k_o are presented in Figs. 2 and 3, but we are concerned first with their qualitative behavior. The effect of the air gap is to speed up the wave, which is to be expected since more of the wave is now in the air region. The values of β/k_o are therefore lowered somewhat by the air gap. The behavior of α requires more detailed consideration. Since the theory neglects material losses, the value of α is zero in the absence of a gap; the value of α (or α/k_o, when we normalize it to the free space wavenumber) thus represents only the leakage itself.

The curves of α/k_o (or $\alpha\lambda_o/2\pi$) in Fig. 3 are plotted as a function of b/λ_o, where b is the width of the dielectric strip, with the air gap thickness of t/λ_o as a parameter. We first note that, as the width b increases, there appear three main features. First, the curves in the neighborhood of $b/\lambda_o = 0.30$ to 0.35 undergo a change in curvature. This variation occurs in the vicinity of cutoff, as the nature of the attenuation changes from radiative above cutoff to primarily reactive below cutoff. The location of cutoff may also be noted in Fig. 2, where the curves reach $\beta/k_o = 0$. Second, we observe a general decrease in the value of α as b increases. As one moves away from cutoff, the angle that the pair of surface waves makes with the side walls of the dielectric strip becomes closer to grazing, with the result that the amount of TE-TM coupling becomes reduced. The leakage power is therefore correspondingly reduced.

The third main qualitative feature in Fig. 3 is the presence of a pronounced dip in the vicinity of $b/\lambda_o = 1.2$. This dip is due physically to the mode-converted TM waves that bounce back and forth at an angle between the sides of the dielectric strip. At appropriate widths, a cancellation effect occurs and the value of α is reduced sharply. It is therefore interesting to note that the α itself is due to the leaking TEM wave in the parallel plate regions, but the sharp dip in the value of α relates to the TM waves in the dielectric strip region.

Some similar qualitative features in the behavior of α as a function of strip width was found for leakage from dielectric strip waveguides [5]. The same TE-TM mode conversion at the strip sides produced both the α itself and the sharp cancellation effects in those cases as well.

3. Effects Due to the Gap: Numerical Results

The air gap thickness t/λ_o is a parameter in the curves of $(\beta/k_o)^2$ and α/k_o in Figs. 2 and 3. The changes in the value of β due to the air gap may be noted from Fig. 2. We see first of all that the change seems to be only weakly dependent on the strip width b, a fact that simplifies our conclusions for the phase constant β. The presence of the gap lowers the value of β, as mentioned earlier, and it is seen that for gaps less than $0.01\lambda_o$ the effect is negligible. Since the spacing between the top and bottom plates in our numerical example is $0.423\lambda_o$, an air gap of $0.01\lambda_o$ corresponds approximately to 2.5% of the total plate spacing. At t/λ_o about 0.02, or about 5% of the plate spacing, we begin to feel the effect in β.

From Fig. 3, on the other hand, we observe that the amount of leakage depends very strongly on the dielectric strip width b, both because of the general decrease in α as b increases and because of the pronounced cancellation effect occurring near $b/\lambda_o = 1.2$. For this reason, it is useful to also plot the leakage constant

α/k_o (or $\alpha\lambda_o/2\pi$) vs. t/λ_o , as in Fig. 4. In this figure, the leakage values are presented for only three values of b/λ_o , but more can be plotted by inspection from Fig. 3. It is readily seen that when the strip width b is larger for a given gap, the amount of leakage is lower.

To assess the relative magnitude of the leakage, it is useful to compare it with measured values of metal wall and dielectric losses encountered in NRD guide. Yoneyama has found that for teflon the measured wall and dielectric losses at 50 GHz amount to about 5 dB/m. The ordinate quantity in Figs. 3 and 4, $\alpha\lambda_o/2\pi$, expresses the leakage in terms of nepers per wavelength, divided by 2π. The measured losses at 50 GHz thus translate into the value 5.5×10^{-4} on the ordinate scale in Figs. 3 and 4. When we superimpose that value on these curves, we obtain at least one quantitative measure of when we can ignore the leakage and when we must be careful.

With that measure, we see that a gap of $t/\lambda_o = 0.004$ can be ignored for any value of b/λ_o . For $t/\lambda_o = 0.01$, which is about 2.5% of the plate spacing, we note that for $b/\lambda_o > 0.5$ or so the leakage is less than the measured material losses. For b/λ_o about 1.2, on the other hand, the leakage is negligible for all gap thicknesses. In general, one can readily determine the combinations of t and b that permit one to safely neglect the presence of a gap.

At the other end of the leakage scale, we see that sizeable values of leakage can be obtained for larger gap thicknesses. For example, for $t/\lambda_o = 0.15$, which is about one-third of the plate spacing, and for a dielectric strip width $b/\lambda_o = 0.60$, the value of $\alpha\lambda_o/2\pi$ is about 2×10^{-2} , so that the attenuation per wavelength becomes as large as 1 dB/λ_o . If we design a leaky wave antenna to radiate 90% of its power, and absorb the remaining 10% in a load, then such strong leakage would permit the antenna to be only about 10 wavelengths long, and have a beamwidth of about 7°. For a narrower beam, which one usually prefers, one simply reduces the gap size appropriately. In an actual design, the strip width b/λ_o would first be specified to correspond to the value of β/k_o that yields the desired angle of radiation. Then, the gap size would be determined so as to achieve the desired beam width. The data in Figs. 2 and 3 (or similar data for other parameter values) readily furnish the required design values.

The calculations discussed here thus permit one to first know the qualitative effects produced by an air gap in NRD guide, and then, for small gaps, to determine what gap size can be permitted before it influences device performance, or for large gaps, to be able to design a new type of leaky wave antenna.

REFERENCES

1. T. Yoneyama and S. Nishida, "Nonradiative Dielectric Waveguide for Millimeter-Wave Integrated Circuits," IEEE Trans. on Microwave Theory Tech., Vol. MTT-29, No. 11, pp. 1188-1192, November 1981.

2. T. Yoneyama and S. Nishida, "Nonradiative Dielectric Waveguide Circuit Components," International Conference on Infrared and Millimeter Waves, Miami, Florida, December 1981.

3. T. Yoneyama, F. Kuroki and S. Nishida, "Design of Nonradiative Dielectric Waveguide Filter," Digest IEEE International Microwave Symposium, pp. 243-244, San Francisco, CA, May 30-June 1, 1984.

4. S. T. Peng and A. A. Oliner, "Guidance and Leakage Properties of a Class of Open Dielectric Waveguides, Part 1: Mathematical Formulations," IEEE Trans. Microwave Theory Tech., Vol. MTT-29 (Special Issue on Open Guided Wave Structures), pp. 843-855, September 1981.

5. A. A. Oliner, S. T. Peng, T. I. Hsu and A. Sanchez, "Guidance and Leakage Properties of a Class of Open Dielectric Waveguides, Part II: New Physical Effects," same as reference 4.

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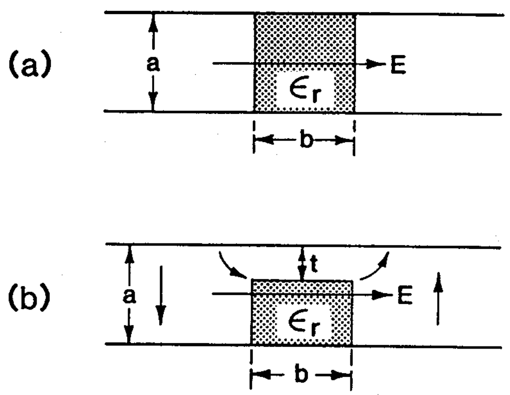

Fig. 1 (a) NRD (nonradiative dielectric) guide, which is like H guide (rotated through 90°), except that spacing a is made $<\lambda_o/2$ to insure that discontinuities are reactive.

(b) Structure obtained when an air gap is present between the top metal plate and the dielectric strip. The modifications produced in the electric fields are also shown.

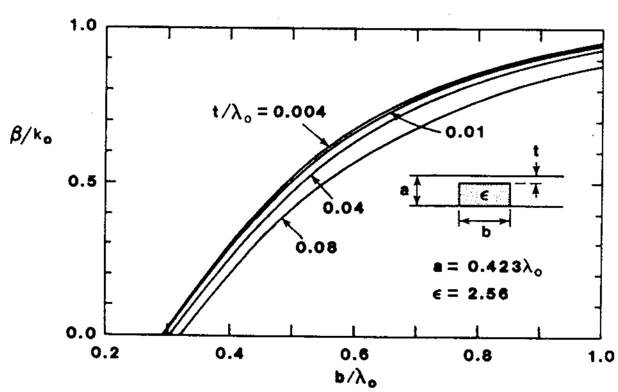

Fig. 2 Curves of $(\beta/k_o)^2$ (or effective dielectric constant) as a function of b/λ_o, with t/λ_o as a parameter. Quantities b and t are the dielectric strip width and air gap thickness, respectively, as shown in the inset, and k_o ($=2\pi/\lambda_o$) and β are respectively the free space wavenumber and the phase constant of the guided mode.

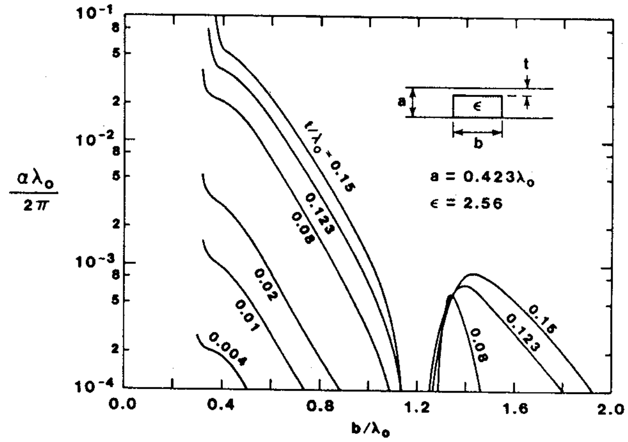

Fig. 3 Curves of $\alpha\lambda_o/2\pi$ as a function of b/λ_o, with t/λ_o as a parameter. Quantities b and t are defined in the inset, and λ_o and α are respectively the free space wavelength and the leakage constant due to the presence of the air gap.

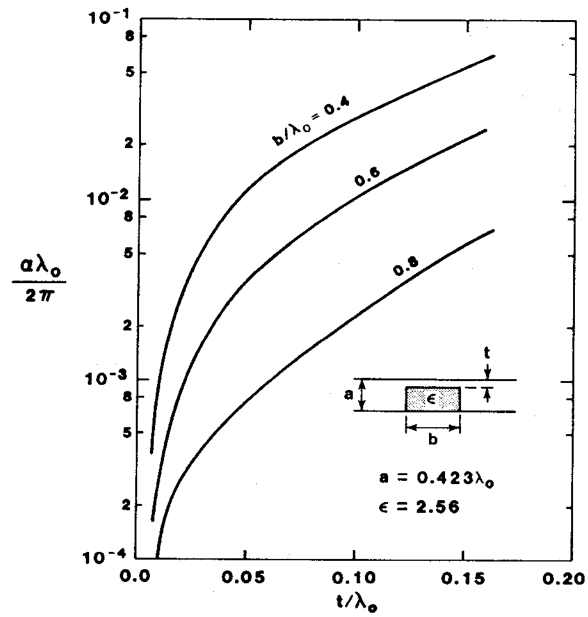

Fig. 4 Curves showing the variation of the leakage constant α (normalized to $k_o = 2\pi/\lambda_o$) with air gap thickness t/λ_o, with the dielectric strip width b/λ_o as a parameter.