Y Dielectric Waveguide for Millimeter- and Submillimeter-Wave

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***Abstract*—A new type of waveguide structure having *Y* cross section is presented and investigated theoretically. This waveguide is suitable for millimeter- and submillimeter-wave and facilitates supporting the waveguide with little field disturbance. Numerical results are presented for the dispersion characteristics, the transmission losses, and the power distributions using the generalized telegraphist's equations. The transmission characteristics of a triangular dielectric waveguide are also investigated as a special case.**

I. INTRODUCTION

RECENTLY there has been strong interest in dielectric waveguides for use as a transmission medium in millimeter- and submillimeter-wave regions. Various types of dielectric waveguides have been proposed and studied by a number of authors [1]–[7].

When we use dielectric waveguides as a transmission line, however, there still remain some problems. In dielectric waveguides, some of the electromagnetic energy propagates outside the dielectric as well as inside. Generally it is impossible to support the dielectric waveguides without disturbing the guided fields unless the waveguides are specially designed. If we surround the dielectric waveguide with another dielectric material having a slightly lower dielectric constant, just as the optical fiber, in order to support the waveguide with little field disturbance, the transmission losses become very high especially in a submillimeter-wave region. This is because the losses of the dielectric materials, which we can obtain now, are too high to fabricate a low-loss dielectric rod waveguide which confines most of the energy inside the dielectric. Hence a special guiding structure is required to fabricate a low-loss dielectric waveguide in millimeter- and submillimeter-wave regions.

In this paper, a new type of waveguide structure is presented to solve these problems and is investigated theoretically. Fig. 1(a) depicts the cross section of the new dielectric waveguide, which we will refer to as the *Y* dielectric waveguide (YDG), with a rectangular hypothetical electric boundary needed for analysis. In the YDG, the confinement of the electromagnetic energy occurs mainly in the center part of the waveguide. Since a lot of energy propagates in the air near the center part, it is possible to reduce the transmission losses due to the dielectric. The amount of the guided energy in the air might be controlled by varying the waveguide parameters and the operating frequency. On the other hand, at the three edges of the YDG, little energy propagates. This feature of the YDG facilitates supporting the YDG with little field disturbance and with low transmission losses.

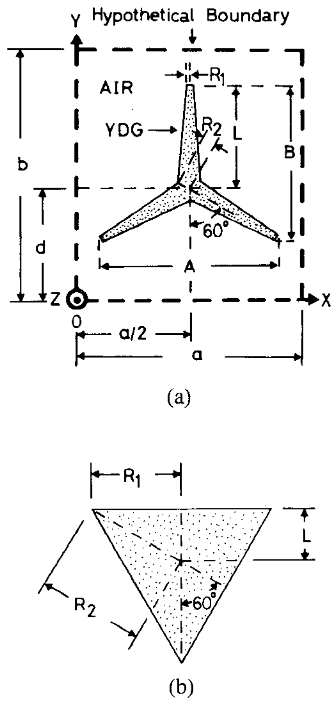

Fig. 1. (a) Cross section of the YDG with a rectangular hypothetical electric boundary. (b) Cross section of the triangular dielectric waveguide as a special case of the YDG with $R_1:R_2:L=\sqrt{3}:2:1$.

For the analysis of the YDG we use the generalized telegraphist's equations, proposed by Schelkunoff [8], which avoid writing the complex boundary conditions and require a hypothetical electric boundary, as shown in Fig. 1(a). Though the method is based upon a closed waveguide model, it has been shown that this analysis can give good results for the original open waveguide structure [9] and [10]. Numerical results are presented for the dispersion characteristics, the transmission losses and the power distributions.

The transmission characteristics of the dielectric waveguide having an equilateral triangular cross section, which we will refer to as the triangular dielectric waveguide (Fig. 1(b), are also investigated as a special case of the YDG.

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II. Method of Analysis

The geometry of YDG is shown in Fig. 1(a) with a rectangular hypothetical electric boundary. The parameters R_1, R_2, and L determine the shape of the YDG. In order to confine the energy in the center part of the YDG strongly, we consider the YDG which has tapers in its width as shown in Fig. 1(a). It is assumed that the dielectric constant of the YDG is ϵ_r and that of the air, which surrounds the YDG, is 1.0. And it is also assumed that the dielectric is isotropic and nonmagnetic. The parameters a and b determine the size of the hypothetical boundary and the parameter d determines the position of the YDG in the hypothetical boundary plane. As the detail of the equations may be found in [8] and [9], we only summarize the method of analysis here.

First, we expand the transverse electromagnetic fields $\boldsymbol{E}_t$ and $\boldsymbol{H}_t$ of Fig. 1(a) in terms of the normal modes of the metallic rectangular waveguide having the same dimension as the hypothetical boundary

$$\boldsymbol{E}_t=\sum_i^{\infty} V_{(i)}(Z)\boldsymbol{e}_{(i)}+\sum_j^{\infty} V_{[j]}(Z)\boldsymbol{e}_{[j]} \tag{1a}$$

$$\boldsymbol{H}_t=\sum_i^{\infty} I_{(i)}(Z)\boldsymbol{h}_{(i)}+\sum_j^{\infty} I_{[j]}(Z)\boldsymbol{h}_{[j]} \tag{1b}$$

where $\boldsymbol{e}$ and $\boldsymbol{h}$ are the mode functions of the rectangular waveguide and $V(Z)$, $I(Z)$ are mode voltage and mode current, respectively. The subscript in parentheses denotes TM mode and that in brackets denotes TE mode. These single subscripts are a shorthand notation for usual double subscripts such as mn.

Next, in order to obtain the unknowns mode voltages $V(Z)$, mode currents $I(Z)$, and the phase constant β in the Z direction, we derive the generalized telegraphist's equations from Maxwell's equations. If we approximate (1) with N terms for TM mode and M terms for TE mode and consider the sinusoidal propagation in the Z direction, the generalized telegraphist's equations are transformed into an algebraic eigenvalue equation. Among the eigenvalues β^2 calculated from the eigenvalue equation, eigenvalues corresponding to the surface wave mode satisfy

$$\sqrt{\epsilon_r}>\beta/k_0>1.0 \tag{2}$$

where k_0 is the free-space wavenumber. In this way, the phase constant β, mode voltages $V(Z)$, and mode currents $I(Z)$ are obtained and transverse electromagnetic fields $\boldsymbol{E}_t$, $\boldsymbol{H}_t$ are determined by (1).

We evaluate the power distribution by calculating

$$\boldsymbol{P}_z=\frac{1}{2}\,\mathrm{Re}\,(\boldsymbol{E}_t\times\boldsymbol{H}_t^*). \tag{3}$$

The attenuation constant α is calculated by

$$\alpha=\frac{W}{2P} \tag{4}$$

provided that the dielectric losses are sufficiently small and that the fields disturbance is negligible. P is the total power propagating in the Z direction and W is the dielectric losses per unit length, and these are given by

$$P=\iint_S \frac{1}{2}\,\mathrm{Re}\,(\boldsymbol{E}_t\times\boldsymbol{H}_t^*)\cdot\boldsymbol{a}_z dS \tag{5}$$

$$W=\iint_{S'} \frac{\omega\epsilon_0\epsilon_r \tan\delta|\boldsymbol{E}_t|^2}{2}dS' \tag{6}$$

where S denotes the cross section of the hypothetical boundary and S' denotes that of the YDG, $\boldsymbol{a}_z$ is the unit vector in the Z direction, ω is the angular frequency, ϵ_0 is the dielectric permittivity of the free space and $\tan\delta$ is the loss tangent of the dielectric material.

III. Numerical Results and Discussion

A. Expanding Modes

As Fig. 1(a) has a symmetrical axis ($0Y$ axis shifted to $X=a/2$), the modes may be classified into two groups: the even modes, which have a magnetic wall at $X=a/2$, and the odd modes, which have an electric wall in the same place. The expanding modes for the modes of these two groups may be chosen as follows, by taking account of the symmetry of each kind of modes.

For the even modes:

$$\mathrm{TM}_{(mn)}\text{ mode}\begin{cases} m=1,3,5,\cdots\\ n=1,2,3,\cdots\end{cases}$$

$$\mathrm{TE}_{[mn]}\text{ mode}\begin{cases} m=1,3,5,\cdots\\ n=0,1,2,\cdots.\end{cases} \tag{7}$$

For the odd modes:

$$\mathrm{TM}_{(mn)}\text{ mode}\begin{cases} m=2,4,6,\cdots\\ n=1,2,3,\cdots\end{cases}$$

$$\mathrm{TE}_{[mn]}\text{ mode}\begin{cases} m=0,2,4,\cdots\\ n=0,1,2,\cdots\end{cases} \tag{8}$$

(with the exception of $m=n=0$).

In practice the number of expanding modes is bounded, so it might be better to select modes which are the most strongly coupled to the one under consideration. But generally this is impossible, as it depends upon the mode under consideration. Hereupon we choose the same number of m and n in (7) and (8) in numerical order and select the same number of $\mathrm{TM}_{(mn)}$ modes and $\mathrm{TE}_{[mn]}$ modes as expanding modes where mn is every combination of m and n selected.

In this paper, we will concern ourselves with only the even modes.

B. Triangular Dielectric Waveguide

The triangular dielectric waveguide is a special case of the YDG with $R_1:R_2:L=\sqrt{3}:2:1$, as shown in Fig. 1(b). In this section, we present the transmission characteristics of the triangular dielectric waveguide.

Table I compares the phase constant and the transmission losses for the fundamental mode in the triangular dielectric waveguide with the number of expanding modes in order to estimate the sufficient number of the expanding modes. According to Table I, it is sufficient to approximate

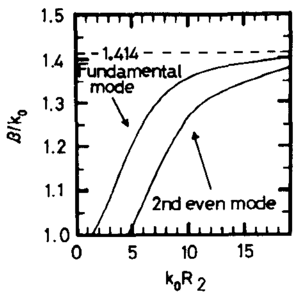

Fig. 2. Dispersion characteristics of the triangular dielectric waveguide with $\epsilon_r=2.0$, $R_1/R_2=0.866$, $L/R_2=0.5$, and $b/d=2.0$.

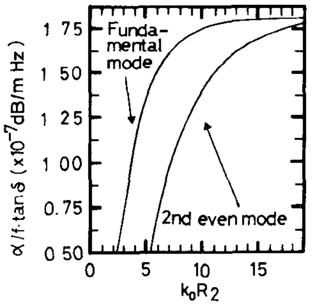

Fig. 3. Transmission losses of the triangular dielectric waveguide with $\epsilon_r=2.0$, $R_1/R_2=0.866$, $L/R_2=0.5$, and $b/d=2.0$.

TABLE I
COMPARISON OF PHASE CONSTANT AND TRANSMISSION LOSSES WITH NUMBER OF EXPANDING MODES: $\epsilon_r=2.0$, $k_0R_2=18.14$, $R_1/R_2=0.866$, $L/R_2=0.5$, $a/A=2.0$, $b/B=2.0$, $b/d=2.0$

Number of Expanding Modes	Phase Constant β/k_0	Transmission Losses $\alpha/f\cdot\tan\delta$ (x 10^{-7} dB/m·Hz)
32	1.381	1.759
50	1.391	1.801
72	1.396	1.813
98	1.397	1.816
128	1.397	1.815

(1) with 128 expanding modes to obtain good results. In the later calculation, the number of expanding modes is always 128: 64 TM modes and 64 TE modes.[1]

Figs. 2 and 3 show the dispersion characteristics and the transmission losses for the fundamental mode and the second even mode in the triangular dielectric waveguide with $b/d=2.0$ and $\epsilon_r=2.0$. The phase constant is normalized to β/k_0 and the transmission losses are expressed in terms of $\alpha/f\cdot\tan\delta$ where f stands for frequency. As the frequency decreases, a/A and b/B, which determine the size of the hypothetical boundary, are varied from 2.0 to 11.0 in order to keep the influence[2] of the hypothetical boundary small at every frequency.

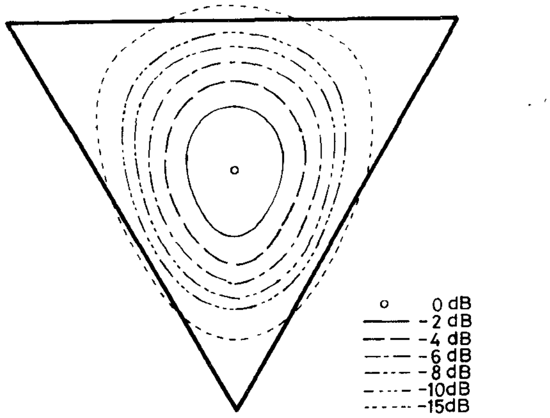

Fig. 4. Power distribution for the fundamental mode in the triangular waveguide with $\epsilon_r=2.0$, $k_0R_2=14.51$, $R_1/R_2=0.866$, $L/R_2=0.5$, $a/A=3.0$, $b/B=3.0$, and $b/d=2.0$.

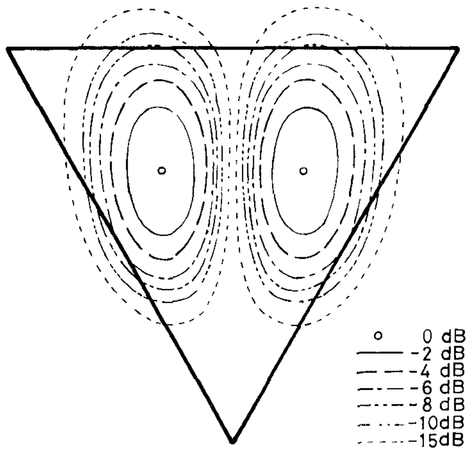

Fig. 5. Power distribution for the second even mode in the triangular dielectric waveguide with $\epsilon_r=2.0$, $k_0R_2=14.51$, $R_1/R_2=0.866$, $L/R_2=0.5$, $a/A=3.0$, $b/B=3.0$, and $b/d=2.0$.

From these figures it has become clear that in the frequency range k_0R_2 more than 10, the electromagnetic energy is confined in the dielectric waveguide so strongly that both the phase constant and the transmission losses remain large in value. On the other hand, as the normalized frequency k_0R_2 becomes lower than 10, this confinement of energy becomes weak so that the transmission losses decrease abruptly.

Figs. 4 and 5 show the power distribution for the fundamental mode and the second even mode, respectively. In these figures the magnitude of the power is expressed in terms of decibels referenced to the maximum value calculated by (3). Recently the dispersion characteristics and the power distribution for the fundamental mode in the triangular dielectric waveguide with little refractive index dif-

[1]For 128 expanding modes, about 700 s of ACOS 900 computing time were required for the calculation of β, α, and the power distribution for the first three even modes at one frequency.

[2]For a detailed discussion on the influence of the hypothetical boundary, refer to Ogusu [9] and [10].

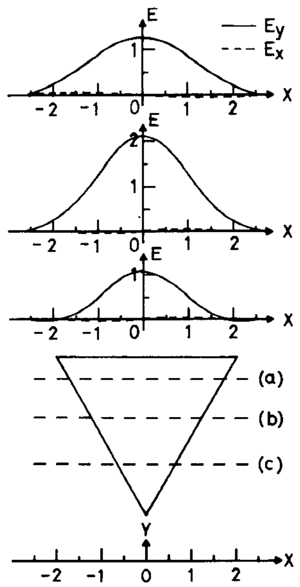

Fig. 6. Electric field distribution for the fundamental mode in the triangular dielectric waveguide with $\epsilon_r=2.0$, $k_0R_2=14.51$, $R_1/R_2=0.866$, $L/R_2=0.5$, $a/A=3.0$, $b/B=3.0$, and $b/d=2.0$.

ference were computed using the modified finite-element technique [11] and the results may be compared. Fig. 6(a), (b), and (c) show the electric field distribution for the fundamental mode as a function of X on the three lines indicated in Fig. 6(d). In Fig. 6, the origin of the horizontal dimension X is transferred to the center and both E and X are arbitrarily scaled. As is evident from Fig. 6, the E_y component is much greater than the E_x component so that the electric lines of force for the fundamental mode are almost parallel to the Y axis at this frequency.

C. Y Dielectric Waveguide (YDG)

In this section we present the transmission characteristics of the YDG, which is proposed in this paper to be the transmission line in millimeter- and submillimeter-wave regions.

Figs. 7 and 8 show the dispersion characteristics and the transmission losses for the fundamental mode and the second even mode in the YDG with $d=b/2-L/4$ and $\epsilon_r=2.0$. The reason why d is set to $b/2-L/4$ is to place the center of the X and Y dimension of the YDG (which are A and B in Fig. 1(a)) in the center of the hypothetical boundary plane. As the frequency decreases, a/A and b/B are varied from 1.5 to 6.0 in order to keep the influence of the hypothetical boundary small at every frequency. The reason why the values of a/A and b/B for the YDG are set smaller than that for the triangular dielectric waveguide is as follows. As will be shown later, the electromagnetic energy in the YDG is strongly confined in the center part and at the three edges, little energy propagates, so that we can allow the hypothetical boundary to come nearer to the YDG compared with the case for the triangular dielectric waveguide. The cutoff frequency for the fundamental mode both in the YDG and in the triangular dielectric waveguide

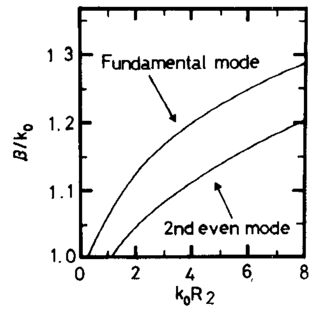

Fig. 7. Dispersion characteristics of the YDG with $\epsilon_r=2.0$, $R_1/R_2=0.037$, $L/R_2=10.63$, and $d=b/2-L/4$.

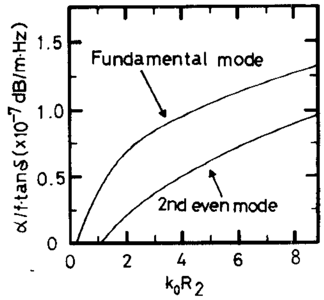

Fig. 8. Transmission losses of the YDG with $\epsilon_r=2.0$, $R_1/R_2=0.037$, $L/R_2=10.63$, and $d=b/2-L/4$.

may be zero theoretically. Right at the cutoff, the mode fields extend greatly beyond the dielectric waveguide so that the hypothetical boundary should be detached infinitely far away from the waveguide and a great number of expanding modes are required. Hence the maximum values of a/A and b/B are set to 6.0 for the YDG and 11.0 for the triangular dielectric waveguide.

Figs. 9 and 10 show the power distribution for the fundamental mode and the second even mode, respectively. As is evident from these figures, the electromagnetic energy in the YDG is strongly confined in the center part and at the three edges little energy propagates. This feature of the YDG facilitates supporting the YDG with little field disturbance.

D. Discussion

Using the results presented in the preceding two sections, we can design dielectric waveguides. First, we show some examples. It is assumed that dielectric waveguides are fabricated with Polyethylene ($\epsilon_r=2.0$, $\tan\delta=10^{-4}$).

From the results in Figs. 2 and 3, the parameters for the triangular dielectric waveguide with 0.5 dB/m transmission losses at 100 GHz are determined as $2R_1=1.90$ mm, $R_2=1.10$ mm, and $L=0.55$ mm where $2R_1$ represents the length of one side of the equilateral triangle. In this case, the normalized phase constant[3] β/k_0 is found to be 1.05 and the second even mode is in cutoff.

[3]The present method gives results with good accuracy except for the vicinity of the cutoff region, as shown in [9]. Hence the accuracy of the found values of β/k_0 is good.

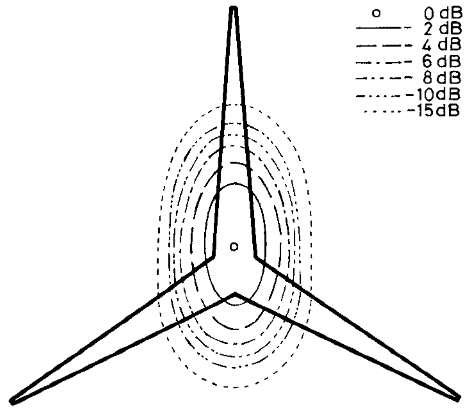

Fig. 9. Power distribution for the fundamental mode in the YDG with $\epsilon_r=2.0$, $k_0R_2=3.35$, $R_1/R_2=0.037$, $L/R_2=10.63$, $a/A=3.0$, $b/B=3.0$, and $d=b/2-L/4$.

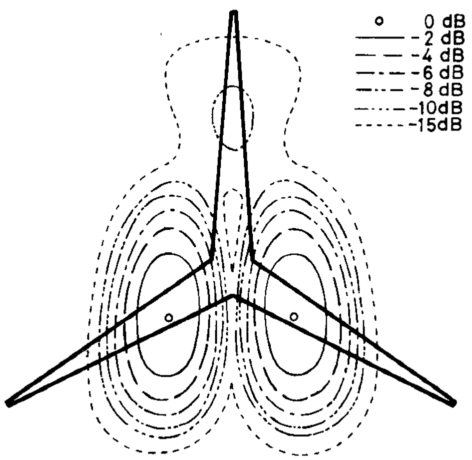

Fig. 10. Power distribution for the second even mode in the YDG with $\epsilon_r=2.0$, $k_0R_2=3.35$, $R_1/R_2=0.037$, $L/R_2=10.63$, $a/A=3.0$, $b/B=3.0$, and $d=b/2-L/4$.

Similarly, from the results in Figs. 7 and 8, the parameters for the YDG with 0.5 dB/m transmission losses at 100 GHz are determined as $R_1=0.023$ mm, $R_2=0.621$ mm, and $L=6.60$ mm. The normalized phase constant[3] in this case is 1.09. In this manner, the YDG has suitable size in millimeter- and submillimeter-wave regions.

In this paper, the parameters ϵ_r, R_1, R_2, and L, which characterize the YDG, are not varied. But by varying these parameters and the operating frequency, the power distribution might be easily controlled. Hence the YDG with proper power distribution could be obtained.

IV. Conclusion

The YDG has been presented as a transmission line in millimeter- and submillimeter-wave regions and investigated theoretically. The transmission characteristics of the triangular dielectric waveguide are also investigated as a special case of the YDG.

We have shown that the YDG facilitates supporting the waveguide with little field disturbance and with low transmission losses. The power distribution might be easily controlled by varying the waveguide parameters and the operating frequency.

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References

[1] E. A. J. Marcatili, "Dielectric rectangular waveguide and directional coupler for integrated optics," *Bell Syst. Tech. J.*, vol. 48, pp. 2071–2102, Sept. 1969.

[2] J. E. Goell, "A circular-harmonic computer analysis of rectangular dielectric waveguide," *Bell Syst. Tech. J.*, vol. 48, pp. 2133–2160, Sept. 1969.

[3] D. Marcuse and W. L. Mammel, "Tube waveguide for optical transmission," *Bell Syst. Tech. J.*, vol. 52, pp. 423–435, Mar. 1973.

[4] R. Pregla, "A method for the analysis of coupled rectangular dielectric waveguides," *Arch. Elek. Übertragung*, vol. 28, pp. 349–357, Sept. 1974.

[5] D. Marcuse, *Theory of Dielectric Optical Waveguides*. New York: Academic, 1974.

[6] W. McLevige, T. Itoh, and R. Mittra, "New waveguide structures for millimeter wave and optical integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 788–794, Oct. 1975

[7] T. Itoh, "Inverted strip dielectric waveguide for millimeter-wave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 821–827, Nov. 1976.

[8] S. A. Schelkunoff, "Generalized telegraphist's equations for waveguides," *Bell Syst. Tech. J.*, vol. 31, pp. 784–801, July 1952.

[9] K. Ogusu, "Numerical analysis of the rectangular dielectric waveguide and its modifications," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 874–885, Nov. 1977.

[10] ——, "Measurements of dispersion characteristics and field distributions in rectangular-dielectric waveguide and its modifications," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 169-171, Mar. 1978.

[11] C. Yeh, K. Ha, S. B. Dong, and W. P. Brown, "Single-mode optical waveguides," *Appl. Optics*, vol. 18, no. 10, pp. 1490–1504, May 1979.