O-Guide and X-Guide: An Advanced Surface Wave Transmission Concept*

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Summary—**This paper describes the O-guide and X-guide which are proposed by the authors and are the advanced surface waveguides composed of thin dielectric sheets. The results of an analysis of the TE fundamental mode in the O-guide are described, and the theoretical characteristics as a transmission line are discussed. The practical guides are suitable especially for the SHF region and guides can be obtained which have lower attenuation constants than coaxial lines, G-lines, and rectangular waveguides.**

Introduction

It is the principle of surface wave transmission to convey an electromagnetic wave along the boundary surface of a medium which is located in free space and in which the propagation velocity of the wave is lower than in free space. This is accomplished by making the wave concentrate in the vicinity of the surface of this medium. The G-line[1] which was proposed by G. Goubau in 1950 is a typical surface wave transmission line, and is very convenient because of its simple construction; it also has several defects as a transmission line, namely, large conductor loss, small concentration efficiency of the wave, and interference from the external field.

Here the authors propose "Thin Dielectric Sheet Waveguides" as more advanced surface wave transmission lines. Two examples are described below, and they are called respectively "O-guide" and "X-guide" and designed according to the principle that a thin dielectric plate placed parallel to the electric field has a more effective concentrating action than one located perpendicularly; in the case of a thin magnetic plate such as a ferrite, the relationship is just the opposite. It is quite the same in principle to use magnetic substances, but unfortunately there are very few practical materials available.

The waveguides mentioned above have two merits: they have no conductor loss and excellent efficiency of concentration: better results can be realized by shielding the above lines with metal because interference from the external field will in this manner be eliminated.

Plane Wave

In this paper the rationalized MKS system of units is used throughout.

Let us first consider the plane wave. Suppose a thin dielectric plate having a thickness of $2t$, and a dielectric constant $\epsilon^*\epsilon_0$, where ϵ^* is a relative dielectric constant and ϵ_0 is the constant of the free space, is placed in the y-z plane in the infinite free space as shown in Fig. 1. We shall also suppose that an electromagnetic plane wave is propagating along the dielectric plane in the z-direction; and that in the case of Fig. 1(a) the electric field has only a y-component; in the case of Fig. 1(b), the magnetic field has only a y-component. Accordingly, the mode of the wave in Fig. 1(a) is regarded as a TE mode and the one in Fig. 1(b) as a TM mode.

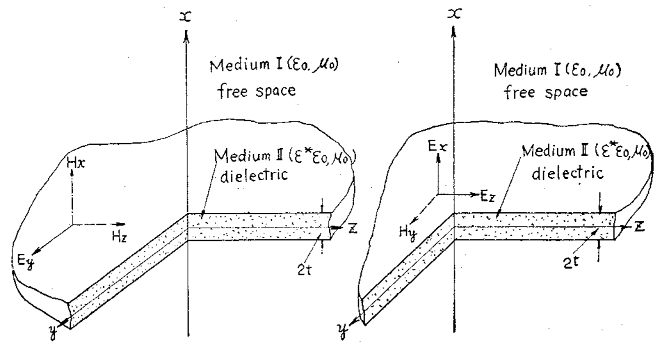

Fig. 1—(a) TE mode, (b) TM mode.

Now we shall observe the field in the medium I, because the one in the medium II is not important in our case. Let us consider the field component equations in the medium I as a function of x, where x is the distance from y-z plane. Here all field quantities are understood to contain the common factors which are independent of x.

Solving the equations analytically, we can obtain the following equations for Fig. 1(a):

$$E_y \simeq E_{y0} e^{-\alpha_a x}, \tag{1}$$

where E_{y0} is a constant and α_a can be expressed as follows provided that t is very small in comparison with the wavelength,

$$\alpha_a \simeq k^2 t(\epsilon^* - 1), \tag{2}$$

where k is the free space propagation constant and can be expressed as

$$k = \omega\sqrt{\epsilon_0\mu_0} = \frac{2\pi}{\lambda_0}, \tag{3}$$

where ω is angular frequency, μ_0 is the permeability of the free space and λ_0 is the wavelength in free space.

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[1] G. Goubau, "Surface waves and their application to transmission line," *J. Appl. Phys.*, vol. 21, pp. 1119–1128; November, 1950. See also Goubau, "Single-conductor surface-wave transmission line," Proc. IRE, vol. 39, pp. 619–624; June, 1951.

For Fig. 1(b) we obtain the following:

$$H_y \simeq H_{y0} e^{-\alpha_b x}, \tag{4}$$

where H_{y0} is a constant and α_b can be expressed as follows under the same condition as for (1):

$$\alpha_b \simeq k^2 t \frac{\epsilon^* - 1}{\epsilon^*} \cdot \tag{5}$$

Comparing (2) with (5), it can be concluded that the thin dielectric plate in the case of Fig. 1(a) is more effective on the concentration of the wave than the one in the case of Fig. 1(b), namely, a thin dielectric plate placed parallel to the electric field has a more effective concentrating action than one located perpendicularly.

By the above reasoning, the G-line has a poorer efficiency of concentration, as stated in the introduction of this paper.

Now, let us pay attention only to the former type and consider a physically realizable construction of the transmission line because the construction discussed above is that of the infinite plane and is physically unobtainable. We can easily find two types of the practical lines which are illustrated in Fig. 2(a) and Fig. 2(b).

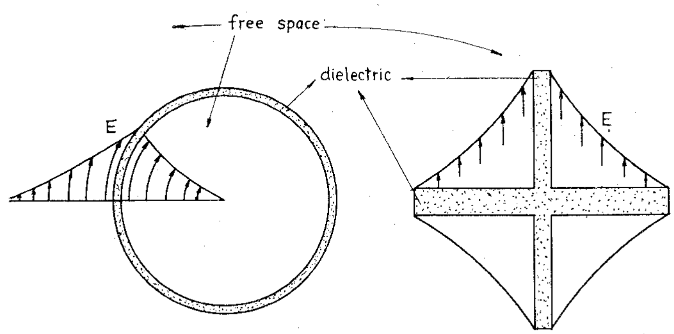

Fig. 2—(a) O-guide cross section, (b) X-guide cross section.

We can obtain the construction shown in Fig. 2(a) by transforming the whole system in Fig. 1(a) to cylindrical co-ordinates and the construction shown in Fig. 2(b) by combining the plate in y-z plane with the one in z-x plane to form a two-dimensional concentrating action.

Since the H-guide[2] which was similar to these lines was reported previously, let us call these lines "O-guide" in the case of Fig. 2(a) and "X-guide" in the case of Fig. 2(b).

The transmission mode that should be noted in the O-guide is the TE mode and in the X-guide the hybrid mode in which the wave has both the electric and magnetic components in the z-direction.

In the X-guide shown in Fig. 2(b), the horizontal dielectric plate must have $\epsilon^* t$ of a larger value than that of the vertical one, as is clearly indicated in the same figure, for the reason shown in Fig. 1.

[2] F. J. Tischer, "H-guide, A new microwave concept," *Tele-Tech.*, vol. 15, pp. 50, 51, 130, 134, 136; November, 1956.

O-Guide

Now let us suppose that there is a dielectric cylinder having a thin wall of a thickness T, a radius a, and a dielectric constant $\epsilon^*\epsilon_0$ in the infinite free space as shown in Fig. 3. We assume a wave of TE mode is propagating along the z-axis.

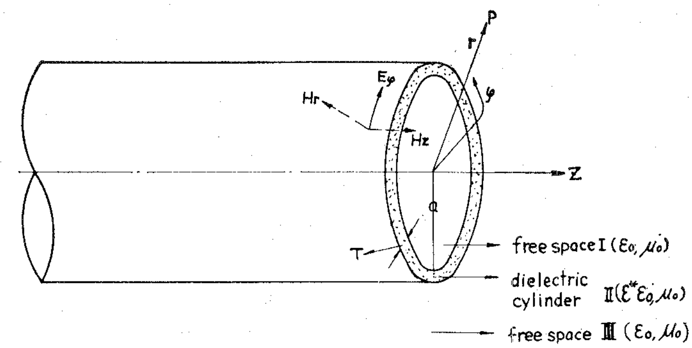

Fig. 3.

Starting from Maxwell's equations and using the cylindrical co-ordinates as shown in Fig. 3, we obtain the following sets of equations for the field components; if the thickness T is very small compared with the radius a and the wavelength λ and all the field quantities are understood to contain the common factors $\exp\{j(\omega t - B_z Z)\}$, where j is $\sqrt{-1}$, t is time, and other notations as defined below:

$$\left.\begin{aligned} E_\phi{}^{\mathrm{I}} &= \frac{-j\omega\mu_0}{\alpha_r} A I_1(\alpha_r r), \\ H_r{}^{\mathrm{I}} &= \frac{j\beta_z}{\alpha_r} A I_1(\alpha_r r), \\ H_z{}^{\mathrm{I}} &= A I_0(\alpha_r r), \end{aligned}\right\} \tag{6}$$

$$\left.\begin{aligned} E_\phi{}^{\mathrm{III}} &= \frac{j\omega\mu_0}{\alpha_r} B K_1(\alpha_r r), \\ H_r{}^{\mathrm{III}} &= \frac{-j\beta_z}{\alpha_r} B K_1(\alpha_r r), \\ H_z{}^{\mathrm{III}} &= B K_0(\alpha_r r) \end{aligned}\right\} \cdot \tag{7}$$

Here A and B are the arbitrary constants. Both are related by the boundary condition, and I_n and K_n are respectively the first and second kind of the modified Bessel functions. The meanings of other notations are as follows:

The lower suffix denotes co-ordinate.
The upper suffix denotes the medium.

ω = angular frequency,
α_r = propagation constant in r-direction,
β_z = propagation constant in z-direction.

The following equation is given by the relation among α_r, β_z, and k;

$$\beta_z{}^2 = k^2 + \alpha_r{}^2. \tag{8}$$

Substituting (6) and (7) in the equations of the boundary condition at $r=a$, we get following two relations:

$$\frac{A}{B} = -\frac{K_1(\alpha_r a)}{I_1(\alpha_r a)}, \tag{9}$$

$$\{I_1(\alpha_r a)K_1(\alpha_r a)\}^{-1} = (\epsilon^* - 1)Tak^2 \equiv Y. \tag{10}$$

Eq. (10) is called the "characteristic equation." From this equation, the constant α_r which shows the concentration can be determined if the value of $Y \equiv (\epsilon^* - 1)Tak^2$ is given, where Y is decided by the construction.

In the case of Fig. 1(a) there is no cut-off phenomenon, but in the case of Fig. 3, namely that of a cylinder, there occurs a phenomenon resembling "cut-off." This means that the surface wave cannot exist at the frequency lower than the cut-off frequency.

The cut-off wavelength λ_c can be expressed through (10), since $I_1(x)K_1(x) \leqq 0.5$ for real number x,

$$\lambda_c = \pi\sqrt{2(\epsilon^* - 1)Ta}. \tag{11}$$

The attenuation of this guide is caused only by the dielectric loss and of course no loss is caused by the conductor loss. After calculating the transmitted power and the dielectric loss, we obtain the following expression as the attenuation constant $\bar{\alpha}_z$;

$$\bar{\alpha}_z = \frac{\alpha_r \epsilon^* T k^2 \tan\delta}{\beta_z} A(X), \tag{12}$$

where

$$A(X) = \frac{\{K_1(X)\}^2}{(\mu+1)X\left(\frac{1}{4}\{K_0(X)+K_2(X)\}^2 - \left(1+\frac{1}{X^2}\right)\{K_1(X)\}^2\right)} \tag{13}$$

$$\mu = \mu(X) = \frac{\{K_1(X)\}^2\left(\left(1+\frac{1}{X^2}\right)\{I_1(X)\}^2 - \frac{1}{4}\{I_0(X)+I_2(X)\}^2\right)}{\{I_1(X)\}^2\left(\frac{1}{4}\{K_0(X)+K_2(X)\}^2 - \left(1+\frac{1}{X^2}\right)\{K_1(X)\}^2\right)} \tag{14}$$

$$X = \alpha_r a,$$

$\tan\delta$ = loss factor of the dielectric.

It can be concluded from these equations that the attenuation constant is proportional to $\tan\delta$, and approximately proportional to the third power of frequency. And if the concentrating action is constant, *i.e.*, if Y is constant, it can be shown that the attenuation constant is inversely proportional to $\epsilon^*/\epsilon^* - 1$. On account of the above, dielectric materials of higher ϵ^* and smaller $\tan\delta$ are better suited for the purpose.

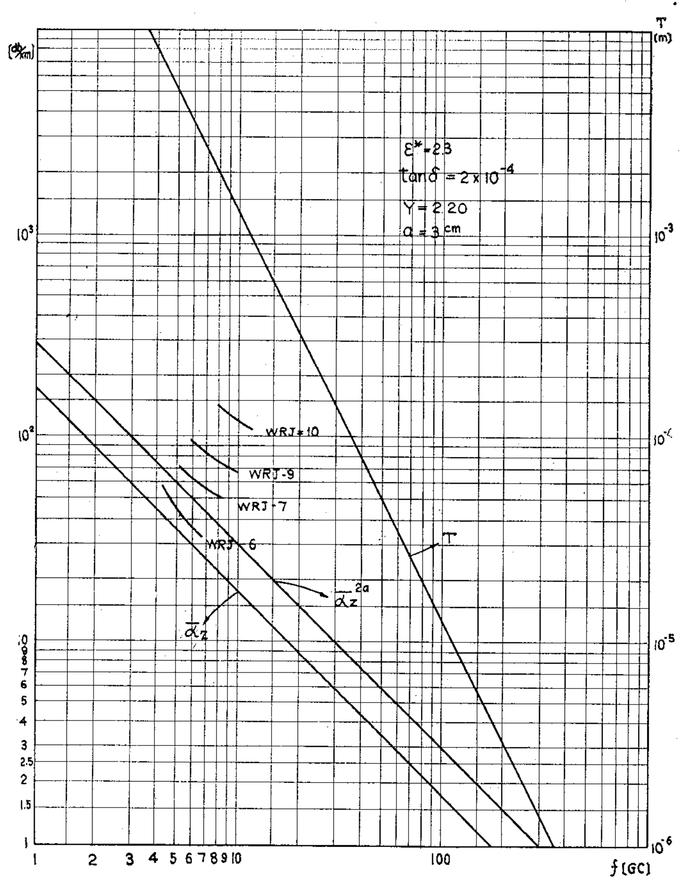

Fig. 4.

Fig. 4 shows the frequency characteristic of a polyethylene cylinder, with a diameter of 3 cm, supposing $Y=2.20$, $\epsilon^*=2.3$, and $\tan\delta = 2\times10^{-4}$. In this figure, the curve denoted T shows the necessary thickness required to keep $Y=2.20$. And the curve denoted $\bar{\alpha}_z$ shows the attenuation characteristic mentioned above. It should be noted that $\bar{\alpha}_z$ decreases as the frequency increases.

$\bar{\alpha}_z^{2a}$ means the attenuation constant when the transmitted power through the space outside the cylinder of a radius $2a$ is completely neglected. Consequently if the shield be placed at the position of the radius $2a$, the attenuation constant should not exceed $\bar{\alpha}_z^{2a}$. The curves designated WRJ-6, 7, 9, and 10 in the same figure show the attenuation constants for the rectangular wave guides WRJ-6, 7, 9, and 10 which correspond to respectively WR 159, 137, 112, and 90 specified in RETMA Standards. These curves are shown for comparison. Comparing these curves shows that this guide has much lower loss than conventional rectangular waveguides.

Miscellaneous

From the point of view of the practical application, the SHF region may be most suitable for these guides, but some problems in the shielding, supports, bends, and launching must be solved in order to use this waveguide in practice. The authors have some ideas for solving these problems, but no experiments have yet been done.

Conclusion

The advanced surface wave transmission lines composed of thin dielectric sheets are suitable, especially for SHF region, and have lower loss than the coaxial lines, G-lines, H-guides, and rectangular waveguides.

Corrections

H. A. Wheeler and H. L. Bachman, authors of "Evacuated Waveguide Filter for Suppressing Spurious Transmission from High-Power S-Band Radar," which appeared on pages 154–162 of the January, 1959 issue of these Transactions, have submitted the following corrections;

Table I, just above (7) and (8), is changed to read:

At f_1 and f_2:

Table II, (10), is changed to read:

$$f_4^2 = f_7^2 + \frac{f_8^2 - f_7^2}{1 + \frac{f_7^2}{f_8^2}\left(\frac{f_8^2 - f_5^2}{f_7^2 - f_5^2}\right)^2}.$$

Page 160, at the end of second column, "The reflection loss" is deleted.

Page 161, at the beginning of first column, "by about 0.2 db. The sum of these effects holds the dissipation loss" is deleted. Insert these words after the third line below the short table (Metal walls, etc.).

J. F. Cline and B. M. Schiffman wish to call attention to a typographic error in an equation in their article "Tunable Passive Milticouplers Employing Minimum-Loss Filters," which appeared on pages 121–127 of the January, 1959 issue of these Transactions. The error occurs in (11) on page 125. The radical sign should terminate at the end of the binomial and before the final −1. The equation should read as follows:

$$\frac{Q_T}{Q_U} = \frac{3}{2}\left(\sqrt{1 + \frac{8}{9}\left(10^{L_0/20} - 1\right)} - 1\right). \quad (11)$$