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Filled Image Guide for Millimeter-Wave Circuits

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Abstract

In this paper the method of optimal design is dealt with for six parameters selected by the Orthogonal Array Table (OAT). A lot of sets of parameters are presented, by which the filled image guides have optimal propagation properties. The guiding ability is strengthened greatly as the hollow core is filled with another dielectric material.

I. Introduction

The hollow image guide presented by T.Itoh (1981) is a variant of image guide. It makes the design process more flexible. [1,2]

In this paper the conditions are derived which the three lower modes satisfy respectively in a filled image guide. A lot of sets of parameters are presented, by which the filled image guides have optimal propagation properties.

II. The conditions of the existing three lower modes

The eigenvalue equations describing wave propagation in a filled image guide shown as Fig. 1 are:

$$(\varepsilon_{r_2}^2 \eta_1 \eta_3 \,\mathrm{th}\,\eta_1 h - \varepsilon_{r_1} k_y^2) \sin k_y t + (\varepsilon_{r_2} k_y \eta_1 \,\mathrm{th}\,\eta_1 h + \varepsilon_{r_1} \varepsilon_{r_2} k_y \eta_3) \cos k_y t = 0 \quad (1a)$$

$$k_y' \sin k_y' b - \varepsilon_{r_2} \eta_3 \cos k_y' b = 0 \quad (1b)$$

$$(k_x^2 \sin k_x w - k_x \xi_3 \cos k_x w) - (k_x \cos k_x w + \xi_3 \sin k_x w)\, \xi_1 \begin{Bmatrix} \mathrm{th}\,\xi_1 c \\ \mathrm{cth}\,\xi_1 c \end{Bmatrix} = 0, \quad p = \begin{matrix} 1, 3, 5, \cdots \\ 2, 4, 6, \cdots \end{matrix} \quad (1c)$$

for E^y_{pq} modes,

$$\xi_1 \varepsilon_{r_2} (k_x \cos k_x w + \varepsilon_{r_2} \xi_3 \sin k_x w) + k_x \varepsilon_{r_1} (\varepsilon_{r_2} \xi_3 \cos k_x w - k_x \sin k_x w) \begin{Bmatrix} \mathrm{th}\,\xi_1 c \\ \mathrm{cth}\,\xi_1 c \end{Bmatrix} = 0, \quad p = \begin{matrix} 1, 3, 5, \cdots \\ 2, 4, 6, \cdots \end{matrix} \quad (2a)$$

$$(k_x'^2 - \varepsilon_{r_2}^2 \xi_3'^2) \sin 2k_x' a - 2\varepsilon_{r_2} \xi_3' k_x' \cos 2k_x' a = 0 \quad (2b)$$

$$(\eta_1 \eta_3 \,\mathrm{cth}\,\eta_1 h - k_y^2) \sin k_y t + (\eta_3 k_y + \eta_1 k_y \,\mathrm{cth}\,\eta_1 h) \cos k_y t = 0 \quad (2c)$$

for E^x_{pq} modes, where

$$t = b - h \qquad w = a - c \qquad k_0 = 2\pi f \sqrt{\varepsilon_0 \mu_0}$$

$$\eta_1 = [(\varepsilon_2 - \varepsilon_1) k_0^2 - k_y^2]^{1/2} \qquad \varepsilon_1 = \begin{cases} \varepsilon_{r_1}, & E^y_{pq} \\ \varepsilon_{e_1}, & E^x_{pq} \end{cases} \qquad \varepsilon_2 = \begin{cases} \varepsilon_{r_2}, & E^y_{pq} \\ \varepsilon_{e_2}, & E^x_{pq} \end{cases}$$

$$\eta_3 = [(\varepsilon_2 - 1) k_0^2 - k_y^2]^{1/2}$$

$$\xi_1 = [(\varepsilon_2 - \varepsilon_1) k_0^2 - k_x^2]^{1/2} \qquad \varepsilon_1 = \begin{cases} \varepsilon_{e_1}, & E^y_{pq} \\ \varepsilon_{r_1}, & E^x_{pq} \end{cases} \qquad \varepsilon_2 = \begin{cases} \varepsilon_{e_2}, & E^y_{pq} \\ \varepsilon_{r_2}, & E^x_{pq} \end{cases}$$

$$\xi_3 = [(\varepsilon_2 - 1) k_0^2 - k_x^2]^{1/2}$$

$$\xi_3' = [(\varepsilon_{r_2} - 1) k_0^2 - k_x'^2]^{1/2}$$

$$\varepsilon_{e_1} = \varepsilon_{r_2} - k^2/k_0^2 \qquad k = \begin{cases} k_y, & E^y_{pq} \\ k_x, & E^x_{pq} \end{cases} \qquad k' = \begin{cases} k_y', & E^y_{pq} \\ k_x', & E^x_{pq} \end{cases}$$

$$\varepsilon_{e_2} = \varepsilon_{r_2} - k'^2/k_0^2$$

Using the same procedure with [3] we derive the conditions which the three lower modes satisfy respectively in a filled image guide from the eigenvalue equations. These are:

The lowest mode E^y_{11} mode always exists no matter how low the frequency is.

$$k_y > k_y' \quad (3a)$$

$$K_1 \geq \frac{3\pi}{2} \quad \text{or} \quad \begin{cases} \frac{3\pi}{2} > K_1 > \frac{\pi}{2} \\ \tan K_1 - \sqrt{\frac{\varepsilon_{e_1} - 1}{\varepsilon_{e_2} - 1}} \cot\left(\sqrt{\frac{\varepsilon_{e_1} - 1}{\varepsilon_{e_2} - 1}} \frac{c}{w} K_1\right) \geq 0 \end{cases} \quad (3b)$$

for E^y_{21} mode (p=2, q=1), where $K_1 = \sqrt{\varepsilon_{e_2} - 1}\, k_0 w$.

$$k_x > k_x' \quad (4a)$$

$$\tan K_2 - \frac{\varepsilon_{r_2}}{\varepsilon_{r_1}} \sqrt{\frac{\varepsilon_{r_1} - 1}{\varepsilon_{r_2} - 1}} \cot\left(\sqrt{\frac{\varepsilon_{r_1} - 1}{\varepsilon_{r_2} - 1}} \frac{c}{w} K_1\right) \geq 0 \quad (4b)$$

$$K_3 \geq \frac{3\pi}{2} \quad \text{or} \quad \begin{cases} \frac{3\pi}{2} > K_3 > \frac{\pi}{2} \\ \tan K_3 - \sqrt{\frac{\varepsilon_{e_1} - 1}{\varepsilon_{e_2} - 1}} \cot\left(\sqrt{\frac{\varepsilon_{e_1} - 1}{\varepsilon_{e_2} - 1}} \frac{h}{t} K_3\right) \geq 0 \end{cases} \quad (4c)$$

for E^x_{12} mode (p=1, q=2) where

$$K_2 = \sqrt{\varepsilon_{r_2} - 1}\, k_0 w, \qquad K_3 = \sqrt{\varepsilon_{e_2} - 1}\, k_0 t$$

As for the hollow image guide (ε_{r_1}=1), E_q.(4b) becomes

$$\tan K_2 - \frac{w}{c} \frac{\varepsilon_{r_2}}{K_2} \geq 0 \quad (4b')$$

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III. The propagation properties

In this paper the method of optimal design is dealt with for six parameters: a,c,b,h, ε_{r_1} and ε_{r_2} selected by the Orthogonal Array Table (OAT), [4] which affect the single-mode bandwidth, the external field divergence, the conductor and the dielectric losses. Some sets of optimal parameters are selected out. Some of them are:

(1) a=1.5mm, c=0.5mm, b=2.0mm, h=1.0mm, ε_{r_1} =2.25, ε_{r_2}=3.78. It has widest single-mode bandwidth: 85.90 GHz. But the external field divergence is great and the dielectric loss is high.

(2) a=3.4mm, c=1.1mm, b=3.8mm, h=0.9mm, ε_{r_1} =2.25, ε_{r_2}=3.78. It has smallest external field divergence: P_o/P_i=0.077

(3) a=3.4mm, c=0.9mm, b=2.1mm, h=0.6mm, ε_{r_1} =1, ε_{r_2}=3.78 It has lowest dielectric loss: 0.006323 dB/cm. But the external field divergence is greatest.

(4) a=3.0mm, c=2.0mm, b=4.2mm, h=0.9mm, ε_{r_1} =1, ε_{r_2}=3.78 It has lowest conductor loss: 0.000635 dB/cm.

From the calculations both the filled image guide and the hollow image guide possess similar wide single-mode bandwidth. The guiding ability is strengthened greatly, if the hollow core is filled with another dielectric material, the dielectric constant of which is lower than one of the dielectric strip, most of the energy is carried in the strip, so that external field divergence decreases. This makes the design process more flexible. In general, it is unable to be satisfied together that the external field divergence is small and the dielectric loss is low.

It is found in the calculations that using teflon or fused quartz as the strip in a hollow image guides has optimal propagation properties. From a rough estimate, the first high order mode is E^y_{21} mode as the factor (a-c)/(b-h) is greater than about 1. Otherwise the first high order mode is E^x_{12} mode as to the hollow image guide. But the first high order mode is always E^x_{12} mode as to the filled image guide, it is not concerned in the selection of the sizes.

The dispersion properties of the filled image guide are show in Fig 2.

The properties of external field divergence are shown in Fig. 3. The value of the external field divergence $\log(p_0/p_i)$ decreases, as the frequency increases.

The properties of dielectric loss are illustrated in Fig. 4. The dielectric loss increases with frequency.

The properties of conductor loss are indicated in Fig. 5. The conductor loss has peak value at certain frequency.

Fig. 3-Fig. 5 are the properties of the lowest mode E^y_{11}, where curve 1 is obtained by calculations using the set of the parameters which are a=3.35mm, c=1.05mm, b=3.55mm, h=0.85mm, ε_{r_1} =2.25, ε_{r_2} =3.78, and curve 2 is obtained by calculations using the set of the parameters which are a=2.4mm, c=0.8mm, b=3.4mm, h=0.4mm, ε_{r_1} =1, ε_{r_2}=3.78.

Reference

[1] T. Itoh and J. Rivera, A Comparative Study of Millimeter Wave Transmission Lines, 6th Inter. Conference on Infrared and Millimeter Waves, Digest, W-4-1, Miami Beach, FLA, Dec. 1981.

[2] J.F. Miao and T. Itoh, IEEE Trans. on MTT-30, (1982), 1826.

[3] Mei-Qi Shi, Ding-Hua Jiang, Inter. J.IR & MM Waves Vol-5, No. 12, Dec. 1984, 1605.

[4] The Chinese Association of Applied Statistics, Three steps group, computer aided designs with three steps.

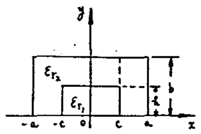

Fig. 1. Filled image guide

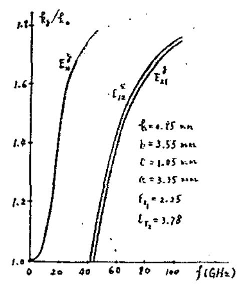

Fig. 2. Dispersion properties of the filled image guide

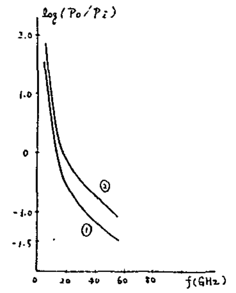

Fig. 3. Properties of external field divergence

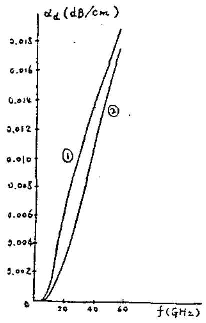

Fig. 4. Properties of dielectric loss

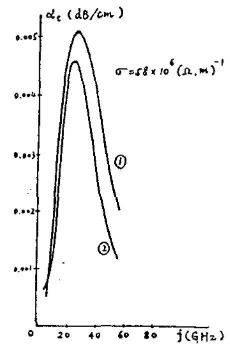

Fig. 5. Properties of conductor loss