A SOLUTION OF THE EARTHED FIN LINE WITH FINITE METALLIZATION THICKNESS

Adalbert Beyer and Ingo Wolff
Department of Electrical Engineering
University of Duisburg
Bismarckstrasse 81
D-4100 Duisburg
Fed.Rep. of Germany

ABSTRACT

A method is presented which solves the eigenvalue problem of an earthed fin line considering finite metallization thickness as well as a longitudinal slit in the metal waveguide-mount. Numerical and experimental results are given for the unilateral fin line.

Introduction

In earthed fin lines metal fins are printed on a dielectric substrate, which bridge the walls of a rectangular waveguide (Fig.1).

Up to now several papers have been published describing experimental and theoretical investigations of fin lines[1,2,6,7]. The agreement of measured and calculated propagation constants generally is unsatisfactory. This especially is true for high millimeterwave frequencies. The discrepancies result from neglecting the effects of the finite metallization thickness of the fins and from neglecting the effects of the slits in the fin line mounts, Fig.1.

Only for very thin metallization layers (e.g.evaporated gold or copper layers with 1...5 μm thickness) the assumption of vanishing metallization thickness is justified as an approximation. In practical cases however, where commercially available copper clad substrate materials are used with copper thicknesses ranging between 20 μm and 100 μm, errors of 5% to 8% (E-band values) in the effective dielectric constant ε_{eff} of the fin lines are due to disregarding the effects of the finite metallization thickness. This is especially true in the case of low impedance fin lines needed in semiconductor circuits, where the slot width 2s is very small compared to the narrow wall dimension b of the waveguide mount, Fig. 2.

The effects due to the slit in the waveguide mount, Fig.1a, especially are important for small fin lines in the higher millimeter wave frequency range, e.g. at E-band, although the connected errors can be reduced by reducing the slit-height c, Fig.2. Errors of 3% to 5% can occur in the effective dielectric constant ε_{eff} due to neglecting the effects of the slit in the waveguide mount. However, unlike the errors due to the finite metallization thickness, these errors are most critical for high impedance fin lines which are important in filters and transitions, where the slot width is large ($2s \cong b$).

The Mathematical Method

In the following a calculation method for all known fin line configurations (Fig.1b,c,d) is represented which takes into account both the finite metallization thickness and the finite longitudinal slit in the waveguide mount. In view of the fact that the bilateral fin line has been treated in several papers[2,7] while the unilateral fin line has been treated more scarcely, the method presented in this paper is applied to the unilateral fin line.

The present treatment is based on the ridge-loaded waveguide model for unilateral earthed fin lines[4,5] additionally taking into account the finite thickness of the metal fin, the longitudinal slit of the waveguide mount and the cross-sectional symmetry with respect to the x-axis.

Let Fig.2 represent the cross section of an unilateral fin line with conducting boundary ℓ. The electromagnetic field in each subregion (1),(2),(3) or (4) can be described using scalar functions Φ and Ψ. It can be shown that the electromagnetic fields of e.g. subregion (2) can be matched to the electromagnetic fields e.g. subregion (3) over their common interface, in the example mentioned, at $x=a/2-d_1$.

As an example the calculation method is demonstrated for the odd TE-modes[5]. Applying the continuity of the odd TE-mode field Ψ at the interface $x=a/2-d_1$, it results:

$$\sum_{n=0}^{\infty} G_n \sin\{k_{xn}^{(2)}(\frac{a}{2}-d_1)\}\cos\{k_{yn}^{(2)}(y-\frac{b'}{2})\} = \sum_{l=0}^{\infty} N_l \sin\{k_{xl}^{(3)}(\frac{a}{2}-d_1)\}\cos\{k_{yn}^{(3)}(y-s)\}, \quad (1)$$

where

$$k_{xn}^{(i)2} + k_{yn}^{(i)2} + \beta_n^2 = \varepsilon_r^{(i)} \cdot k_0^2 \quad , i=1,2,3,4 \quad (2)$$

and

$$k_0^2 = \omega^2 \varepsilon_0 \mu_0 . \quad (3)$$

The $E_y^{(2)}$ and $E_y^{(3)}$ fields at both sides of the interface $x=a/2-d_1$ may be represented by an integral expression[5] which yields the coefficients G_n and N_l:

$$G_n = \frac{\nu_n \cdot \int_{-b'/2}^{b'/2} E_y^{(2)}(\frac{a}{2}-d_1,y)\cos\{k_{yn}^{(2)}(y-\frac{b'}{2})\}\,dy}{j\omega\mu k_{xn}^{(2)} b' \cos\{k_{xn}^{(2)}(\frac{a}{2}-d_1)\}} \quad (4)$$

and

$$N_l = \frac{\nu_l \cdot \int_{-s}^{s} E_y^{(3)}(\frac{a}{2}-d_1,y)\cos\{k_{yn}^{(3)}(y-s)\}\,dy}{j\omega\mu k_{xl}^{(3)}\, 2s \cos\{k_{xl}^{(3)}(\frac{a}{2}-d_1)\}} , \quad (5)$$

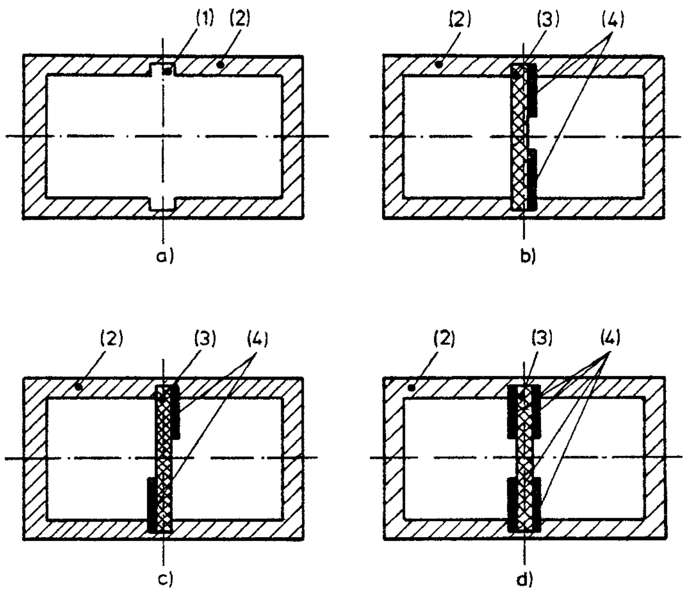

Fig.1: Cross sections of earthed fin lines: a) waveguide mount, b) unilateral fin line, c) antipodal fin line, d) bilateral fin line.
(1) slit, (2) metal wall, (3) dielectric substrate, (4) metal fin.

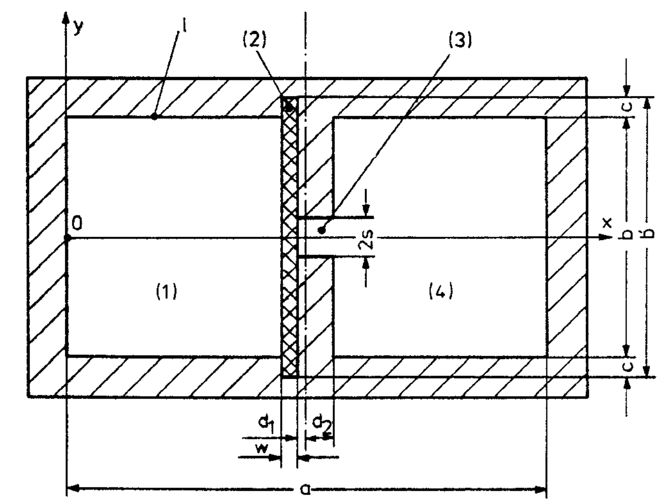

Fig.2: Cross section of the unilateral earthed fin line for E-band. a=3.099±0.02 mm, b=1.549±0.02 mm, 2.2 mm, d_1=0.01 mm, d_2=0.06 mm, w=0.05 mm, c=0.326 mm, 0.05 mm≤s≤0.5mm.

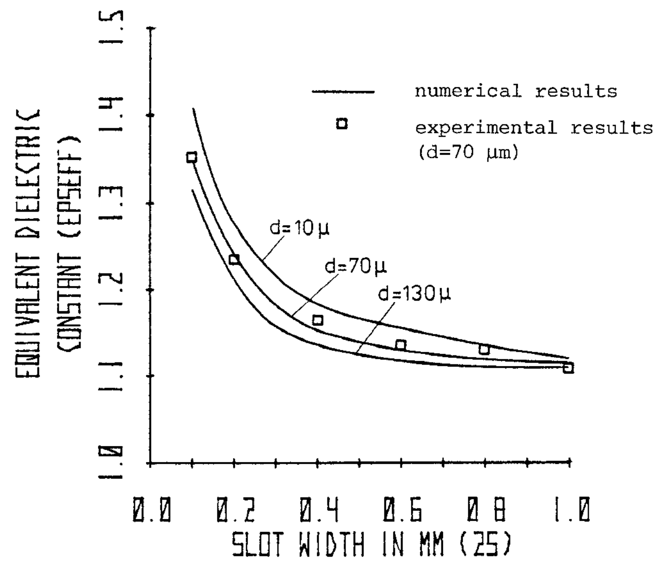

Fig.3: Equivalent dielectric constant ε_{eff} of unilateral fin lines versus the slot width 2s and with the metallization thickness d as a parameter. Cross section of employed fin line as given in Fig.2, with the metallization thickness $d=d_1+d_2$.

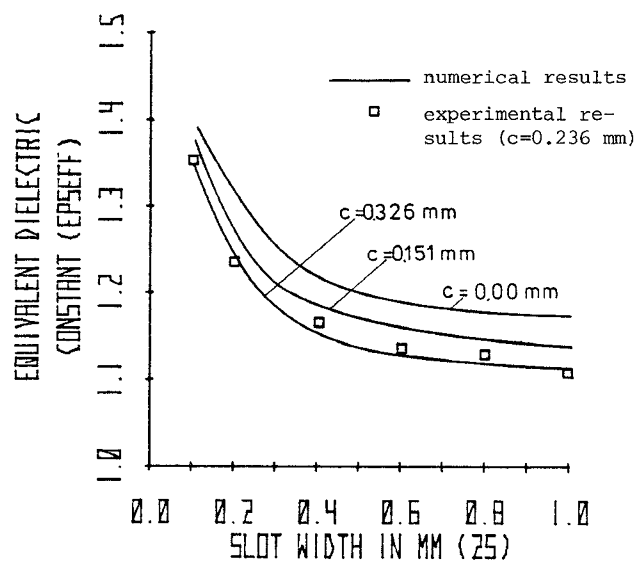

Fig.4: Equivalent dielectric constant ε_{eff} of unilateral fin lines versus the slot width 2s and with the height of the longitudinal slit c as a parameter. Cross section of employed fin line as given in Fig.2, with the metallization thickness d=70 µm.

where $\nu_n=\nu_l=1$ for n=l=0 and $\nu_n=\nu_l=2$ for n>0 and l>0 (Neumann's numbers). Substitutions of (4) and (5) into (1) gives

$$\sum_{n=0}^{\infty} \frac{\nu_n \cdot \tan\{k_{xn}^{(2)}(\frac{a}{2}-d_1)\}\cdot\cos\{k_{yn}^{(2)}(y-\frac{b'}{2})\}}{k_{xn}^{(2)} b'} \times$$

$$\int_{-b'/2}^{b'/2} E_y^{(2)}(\frac{a}{2}-d_1,y)\cos\{k_{yn}^{(2)}(y-\frac{b'}{2})\}\,dy =$$

$$\sum_{n=0}^{\infty} \frac{\nu_n \cdot \tan\{k_{xl}^{(3)}(\frac{a}{2}-d_1)\}\cdot\cos\{k_{yl}^{(3)}(y-s)\}}{2k_{xl}^{(3)} s} \times$$

$$\int_{-s}^{s} E_y^{(3)}(\frac{a}{2}-d_1,y)\cos\{k_{yl}^{(3)}(y-s)\}\,dy\,. \qquad (6)$$

This is an integral eigenvalue equation, which can be solved numerically.

Theoretical and Experimental Results

Equations (1) to (6) were applied to the geometry shown in Fig.2 (E-band fin line). The method in general converges very rapidly: In all the cases investigated a minimum number of only 10 modes in the slot (subregion (3)) and in the substrate (subregion (2)) is needed for a sufficient accuracy of the calculated eigenvalues.

The experimental verification of the theoretical results was restricted to the fundamental mode on the fin line. Measurements were made using a precision slot line and a movable short in the fin line section. The fin lines employed in the experiments were 24.2 mm long, which corresponds to more than 3 wavelengths at the lowest measuring frequency. The fin line substrate used in the experiments was Kapton foil (ε_r=3.0, w=0.05 mm) clad with rolled copper (d=70 μm).

The effective permittivity of the fin line was calculated from the measured operating frequency and wavelength using eq. (7)[3,4]

$$\lambda_g = \frac{\lambda_0}{\{\varepsilon_{eff} - (\frac{\lambda_0}{\lambda_c})^2\}^{1/2}} \qquad (7)$$

where λ_g is the wavelength on the fin line, λ_0 is the free-space wavelength and λ_c is the cutoff wavelength for an equivalent airfilled ridge-loaded waveguide.

The movable short employed in the measurements was especially designed for the purpose: It consists of a metallic conducting spring-contact which bridges the fins and which is moved along the fin line by a vernier mechanism. The resulting measurement accurary for the wavelength is ±0.5%.

In Fig.3 the measured and calculated effective dielectric constant ε_{eff} is plotted versus the slot width 2s, with the thickness of the metallization d as parameter. The value d=10 μm corresponds to lines using e.g. gold plated fins, d=70 μm corresponds to lines using e.g. commercially available copper clad substrate materials like RT/Duroid and d=130 μm corresponds to a fin line structure comparable to ordinary ridge waveguide. In this figure the effects due to the slit in the waveguide mount are included. The thickness of the dielectric substrate was w=0.05 mm.

In Fig.4 the measured and calculated effective dielectric constant ε_{eff} is plotted versus the slot width 2s, with the depth c of the longitudinal slit in the waveguide mount as parameter. The zero-depth curve corresponds to the idealized model for the fin line mount, while the realistic (experimental) case is calculated using a value of c=0.326 mm. In these curves the effect due to the finite metallization thickness (d=70 μm) is included. The agreement of the experimental and theoretical values basing on this realistic calculation model is very good. The results of the method presented will be compared with results known from other methods described in the literature. Especially the influence of the metallization thickness and the fin line mount on the dispersion characteristic of the equivalent dielectric constant will be discussed in comparison with other solutions.

Using the described method the electromagnetic fields of the fin line can be calculated in each subregion. From these fields the voltage over the slit and the total longitudinal current can be computed. These values will be used to define the characteristic impedance of the fin line in dependence on the geometrical dimensions and the dielectric constant of the substrate material. The dependences of the characteristic impedances on the geometrical and electrical parameters will be calculated and compared to the results of other publications.

References

1 Hoefer, W.J.R., Ros, A.: Fin Line Parameters Calculated with the TLM-Method. 1979 IEEE MTT-S Intern. Microwave Symposium Digest, Orlando, pp. 341-343.

2 Hofmann, H.: Dispersion of Planar Waveguides for Millimeter-Wave Application. Archiv für Elektronik und Übertragungstechnik, Vol. 31(1977), pp. 40-44.

3 Meier, P.J.: Equivalent Relative Permittivity and Unloaded Q Factor of Integrated Finline. Electronics Letters, Vol. 9(1973), pp. 162-163.

4 Meier, P.J.: Integrated Fin-Line Millimeter Components. IEEE Trans. MTT, Vol. MTT-22 (1974), pp. 1209-1216.

5 Montgomery, J.P.: On the Complete Eigenvalue Solution of Ridged Waveguide. IEEE Trans. MTT, Vol. MTT-19 (1971), pp. 547-555.

6 Saad, A.M.K. and Begeman, G.: Electrical Performance of Fin Lines of Various Configurations. IEE J. Microwaves, Opt., Acoust (MOA), Vol. 1 (1977), pp. 81-88.

7 Saad, A.M.K. and Schünemann, K.: A Simple Method for Analyzing Fin Line Structures. IEEE Trans. MTT, Vol. MTT-26 (1978), pp. 1002-1007.