Non-Uniform Finlines on Anisotropic Substrates

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Abstract

Serious errors occur in the analysis of quasi-planar circuits, particulary at millimeter wavelengths, if the anisotropy of the substrates is neglected. This paper addresses the problem of non-uniform finlines (tapered sections) on anisotropic substrates. A solution of the generalized telegraphist's equation is described which takes into account the second-order effects such as dielectric and magnetic losses, finite metallization thickness, and substrate mounting grooves. Numerical and experimental data are presented and compared.

1 Introduction

The importance of substrate anisotropy and its impact on integrated circuits performance have been vividly demonstrated in a survey paper by Alexopoulos [1]. Serious errors occur if the effect of anisotropy in seemingly isotropic substrates is neglected in the analysis of quasi-planar circuits, particulary at higher frequencies. On the other hand, the selection of monocrystalline, anisotropic substrate materials for millimeter-wave circuits provides important advantages such as exellent reproducibility, easy combination with semiconductors, and high electrical and mechanical quality. Furthermore, a number of nonreciprocal components can be realized on gyromagnetic substrates without the need of an additional dielectric layer.

Several techniques have been reported in the literature ([1], [2]) which are suitable for the modelling of uniform transmission lines on anisotropic substrates. However, no information is available on the design of non-uniform anisotropic structures which are vital for the realization of broad-band transitions to rectangular waveguides or other planar media. To date, only methods for the design of transitions on isotropic substrates have been reported [3],[5],[6],[7],[8].

2. Theoretical Background

In this paper we present a first successful analysis of finline tapers on anisotropic substrates, leading to a near-optimum design. Fig. 1 shows a typical finline taper profile. To study the propagation of waves in this structure, its longitudinal section is subdivided into three regions (1) to (3).

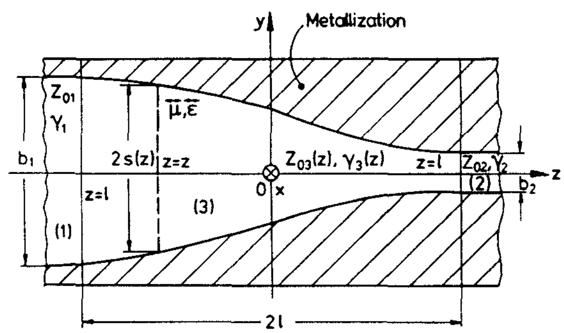

Fig. 1: Longitudinal section of a tapered unilateral finline on anisotropic substrate

The waves on the uniform sections (1) and (2) can be calculated e.g. with the method given in [2].

The field problem in the non-uniform section (3) can be solved with the generalized telegraphists's equations for waveguides of varying cross-section containing anisotropic media. Most of the technically interesting anisotropic substrates possess uniaxial properties. Thus, their dielectric behaviour can be described by a cross-tensor:

$$\overleftrightarrow{\varepsilon} = \varepsilon_0 \begin{bmatrix} \varepsilon_{xx} & 0 & \varepsilon_{xz} \\ 0 & \varepsilon_{yy} & 0 \\ \varepsilon_{zx} & 0 & \varepsilon_{zz} \end{bmatrix} . \quad (1)$$

If ferrite substrates are considered with a DC premagnetization field in the y-direction, the permeability tensor takes the form

$$\overleftrightarrow{\mu} = \mu_0 \begin{bmatrix} \mu_{xx} & 0 & \mu_{xz} \\ 0 & \mu_{yy} & 0 \\ \mu_{zx} & 0 & \mu_{zz} \end{bmatrix} . \quad (2)$$

In the following, it will be assumed that the electromagnetic properties of the substrate are described by the above mentioned cross-tensors (1) and (2), and that the conductivity of the substrate will be taken into account by complex elements of the permittivity tensor. In the same way dielectric and magnetic losses in the substrate can also be included in the form of complex values of μ and ε. Under these conditions the generalized telegraphists's equation become

$$-\frac{d U_m}{dz} = \gamma_m Z_m I_m - \sum_{n=0}^{\infty} (C_{mn} U_n - D_{mn} Z_n I_n) \quad (3)$$

and

$$-\frac{d I_m}{dz} = \frac{\gamma_m}{Z_m} U_m + \sum_{n=0}^{\infty} (A_{mn} U_n + B_{mn} Z_n I_n), \quad (4)$$

where U_m and I_m are the m-th modal voltage and current, respectively, Z_m is the modal characteristic impedance and γ_m is the modal propagation coefficient of the non-uniform finline. The coupling coefficients A_{mn} to D_{mn} are given by surface integrals of the associated orthogonal eigenfunctions of the structure, taken over the whole finline cross-section. All these values depend on the longitudinal coordinate z because of different cross-sections.

In the first approximation, that is the case of smooth tapers, the differential equations (3) and (4) lead to the Riccati type given by

$$\frac{d\Gamma_3(z)}{dz} - 2\,\Gamma_3(z)\,\gamma_3(z) + \left[1 - \Gamma_3^2(z)\right]\left\{\frac{1}{2}\,\frac{\ln Z_{03}(z)}{dz} - C_{11}\right\} = 0 \quad (5)$$

where $\Gamma_3(z)$ and $\gamma_3(z)$ are the voltage reflection coefficient and the propagation factor, respectively, and their solutions can be obtained as suggested in [3]. For this purpose, the contour-function f(z) needs to be defined as:

$$f(z) = \begin{cases} 0 & -\infty < z < -l \\ \frac{1}{2}\,\frac{\ln Z_{03}(z)}{dz} & -l < z < +l \\ 0 & +l < z < +\infty \end{cases} \quad (6)$$

The value of $Z_{03}(z)$ represents the characteristic impedance of the dominant mode in the inhomogeneous finline which is a function ofthe effective dielectric number ε_{eff}. This quantity is given by

$$\varepsilon_{eff} = \left(\frac{\beta}{\beta_0}\right)^2 \quad (7)$$

where β is the phase constant. While the characteristic impedance $Z_{03}(z)$ is for inhomogeneous finlines on anisotropic dielectric substrates at $z = z_0$ always unequivocal, for ferrite substrates it becomes ambigous, because of the nonreciprocal behaviour of the ferrite. Following, it will be expected that the tapers on ferrite substrates, in opposition to those on anisotropic dielectic substrates, possess nonreciprocal transmission characteristics.

The present method of solving for the Riccati's differential equation given by (5), is based on the knowlege of the effective dielectric number ε_{eff} as a function of the z-coordinate. The calculation of this quantity can be summed in few steps according to the method published in [2]:

1) Define the geometry of an arbitrary cross-section of the unilateral finline on an anisotropic substrate;
2) Express all fields in the subregions containing only one homogeneous medium;
3) Apply the continuity of fields at all interfaces between the chosen subregions;
4) Combine the sets of continuity equations and
5) Determine the system of eigen value equations;
6) The solution of this system leads to the phase constant, and this through Eqn. (7), to the effective dielectric number as requested.

This method is very advantageous and accurately, because it allows the consideration even of second-order effects like the metallization thickness, the influence of the substrate mounting grooves, dielectric and magnetic losses.

Next, the voltage reflection factor $\Gamma_3(z)$, the propagation factor $\gamma_3(z)$, as well as the contour-function f(z) will be expanded each into series according to [3]. All of these series are substituted into the Riccati's differential equation (5), and, using a suitable subdivision of the length of the taper section (Fig. 1) a system of Riccati's differential equations will be obtained. By help of an optimization criterion, the unknown coefficients of series mentioned above can be determined. Making use this method, the taper can be optimized as

1) A minimum length transition with a minimum return loss, that is, as a near optimum taper [5] with a given cutoff frequency, or as
2) A minimum length transition for a given frequency band, with a return loss which remains below a set limit.

3 Numerical and Experimental Results

a) Tapers on anisotropic dielectric substrates

As mentioned, the solution for the non-uniform taper on anisotropic substrate is derived from the solution of uniform anisotropic finline sections. Fig. 2 shows the effective dielectric constant ε_{eff} of some uniform finlines on anisotropic substrates as a function of the slot width 2s, calculated by help of the method summarized in part 2.

These results must be taken into account while solving the Riccati's differential equation (5) for non-uniform finlines on the same substrate. It can be realized that the values of the effective dielectric constant dependend on slot width and frequency, furthermore, this quantity is a function of the rotation angle between the crystal- and geometrical axes.

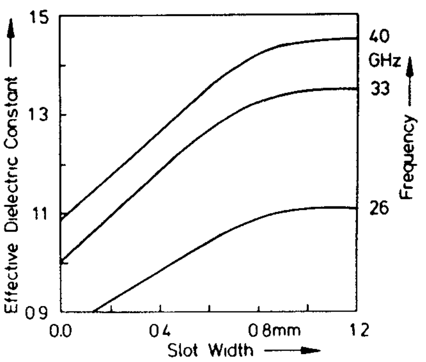

Fig. 2: Effective dielectric constant of an unilateral finline on anisotropic substrates for the Ka-band (a = 7.112 mm, b = 3.556 mm, height of substrates: 4.056 mm, thickness of the substrates: 250 μm, thickness of the metallization: 17.5 μm). The technical specifications of substrates are: PTFE cloth rotated by 30°: $\varepsilon_{xx} = \varepsilon_{zz} = 2.77$, $\varepsilon_{yy} = 2.88$, $\varepsilon_{xz} = \varepsilon_{zx} = -0.19$.

During subsequent numerical optimizations, several shapes of tapers have been analyzed. One of these tapers is the linear taper, which both numerical and technological is very simple to realize. The transmission properties of a circular arc taper seems to be better in comparison to those of linear taper. The contour-function of this kind of taper is realized by means of two circular arcs; it is not only continous but it is also continously differentiable [4]. The technological realization of this taper needs a plotter or cutting set up of low dynamic accuracy. Much better transmission properties can be reached by use of near optimum taper [5]. The taper design for the near optimum taper improves the properties of the optimum taper, which is also called as the Dolph-Chebyshev taper, in that manner that it takes into account the impedance steps at each ends of taper. It has the consequence that the appropriate near optimum taper will be a little bit longer.

The voltage reflection factor of a taper as function of its length is a ripple curve [5]. For instance, Fig. 3 shows this value of several tapers as a function of the length at a frequency of 33 GHz on a PTFE cloth substrate with the specifications given in Fig. 2.

From the results of Fig. 3 it is clearly recognized that the near optimum taper leads to the minimum length and it possesses a minimum value of the ripple function defined in [5]. This quantity delivers the maximum allowable voltage reflection factor; for example in the case of the near optimum taper it has a value of 0.2 at the frequency f = 33 GHz. On the other hand, the near optimum taper is most difficult to realize.

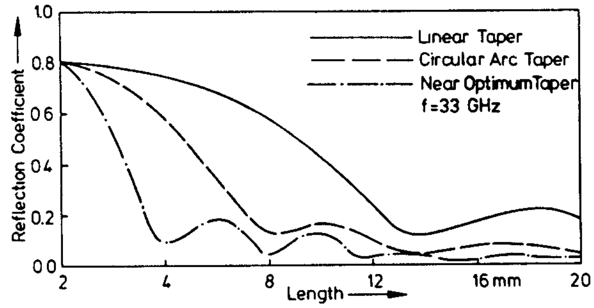

Fig. 3: The reflection coefficient of several tapers on anisotropic substrate (Technical specifications: see Fig. 2)

b) Tapers on ferrite substrates

For the investigation of tapers on ferrite substrates its electromagnetic properties must be taken into account. For instance, it is very important to know, which kind of electromagnetic modes will be excited, when the operating frequency and/or the strength of the DC magnetic field is changed. Fig. 4 shows the internal magnetic field strength as a function of the operating frequency for the ferrite material TT2-111/Trans. Tech., USA.

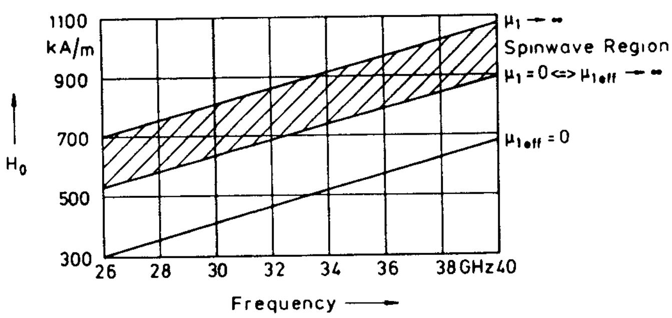

Fig. 4: Internal magnetic field strength versus frequency for constant values of μ_{1eff} and μ_1.

It is well known that isolators in the millimeterwave range require very high values of DC magnetic field. If the tapers in connection with an isolator arrangement should be used, spinwaves can be appeared in them. As Fig. 4 shows this is the case in the frequency band between 26 GHz to 30 GHz for an internal magnetic field strength of 700 kA/m.

For the orientation of the premagnetization DC field the y-direction has been chosen, so that for the permeability tensor of a saturated ferrite the Eqn. (2) is yielded. By help of this expression a premagnetized ferrite slab was investigated. Fig. 5 shows the voltage reflection factor versus the frequency with the following electrical and geometrical dimensions: waveguide: WR 28, thickness of the centered ferrite slab: 1 mm, length of the ferrite probe: 75 mm, strength of the DC magnetic field: 800 kA/m.

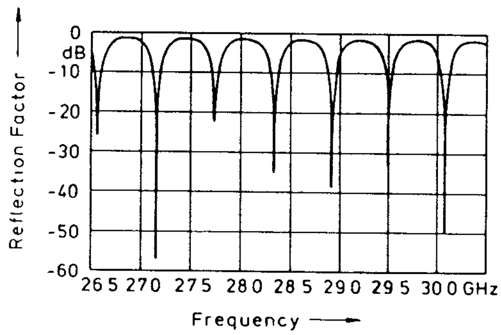

Fig. 5: Voltage reflection factor of ferrite substrate without metallization as a function of the frequency. (Material has been assumed to be lossless.)

It can be recognized that in this probe the portion of spinwaves is increased with increasing of the frequency.

A back-to-back-taper section on a ferrite material (TT2-111/ Trans. Tech., USA) has been calculated with this method, and measured. Fig. 6 shows the voltage reflection factors, which were obtained by help an automatic measurement set up.

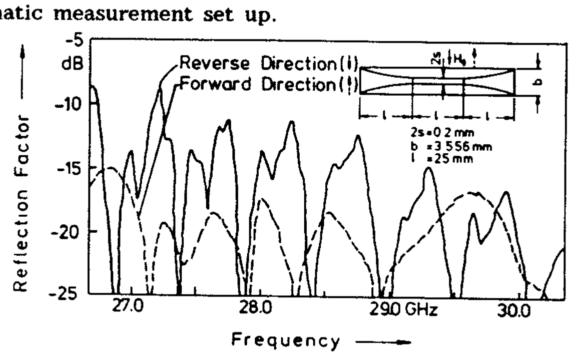

Fig. 6: The measured scattering parameters of a back-to-back-taper section as a function of the frequency.

Comparing Fig. 3 and Fig. 6 it can clearly be realized that tapers on ferrite substrates have significant non-reciprocal properties. Thus, it is hardly possible to reach the near optimum properties of a taper for both direction of wave propagation. Fig. 6 also shows that in the ferrite substrate at frequencies around 30 GHz spinwaves appear (s. results of Fig. 4). That means that the values of the voltage reflection factor are decreased. It should be noted, however, that the transmission properties of tapers on ferrite substrates can be improved by tapering each end of the ferrite [4],[8].

4. Summary

In summary, this paper extends theoretical results for uniform finlines on anisotropic substrates to tapered sections, thus paving the way for the design of optimal transitions to waveguides or other planar transmission media. Based on orthogonal series expansion, the method can include important second order effects such as finite metallization thickness, substrate mounting grooves, and dielectric losses. Numerical and experimental results show the applicability of the method presented here.

References

1 Alexopoulos, N. G.: Integrated-circuit structures on anisotropic substrates. IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-33, No. 10, pp. 847-881, October 1985.

2 Beyer, A. an Köther, D.: Analysis of the transmission properties of grounded finlines on anisotropic substrate. 1987 IEEE MTT-S International Microwave Symposium Digest (Las Vegas/USA), pp. 323-326.

3 Beyer, A.: Analysis of the transmission characteristics of inhomogeneous grounded finlines. IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-33, No. 2, pp. 145-149, February 1985.

4 Beyer, A. and Köther, D.: Design of circular arc finline tapers. International Journal of Infrared and Millimeter Waves, Volume 7, No. 10, pp. 1465-1481, October 1986.

5 Hecken, R., P.: A near-optimum taper matching section without discontinuities. IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-20, No. 11, pp. 734-739, November 1972.

6 Pramanick, P. and Bartia, P.: A generalized theory of tapered transmission line matching transformers and asymmetric 180° couplers supporting non-TEM modes. 1987 IEEE MTT-S International Microwave Symposium Digest (Las Vegas/USA), pp. 361-364.

7 Schieblich, Ch., Piotrowski, J. K. and Hinken, J. H.: Synthesis of optimum finline tapers using dispersion formulas for arbitrary slot widths and locations. IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-32, No. 12, pp. 1638-1645, December 1984.

8 Verver, C., J. and Hoefer, W. J. R.: Quarter-wave matching of waveguide-to-finline transitions. IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-32, No. 12, pp. 1645-1648, December 1984.