CIRCUIT MODEL OF COPLANAR-WAVEGUIDE (CPW) PHASE-SHIFTER ON GaAs SUBSTRATES

P. Cheung, M. S. Islam, D. P. Neikirk and T. Itoh.

Abstract

We present theoretical and experimental data in the frequency spectrum and doping concentration that show the variation of the effective index of refraction n_{eff} from a "slow wave" mode into the "lossy dielectric" mode for Coplanar-Waveguides (CPW) fabricated on GaAs substrates. We show that this variation can be modeled by an equivalent transmission line circuit model based on a quasi-static approach using two effective physical parameters (i) the thickness of the lossy layer and (ii) the conductivity.

Introduction

Coplanar-Waveguides (CPW) fabricated on semiconductor substrate have been shown to have three principle propagating modes, namely the "skin effect" mode, the "slow wave" mode, and the "lossy dielectric" mode [1]. A typical substrate consists of three layers, a top thin lossless layer, a thicker lossy layer followed by a third lossless layer. The principle mode in which the signal propagates, depends on the conductivity of the substrate, the thickness of the lossy layer and the frequency of operation.

At a fixed frequency, by changing the thickness of the lossy layer the principle propagating mode can be switched from one to another (i.e. from the "slow wave" mode to the "lossy dielectric" mode and vice versa). On the other hand, the operating point of the CPW can be moved from one mode to another by changing the conductivity of the lossy layer.

By changing the propagating mode in which the signal is propagating, the effective index of refraction (n_{eff}) can be changed. The ability to change n_{eff} has been utilized to build variable phase-shifters [2,3] and other related devices [4,5] that rely on a change of n_{eff} to vary the propagation constant of the device.

The variation of n_{eff} has been analysed using both a "full wave" type analysis [6,7] and transmission line equivalent circuit models [8,9] using the quasi-static approach to model the transmission line properties of CPW on a semiconductor. In this paper we show that an equivalent circuit transmsission line model derived from a first order quasi-static approximation can explain the variation of n_{eff} of a CPW on a lossy substrate using two effective physical parameters (i) the thickness of the lossy layer and (ii) the conductivity of the second lossy layer.

The authors are with the Department of Electrical and Computer Engineering, University of Texas at Austin, Austin, TX 78712, U. S. A..

Equivalent Circuit Model

The quasi-static approach was first demonstrated by Kwon et al [9], for the "slow wave" mode. To derive the equivalent circuit model, we consider the example of a parallel plate waveguide with a lossy layer sandwiched between two lossless layers, as given in Fig. 1. The equivalent circuit elements (assuming a quasi-TEM mode) are drawn for each of the layers. The admittance of the circuit is given by:

$$y_t = \frac{-j\omega^2 C_1C_2C_3R_2 + (-\omega C_1C_3)}{\omega(-C_1C_2R_2 - C_1C_3R_2 - C_2C_3R_2) + j(C_1 + C_3)}$$

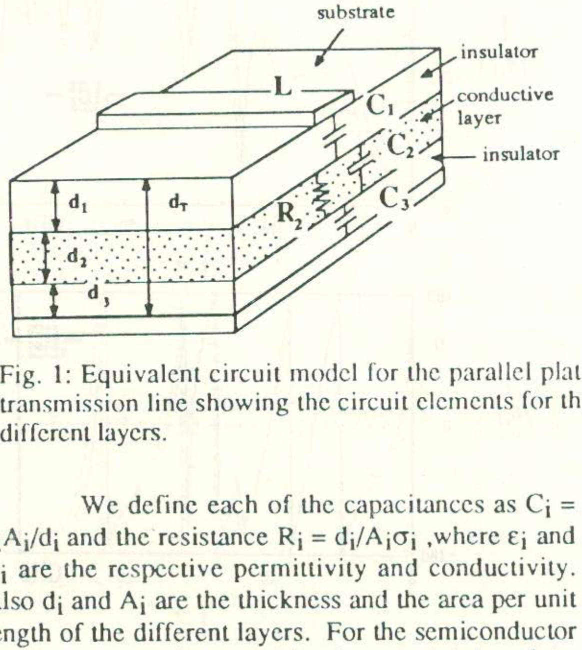

Fig. 1: Equivalent circuit model for the parallel plate transmission line showing the circuit elements for the different layers.

We define each of the capacitances as $C_i = \varepsilon_i A_i/d_i$ and the resistance $R_i = d_i/A_i\sigma_i$,where ε_i and σ_i are the respective permittivity and conductivity. Also d_i and A_i are the thickness and the area per unit length of the different layers. For the semiconductor substrate we are interested in, the permittivity of the different layers are approximately the same. Hence we can make the approximation $\varepsilon_1 \approx \varepsilon_2 \approx \varepsilon_3 = \varepsilon$. Also $A_1 = A_2 = A_3 = A$. Making these approximations for C_i and R_i and substituting expressions for C_i and R_i into y_t, we obtain:

$$y_t = \frac{\frac{\varepsilon\omega_o A}{d_t}\left(\frac{d_2}{d_t}\right) + j\left[1+\left(\frac{\omega_o}{\omega}\right)^2\left(1-\frac{d_2}{d_t}\right)\right]\frac{\varepsilon\omega A}{d_t}}{1+\left(\frac{\omega_o}{\omega}\right)^2\left(1-\frac{d_2}{d_t}\right)^2}$$

where ω_o is defined as σ/ε and $d_t = d_1 + d_2 + d_3$. The impedance of the metal conductors is $z_t = j\omega L$ where $L = 1/c^2 C_{air}$ where C_{air} is the capacitance of an equivalent parallel plate waveguide with air as the dielectric and c is the speed of light. We have excluded the resistance of the metal lines with the assumption that the resistance is small compared to the inductance. (Experimentally this is achieved by making the metal conductors thick to reduce the resistance.) The propagation constant γ is then given by:

$$\gamma = \sqrt{z_t y_t}$$

where y_t and z_t are given above. Expanding the above, we obtain for the phase constant β the expression:

$$\beta = \sqrt{\frac{(\omega L)\Bigg\{\left(\frac{\varepsilon\omega_o A}{d_t}\right)\left[1+\left(\frac{\omega_o}{\omega}\right)^2\right]+\left[1+\left(\frac{\omega}{\omega_o}\right)^2\right]\Bigg)\Bigg\}^{1/2}}{\left[1+\left(\frac{\omega_o}{\omega}\right)^2\left(1-\frac{d_2}{d_t}\right)^2\right]}}\ \sin\left(\frac{\theta}{2}+\frac{\pi}{4}\right)$$

where θ is define as:

$$\theta = \tan^{-1}\left[\frac{\omega}{\omega_o}\frac{d_t}{d_2}+\frac{\omega_o}{\omega}\left(\frac{d_t}{d_2}-1\right)\right]$$

Note that β is now a function of d_2/d_t, ω_o (which is dependent on σ) and the frequency ω. The effective index of refraction n_{eff} is calculated as:

$$n_{eff} = \frac{\beta_g}{\beta_o} = \frac{\lambda_o}{\lambda_g}$$

where $\beta_g = 2\pi/\lambda_g$ and $\beta_o = 2\pi/\lambda_o$. λ_g is the guide wavelength and λ_o is the free space wavelength. Although the circuit model is derived from a consideration of the parallel plate transmission line model, phenomenologically, the same equation applies to the CPW too. This is because the propagation constant is independent of the dimension of the guide and is dependent only on the "effective thickness" of the lossy layer (d_2) to the total thickness (d_t) of the substrate, as well as the "effective conductivity" (σ) of the lossy layer only. To determine how well phenomenologically the circuit model describes the n_{eff} for the CPW, we compare the n_{eff} calculated from the above model with the n_{eff} obtained from experimental values.

Experimental Results

A schematic of the device tested is given in Fig. 2. The CPW was fabricated by a lift-off technique using a cholorobenzene soak process. A metal scheme of chrome/silver/gold with a total thickness of approximately 1 µm was used for the metal conductors. The substrate is an MBE-grown epitaxial GaAs layer (2µm thick, p-type doped, $1\times10^{14}/cm^3$) on a SI GaAs substrate. The measurement of the device was carried out with two instruments, an HP4194 gain phase analyzer and an HP8510 network analyzer in conjunction with wafer probes made by Design Technique.

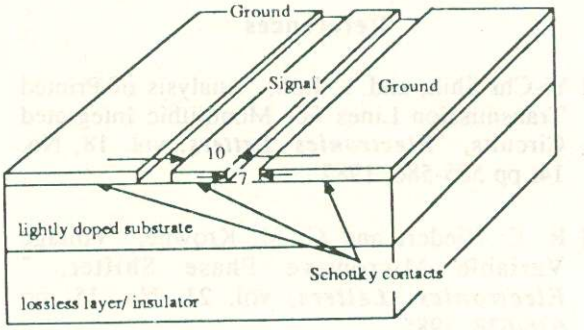

Fig. 2: Schematic of the CPW dimension and substrate. The central conductor width is 10µm while the gap width is 7µm.

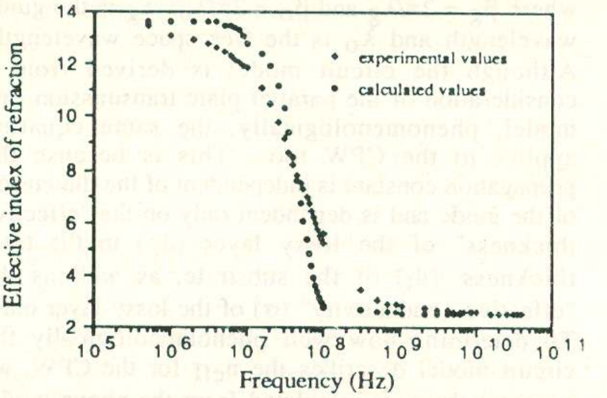

Fig. 3: n_{eff} values from the circuit model and measurements.

The measured and calculated results are given in Fig. 3. The measured data show that from 1MHz to about 100MHz, the n_{eff} is about 12, hence the signal is propagating in the "slow wave" mode. The transition to the "lossy dielectric" mode occurs about 100MHz and the n_{eff} drops rapidly to about 3. The calculated values of n_{eff} using the above model are also plotted in the same graph. The results show that the model has a good fit to the experimental data using just two effective physical parameters. To obtain the fit of this model, a ratio of 0.965 of the lossy layer to the total thickness of the substrate was required. At the same time an effective conductivity of only 0.001(ohm cm)$^{-1}$ was required.

Conclusion

We have presented an equivalent circuit model derived from a quasi-static TEM parallel plate transmission line. With two effective physical parameters , i.e the thickness of the lossy layer and its conductivity, the model showed a good correlation for the n_{eff} with experimental values measured for a prototype CPW phase-shifter. While the fit is not exact, the model shows well the overall trend of the variation of n_{eff} with frequency well. Using this model allows a simple evaluation of the CPW phase-shifter.

References

[1] Yi-Chi Shih, and T. Itoh, "Analysis of Printed Transmission Lines For Monolithic Integrated Circuits, "*Electronics Letters*, vol. 18, No. 14, pp 585-586, 1982.

[2] R. E. Niedert and C. M. Krowne, "Voltage Variable Microwave Phase Shifter, " *Electronics Letters*, vol. 21, No. 15, pp 636-638, 1985.

[3] V. M. Hietala,Y. R. Kwon, and K. S. Champlin, "Broadband Continuously Variable Microwave Phase-Shifter Employing A Distributed Schottky Contact on Silicon," *Electronics Letters*, vol. 23, No. 13, pp 675-677, 1987.

[4] P. L. Fleming, T. Smith, H. E. Carlson, and W. A. Cox, "GaAs SAMP Device for Ku-Band Switching," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, No.12, pp. 1032-1035, Dec. 1979.

[5] M. S. Islam, P. Cheung, C. Y. Chan, D. P. Neikirk, and T. Itoh, "Optically-Controlled Tunable CPW Resonators", to be presented at the 1990 *IEEE/MTT-S International Microwave Symposium*, Dallas, Texas, May 8-10, 1990.

[6] Y. Fukuoka, Yi-Chi Shih, and T. Itoh, "Analysis of Slow-Wave Coplanar Waveguide for Monolithic Integrated Circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, No.7, pp. 567-573, July 1983.

[7] M. Aubourg, J. P. Villotte, F. Godon, Y. Garault, P. Kennis, P. Prietich, C. Seguinot and Ph. Gelin, "Analysis of M.I.S. or Schottky Coplanar Lines using the F.E.M. and the S.D.A.," *IEEE MTT-S Int. Microwave Symp. Dig.* , Boston, pp. 396-398, June 1983.

[8] C. Seguinot, P. Kennis, and P. Pribetich, "Desktop Computer appraisal of potential slow-wave propagation characteristic for Schottky Coplanar lines," *Electron. Lett.*, vol. 19, no. 25, pp. 1065-1067, Dec. 1983.

[9] Y. R. Kwon, V. M. Hietala, and K. S. Champlin, " Quasi-TEM Analysis of "Slow-Wave" Mode Propagation on Coplanar Microstructure MIS Transmission LInes," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-36, pp. 545-551, June 1987.

Acknowledgments

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