Closed-form Dispersion Models of Slot-Line with Conductor Thickness

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Abstract **- The CAD oriented closed-form model is presented to compute frequency dependent effective relative permittivity and characteristic impedance of a slot-line with finite conductor thickness in the range $3\mu m - 50\mu m$. The dielectric loss and conductor loss for slot lines have been computed using the closed-form model. The results have been verified and are found to be in excellent agreement with the practical and theoretical data available in the literature.**

I. INTRODUCTION

The slot-line is a novel transmission line that may be used in association with, or as an alternative to microstrip. The applications of slot-line in microwave integrated circuits have been relatively limited. One of the main reasons might be the non-availability of closed-form expressions for the slot-line's effective relative permittivity and characteristic impedance including conductor thickness. Earlier the investigators had computed the frequency dependent effective relative permittivity $\varepsilon_{\text{reff}}(\text{f})$ and frequency dependent characteristic impedance $\text{Z}_0(\text{f})$ by the Spectral Domain Analysis (SDA) that also accounts the effect of finite conductor thickness on both parameters. However, the SDA is not suitable for the CAD purpose. No simple closed-form expressions are available to compute the losses of a slot-line. This communication suggests empirical models to account the effect of the conductor thickness on the $\varepsilon_{reff}(f)$ and $Z_0(f)$ and closed –form expressions for the computation of the dielectric loss and the conductor loss of the slot-line. The validity of the proposed models is tested in the frequency range 2GHz – 60GHz and conductor thickness $3\mu m - 50\mu m$. The results for losses have been verified in the frequency range 2GHz – 18GHz.

II. CONDUCTOR THICKNESS BASED EFFECTIVE RELATIVE PERMITTIVITY AND CHARACTERISTIC IMPEDANCE

Garg and Gupta [5] reported the closed-form model to compute the normalized frequency dependent guided wavelength (λ_g): $\lambda_g / \lambda_0 = 1/\sqrt{\varepsilon_{reff}(f)}$ and frequency dependent characteristic impedance ($Z_0(f)$) by curve- fitting the graphical data obtained from Mariani et al. [9] that is based on the equivalent waveguide model supporting the quasi - TE_{10} mode. These models works for $9.7 \le \varepsilon_r \le 20$, $0.02 \le w/h \le 1.0$, $0.01 \le h/\lambda_0 \le 0.25/\sqrt{(\varepsilon_r - 1)}$. Acclaimed average accuracy is 2% against the graphical results based on the equivalent waveguide model. Janaswamy and Schaubert [6] extended the model for $2.22 \le \varepsilon_r \le 9.8$, $0.0015 \le w/\lambda_0 \le 1.0$, $0.006 \le h/\lambda_0 \le 0.06$ by curve–fitting the SDA results. This model has also average accuracy of 2% and maximum error about 5%. These two models have been combined together as a single closed-form model for slot-line and thus covering the permittivity range $2.22 \le \varepsilon_r \le 20$.

The closed-form model for the effective relative permittivity of a slot-line with zero conductor thickness could be written in the parametric form,

$$\lambda_g / \lambda_0 = 1/\sqrt{\varepsilon_{reff}(f, t=0)} = f_1(\varepsilon_r, w/h, h/\lambda_0, t=0) \qquad (1)$$

The expressions for the function f_1 are obtained from [5, 6]. The effect of conductor thickness on $\varepsilon_{reff}(f,t)$ is accounted in model 1 given below, that was suggested for the microstrip line [10, 11]. However, for the slot-line case, it degrades at high frequency. We suggest the introduction of an empirical correction factor $(t/\lambda_0)^p$ in the model.

Model 1:
$$\varepsilon_{reff}(f,t) = \varepsilon_{reff}(f, t=0) - \left\{ \left(\frac{\varepsilon_r - 1}{4.6} \frac{t/h}{\sqrt{w/h}} \right) - \left(\frac{t}{\lambda_0} \right)^p \right\} \qquad (2a)$$

$$p = 0.0006 f^2 - 0.0369 f + 0.7714 \qquad (2b)$$

where, f is frequency in GHz; t, h, w, λ_0, λ_g, ε_r are conductor thickness, substrate thickness, slot-width, free-space wavelength, guided wavelength and relative permittivity of substrate respectively. The conductor thickness decreases the effective relative permittivity. Fig. 1(a) compares the model at frequency 2GHz and 10GHz for the slot-line on substrate having ε_r = 2.5, 9.8 and 20, $w/h = 0.5$ against the conductor thickness 0 - 90 μm. The model 1 has average deviation 2.16%. The maximum deviation in model occurs only at one frequency point. We note that original model itself has average error 2% and maximum error 5% against the SDA for the zero conductor thickness.

The dispersive characteristic impedance of a slot-line with zero conductor thickness can be computed from the closed-form model that can be expressed in the functional form as

$$Z_0(f, t=0) = f_2(\varepsilon_r, w/h, h/\lambda_0, t=0) \qquad (3)$$

The full expressions for the function f_2 can be obtained from [5, 6]. The strip conductor thickness t alters the slot-width. Thus, to account the effect of the conductor thickness t on the characteristic impedance, the physical slot-width w in above expression can be replaced by the equivalent slot-width: $w_{eq} = w - \Delta w$. The incremental slot-width Δw can be computed from the following expression, primarily used with microstrip line [12]

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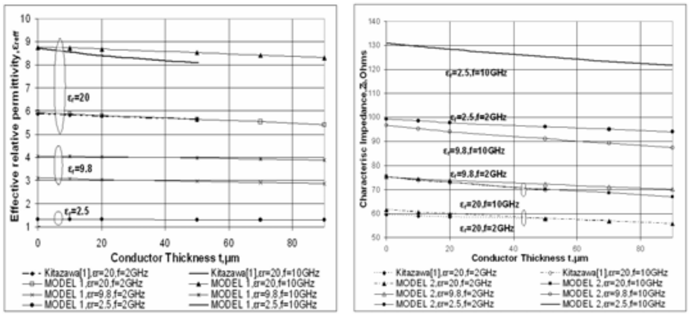
Model 2:
$$\Delta w = \frac{t}{\pi}\left[1 + \ln(4) - 0.5\ln\left(\left[\frac{t}{h}\right]^2 + \left[\frac{t}{\pi\, w}\right]^2\right)\right] \quad (4)$$



(a) (b)

Fig. 1: Comparison against SDA results [1] of ε_r=2.5, 9.8 and 20 for w/h=0.5 at f=2 and 10GHz for (a) Effective relative permittivity, and (b) Characteristic impedance.

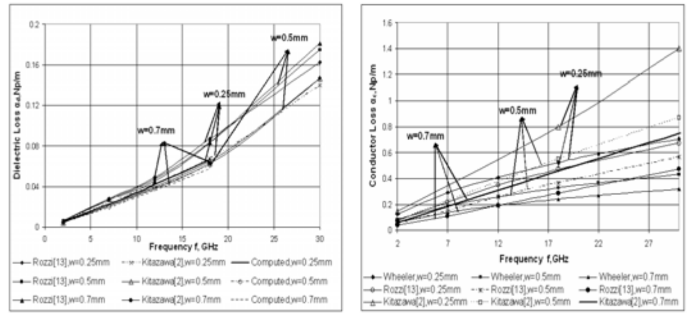
The characteristic impedance also decreases with increase in the conductor thickness. The computed characteristic impedance of slot-line using closed-form model 2 is compared against the SDA results in Fig. 1(b) at frequency 2GHz and 10GHz for the slot-line on substrate having $\varepsilon_r =$ 2.5, 9.8 and 20, $w/h = 0.5$ against the conductor thickness 0 - 90 μm. The maximum deviation of 10% occurs only at 2GHz where waveguide model based closed-form is not accurate due to the unrealistic cut-off behavior [4]. On average, the model 2 follows the SDA results within 2% deviation.

III. LOSSES

Fig. 2(a) and (b) show the dielectric losses and the conductor losses for slot line together with the published data [2], [13]. The dielectric losses α_d, results obtained are lesser than those in [13] but are in closer approximation with [2]. The Wheeler incremental inductance formulation has been used for computing the conductor losses in slot lines. It is seen that the conductor loss increases with frequency but decreases with conductor thickness. The conductor loss α_c, values are larger than those in [13] but are slightly comparable to those in [2]. The results have been verified against the SDA results in 2GHz – 18GHz for the conductor thickness 6μm, $\varepsilon_r = 9.8$, $h = 0.635mm$, $0.1 \le w/h \le 1.0$, $0.01 \le h/\lambda_0 \le 0.25/\sqrt{(\varepsilon_r - 1)}$.

IV. CONCLUSION

The closed-form dispersion models are presented to compute effective relative permittivity and characteristic impedance of a slot-line with finite conductor thickness. The models have average accuracy of about 2% against the SDA results in 2GHz–60GHz for the conductor thickness 3μm-50μm, $2.22 \le \varepsilon_r \le 20$, $0.02 \le w/h \le 1.0$, $0.01 \le h/\lambda_0 \le 0.25/\sqrt{(\varepsilon_r - 1)}$. The dielectric losses and conductor losses for slot lines have been computed using the closed- form models in 2GHz – 18GHz, which are in close agreement with the experimental results.



(a) (b)

Fig. 2: (a) Dielectric losses, and (b) Conductor losses of slot line for ε_r=9.8, t=6um, h=0.635mm compared against SDA results [2,13].

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