Short Papers

End Effect in a Shorted Slot

JEFFREY B. KNORR AND JUAN SAENZ

***Abstract*—An investigation of the end effect in a shorted-slot line is described. It is shown that the apparent position of the short is a small fraction of a wavelength beyond the end of the slot. The reactance seen at the end of the slot is, therefore, inductive. Experimental curves are presented which show normalized inductive reactance versus frequency for substrates with $\epsilon_r = 12$ and $\epsilon_r = 20$ for several slot widths.**

I. Introduction

Slot line is an open boundary structure which guides a wave having appreciable energy stored outside the region of the slot [1]. A proper short circuit for the slot field would consist of a conducting plane normal to the axis of the slot. In most cases, however, a slot line would be shorted by merely ending the slot or equivalently, filling the slot with a conducting surface lying in the plane of the slot rather than perpendicular to its axis. In such a case, current flows around the end of the slot and there is appreciable energy storage behind the termination. The situation is illustrated in Fig. 1. The net result is a predominance of stored magnetic energy, giving rise to an inductive reactance as seen at a reference plane normal to the slot axis and coincident with the end of the slot.

This effect was noted by Mariani and Agrios [2] during the construction of slot-line filters. No data concerning this effect were presented by them, however. It is the purpose of this short paper to present experimental data showing the nature of this effect.

II. Reactance of a Shorted Slot

In the experiments described here, the normalized inductive reactance of shorted slots was determined from VSWR measurements. The voltage nulls were located and reactance was computed from

$$x = -\tan 2\pi d/\lambda' \qquad (1)$$

where d is distance from the voltage null to the aforementioned reference plane (end of slot) and λ' is the slot wavelength.

The shorted slots were constructed on Custom Materials HiK-707 substrates with dielectric constants of $\epsilon_r = 12$ and $\epsilon_r = 20$. The metallization was the manufacturer's 1-oz copper. Measurement has shown that the slot wavelength obtained with this surface is close to the theoretical value [3]. The substrates were 0.121 and 0.125 in thick, respectively, exclusive of the copper surface. Measurements were recorded for three different slot widths with each of these substrates.

Figs. 2 and 3 show the experimental data points and curves of normalized (inductive) reactance versus thickness to wavelength ratio, D/λ. The reactance is seen to increase both with frequency and slot width.

Figs. 2 and 3 were next used to plot a family of curves giving reactance versus W/D with D/λ as a parameter. These curves were in turn used to generate curves giving reactance versus D/λ with the parameter W/D ranging in value from 0.2 to 1.0; Figs. 4 and 5 show the families of curves obtained by this procedure.

The end effect shown in Figs. 2–5 is seen to be significant. The electrical length of the shorted slots is up to 0.1 λ' greater than the physical length. In designing a resonant slot, for example, it would be important to compensate for this effect in order to realize the desired resonant frequency. A half-wavelength slot could require a length correction of up to 20 percent depending upon D/λ, W/D, and ϵ_r. Similarly, compensation is necessary in designing microstrip-slot transitions since the slot is terminated in a short circuit.

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The authors are with the Department of Electrical Engineering, Naval Postgraduate School, Monterey, Calif. 93940.

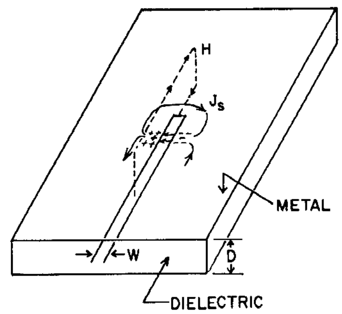

Fig. 1. Field and current distribution in the vicinity of a short circuit in slot line.

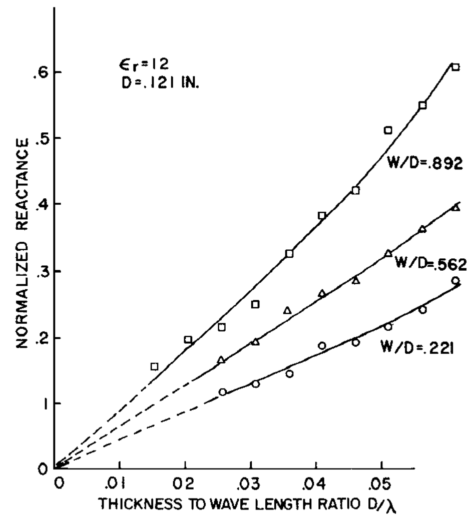

Fig. 2. Measured short-circuit reactance referred to a plane coincident with end of slot on a substrate with $\epsilon_r = 12$.

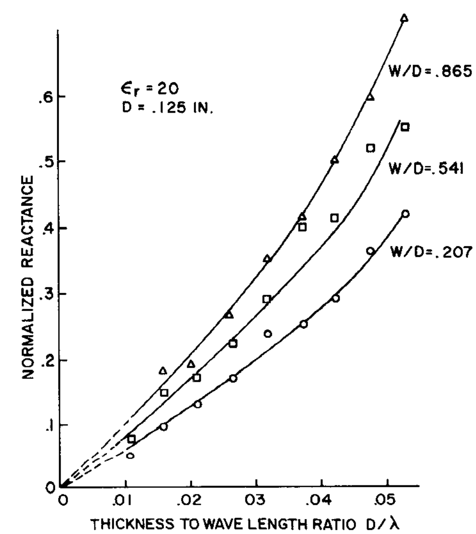

Fig. 3. Measured short-circuit reactance referred to a plane coincident with end of slot on a substrate with $\epsilon_r = 20$.

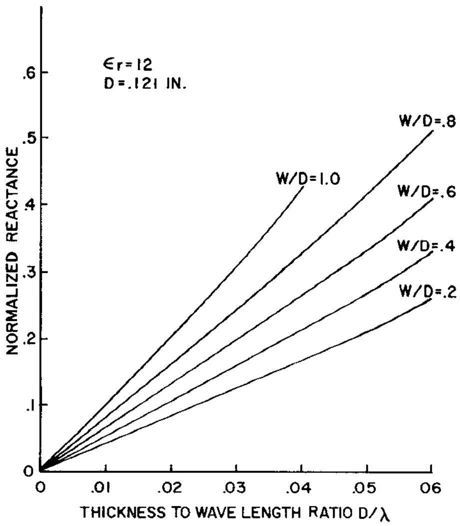

Fig. 4. A family of short-circuit-reactance curves derived from Fig. 2 for $\epsilon_r = 12$.

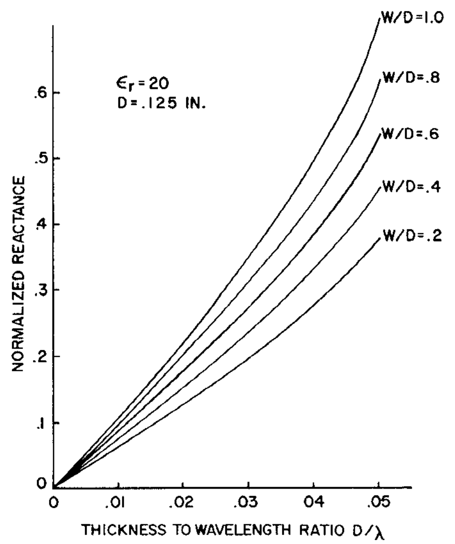

Fig. 5. A family of short-circuit-reactance curves derived from Fig. 3 for $\epsilon_r = 20$.

III. Conclusions

It has been shown that a significant end effect exists when a slot line is shorted. The apparent position of the short is located some distance beyond the end of the slot. At a reference plane coincident with the end of the slot the termination appears as an inductive reactance which increases with both W/D and D/λ. The effect is not linear.

Experimental data have been used to generate families of curves which should prove useful for design purposes until such time as theoretical results on this effect are available. They will also be useful as a basis for comparison when a theory is developed.

Acknowledgment

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Slot Line with Thick Metal Coating

T. KITAZAWA, Y. FUJIKI, Y. HAYASHI, AND M. SUZUKI

***Abstract*—Formulas and curves are given for the phase constant of slot line with metal-coating thickness greater than zero. Change in the phase constant is about a 1-percent decrease even though metal-coating thickness is 2 percent of the slot width.**

Slot line has been approximately analyzed by Cohn [1] and recently a rigorous solution was obtained by Itoh and Mittra [2]. These theories, however, neglect the effect of the metal-coating thickness. In this short paper we analyze slot line with metal-coating thickness greater than zero and evaluate this effect.

A cross section of slot line is shown in Fig. 1. In this short paper the network analytical methods of electromagnetic fields [3] are employed. First we express the transverse fields $\boldsymbol{E}_t$, $\boldsymbol{H}_t$ in the regions $z>t$, $t>z>0$, $0>z>-h$, and $-h>z$ by the following Fourier integral:

1) $z>t$, $0>z>-h$, and $-h>z$; $-\infty<x<\infty$

$$\left.\begin{matrix}\boldsymbol{E}_t\\ \boldsymbol{H}_t\end{matrix}\right\} = \frac{1}{\sqrt{2\pi}}\sum_{l=1}^{2}\int\int_{-\infty}^{\infty} e^{-j\beta y}\left\{\begin{matrix}V_l(\alpha,\beta;z)\boldsymbol{f}_l(\alpha,\beta;x)\\ I_l(\alpha,\beta;z)\boldsymbol{g}_l(\alpha,\beta;x)\end{matrix}\right\} d\alpha d\beta \quad (1)$$

where

$$\boldsymbol{f}_1 = \frac{j}{\sqrt{2\pi}K}(\boldsymbol{x}_0\alpha + \boldsymbol{y}_0\beta)e^{-j\alpha x}, \qquad \boldsymbol{g}_1 = \frac{-j}{\sqrt{2\pi}K}(\boldsymbol{x}_0\beta - \boldsymbol{y}_0\alpha)e^{-j\alpha x}$$

$$\boldsymbol{f}_2 = \frac{j}{\sqrt{2\pi}K}(\boldsymbol{x}_0\beta - \boldsymbol{y}_0\alpha)e^{-j\alpha x}, \qquad \boldsymbol{g}_2 = \frac{j}{\sqrt{2\pi}K}(\boldsymbol{x}_0\alpha + \boldsymbol{y}_0\beta)e^{-j\alpha x}$$

$$K = \sqrt{\alpha^2+\beta^2}. \quad (2)$$

2) $t>z>0$; $|x|\leq W/2$

$$\left.\begin{matrix}\boldsymbol{E}_t\\ \boldsymbol{H}_t\end{matrix}\right\} = \frac{1}{\sqrt{2\pi}}\sum_{l=1}^{2}\int_{-\infty}^{\infty}\sum_{n=0}^{\infty}\epsilon_l(n)e^{-j\beta y}\left\{\begin{matrix}V_l(\alpha_n,\beta;z)\boldsymbol{f}_l(\alpha_n,\beta;x)\\ I_l(\alpha_n,\beta;z)\boldsymbol{g}_l(\alpha_n,\beta;x)\end{matrix}\right\} d\beta \quad (3)$$

where

$$\epsilon_l(n) = \begin{cases} 0 & (n=0,\ l=1)\\ 1/\sqrt{2} & (n=0,\ l=2)\\ 1 & (n\neq 0)\end{cases}$$

$$\boldsymbol{f}_1 = \frac{-1}{K_n}\sqrt{\frac{2}{W}}(\boldsymbol{x}_0\alpha_n\cos(\alpha_n x) - \boldsymbol{y}_0 j\beta\sin(\alpha_n x))$$

$$\boldsymbol{g}_1 = \frac{-1}{K_n}\sqrt{\frac{2}{W}}(\boldsymbol{x}_0 j\beta\sin(\alpha_n x) + \boldsymbol{y}_0\alpha_n\cos(\alpha_n x))$$

$$\boldsymbol{f}_2 = \frac{1}{K_n}\sqrt{\frac{2}{W}}(\boldsymbol{x}_0 j\beta\cos(\alpha_n x) - \boldsymbol{y}_0\alpha_n\sin(\alpha_n x))$$

$$\boldsymbol{g}_2 = \frac{1}{K_n}\sqrt{\frac{2}{W}}(\boldsymbol{x}_0\alpha_n\sin(\alpha_n x) + \boldsymbol{y}_0 j\beta\cos(\alpha_n x))$$

$$\alpha_n = 2n\pi/W, \qquad K_n = \sqrt{\alpha_n^2+\beta^2}. \quad (4)$$

3) $t>z>0$; $|x|>W/2$

$$\boldsymbol{E}_t = 0, \qquad \boldsymbol{H}_t = 0 \quad (5)$$

where $\boldsymbol{x}_0$, $\boldsymbol{y}_0$, and $\boldsymbol{z}_0$ are unit vectors along the x, y, and z axis, respectively, and $l=1$ and $l=2$ represent E waves ($H_z=0$) and H waves ($E_z=0$), respectively. V_l and I_l are mode voltages and mode currents, and $\boldsymbol{f}_l$ and $\boldsymbol{g}_l$ are vector-mode functions which satisfy boundary conditions

$$E_y = 0, \quad \frac{\partial H_y}{\partial x} = 0 \qquad x = \pm\frac{W}{2}, \quad 0<z<t \quad (6)$$

and the following orthonormal properties:

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T. Kitazawa, Y. Fujiki, and M. Suzuki are with the Faculty of Engineering, Hokkaido University, Sapporo (060), Japan.

Y. Hayashi was with the Faculty of Engineering, Hokkaido University, Sapporo (060), Japan. He is now with the Kitami Institute of Technology, Kitami, Japan.