Coupled Slot Line Field Components

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Abstract —The paper presents expressions for the odd- and even-mode electric field components and the magnetic field components in the air and dielectric regions of the coupled slot line structure. These expressions are numerically computed and the fields in the cross section and the longitudinal section are illustrated.

I. Introduction

The SLOT LINE on a dielectric substrate [1] is a very useful transmission line for MIC applications [2]–[4]. Recently Cohn [5] has presented expressions for the electric field and the magnetic field components in the dielectric region and the air regions of a slot line.

In this paper, expressions for the odd- and even-mode electric field components and also the magnetic field components in the dielectric region and the air regions of the coupled slot line structure are presented. These expressions are numerically computed at various points in the dielectric region and the air regions of the structure. The odd- and even-mode electric field and also the magnetic field in the cross section, and the odd- and even-mode magnetic field in the longitudinal section through the slot, are illustrated.

II. Derivation of the Field Components

The coupled slot line on a dielectric substrate is illustrated in Fig. 1(a). For the case of odd excitation, a magnetic wall is placed at the $y=0$ plane; it then suffices to restrict the analysis to the right half of the structure. A similar simplification is possible for the case of even excitation except that the magnetic wall at the $y=0$ plane is replaced by an electric wall. As in the earlier analysis [6] the coupled slot-line problem is reduced to a rectangular waveguide problem by inserting electric walls in the planes perpendicular to the slot at $x=0$ and $x=a=\lambda'/2$ (λ' is the slot mode wavelength) and magnetic wall at $y=b$; and this is illustrated in Fig. 1(b) and (c).

On the air side of the slot ($z\leq 0$), the E_y and E_z components of the electric field and H_x, H_y, and H_z components of the magnetic field exist. From Maxwell's equations it follows that the E_x component of the electric field on the air side of the slot is zero. On the substrate side of the slot these plus E_x component of the electric field exist. The E_y component of the electric field and the H_x component of the magnetic field are determined as explained in an earlier analysis [6], while the rest of the electric field and the magnetic field components are determined by the application of Maxwell's equations. The detailed derivation of the field components is presented elsewhere [7].

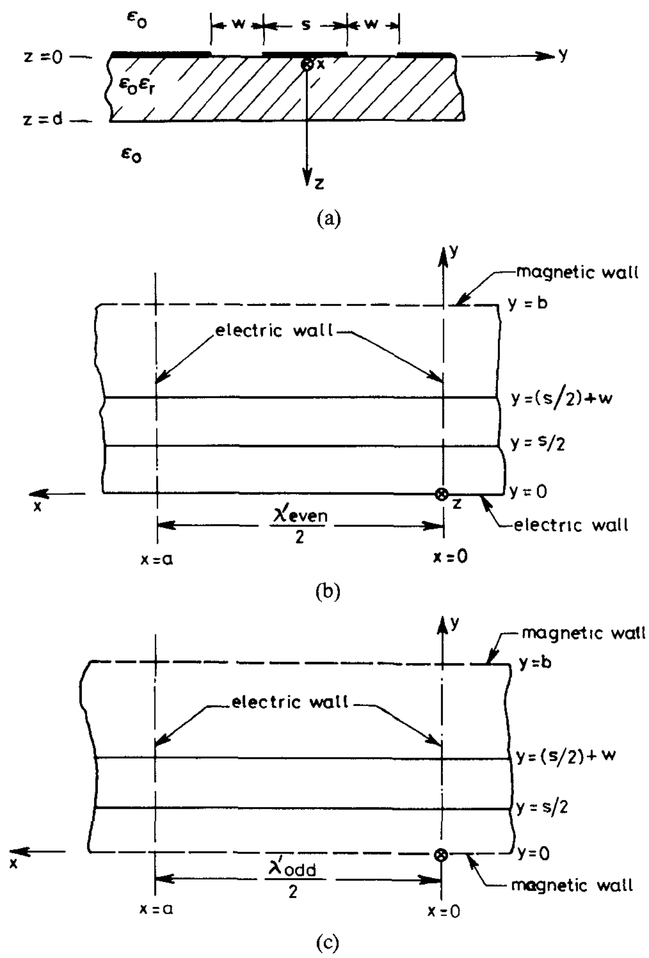

Fig. 1. (a) Schematic of the coupled slot line. Development of waveguide model for coupled slot line field components: (b) an electric wall is placed at the plane $y=0$ for the even mode of excitation; and (c) the electric wall is replaced by a magnetic wall for the odd mode of excitation.

The rectangular coordinates x, y, z, the slot width w, substrate thickness d, distance of separation between the slots s, and relative permittivity of the substrate material ϵ_r are indicated in Fig. 1(a). A factor $\exp j(\omega t - 2\pi x/\lambda')$ is assumed for each field component, implying wave propagation in the $+x$ direction only; V_0 is the voltage directly across the slot

$$V_0 = \int_{s/2}^{s/2+w} E_y\, dy. \tag{1}$$

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III. Odd-Mode Field Components

A. Air Side of the Slot $z \leqslant 0$

$$E_y = \frac{2V_0}{b} \sum_{n>0}^{\infty} \left[\frac{\sin n\pi\delta/2}{n\pi\delta/2} \sin n\pi\bar{\delta}/2 \right] \sin\frac{n\pi y}{b} e^{-\gamma_n |z|} \quad (2)$$

$$E_z = -\frac{2V_0}{b} \sum_{n>0}^{\infty} \frac{1}{F_n} \left[\frac{\sin n\pi\delta/2}{n\pi\delta/2} \sin n\pi\bar{\delta}/2 \right] \cdot \cos\frac{n\pi y}{b} e^{-\gamma_n |z|} \quad (3)$$

$$H_x = -j\frac{2V_0}{\eta b}\left(\frac{\lambda}{\lambda'}\right)^2 \frac{2b}{\lambda} \sum_{n>0}^{\infty} \frac{1-(\lambda'/\lambda)^2}{nF_n} \cdot \left[\frac{\sin n\pi\delta/2}{n\pi\delta/2} \sin n\pi\bar{\delta}/2 \right] \sin\frac{n\pi y}{b} e^{-\gamma_n |z|} \quad (4)$$

$$H_y = \frac{2V_0}{\eta b}\frac{\lambda}{\lambda'} \sum_{n>0}^{\infty} \frac{1}{F_n} \left[\frac{\sin n\pi\delta/2}{n\pi\delta/2} \sin n\pi\bar{\delta}/2 \right] \cdot \cos\frac{n\pi y}{b} e^{-\gamma_n |z|} \quad (5)$$

$$H_z = \frac{2V_0}{\eta b}\frac{\lambda}{\lambda'} \sum_{n>0}^{\infty} \left[\frac{\sin n\pi\delta/2}{n\pi\delta/2} \sin n\pi\bar{\delta}/2 \right] \sin\frac{n\pi y}{b} e^{-\gamma_n |z|}. \quad (6)$$

B. Substrate Side of the Slot $0 \leqslant z \leqslant d$

$$E_x = j\frac{2V_0}{\lambda'} \sum_{n>0}^{\infty} \frac{2}{n\left[1+(2b/n\lambda')^2\right]} \left[\frac{\sin n\pi\delta/2}{n\pi\delta/2} \sin n\pi\bar{\delta}/2 \right] \cdot \left\{ \cos\frac{n\pi y}{b} [\coth q_n - \tanh r_n] \sinh \gamma_{n1} z \right\} \quad (7)$$

$$E_y = \frac{2V_0}{b} \sum_{n>0}^{\infty} \left[\frac{\sin n\pi\delta/2}{n\pi\delta/2} \sin n\pi\bar{\delta}/2 \right] \sin\frac{n\pi y}{b} \cdot \left\{ \cosh \gamma_{n1} z - \left[\frac{\tanh r_n + (2b/n\lambda')^2 \coth q_n}{1+(2b/n\lambda')^2} \right] \sinh \gamma_{n1} z \right\} \quad (8)$$

$$E_z = -\frac{2V_0}{b} \sum_{n>0}^{\infty} \frac{1}{F_{n1}} \left[\frac{\sin n\pi\delta/2}{n\pi\delta/2} \sin n\pi\bar{\delta}/2 \right] \cos\frac{n\pi y}{b} \cdot \{\sinh \gamma_{n1} z - \tanh r_n \cosh \gamma_{n1} z\} \quad (9)$$

$$H_x = j\frac{2V_0}{b\eta}\left(\frac{\lambda}{\lambda'}\right)^2 \frac{2b}{\lambda} \sum_{n>0}^{\infty} \frac{1}{nF_{n1}} \cdot \left[\frac{\sin n\pi\delta/2}{n\pi\delta/2} \sin n\pi\bar{\delta}/2 \right] \cdot \sin\frac{n\pi y}{b} \left\{ \left[\frac{F_{n1}^2 \coth q_n - \epsilon_r(\lambda'/\lambda)\tanh r_n}{1+(2b/n\lambda')^2} \right] \cosh \gamma_{n1} z - \left[1-\epsilon_r(\lambda'/\lambda)^2\right] \sinh \gamma_{n1} z \right\} \quad (10)$$

$$H_y = -\frac{2V_0}{\eta b}\frac{\lambda}{\lambda'} \sum_{n>0}^{\infty} \frac{1}{F_{n1}} \left[\frac{\sin n\pi\delta/2}{n\pi\delta/2} \sin n\pi\bar{\delta}/2 \right] \cos\frac{n\pi y}{b} \cdot \left\{ \left[\frac{F_{n1}^2 \coth q_n + \epsilon_r(2b/n\lambda)^2 \tanh r_n}{1+(2b/n\lambda')^2} \right] \cdot \cosh \gamma_{n1} z - \sinh \gamma_{n1} z \right\} \quad (11)$$

$$H_z = \frac{2V_0}{\eta b}\frac{\lambda}{\lambda'} \sum_{n>0}^{\infty} \left[\frac{\sin n\pi\delta/2}{n\pi\delta/2} \sin n\pi\bar{\delta}/2 \right] \sin\frac{n\pi y}{b} \cdot [\cosh \gamma_{n1} z - \coth q_n \sinh \gamma_{n1} z]. \quad (12)$$

C. Substrate Side of the Slot $z \geqslant d$

The expressions for the field components on the substrate side of the slot $z \geqslant d$, are derived from (7)–(12) by replacing $\gamma_{n1} z$ by $\gamma_{n1} d$. Further, the equations are multiplied by the factor $\exp[-\gamma_n(z-d)]$ indicating that the fields decay exponentially. Symbols not defined above are $\eta = 376.7\ \Omega$, $\delta = w/b$, $\bar{\delta} = (s+w)/b$, and

$$F_n = \frac{b\gamma_n}{n\pi} = \sqrt{1+\left(\frac{2bv}{n\lambda}\right)^2} \quad (13)$$

$$F_{n1} = \frac{b\gamma_{n1}}{n\pi} = \sqrt{1-\left(\frac{2bu}{n\lambda}\right)^2} \quad (14)$$

$$v = \sqrt{(\lambda/\lambda')^2 - 1} \qquad u = \sqrt{\epsilon_r - (\lambda/\lambda')^2} \quad (15)$$

$$r_n = \gamma_{n1} d + \tanh^{-1}\left(\frac{F_{n1}}{\epsilon_r F_n}\right) \quad (16)$$

$$q_n = \gamma_{n1} d + \coth^{-1}\left(\frac{F_n}{F_{n1}}\right). \quad (17)$$

IV. Even-Mode Field Components

A. Air Side of the Slot $z \leqslant 0$

$$E_y = \frac{2V_0}{b} \sum_{n\geqslant 0}^{\infty} \left[\frac{\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}\right]}{\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}} \cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi\bar{\delta}}{2}\right] \right] \cdot \cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi y}{b}\right] e^{-\gamma_n |z|} \quad (18)$$

$$E_z = \frac{2V_0}{b} \sum_{n\geqslant 0}^{\infty} \frac{1}{F_n} \left[\frac{\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}\right]}{\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}} \cdot \cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi\bar{\delta}}{2}\right] \right] \cdot \sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi y}{b}\right] e^{-\gamma_n |z|} \quad (19)$$

$$H_x = -j\frac{2V_0}{\eta b}\left(\frac{\lambda}{\lambda'}\right)^2\frac{2b}{\lambda}\sum_{n\geqslant 0}^{\infty}\frac{1-(\lambda'/\lambda)^2}{\left(\frac{2n+1}{2}\right)F_n}\left[\frac{\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}\right]}{\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}}\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi\bar{\delta}}{2}\right]\right]\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi y}{b}\right]e^{-\gamma_n|z|} \tag{20}$$

$$H_y = -\frac{2V_0}{\eta b}\frac{\lambda}{\lambda'}\sum_{n\geqslant 0}^{\infty}\frac{1}{F_n}\left[\frac{\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}\right]}{\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}}\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi\bar{\delta}}{2}\right]\right]\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi y}{b}\right]e^{-\gamma_n|z|} \tag{21}$$

$$H_z = \frac{2V_0}{\eta b}\frac{\lambda}{\lambda'}\sum_{n\geqslant 0}^{\infty}\left[\frac{\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}\right]}{\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}}\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi\bar{\delta}}{2}\right]\right]\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi y}{b}\right]e^{-\gamma_n|z|} \tag{22}$$

B. Substrate Side of the Slot $0 \leqslant z \leqslant d$

$$E_x = -j\frac{2V_0}{\lambda'}\sum_{n\geqslant 0}^{\infty}\frac{1}{\left(\frac{2n+1}{2}\right)\left[1+\left\{\frac{2b}{\left(\frac{2n+1}{2}\right)\lambda'}\right\}^2\right]}\left\{\left[\frac{\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}\right]}{\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}}\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi\bar{\delta}}{2}\right]\right]\right.$$
$$\left.\cdot\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi y}{b}\right][\coth q_n - \tanh r_n]\sinh\gamma_{n1}z\right\} \tag{23}$$

$$E_y = \frac{2V_0}{b}\sum_{n\geqslant 0}^{\infty}\left[\frac{\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}\right]}{\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}}\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi\bar{\delta}}{2}\right]\right]$$
$$\cdot\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi y}{b}\right]\left\{\cosh\gamma_{n1}z - \left[\frac{\tanh r_n + \left[2b/\left(\frac{2n+1}{2}\right)\lambda'\right]^2\coth q_n}{1+\left[2b/\left(\frac{2n+1}{2}\right)\lambda'\right]^2}\right]\sinh\gamma_{n1}z\right\} \tag{24}$$

$$E_z = \frac{2V_0}{b}\sum_{n\geqslant 0}^{\infty}\frac{1}{F_n}\left[\frac{\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}\right]}{\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}}\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi\bar{\delta}}{2}\right]\right]\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi y}{b}\right]\{\sinh\gamma_{n1}z - \tanh r_n\cosh\gamma_{n1}z\} \tag{25}$$

$$H_x = j\frac{2V_0}{\eta b}\left(\frac{\lambda}{\lambda'}\right)^2\frac{2b}{\lambda}\sum_{n\geqslant 0}^{\infty}\frac{1}{\left(\frac{2n+1}{2}\right)F_{n1}}\left[\frac{\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}\right]}{\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}}\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi\bar{\delta}}{2}\right]\right]$$
$$\cdot\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi y}{b}\right]\left\{\left[\frac{F_{n1}^2\coth q_n - \epsilon_r(\lambda'/\lambda)^2\tanh r_n}{1+\left[2b\Big/\left(\frac{2n+1}{2}\right)\lambda'\right]^2}\right]\cosh\gamma_{n1}z - \left[1-\epsilon_r(\lambda'/\lambda)^2\right]\sinh\gamma_{n1}z\right\} \tag{26}$$

$$H_y = \frac{2V_0}{\eta b}\frac{\lambda}{\lambda'}\sum_{n\geq 0}^{\infty}\frac{1}{F_{n1}}$$
$$\cdot\left[\frac{\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}\right]}{\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}}\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi\bar{\delta}}{2}\right]\right]$$
$$\cdot\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi y}{b}\right]$$
$$\cdot\left\{\left[\frac{F_{n1}^2\coth q_n + \epsilon_r\left[2b\Big/\left(\frac{2n+1}{2}\right)\lambda\right]^2\tanh r_n}{1+\left[2b\Big/\left(\frac{2n+1}{2}\right)\lambda'\right]^2}\right]\cdot\cosh\gamma_{n1}z - \sinh\gamma_{n1}z\right\} \quad (27)$$

$$H_z = \frac{2V_0}{\eta b}\frac{\lambda}{\lambda'}\sum_{n\geq 0}^{\infty}\left[\frac{\sin\left[\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}\right]}{\left(\frac{2n+1}{2}\right)\frac{\pi\delta}{2}}\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi\bar{\delta}}{2}\right]\right]$$
$$\cdot\cos\left[\left(\frac{2n+1}{2}\right)\frac{\pi y}{b}\right]\left[\cosh\gamma_{n1}z - \coth q_n \sinh\gamma_{n1}z\right]. \quad (28)$$

C. Substrate Side of the Slot $z \geq d$

The expressions for the field components on the substrate side of the slot $z \geq d$ are derived from (23)–(28) by replacing $\gamma_{n1}z$ by $\gamma_{n1}d$ and multiplying by the factor $\exp[-\gamma_n(z-d)]$. Symbols not defined above are

$$F_n = \frac{b\gamma_n}{\left(\frac{2n+1}{2}\right)\pi} = \sqrt{1+\left(\frac{2bv}{\left(\frac{2n+1}{2}\right)\lambda}\right)^2} \quad (29)$$

$$F_{n1} = \frac{b\gamma_{n1}}{\left(\frac{2n+1}{2}\right)\pi} = \sqrt{1-\left(\frac{2bu}{\left(\frac{2n+1}{2}\right)\lambda}\right)^2}. \quad (30)$$

V. Numerical Results

Figs. 2 and 3 illustrate the computed electric field and the magnetic field, respectively, in the cross section of the coupled slot line structure for the odd-mode of excitation. The relative permittivity ϵ_r is taken as 16, $d/\lambda = 0.07$, $s/d = 1$, $w/d = 0.4$, frequency equal to 3 GHz and $b \to \infty$. Since the expressions involve summing an infinite series, the following criterion for terminating the series at n_t is adopted: $n_t = n_0/(1+z/z_1)$, where n_0 and z_1 are constants. In the above case $n_0 = 1000$ and $z_1 = 0.005$ in is found suitable. Hence 1000 terms are used at $z = 0$, and 10 terms at $z = 0.5$ in. It is observed that the electric field lines extend across the slot while the magnetic field lines are perpendicular to the air–dielectric interface in the slot. The electric and magnetic field in the right half of the structure are in a direction opposite to the electric and magnetic field in the left half of the structure. Furthermore, part of the magnetic field lines encircle the center conducting strip separating the two slots. At this instance it may be pointed out that the coupled slot line structure for the odd-mode of excitation reduces to a coplanar waveguide (CPW) [8]. Hence it should be possible to realize coplanar waveguide circulators whose function is dominated by the transverse magnetic field component [9]. The longitudinal view in Fig. 4 shows that in the air regions the magnetic field lines curve and return to the slot at half-wavelength intervals. Consequently, a wave propagating along the structure has an elliptically polarized magnetic field. Hence it should be possible to successfully exploit the elliptically polarized magnetic field in the design of coplanar waveguide reso-

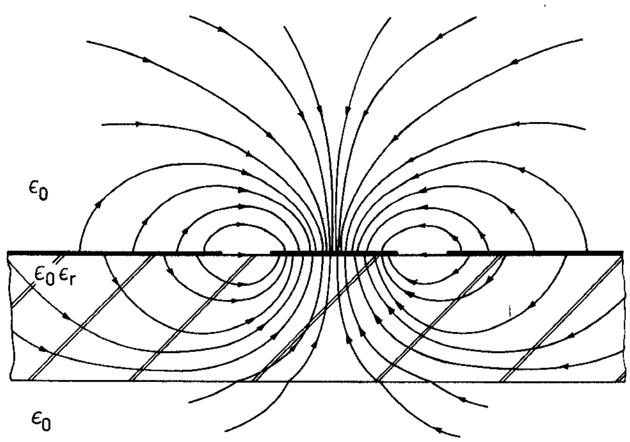

Fig. 2. Electric field distribution in the cross section ($x = 0$ plane) for the odd mode.

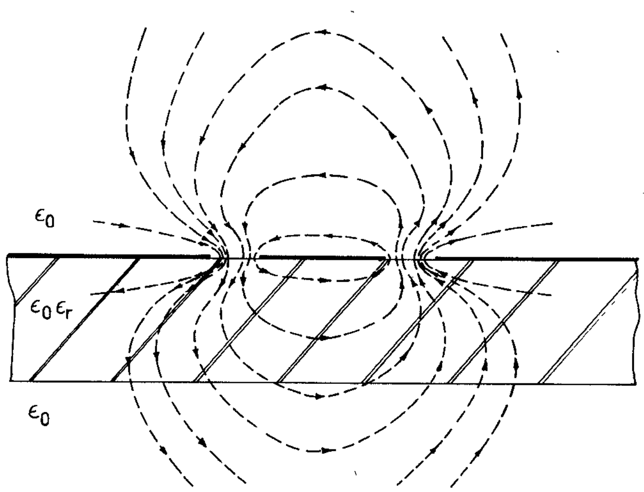

Fig. 3. Magnetic field distribution in the cross section ($x = 0$ plane) for the odd mode.

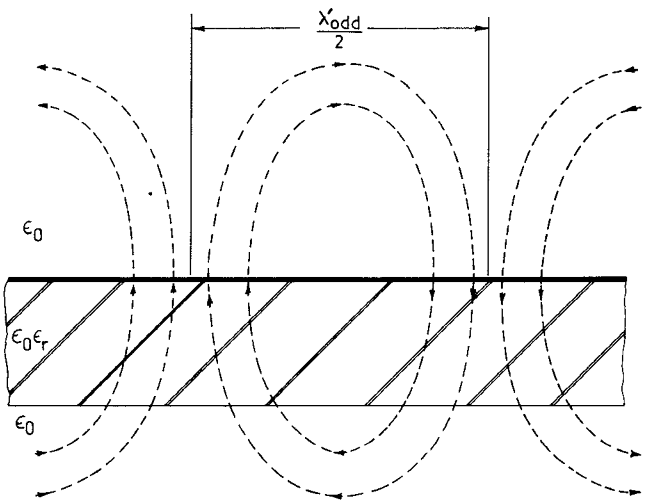

Fig. 4. Magnetic field in the longitudinal section ($y=(s/2+w/2)$ plane) through the slot for the odd mode.

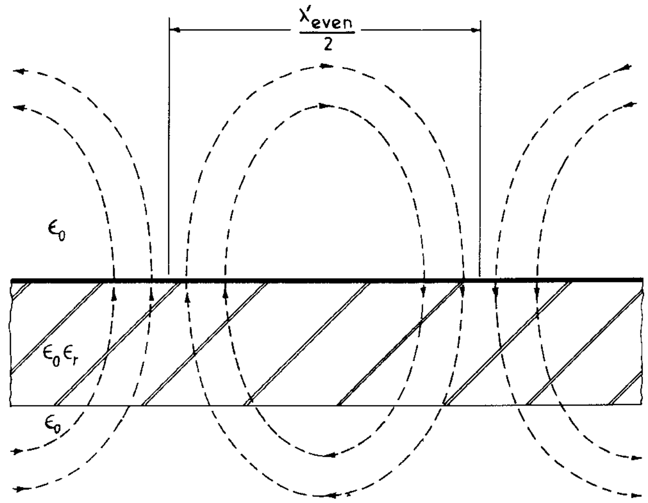

Fig. 7. Magnetic field in the longitudinal-section ($y=(s/2+w/2)$ plane) through the slot for the even mode.

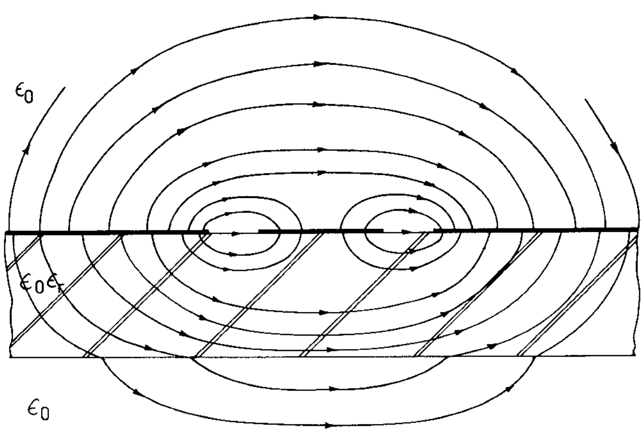

Fig. 5. Electric field distribution in the cross section ($x=0$ plane) for the even mode.

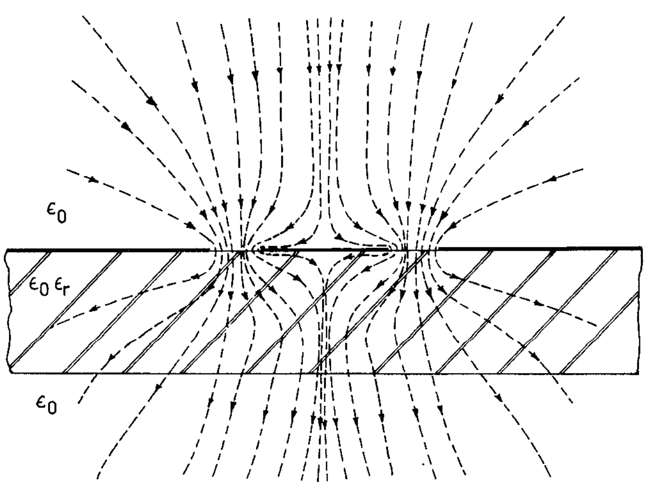

Fig. 6. Magnetic field distribution in the cross section ($x=0$ plane) for the even mode.

nance isolators and differential phase shifters [8]. A knowledge of the field components should also prove useful in the design of mode launchers, such as, between slot line and coplanar waveguide and, between coplanar waveguide and microstrip line [4].

Figs. 5 and 6 illustrate the computed electric field and magnetic field, respectively, in the cross section, for the even-mode of excitation. It is observed that the electric field lines extend across the slot while the magnetic field lines are perpendicular to the air–dielectric interface in the slot. The electric and the magnetic field in the right half of the structure are in the same direction as the electric and the magnetic field in the left half of the structure. Furthermore, the magnetic field lines are almost plane at the center of the slots and warp into a curved surface at the edges of the conductors. It is interesting to note that for small values of the slot separation, the metal strip separating the slots has negligible effect on the propagating wave and, the wave propagates as if it were in a slot line of width $(2w+s)$ [10]. By gradually increasing the distance of separation between the slots the two waves are decoupled and in the limit $s\to\infty$ they propagate as two independent waves in a slot line of width w. The longitudinal view in Fig. 7 shows that in the air regions the magnetic field lines curve and return to the slot at half-wavelength intervals. Consequently, a wave propagating along the slot line has an elliptically polarized magnetic field. Hence, it should be possible to successfully design planar ferrite phase shifters [2].

VI. Conclusion

The paper presents expressions for the odd- and even-mode electric field components and the magnetic field components in the air and dielectric regions of the coupled slot line structure. These expressions are numerically computed and the fields in the cross section and the longitudinal-section are illustrated. In the cross section the electric field extends across the slot while the magnetic field is perpendicular to the air–dielectric interface in the slot. In the longitudinal section through the slot, the magnetic field is elliptically polarized.

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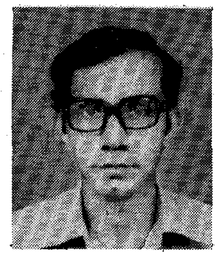

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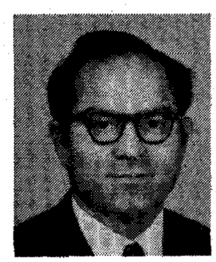

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