Variational Solutions on Two Opposite Narrow Resonant Strips in Waveguide

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Abstract —**A variational analysis with experimental verification is made to calculate the discontinuities due to the two opposite narrow resonant strips in waveguide. The current ratio between the strips is determined and the mutual interactions are calculated. The analysis gives a closed-form solution which is quite general and which can be used to illustrate several special cases.**

I. Introduction

THIS PAPER reports an analysis of two narrow, transverse, resonant strips located at the opposite sides of a rectangular waveguide. The variational method is used to determine the current ratio between the strips. The current distribution is then used for impedance calculation. The mutual coupling between the strips can be obtained from the total impedance.

Various strips in rectangular waveguide have been analyzed in the past. These include a single inductive strip [1], a single capacitive strip [2], [3], two inductive strips [4]–[7], and three strips [8]–[10]. The results for strips can be applied to round posts by using a post-diameter-to-strip-width equivalence factor [11], [12] and the effect of phase variation of the field across the post [13], [14].

This paper reports an analysis on two resonant strips located at the opposite sides of the waveguide transverse plane, as shown in Fig. 1. The two strips can be unsymmetrically located and there is no restriction on gap size. The strips can have different widths. The analysis gives a closed-form solution which is quite general, and several special cases can be derived. Two special cases of this structure, shown in Fig. 2, are of significant practical interest, and have not been analyzed previously. The case shown in Fig. 2(a) consists of an inductive strip and a capacitive strip. The other case is a single strip with a gap, as shown in Fig. 2(b). These two cases will be discussed in detail. Other special cases are also mentioned briefly.

These circuits should have many applications in the design of compact waveguide filters and matching networks, in the determination of diode mounting circuits, and in the study of multidiode circuits. The resulting current distribution and mutual coupling effects between the strips provide some physical insight into the multiple-strip interactions.

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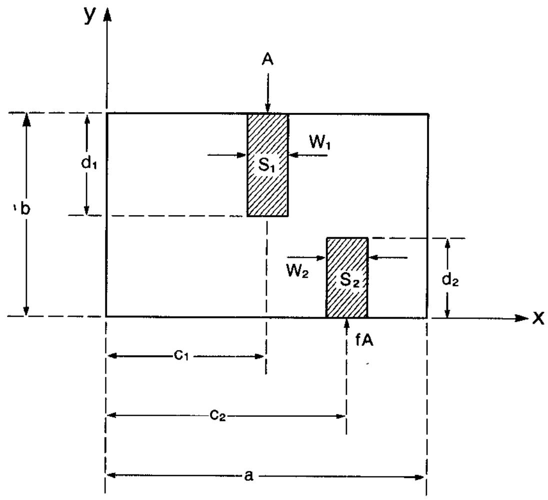

Fig. 1. Cross section of rectangular waveguide with two capacitive strips located at opposite sides of the same transverse plane.

Restriction of the analysis to narrow strips does not significantly limit the practical applicability of the results in circuit design.

II. Theoretical Analysis

The structure to be analyzed is shown in Fig. 1. The strip is assumed to be infinitesimally thin, and to be sufficiently narrow that the current does not vary appreciably with x. Both the strips and the waveguide are assumed to be formed of material having infinite conductivity. The strips are located at $z = 0$.

Considering a dominant-mode incident electric field

$$\vec{E}_i = \sin\left(\frac{\pi x}{a}\right)\exp(-\Gamma_{10} z)\hat{y} \tag{1}$$

the resulting scattered field can be given by

$$\vec{E}_s = -j\omega\mu_0 \int_s \overline{G}(\vec{r}|\vec{r}')\cdot J(\vec{r}')\,d\vec{r}' \tag{2}$$

where the integration is carried out over the entire strip surface $S = S_1 + S_2$ and the dyadic Green's function used here can be found from Tai [15].

Following the procedure set out in [2], the total normalized shunt susceptance $\overline{B}_T$ may be expressed in the follow-

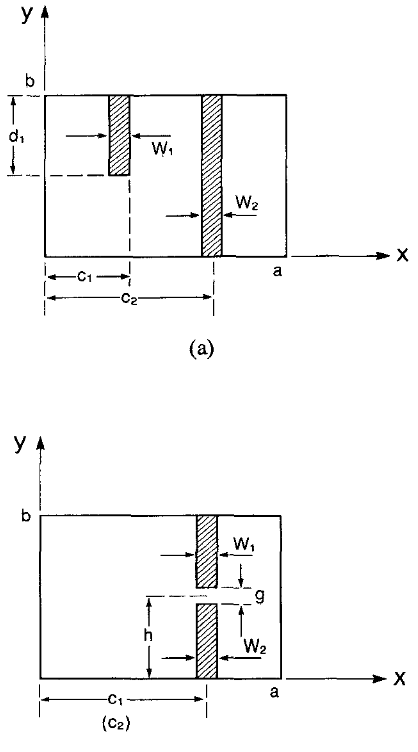

Fig. 2. Two special cases of great interest. (a) One inductive strip and one capacitive strip. (b) A single strip with a gap.

ing variational form:

$$\overline{B}_T = \frac{-2\left[\int_s J_y(x,y)\sin\frac{\pi x}{a}\,dx\,dy\right]^2}{\frac{\gamma_{10}}{k_0^2}} \Bigg/ \left[\left(\sum_{n=2}^{\infty}\sum_{m=0}^{\infty} + \sum_{\substack{m=1\\ \text{at } n=1}}^{\infty}\right)\frac{(2-\delta_m)\left(k_0^2 - \frac{m^2\pi^2}{b^2}\right)}{\Gamma_{nm}} \cdot \int_s\int_s J_y(x,y)J_y(x',y')\sin\frac{n\pi x}{a}\sin\frac{n\pi x'}{a}\cos\frac{m\pi y}{b}\cos\frac{m\pi y'}{b}\,dx\,dx'\,dy\,dy'\right] \quad (3)$$

where

$$\delta_m = \begin{cases} 1 & \text{when } m = 0 \\ 0 & \text{when } m \neq 0 \end{cases}$$

$$\Gamma_{nm} = \left(\frac{m^2\pi^2}{b^2} + \frac{n^2\pi^2}{a^2} - k_0^2\right)^{1/2}$$

$$k_0 = \frac{2\pi}{\lambda}$$

$$\Upsilon_{10} = -j\Gamma_{10} = \left(k_0^2 - \frac{\pi^2}{a^2}\right)^{1/2}$$

$$S = S_1 + S_2$$

and $J_y(x, y)$ is the y-directed current density over the two strips.

Using a method similar to that of Lewin [16], equation (3) can be shown to be stationary for small variations in J_y about its correct value. Use of an approximate form for J_y in (3) yields a lower bound on the true value of the susceptance.

To evaluate $\overline{B}_T$ we employ the following approximate form for the current density $J_y(x, y)$, suitable for use when the strips are narrow [2]. The current is assumed constant across each strip in the x-direction.

$$\begin{aligned} J_y(x,y) = A&\left[u\left(x - c_1 + \frac{w_1}{2}\right) - u\left(x - c_1 - \frac{w_1}{2}\right)\right] \\ &\cdot \sin k_1(y - b + d_1) \\ &- fA\left[u\left(x - c_2 + \frac{w_2}{2}\right)\right. \\ &\left. - u\left(x - c_2 - \frac{w_2}{2}\right)\right]\sin k_2(d_2 - y) \end{aligned} \quad (4)$$

where d_1 and d_2 are the depths of the strips, f is the current density ratio, and A is an amplitude constant. Here, $u(x)$ is the step function defined by

$$u(x) = \begin{cases} 1 & \text{if } x \geq 0 \\ 0 & \text{if } x < 0. \end{cases}$$

The current amplitude is maximum at the interface of the strip and the waveguide wall and decreases sinusoidally until it becomes zero at the end of the strip. The values for k_1 and k_2 can be found by [2]

$$k_1 = \frac{\pi}{2d_1}$$

$$k_2 = \frac{\pi}{2d_2}.$$

The direction of current flow in the second strip is opposite to that in the first strip, and a negative sign is placed on the current amplitude to account for this difference.

Substituting the current density from (4) into (3), we have a closed-form solution for the total normalized susceptance:

$$\bar{B}_T = \frac{-2(F_1 + fF_2)^2}{\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} D_{nm}(P_{nm} + fQ_{nm})^2 + \sum_{n=2}^{\infty} E_n(S_n + fT_n)^2} \tag{5}$$

where

$$F_1 = \frac{1}{k_1}\left[\cos\frac{\pi\left(c_1 + \frac{w_1}{2}\right)}{a} - \cos\frac{\pi\left(c_1 - \frac{w_1}{2}\right)}{a}\right] \cdot (\cos k_1 d_1 - 1)$$

$$F_2 = \frac{1}{k_2}\left[\cos\frac{\pi\left(c_2 + \frac{w_2}{2}\right)}{a} - \cos\frac{\pi\left(c_2 - \frac{w_2}{2}\right)}{a}\right] \cdot (1 - \cos k_2 d_2)$$

$$D_{nm} = \frac{\Upsilon_{10}}{k_0^2} \frac{\left(k_0^2 - \frac{m^2\pi^2}{b^2}\right)}{\Gamma_{nm}} \frac{1}{2n^2}$$

$$P_{nm} = \frac{2k_1 b^2}{b^2 k_1^2 - m^2\pi^2} \cdot \left[\cos\frac{n\pi\left(c_1 - \frac{w_1}{2}\right)}{a} - \cos\frac{n\pi\left(c_1 + \frac{w_1}{2}\right)}{a}\right] \cdot \left[\cos\frac{m\pi(b - d_1)}{b} - (-1)^m \cos k_1 d_1\right]$$

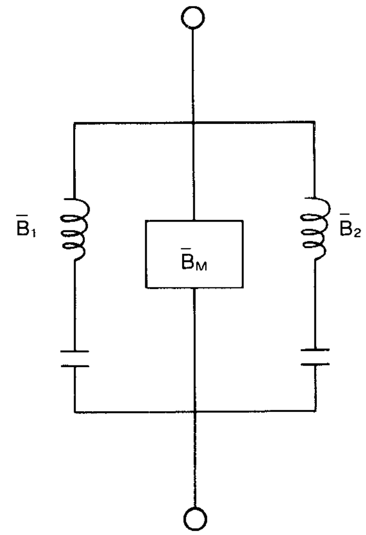

Fig. 3. Equivalent circuit for two-strip obstacle. Note $\bar{B}_T = \bar{B}_1 + \bar{B}_2 + \bar{B}_M$.

$$T_n = \frac{2}{k_2}(\cos k_2 d_2 - 1) \cdot \left[\cos\frac{n\pi\left(c_2 - \frac{w_2}{2}\right)}{a} - \cos\frac{n\pi\left(c_2 + \frac{w_2}{2}\right)}{a}\right]$$

$$E_n = \frac{\Upsilon_{10}}{\Gamma_{no}} \frac{1}{4n^2}.$$

To evaluate $\bar{B}_T$, the value of the current density ratio f must be determined by use of the variational principle. This ratio can be determined by extremizing the variational expression for $\bar{B}_T$.

Putting $\partial\bar{B}_T/\partial f = 0$ yields an equation for f in the form

$$f = \frac{F_2\left(\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} D_{nm}P_{nm}^2 + \sum_{n=2}^{\infty} E_n S_n^2\right) - F_1\left(\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} D_{nm}Q_{nm}P_{nm} + \sum_{n=2}^{\infty} E_n T_n S_n\right)}{F_1\left(\sum_{n=2}^{\infty} E_n T_n^2 + \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} D_{nm}Q_{nm}^2\right) - F_2\left(\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} D_{nm}Q_{nm}P_{nm} + \sum_{n=2}^{\infty} E_n T_n S_n\right)}. \tag{6}$$

$$Q_{nm} = \frac{2k_2 b^2}{m^2\pi^2 - b^2 k_2^2}\left(\cos\frac{m\pi d_2}{b} - \cos k_2 d_2\right) \cdot \left[\cos\frac{n\pi\left(c_2 - \frac{w_2}{2}\right)}{a} - \cos\frac{n\pi\left(c_2 + \frac{w_2}{2}\right)}{a}\right]$$

$$S_n = \frac{2}{k_1}(1 - \cos k_1 d_1) \cdot \left[\cos\frac{n\pi\left(c_1 - \frac{w_1}{2}\right)}{a} - \cos\frac{n\pi\left(c_1 + \frac{w_1}{2}\right)}{a}\right]$$

The mutual coupling susceptance between the two strips is defined by the following equation:

$$\bar{B}_M = \bar{B}_T - (\bar{B}_1 + \bar{B}_2). \tag{7}$$

$\bar{B}_1$ and $\bar{B}_2$ would be the normalized susceptances of one strip if the other strip were absent, i.e., if the interactive coupling effects could be neglected. The equivalent circuit of the two strips is shown in Fig. 3.

III. Experimental Verification and Theoretical Discussion

The theoretical results were verified with the experimental results at X-band. The waveguide has dimensions $a = 0.900$ in and $b = 0.400$ in. The results are shown in Fig. 4.

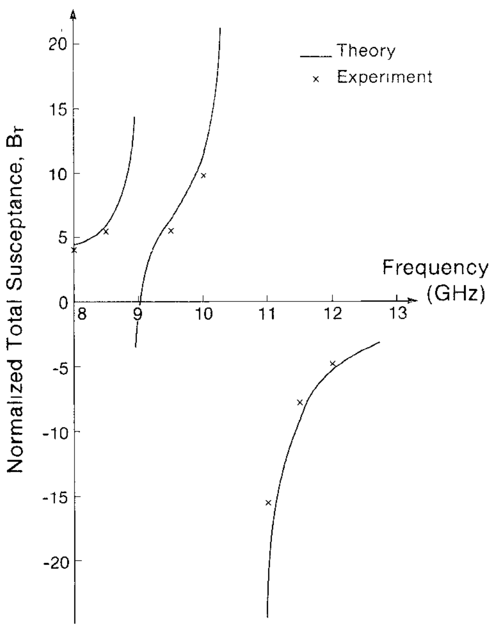

Fig. 4. Normalized values of strip total susceptance as a function of frequency for two strips with $c_1 = 0.45$ in, $w_1 = 0.08$ in, $d_1 = 0.3$ in, $c_2 = 0.67$ in, $w_2 = 0.08$ in, $d_2 = 0.3$ in The solid line shows theoretical results and the crosses show the experimental results.

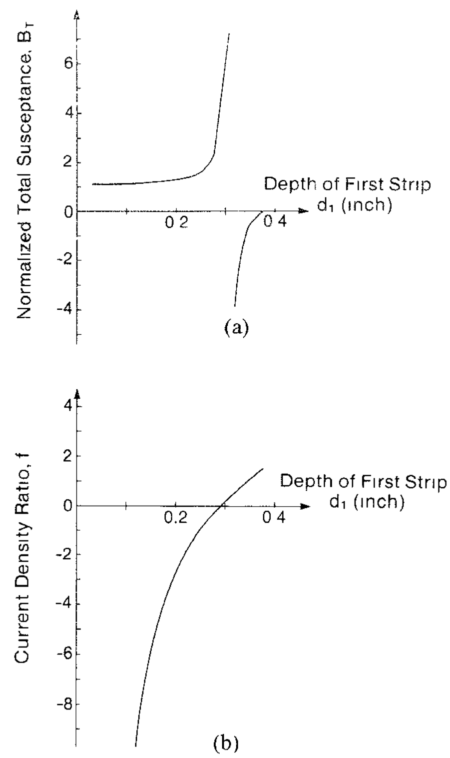

Fig. 5. (a) Normalized total susceptance and (b) current density ratio as a function of the strip insertion at 9 GHz. The following dimensions are used: $w_1 = w_2 = 0.05$ in, $c_1 = 0.3$ in, $c_2 = 0.6$ in, $d_2 = 0.25$ in, $a = 0.9$ in, and $b = 0.4$ in.

Good agreement has been achieved. The principal source of error in the measurements occurs in determination of the insertion depth of the narrow strips.

Figs. 5 and 6 show the variation of the total normalized susceptance as a function of strip depth d_1 for two different frequencies. The two strips have the same width and are symmetrically located. It can be seen that the current density ratio is equal to -1 as the two strips have the same depth, i.e., $d_1 = d_2$. In this case, the current on each strip has the same amplitude. It can be seen that the susceptance and current density ratio can vary over a very wide range. Series or parallel resonances could occur at a certain depth of insertion depending on the operating frequencies. The current density ratio can take any real value, since one strip may be resonant at a certain frequency and will effectively present a short or open circuit across the waveguide.

The analysis can readily used to study the mutual coupling effects between two resonant strips. For simplicity, we consider two strips having the same width and depth symmetrically located on the transverse plane of the waveguide. The normalized total susceptance and mutual coupling susceptance as a function of the interstrip spacing are shown in Figs. 7–9 for three typical cases. If the strip insertion is shallow (Fig. 7), the total susceptance is capacitive and the mutual coupling is small. The coupling is mostly inductive except at very close spacing. As the strip insertion increases, the total susceptance and mutual coupling have much larger values, which can be either inductive or capacitive depending on the strip separation (Fig. 8). For deep insertion, as shown in Fig. 9, the strips act as an inductive element, and the mutual coupling is similar to that of two inductive strips [4].

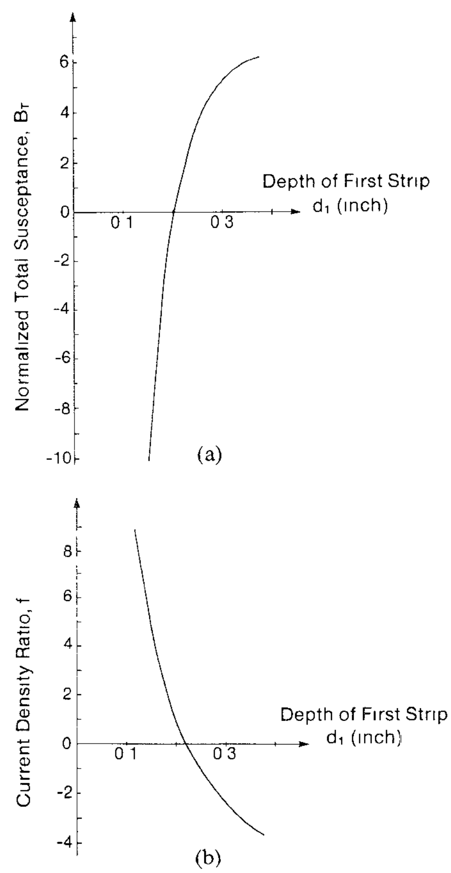

Fig. 6. (a) Normalized total susceptance and (b) current density ratio as a function of the strip insertion at 11 GHz The following dimensions are used: $w_1 = w_2 = 0.05$ in, $c_1 = 0.3$ in, $c_2 = 0.6$ in, $d_2 = 0.25$ in, $a = 0.9$ in, and $b = 0.4$ in

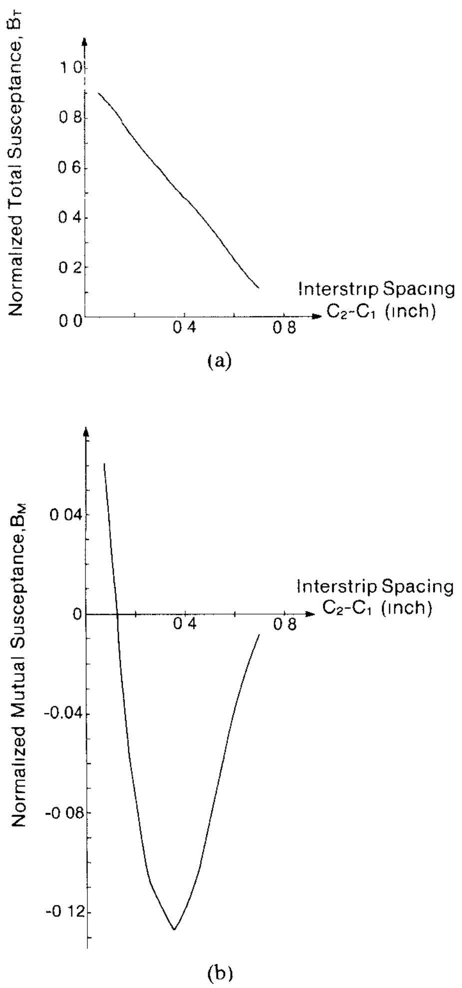

Fig. 7. (a) Normalized total susceptance and (b) mutual coupling as a function of interstrip spacing for the case of the shallow insertion at 11 GHz. The following dimensions are used: $a = 0.9$ in, $b = 0.4$ in, $w_1 = w_2 = 0.05$ in, $d_1 = d_2 = 0.175$ in, and $c_1 = a - c_2$.

IV. One Capacitive Strip and One Inductive Strip

A special case of the above analysis can be applied to two resonant strips with one of the two strips extending across the whole waveguide narrow dimension, as shown in Fig. 2(a). In this case, $d_2 = b$ and $Q_{nm} = 0$; eqs. (5) and (6) become

$$\overline{B}_T = \frac{-2(F_1 + fF_2)^2}{\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} D_{nm}P_{nm}^2 + \sum_{n=2}^{\infty} E_n(S_n + fT_n)^2} \tag{8}$$

and

$$f = \frac{F_2\left(\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} D_{nm}P_{nm}^2 + \sum_{n=2}^{\infty} E_nS_n^2\right) - F_1\sum_{n=2}^{\infty} E_nT_nS_n}{F_1\sum_{n=2}^{\infty} E_nT_n^2 - F_2\sum_{n=2}^{\infty} E_nT_nS_n}. \tag{9}$$

Measurements were carried out with strips in conventional X-band waveguide. Both theoretical and experimental results are shown in Fig. 10 for comparison. The sum of $\overline{B}_1 + \overline{B}_2$ is also shown in the same graph; it differs significantly from the experimental results, thus indicating the significant contribution of $\overline{B}_M$ and $\overline{B}_T$.

The normalized total susceptance and the current density ratio as a function of strip depth are shown in Fig. 11. As in Figs. 5 and 6, the current ratio and total susceptance vary over a wide range. As the strip depth increases, a shunt resonance occurs first, followed by a series resonance.

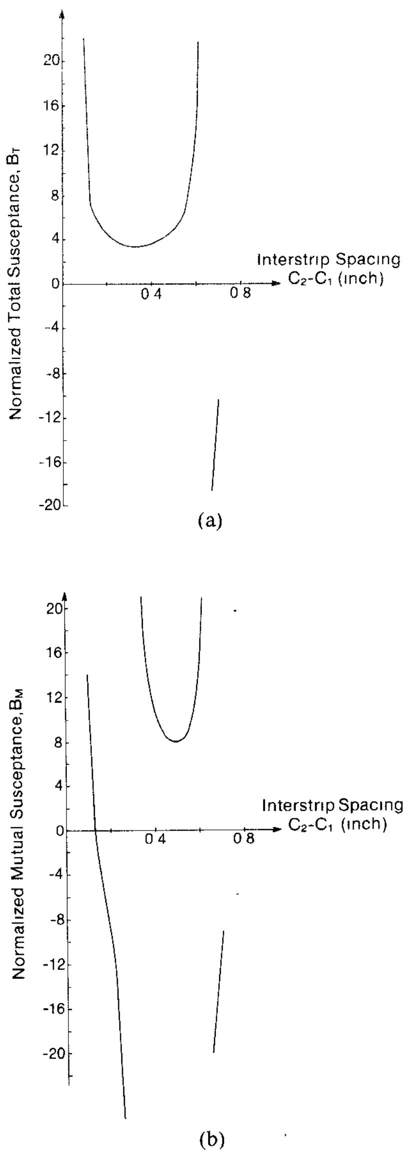

Fig. 8. (a) Normalized total susceptance and (b) mutual coupling as a function of interstrip spacing for the case of moderate strip insertion at 11 GHz. The following dimensions are used: $a = 0.9$ in, $b = 0.4$ in, $w_1 = w_2 = 0.05$ in, $d_1 = d_2 = 0.25$ in, and $c_1 = a - c_2$.

V. Single Strip with a Gap

Another special case of great interest is a single strip with a gap, as shown in Fig. 2(b).

Fig. 12 shows the normalized susceptance as a function of the gap location h, which is given by

$$h = d_2 + \frac{1}{2}(b - d_1 - d_2). \tag{10}$$

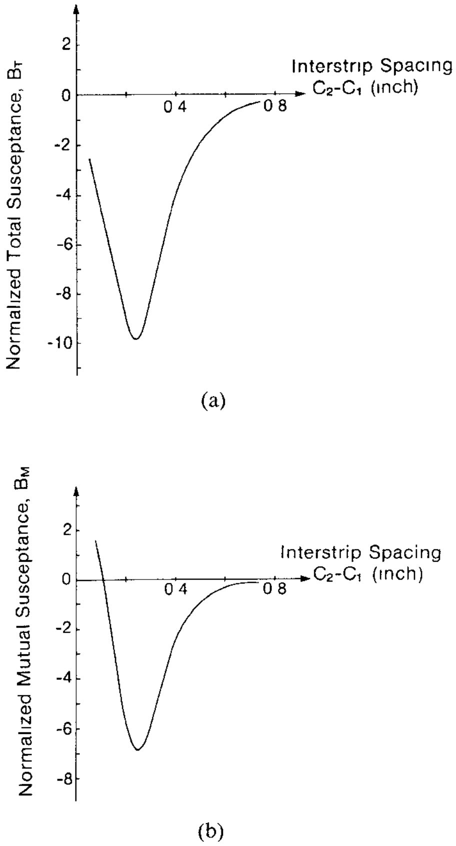

Fig. 9. (a) Normalized total susceptance and (b) mutual coupling as a function of interstrip spacing for the case of deep insertion at 11 GHz. The following dimensions are used: $a = 0.9$ in, $b = 0.4$ in, $w_1 = w_2 = 0.05$ in, $d_1 = d_2 = 0.35$ in, and $c_1 = a - c_2$.

When $h = 0.2$ in $= 0.5\ b$, the gap is located at the center and the current ratio $f = -1$. As h increases, the lower strip gets more influence and the current density ratio becomes larger.

VI. Other Special Cases

The results given by (5) and (6) can be used for other special cases (Fig. 13). These cases have been published before and thus only brief discussion is presented.

A. Two Inductive Strips

The structure is shown in Fig. 13(a). In this case, we have the following conditions

$$d_1 = b$$
$$d_2 = b$$
$$P_{nm} = 0$$
$$Q_{nm} = 0$$
$$f = -f.$$

Equation (5) reduces to

$$\overline{B}_T = \frac{-2(F_1 + fF_2)^2}{\sum_{n=2}^{\infty} E_n (S_n + fT_n)^2}. \tag{11}$$

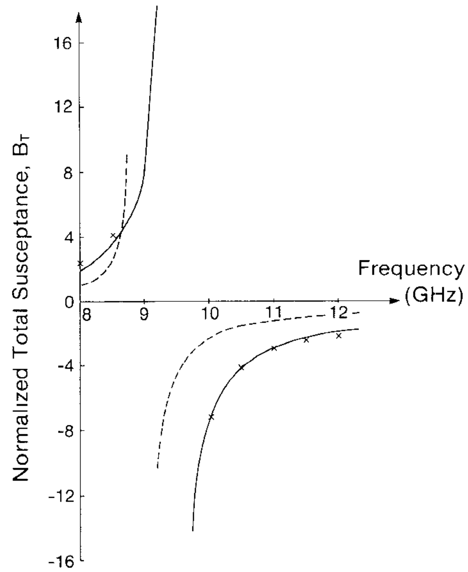

Fig. 10. Normalized total susceptance as a function of frequency compared with experimental results. The two strips have $c_1 = 0.18$ in, $c_2 = 0.7$ in, $d_1 = 0.294$ in, $d_2 = 0.4$ in, and $w_1 = w_2 = 0.133$ in. The solid line shows the theoretical results and the crosses show the experimental results. The dashed line shows the sum of $\overline{B}_1 + \overline{B}_2$

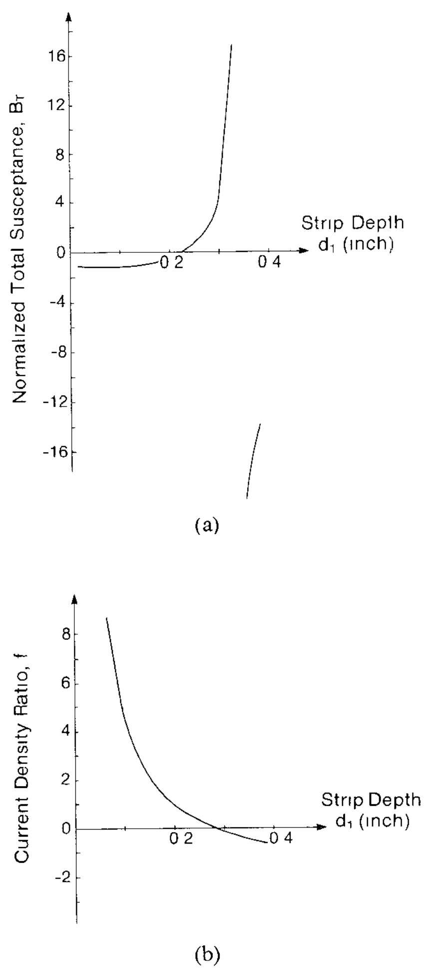

Fig. 11 (a) Normalized total susceptance and (b) current density ratio as a function of the strip depth at 9 GHz. The following dimensions are used for calculation: $w_1 = w_2 = 0.05$ in, $c_1 = 0.3$ in, $c_2 = 0.6$ in, $d_2 = 0.6$ in, $a = 0.4$ in, and $b = 0.4$ in.

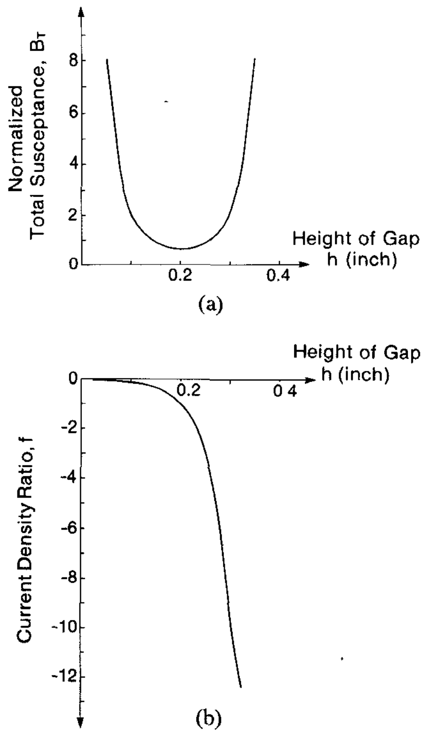

Fig. 12. (a) Normalized total susceptance and (b) current density ratio as a function of gap location at 9 GHz. The following dimensions are used for calculation: $w_1 = w_2 = 0.05$ in, $c_1 = c_2 = 0.45$ in, $g = 0.05$ in, $a = 0.9$ in, and $b = 0.4$ in.

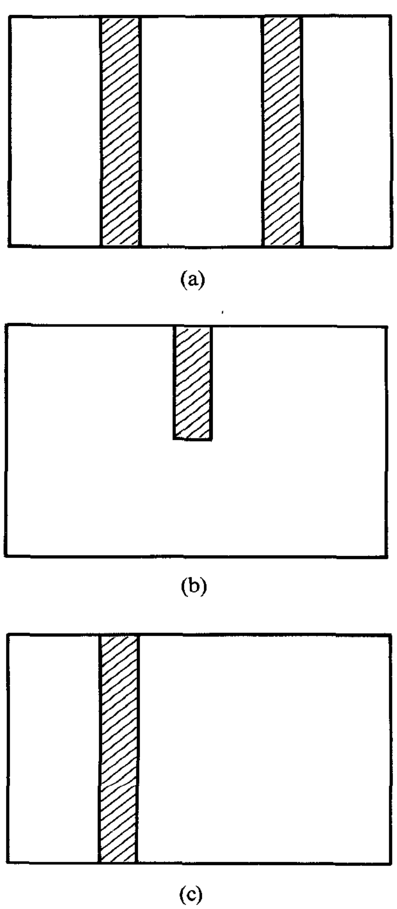

Fig. 13. Other special cases. (a) Two inductive strips. (b) A single capacitive strip. (c) A single inductive strip.

Equation (6) is

$$f = \frac{F_1 \sum_{n=2}^{\infty} E_n T_n S_n - F_2 \sum_{n=2}^{\infty} E_n S_n^2}{F_1 \sum_{n=2}^{\infty} E_n T_n^2 - F_2 \sum_{n=2}^{\infty} E_n T_n S_n}. \tag{12}$$

Equations (11) and (12) are equivalent to the results previously reported in [4].

B. One Single Capacitive Strip

This configuration is shown in Fig. 13(b). If only the first strip exists, we have

$$f = 0.$$

Equation (5) becomes

$$\bar{B}_T = \frac{-2F_1^2}{\sum_{n=2}^{\infty} E_n S_n^2 + \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} D_{nm} P_{nm}^2}. \tag{13}$$

If only the second strip exists, we have

$$f = \infty.$$

Equation (5) becomes

$$\bar{B}_T = \frac{-2F_2^2}{\sum_{n=1}^{\infty} \sum_{m=1}^{\infty} D_{nm} Q_{nm}^2 + \sum_{n=2}^{\infty} E_n T_n^2}. \tag{14}$$

Equations (13) and (14) are equivalent to (10) in [2].

C. One Single Inductive Strip

As shown in Fig. 13(c), the normalized susceptance of this case can be obtained from (5) by setting

$$f = 0$$
$$d_1 = b$$
$$P_{nm} = 0.$$

Equation (5) becomes

$$\bar{B}_T = \frac{-2F_1^2}{\sum_{n=2}^{\infty} E_n S_n^2}. \tag{15}$$

This expression is equivalent to (89) in ch. 8 of [1].

VII. Conclusions

A closed-form expression for the susceptance of two opposite resonant strips in waveguide has been derived. Important information on current density ratio and mutual coupling was obtained. The results agree well with the experimental data and should have direct application in the design of compact filters, matching networks, and diode mounting circuits.

The analysis is quite general and can be used to calculate the obstacle impedance of various configurations, such as a single strip with a gap, a single capacitive strip and an inductive strip, two inductive strips, a single capacitive strip, and a single inductive strip.

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