in MIC coupler isolation. Advantages of this method over spatial domain treatments include absence of singular integrals and efficient treatment of finite strip thickness and upper ground plane effects. The need for scaling techniques to allow analysis of a large dynamic range of strip parameters has been pointed out as a limitation. Good agreement between experimental and computed values of isolation was obtained.

Possible applications of these results could allow improved coupler design, improvement in midband VSWR of Schiffman phase shifters [14], or improved MIC filter response.

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Some Results on the End Effects of Microstriplines

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***Abstract*—A new resonant technique for accurate and reliable measurement of end and gap effects in microstripline has been developed. An investigation of the frequency dependence of end and gap effects in microstrip was performed. There is no apparent frequency variation for the end effects for $w/h=0.5$, 1.0, and 2.0 lines on alumina substrate ($\epsilon_r \cong 9.8$), between 7.0 and 18.0 GHz. A small dependence on resonator mode number of these effects has been observed.**

I. INTRODUCTION

MICROSTRIP open-ends are used in variety of stripline matching and filter circuits. The characterization of small microstrip discontinuities such as cross-over requires a very accurate knowledge of end effects for the resonant structure. Therefore, open-ends constitute an important class of microstrip discontinuity. Static calculations [1]–[3] provide accurate estimates of the capacitance due to the fringe fields at the open. However, the behavior of this shunt capacitance or equivalent series line length l_o with frequency has not been examined in any detail [4]. The present paper reports on the results of an experimental investigation of the frequency dependence of the microstrip open-end capacitance or equivalent line length l_o. An accurate method of measurement which is an extension of the resonant technique has been developed in the course of this work. Furthermore, the frequency dependence of the series gap equivalent circuit line length l_g has also been examined.

The resonances of lengths of straight microstrip resona-

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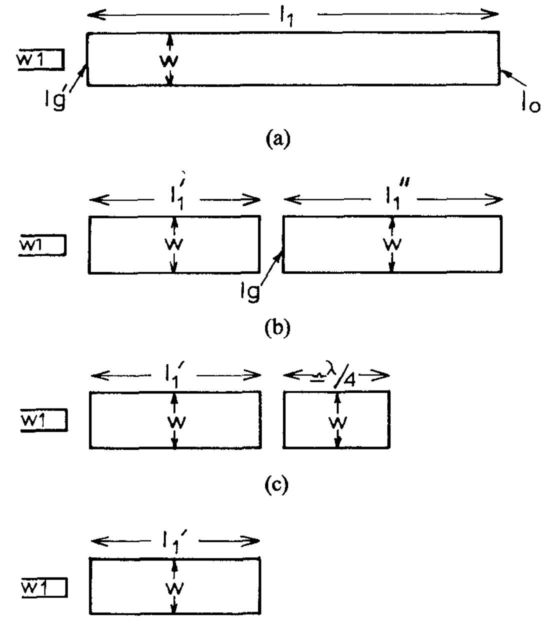

Fig. 1. (a)–(d) Resonators used for end effect measurements. l_o = length added at the plane of the open circuit; l_g' = length added at the plane of the asymmetric series gap; l_g = length added at the plane of the symmetric gap; $w1/h = 1.0$ in all cases.

tors [5] provide estimates of l_o, but the perturbation due to feed-line, and variation of the substrate permittivity; height and line width remain unaccounted for with this method. A modification by Easter *et al.* [6] introduces a quarter wavelength section (approximately corrected for the end effects) at the end of the line, with the same series gap as the gap between feed-line and the resonator, as illustrated in Fig. 1(c). The resonance frequencies with the $\lambda/4$ tail and with the tail etched off, provide accurate estimates of $(l_g - l_o)$. This modification is essentially a substitutional method, and, therefore, the above drawbacks are removed in the $(l_g - l_o)$ results. But the problem due to variations in h, w, and ϵ_r still remain for l_g measurements. An extension to the above technique [6] for l_g measurements has been used for the present work to overcome these variations. Note that l_g is the change in length at a symmetric gap, when the two line widths on either side of the gap are equal; and l_g' is the change in length at asymmetric gap when the two line widths at the gap are unequal.

II. Measurement Method

The resonance frequency of the straight line resonator in Fig. 1(a) is altered due to l_o and l_g'. An electrically centered gap identical to feed-line gap width is etched into this resonator as shown in Fig. 1(b). Note the position of this gap is offset in the center by approximately $(l_g' - l_o)$. With this choice of the position of the gap the same standing wave pattern is produced on the same strip with and without the gap. This split resonator configuration gives rise to odd- and even-mode resonances. The gap inserted can be represented by a capacitive π network or an inverter section and two line lengths l_g, as shown in Fig. 2, where B_i and l_g are given by

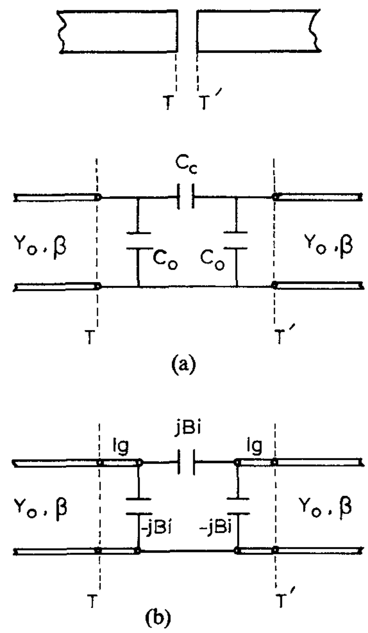

Fig. 2. Equivalent circuit of a gap. (a) = Pi equivalent capacitance circuit. (b) = Inverter and two line lengths equivalent circuit.

$$\beta l_g = \frac{1}{2}\left[\tan^{-1}\left(\frac{\omega C_0}{Y_0}\right) + \tan^{-1}\left(\frac{\omega C_0 + 2\omega C_c}{Y_0}\right)\right]$$

$$l_g \cong (C_0 + C_c)/C_\infty, \qquad \text{for } \frac{\omega C_0 + 2\omega C_c}{Y_0} \ll 1 \tag{1}$$

and

$$\tan^{-1}(B_i/Y_0) = \frac{1}{2}\left[\tan^{-1}\left(\frac{\omega C_0 + 2\omega C_c}{Y_0}\right) - \tan^{-1}\left(\frac{\omega C_0}{Y_0}\right)\right]$$

$$B_i \cong \omega C_c, \qquad \text{for } \frac{\omega C_0 + 2\omega C_c}{Y_0} \ll 1. \tag{2}$$

The resonator l_1 with and without the gap in the middle resonates at the frequencies for which the following relationships are satisfied, respectively,

$$2nv\lambda_1 = l_1 + l_o + l_g' \tag{3}$$

$$vn(\lambda_e + \lambda_o) = l_1' + l_1'' + l_o + l_g' + 2l_g. \tag{4}$$

From (3) and (4), l_g is given by

$$2l_g = (l_1 - l_1' - l_1'') + nv(\lambda_e + \lambda_o - 2\lambda_1) \tag{5}$$

where

- n — 1/2, 1, 3/2, $\cdots$ (for example when $n = 1/2$, $l_1' \cong l'' \cong \lambda/2$),
- v — velocity factor, (λ in microstrip/λ in air),
- λ_1 — wavelength corresponding to the frequency of resonance of l_1 in Fig. 1(a),
- λ_e — even excitation wavelength corresponding to the frequency of resonance of l_1' and l_1'' in the symmetric excitation in Fig. 1(b),
- λ_o — wavelength when l_1' and l_1'' are asymetrically excited in Fig. 1(b).

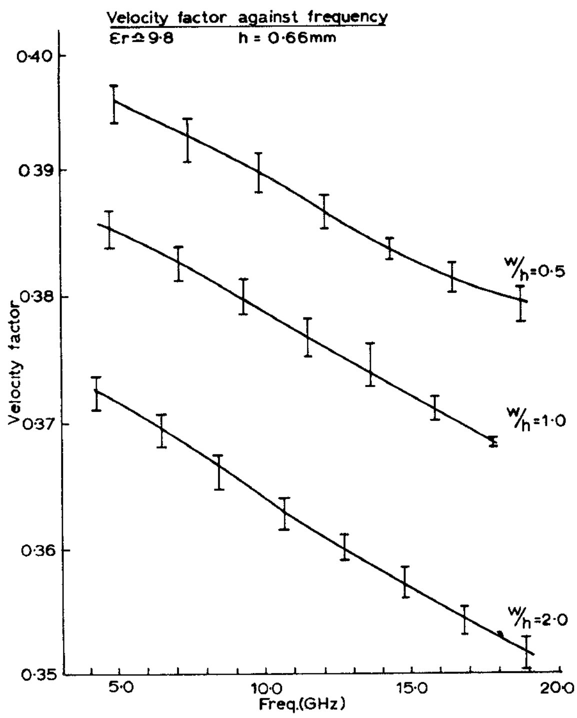

Fig. 3. Velocity factor against frequency.

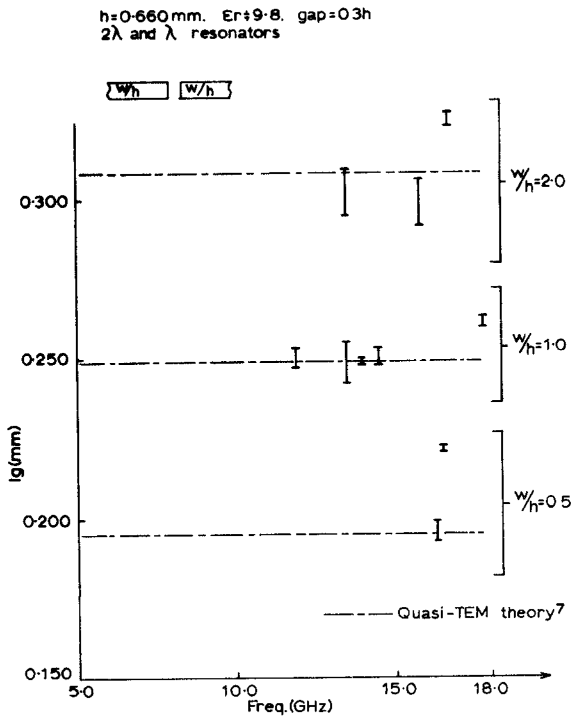

Fig. 5. l_g against frequency (λ and 2λ resonators).

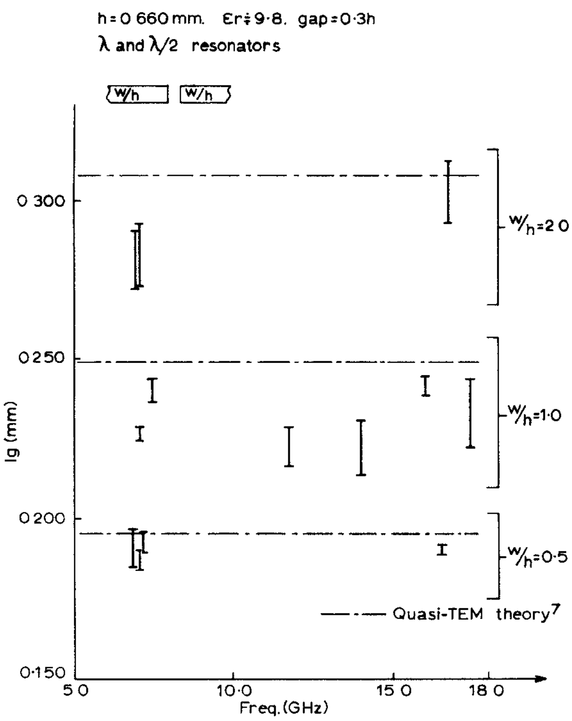

Fig. 4. l_g against frequency (λ and λ/2 resonators).

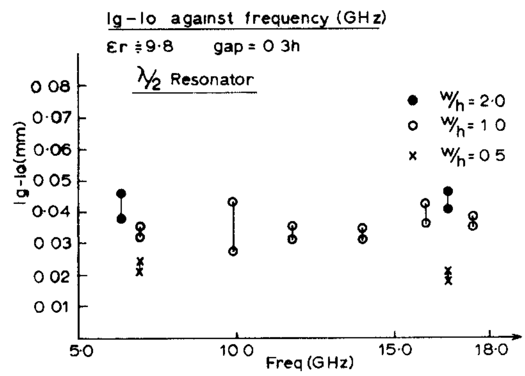

Fig. 6. $(l_g - l_o)$ against frequency (λ and λ/2 resonators).

Note that the expression for l_g is insensitive to small inaccuracies in the velocity factor term. This factor is multiplied by $(\lambda_e + \lambda_o - 2\lambda_1)$ which is the difference of the wavelengths, and hence is small. Thus accuracy is preserved even if v is in error up to a few percent.

In the current experiments, the resonator l_1 in Fig. 1 is laid down for the measurements and is subsequently etched back to other resonator configurations (b), (c), and (d), respectively, for further measurements. Thus the effects due to the variations in ϵ_r, h, and w are reduced. From these measurements the velocity factor, l_o and l_g are obtained.

III. Results

Measurements were made on groups of resonators on 660-μm thick alumina substrates up to 12.4 GHz, and beyond that, were scaled up on 1.00-mm thick substrates up to a scaled frequency of 18-GHz ($\cong$12 GHz on 1.00-mm substrates). This step was taken to retain the superior measurement accuracy which is avilable in the network analyzer below 12.4-GHz frequencies. Two sets of resonator combinations were used, these were λ and λ/2 sets, and the 2λ and λ sets.

All measurements were made on circuits within 5-μm edge definition, and frequencies were measured within 5 MHz. Four samples were taken at each frequency to examine the spread, and this was attributed to substrate variations of permittivity, roughness, and thickness. Loose

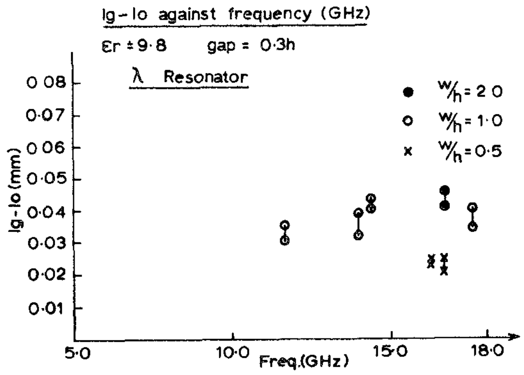

Fig. 7. $(l_g - l_o)$ against frequency (λ and 2λ resonators).

coupling was used in all cases (gap being $0.3h$), and it is estimated that resonator loading is not significant.

The results are presented for velocity factor, l_g and $(l_g - l_o)$ for the two resonator combination sets examined in Fig. 3–7 for $w/h = 0.5$, 1.0, and 2.0, over the frequency range 7 to 18 GHz.

No discernible frequency variation is apparent within the range considered of end effects with frequency within experimental error. The gap and end effects are higher by a small amount, which is only just resolvable for the longer resonators when compared with the short resonators results. This may be attributed to the coupling between the ends of a resonator, which is dependent on the mode number of the resonator. Slight differences between the scaled and true model are present which are possibly due to the variation between the substrate permittivity. Furthermore, the Q-factors on the scaled up model is higher ($\cong 300$) compared to those of the normal lines ($Q \cong 100$) which may also account for the difference.

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