[7] A. K. Saad and G. Begemann, "Electrical performance of fin lines of various configurations, *IEE J. Microwaves, Opt. Acoustics*, vol. 1, pp. 81–88, 1977.
[8] P. J. Meier, "Planar multiport millimeter integrated circuits," in *Proc. Int. Microwave Symp.*, San Diego, CA, 1977, pp. 385–388.
[9] G. Begemann, "An X-band balanced fin-line mixer," in *Proc. Int. Microwave Symp.*, Ottawa, Ont., Canada, 1978, pp. 24–26.
[10] R. Rudokas and T. Itoh, "Passive millimeterwave IC-components made of inverted strip dielectric waveguides," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 978–981, 1976.
[11] E. Kpodzo, K. Schuenemann, and H. El-Hennawy, "A quadriphase modulator in fin-line technique," in *Proc. Int. Microwave Symp.*, Orlando, FL, 1979.
[12] A. K. Saad and K. Schuenemann, "A simple method for analyzing fin-line structures," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 1002–1007, 1978.

Electric Probe Measurements on Microstrip

J. S. DAHELE AND A. L. CULLEN, FELLOW, IEEE

Abstract—**The aim of the experimental investigation reported here is to measure the electric field of microstrip using a field probe. To establish the accuracy of these measurements, the probe is first calibrated against a known field which is obtained by analyzing a wire suspended axially in a rectangular metal tube. Measurements on a simple wire over ground plane circuit indicate that unshielded structures are basically unsuitable for accurate probe calibration.**

Finally, the theoretical results predicted by a numerical analysis program for microstrip, published recently [1], are verified by comparing these with the actual field distribution determined experimentally.

I. Introduction

THE EXISTENCE of complex boundary conditions makes it impossible for microstrip to support a pure TEM, TE, or TM mode. Instead, the propagation takes place via a hybrid TE–TM mode which is usually analyzed using numerical techniques. In view of the mathematical complexity and the approximate nature of its theoretical solution, accurate experimental investigation of microstrip can be of considerable value. Apart from yielding data essential for circuit design, a precise experimental investigation offers a valid means of verifying the accuracy of theoretical results which are exact only for zero-strip thickness and perfectly conducting structure.

The theoretical results used here for comparison are based on the work of Davies and Mirshekar-Syahkal [1], [2] and are obtained from the numerical analysis program for multilayer dielectric with microstrip. This method of analysis uses the spectral-domain approach and is known to converge rapidly.

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J. S. Dahele is with the Electronics Department, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong.
A. L. Cullen is with the Department of Electronic and Electrical Engineering, University College London, London WC1E 7JE, England.

II. Probe Calibration

Before embarking on the measurement of electric field of microstrip, which is not known exactly, it is necessary to calibrate the probe on a circuit which is topologically similar and for which the exact field can be calculated. A simple wire-over-ground circuit, shown in Fig. 1(a), resembles microstrip in many respects and its electric field can be obtained from simple electrostatic theory. The normal component of the electric field in the transverse plane is given by [3]

$$E_y = \frac{\rho_L}{\pi\epsilon}\,\frac{x^2+h^2-y^2}{\{(y+h)^2+x^2\}\{(y-h)^2+x^2\}}. \tag{1}$$

For $x=0$

$$E_y = E_{y_{\max}} = -\frac{\rho_L}{\pi\epsilon}\,\frac{1}{y^2-h^2}$$

$\therefore$

$$|E_Y|^2 = \left|\frac{E_y}{E_{y_{\max}}}\right|^2 = \left\{(y^2-h^2)\frac{x^2+h^2-y^2}{\{(y+h)^2+x^2\}\{(y-h)^2+x^2\}}\right\}^2. \tag{2}$$

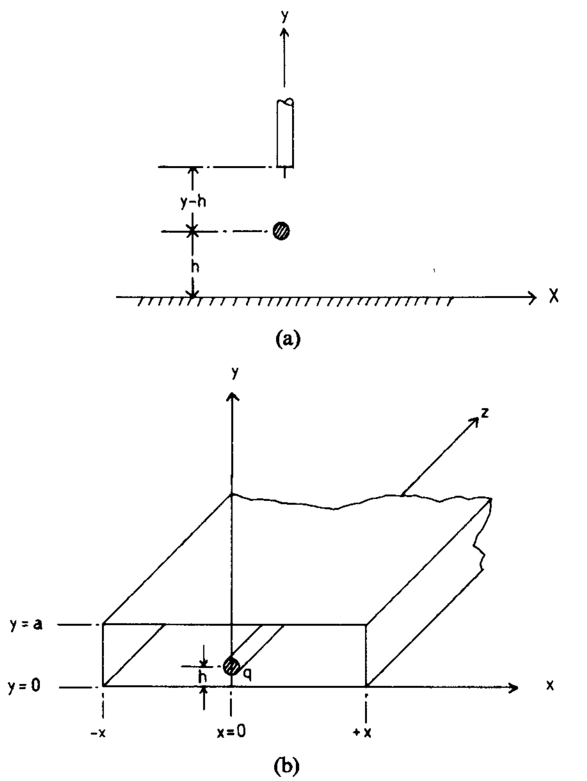

Fig. 1. Wire-over-ground plane. (a) Unshielded. (b) Shielded.

For the case when $y=2h$

$$|E_Y|^2=\left\{3h^2\frac{x^2-3h^2}{(9h^2+x^2)(h^2+x^2)}\right\}^2. \tag{3}$$

For a particular value of h, $|E_Y|^2$ given by (3) is plotted in Fig. 2 where measured results with and without a probe plate are also shown.

For calibration purposes, ideally, the relationship between measured and calculated field should be within a constant scaling factor and the two sets of results should agree exactly when normalized. In this respect, the unshielded wire-over-ground plane is clearly unsuitable for accurate calibration without the probe plate: nulls predicted by the theory are, in fact, measured as shallow minima, and the amplitude at the secondary peaks is about 4 dB higher than expected. For these measurements, the probe was made by removing the screen from a 2-mm section of a long thin semirigid coax, and it was suspected that this might couple to E_x as well as E_y for which it was designed. The results obtained with a metal plate added to the probe circuit to reduce coupling to E_x are shown in Fig. 2, and are seen to agree well with theory in the main lobe region, but not as well around the secondary peaks. It is important to remember, however, that theoretical results in Fig. 2 do not take into account the perturbation due to the probe plate; a direct comparison is, therefore, not strictly valid.

In order to eliminate entirely the problem of stray coupling and pickup, which is seen to exist in the unshielded circuit, a wire suspended axially in a rectangular metal tube, as shown in Fig. 1(b), was considered next. The analysis in the form of a model solution gives the electric field as [3]

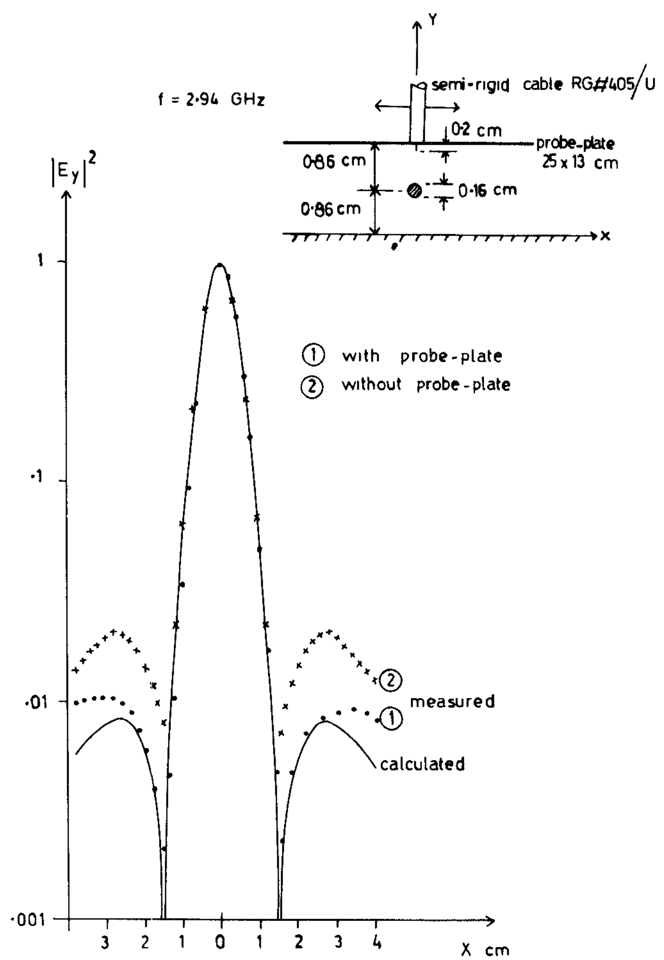

Fig. 2. Field of a wire-over-ground plane. ① with probe plate. ② without probe plate.

$$|E_y|=\frac{q}{4a\epsilon_0}\left[\frac{\sin\pi(h+y)/a}{\cosh\dfrac{\pi x}{a}-\cos\pi\left(\dfrac{h+y}{a}\right)}+\frac{\sin\pi(h-y)/a}{\cosh\dfrac{\pi x}{a}-\cos\pi\dfrac{(h-y)}{a}}\right]. \tag{4}$$

For the case when $y=a=2h$, (4) simplifies to

$$|E_y|=\frac{q}{2a\epsilon_0}\operatorname{sech}\frac{\pi x}{a}. \tag{5}$$

The measured results and those calculated from (4) are normalized and compared in Fig. 3 and the agreement is excellent. The departure from theory for large x is thought to be due to a weakly excited waveguide mode.

These results suggest that for accurate field measurements it is important to shield the structure so as to eliminate spurious coupling to the probe circuit. Therefore, provided the basic structure and the probe arrangement are similar, the field of shielded microstrip can be

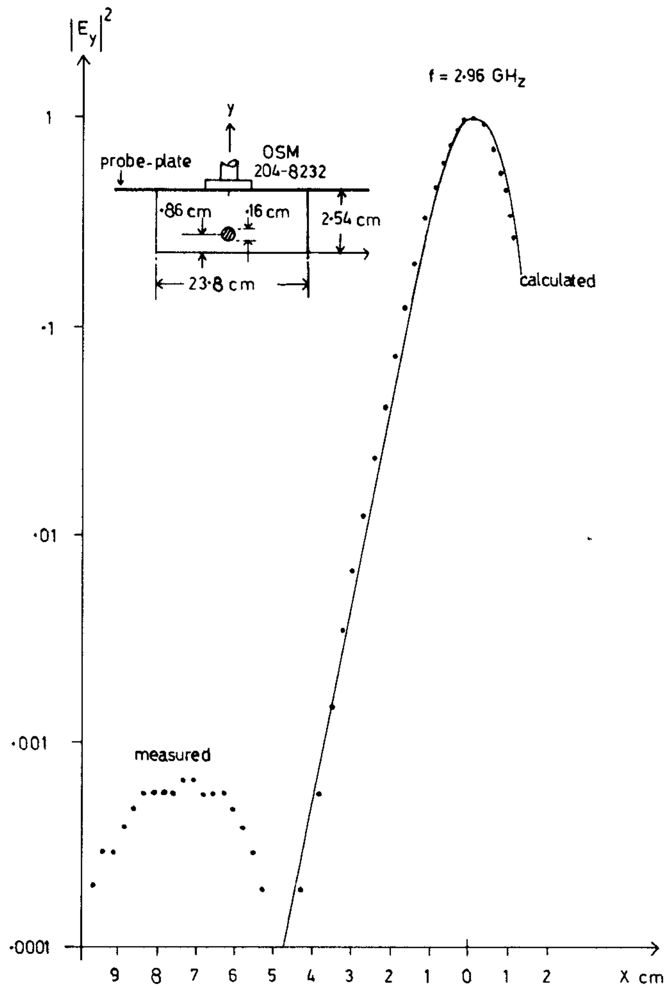

Fig. 3. Field of a wire suspended axially in a rectangular metal tube.

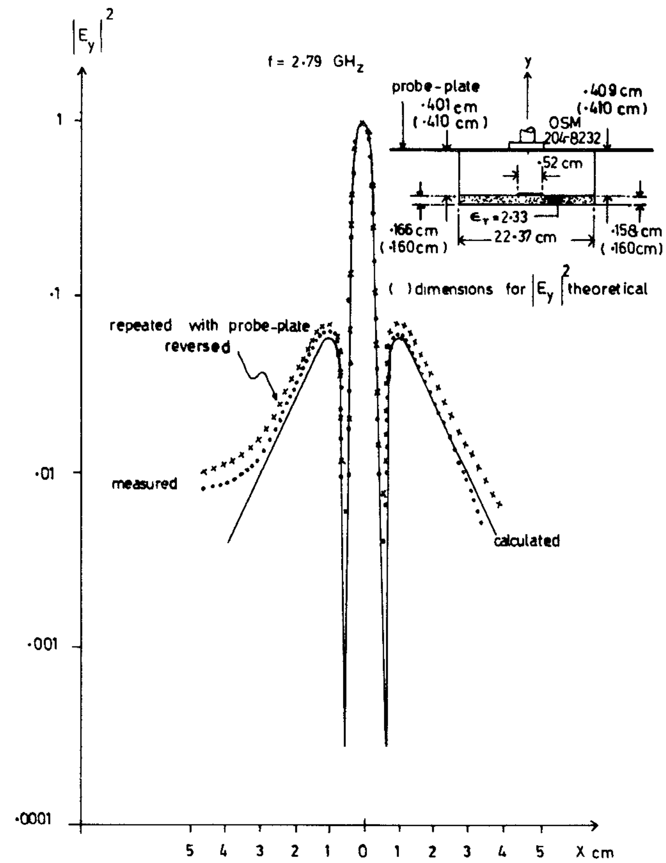

Fig. 4. Field of a microstrip line partially filling a rectangular metal tube.

measured accurately; this is confirmed by the results shown in Fig. 4.

III. Measurement Scheme

Altogether, three different circuits are measured: a wire-over-ground plane, a wire suspended axially in a rectangular metal tube, and a microstrip line partially filling a rectangular metal tube. In each case, the electric field is measured with the probe held above the circuit so that $y > h$. All three circuits are designed as linear short-circuit resonators several wavelengths long at about 3 GHz; in the case of the unshielded wire-over-ground plane the end plates are made sufficiently large to inhibit the antenna mode [4]. In each case, the signal frequency was adjusted so that at resonance the voltage standing wave pattern has a maximum halfway along the length of the circuit. The normal component of the transverse electric field was measured with the probe placed in this position and moving along x axis in small regular steps. This arrangement gives maximum output signal and minimizes the end effects.

For the unshielded circuit, the probe was fabricated by removing the screen and dielectric from a 2-mm section at the end of a long semirigid cable. In order to hold the probe and the cable vertical to the ground plane, the circuit was mounted on a lathe bed with the cable being attached to the stock. This arrangement also enabled the probe position to be adjusted very precisely. For the shielded circuits, the probe was formed by mounting an OSM 204-8232 miniature connector on to the probe plate such that only the 1.2-mm long center conductor protruded into the enclosure.

For shielded circuits, the cover plate was made in three sections as shown in Fig. 5. The end sections are equal in length and the central section is one wavelength wide with the probe mounted in the center. This ensures that for axially symmetric modes the probe is positioned on a voltage maximum; also, the gaps where the end plates join the probe plate coincide with the current minima and hence cause negligible radiation.

In all cases, the RF signal from the probe is measured on a power meter capable of measuring down to 10 μW on the most sensitive range.

IV. Discussion of Results

In Figs. 2 and 3, the measured results are compared with theory for the unshielded and shielded wire, respectively. In the case of the unshielded circuit, where a

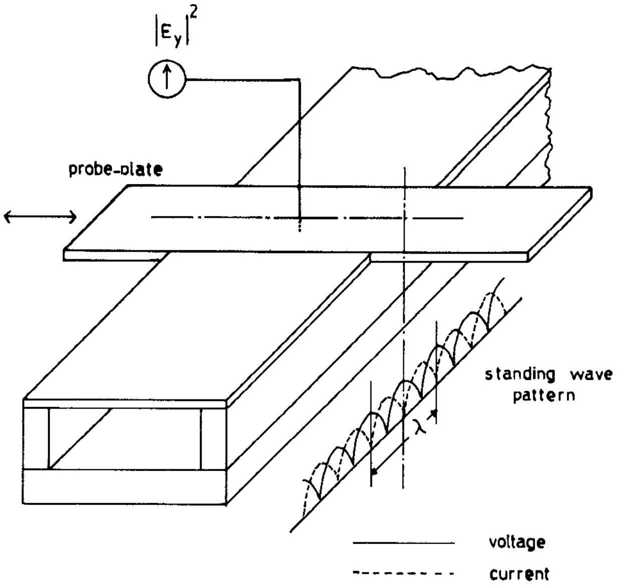

Fig. 5. Details of the enclosure used for field measurements.

considerable spurious coupling to the probe circuit is expected, the disagreement between measurements and theory is so large as to make this circuit unsuitable for probe calibration. Adding a metal plate to the probe circuit improves the agreement, but invalidates a direct comparison with the theoretical results in Fig. 2. The results shown in Fig. 3, on the other hand, show convincingly that with a shielded circuit, extremely accurate field measurements are possible.

In Fig. 4, the measured field distribution of shielded microstrip is compared with results calculated from the numerical analysis program [1]; results measured with the probe plate reversed are also shown. Taking into account the difference between actual dimensions of the enclosure and substrate, and those used in calculating $|E_y|^2$, the agreement between measurements and theory is excellent. These results verify the accuracy of the numerical analysis program and clearly show the power distribution in the microstrip. In a recent paper, similar results are reported by Ermert [5], however, the measurement scheme in the two cases is quite different and a direct comparison of the experimental results, therefore, is difficult.

Acknowledgment

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References

[1] D. Mirshekar-Syahkal and J. B. Davies, "Accurate solution of microstrip and coplanar structures for dispersion and dielectric and conductor losses," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, p. 694, July 1979.

[2] J. B. Davies and D. Mirshekar-Syahkal, "Spectral domain solution of arbitrary coplanar transmission line with multilayer substrate," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, p. 143, Feb. 1977.

[3] J. S. Dahele, "Electric probe measurements on microstrip circuits," PhD dissertation, Univ. of Hong Kong, Mar. 1979.

[4] H. H. Beverage, C. W. Rice, and E. W. Kellogg, "The wave antenna," *Trans. AIEE*, vol. 42, p. 215, 1923.

[5] H. Ermert, "Guiding and radiation characteristics of planar waveguides," *IEE J. Microwaves, Opt. Acoust.*, vol. 2, pp. 59–62, 1979.

Efficient Power Combining

MICHAEL DYDYK, SENIOR MEMBER, IEEE

***Abstract*—The objective of this paper is to establish understanding of the single/multimode oscillator circuits used in combiners.**

A model is developed with emphasis on the selection and realization of the input/output coefficients, optimum stabilizing and output loads, equalizing network synthesis, and other cogent features.

The application of this theory to the highly successful and efficient design of *J*-band pulsed oscillators will be discussed.

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The author is with Motorola, Inc., Government Electronics Division, Scottsdale, AZ 85252.

I. Introduction

THE NEED for higher and higher power, pulsed solid-state microwave oscillators is steadily expanding due to increased complexity of radar, communication, countermeasure, and fuzing systems. One way to meet this demand is to continuously work on the problem of increasing the output power and efficiency of the semiconductors and circuits used to generate the microwave energy.

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