Miniature Electric Near-Field Probes for Measuring 3-D Fields in Planar Microwave Circuits

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***Abstract*— Three-dimensional (3-D) electric near-field probes applicable to the 0.05–20-GHz band have been developed, which can measure both the magnitude and the phase of the microwave field inside of radio-frequency (RF) and microwave circuits. The field probes have very small dimensions and do not need to be connected to the operating device-under-test (DUT), therefore, the circuit properties are nearly not disturbed by the probe. Investigations on different circuits (e.g., antenna, meander lines, filters, and power amplifiers) show that such near-field probes can be applied not only to simple passive circuits, but also to measure the fields inside complex active circuits. These simple, stable, and cheap field probes are very useful for assisting the design of microwave circuits, antenna diagnostics, and testing products in industry.**

***Index Terms*—Field probes, microwave measurements.**

I. Introduction

With the growing complexity of circuit-integration techniques, especially in microwave integrated circuits (MIC's), there exist many problems in circuit design. Conventional network-analyzer techniques can only be applied to the device ports, hence, the designer has no way of controlling the performance of individual internal elements in a large integrated circuit. A nonconducting scanning microwave-field probing techniques has been developed, which measures the surface electric- and magnetic-field distributions of the circuits. Some miniature magnetic-field probes have been reported for measurements in high-frequency planar circuits [1]–[4]. However, such probes appear to be incompatible to strong radiating circuits, e.g., antennas and circuits on substrates with small dielectric constant substrates. An electric-optical probing system provides a very wide bandwidth and good resolution [5]–[8], but such a system is normally applicable only for special substrates (e.g., GaAs). A scanning-force microscope-based test system is used for device internal electric characterization of monolithic microwave integrated circuits (MMIC's) in [9] and [10].

A simple and practical probe using the inner conductor of a coaxial cable has been applied to investigate the electric-field distribution of microwave circuits [11], [12]. The investigation by Dahele and Cullen [11] dealt with the measurement of the electric field of microstrip lines using a coaxial probe, which is first calibrated against a known field, obtained by analyzing a wire suspended axially in a rectangular metal tube. In the work of Frayne [12], a scanning-network coaxial-monopole probe was suggested for use in circuit diagnostics at high frequencies above the normal working range of commercially available network analyzers. Some measurements in the 26–40-GHz band were presented, which agree well with theoretical predictions. A microwave-circuit electric-field imager is reported by Budka and Rebeiz [13]. A monopole scatterer and a dipole scatterer were used for scattering the normal and tangential electric field in the frequency range of 0.5–18 GHz.

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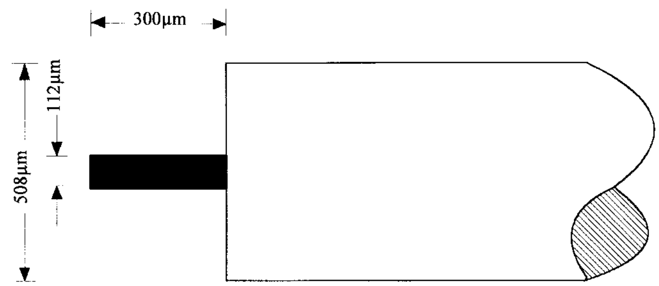


Fig. 1. Coaxial electric-field probe EPZ.

II. The Electric-Field Probes and Instrumentation

The field probes which have been developed must fulfill the following different requirements:

1) it must be certain that the electric-field probe measures only electric-field components and, vice versa, the magnetic-field probe only the magnetic-field components;
2) developed field probes must be small enough to give a good local resolution and not to disturb the measured field;
3) sensitivity of the field probes must be high enough;
4) there should be a possibility to calibrate the probes.

For example, a coaxial monopole may be utilized to measure the surface charge density (normal electric-field component) on the circuit, an electric dipole can be used to measure the tangential-field components in a surface over a circuit, and a magnetic dipole will respond to the local value of the time-derivated magnetic flux over the circuits.

A. The Electric-Field Probe EPZ for Measuring Field in the z-Direction

The electric-field probe EPZ for measuring the electric near field in the z-direction perpendicular to the substrate

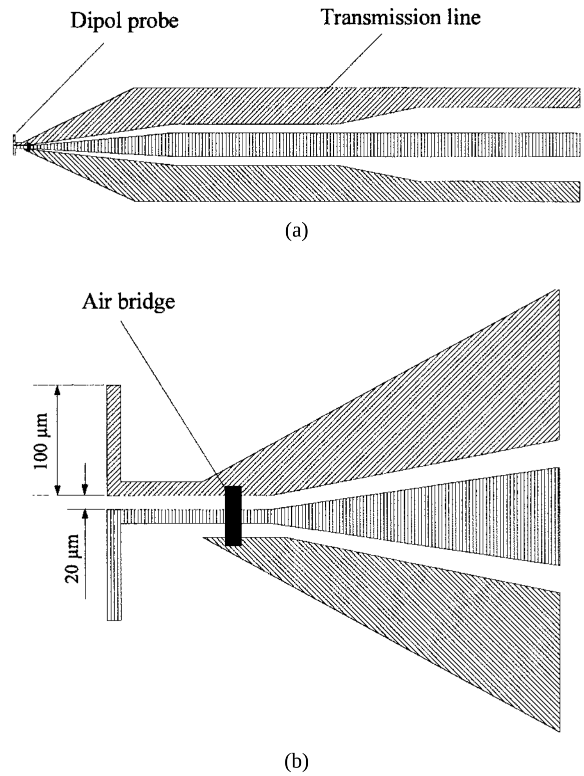


Fig. 2. Dipole electric-field probe EPZ. (a) With transmission line. (b) Expanded without transmission line.

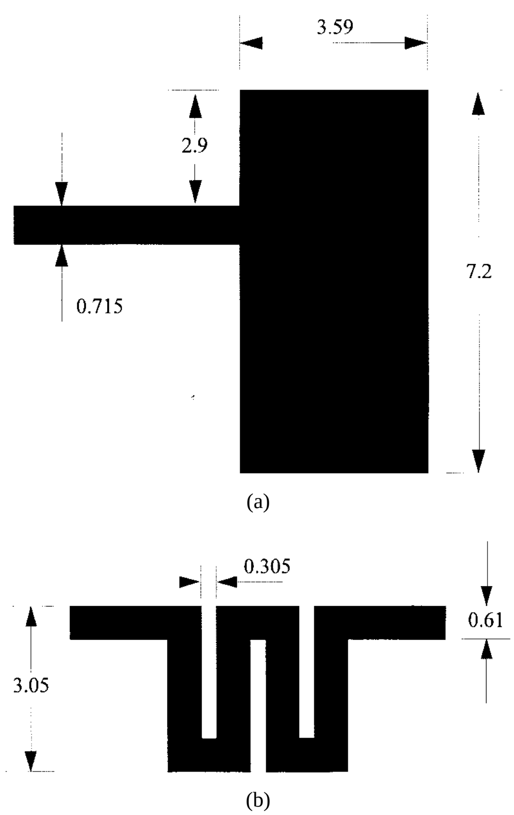


Fig. 3. The structures of (a) patch antenna and (b) meander line, dimensions are in millimeters.

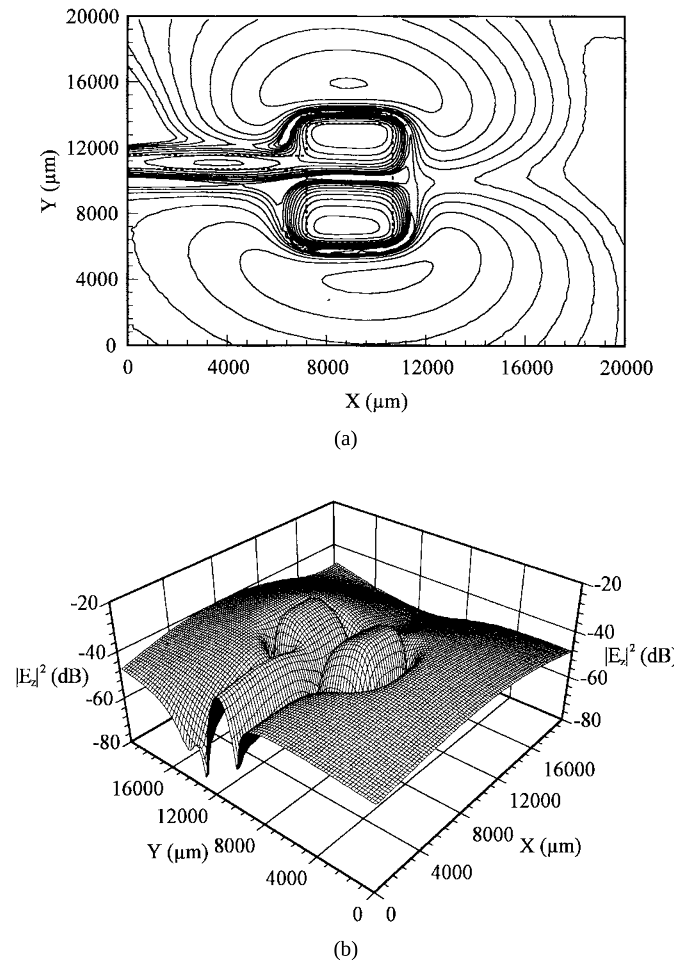


Fig. 4. $|E_z|^2$ distribution for a 13.12-GHz patch antenna. (a) Measured lines of constant field strength. (b) 3-D representation of the measured squared field strength $|E_z|^2$.

plane is a very simple construction fabricated from a 50-Ω semirigid coaxial cable. Several such probes were fabricated with different inner and outer diameters, which can be used for different frequencies and different circuit technologies. The smallest probe consists of a miniature coaxial line with 508-μm outer diameter and an inner conductor diameter of 112 μm. The inner conductor extends 300 μm beyond the outer conducting shield, as shown in Fig. 1.

This field probe is, in principle, a capacitive probe. In an electromagnetic field, an electric current is induced in a capacitor in the form of

$$i = C\frac{du(t)}{dt} \tag{1}$$

where

$$u(t) = AE(t) \tag{2}$$

$$\frac{du(t)}{dt} = A\frac{dE(t)}{dt} \tag{3}$$

and let

$$E(t) = \overline{E} f(t) \tag{4}$$

with

$$|f(t)| \leq 1 \tag{5}$$
$$\frac{dE}{dt} = \overline{E}\frac{df(t)}{dt} \tag{6}$$

so that

$$i = CA\overline{E}\frac{df(t)}{dt} \tag{7}$$

where $\overline{E}$ is the amplitude of the electric-field strength of magnitude E, C is the value of the capacitance, and A is a system constant. For the coaxial cable probe, the induced current mainly is induced by the z-component of the electric field. It is valid that

$$\boldsymbol{E} = E_x\boldsymbol{u}_x + E_y\boldsymbol{u}_y + E_z\boldsymbol{u}_z \tag{8}$$

obeys the condition

$$E_z \gg E_x \quad E_z \gg E_y \tag{9}$$

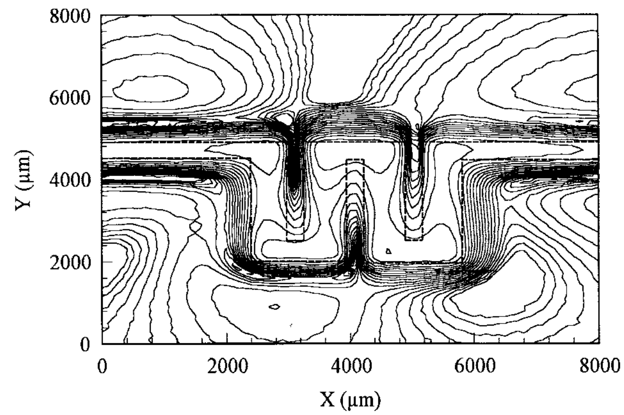
where $\boldsymbol{u}_x, \boldsymbol{u}_y, \boldsymbol{u}_z$ are unit vectors in the x-, y-, and z-directions, respectively. The expression of the probe current induced by the electric field $\boldsymbol{E}$ then is approximately given by

$$i \approx CAE_z\frac{df(t)}{dt}. \tag{10}$$

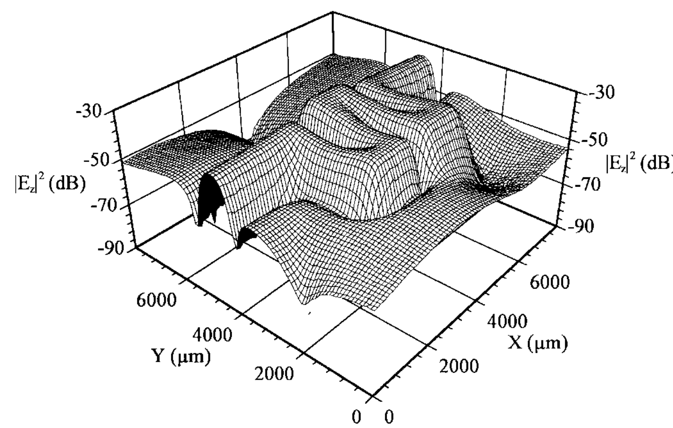
From this expression, it can be seen that the current of the probe to a first approximation is proportional to the z-component of the electric-field strength.

B. The Electric-Dipole Field Probe for Measuring Field in x- and y-Directions

An electric-dipole probe for measuring x- and y-components of the electric field has been developed. It consists of an electric dipole and a coplanar transmission line, as shown in Fig. 2. This construction is etched on a 1.38 × 7.0 mm^2 ceramic substrate ($\varepsilon_r = 9.8$, $h = 250$ μm). The dipole arms are 100-μm-long and the dipole width is 20 μm. The coplanar transmission line has a 50-Ω impedance, which is connected to a 50-Ω coaxial semirigid cable. In order to avoid the transmission line to sense the field, the central conductor of the transmission line is isolated with a nonconducting adhesive, and then the two ground planes are electrically connected with the silver adhesive, so that the probe signal is transmitted symmetrically. Otherwise, the open end of the ground plane radiates an electromagnetic wave, which influences the operation of the device-under-test (DUT) and the measurement.



(a)



(b)

Fig. 5. Measured $|E_z|^2$ distribution for a microstrip meander line at 11.4 GHz. (a) Measured lines of constant field strength. (b) 3-D representation of the measured squared field strength $|E_z|^2$.

The developed measurement setup is already shown in [4]. This is a three-dimensional (3-D) microwave-circuit diagnostic system. It consists of a PC computer, three motors and motor controllers, transmission stages, network analyzer, and AH 1300 test-fixture. The electric-field probe is mounted on a table, movable in three dimensions, and controlled by three motors, which are IW-712 inchworm motors from Burleigh Instruments Inc., but which can be replaced by cheaper step motors. These compact piezoelectric linear motors provide a resolution of 0.5 μm and a travel range of 50 mm. A normal network analyzer is used as a receiver. Alternatively, simple microwave receives can be used for cases where no network analyzer is available for this application. For the measurements here, a Hewlett-Packard 8510 Network Analyzer is used to excite the circuit input with -10 dBm input power and to receive the S_{21} signal from the probe. The movement of the field probe is controlled by a computer program that also overtakes the evaluation of the measurements.

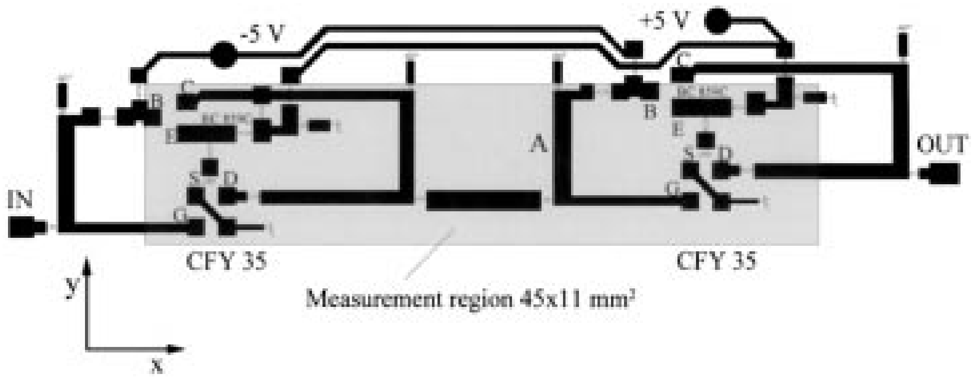


Fig. 6. The layout of an amplifier part of a receiver at 2.46 GHz.

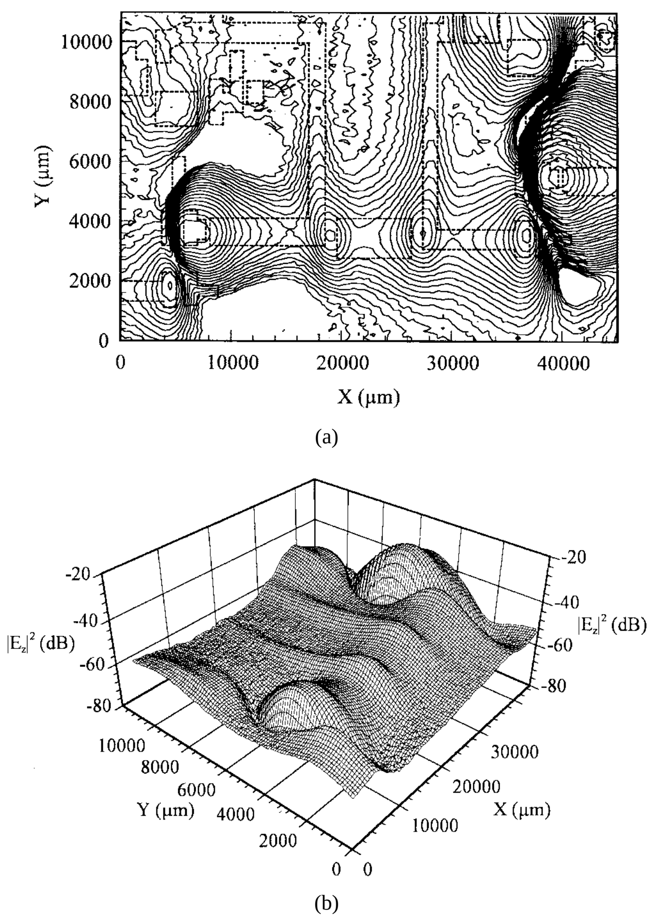


Fig. 7. $|E_z|^2$ distribution for a 2.46-GHz amplifier of a receiver. (a) Measured lines of constant field strength. (b) 3-D representation of the measured squared field strength $|E_z|^2$.

III. Measurement Results

A. Measurement of a Microstrip Patch Antenna at 13.12 GHz with Probe EPZ

The first structure under investigation is a microstrip patch antenna, shown in Fig. 3(a). The microstrip patch antenna is fed by a microstrip line in the same plane. The substrate thickness is $h = 790$ μm and the relative permittivity is $\varepsilon_r = 2.2$. The measurement has been taken over a region of 20 × 20 mm^2. Scanning steps of 200 μm in the x- and y-directions are employed, so that 10 000 field values are measured in each measurement cycle. The probe is placed in a height of 100 μm above the substrate for this measurement. The boundary of the conductor is shown in the contour picture of Fig. 4(a) by broken lines. An asymmetrical radiation field of the antenna in the y-direction is observed due to the asymmetrical excitation of the antenna. In Fig. 4(b), a 3-D presentation of the field is shown where the measured probe signal S_{21} from network analyzer is between −20 and −80 dB.

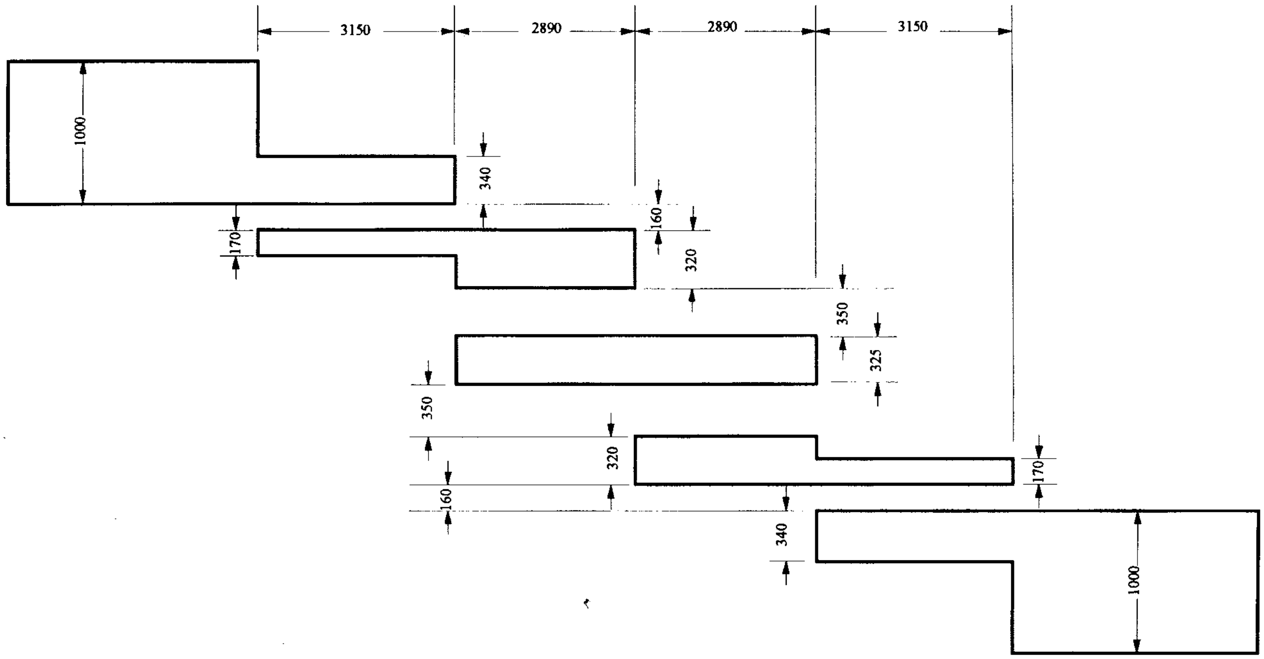
B. Measurement of a Meander Line at 11.4 GHz with Probe EPZ

The next example is a meander-line structure. It consists of a section of closely coupled bends and transmission lines on a ceramic substrate, shown in Fig. 3(b). The substrate height is 635 μm and the relative permittivity is $\varepsilon_r = 9.8$. The measurement is taken over a region of 8 × 8 mm^2. Scanning steps of 100 μm in the x- and y-directions are employed. The probe is placed in a height of 50 μm. The boundary of the conductor is shown in the contour picture of Fig. 5(a) by the broken line. A comparison between measured and calculated results is very good overall.

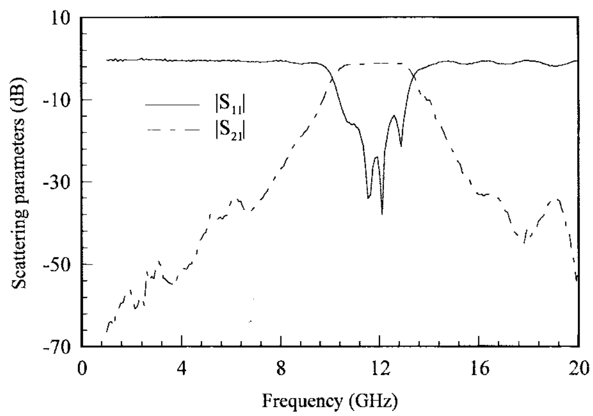
C. Measurement of an Amplifier for a 2.46-GHz Spread-Spectrum Receiver with Probe EPZ

The DUT in this investigation is an amplifier of a 2.46-GHz spread-spectrum receiver. It consists of two filters and a two-stage amplifier, which are produced on RT-Duroid ($\varepsilon_r = 2.33$, $h = 500$ μm) substrate material. The layout of the amplifier part of the receiver is shown in Fig. 6. Both stages of the amplifier use the same GaAs FET CFY 35 (Siemens) for signal amplification and a bipolar transistor BC 859C (Siemens) for bias point setting. Each stage has a gain of approximately 10 dB.

The measured normal component of the electric-field strength in a position 1000 μm above the amplifier surface is shown in Fig. 7. The maximal electric-field strength is measured at the output ports of the two transistors CFY 35. The transistors BC 859C, together with the bias circuitry,



(a)



(b)

Fig. 8. (a) The layout of a bandpass filter (dimensions are in micros). (b) Measured scatting parameters for the bandpass filter.

separate the radio-frequency (RF) field from the dc sources. The power transmission of the RF signal and the good isolation of the dc circuit from the RF can be clearly identified from the measured field distribution. The increase of the measured fields from the input to output port is in good agreement with the gain of 20 dB, as it is measured with a Hewlett-Packard Vector Network Analyzer between the input and output port.

From these measurements, together with a large number of other measurements performed, e.g., on passive components, it can be seen that the electric-field probe measurement technique is a valuable technique for microwave-circuit diagnosis and that it is capable to provide an essential physical insight into possibly available problem areas inside a circuits layout.

D. Measurement of a Bandpass Filter With Probe EPXY

A bandpass filter is used to test the dipole electric-field probe EPXY. The layout of the filter is displayed in Fig. 8(a). It is a four-stage coupled-line filter fabricated on an RT Duroid 6006 substrate ($\varepsilon_r = 6.0,\ h = 635\ \mu$m). Fig. 8(b) displays the measured magnitude of the filter scattering parameters. This bandpass filter has an insertion loss of 2.0 dB in the passband and provides about -15-dB rejection at the frequency 14 GHz.

Figs. 9 and 10 show the tangential electric-field distributions measured by the probe EPXY in the x-direction at 12.8 GHz in the passband and at 14 GHz in the stopband. The probe was scanned across an area of 10 mm $\times$ 20 mm and 100 μm over the filter surface. The results of the measurements show the properties of the filter in the passband and stopband. They agree well with measured results from a network analyzer. For a discussion of measurement errors, the change of the reflection coefficient S_{11}, when the probe enters the field, can be observed. The reflection coefficient of the filter should not be changed during the measurement, but the coupling effects between probe and filter change the reflection coefficient of the filter. The maximal changes of S_{11} in the passband and in

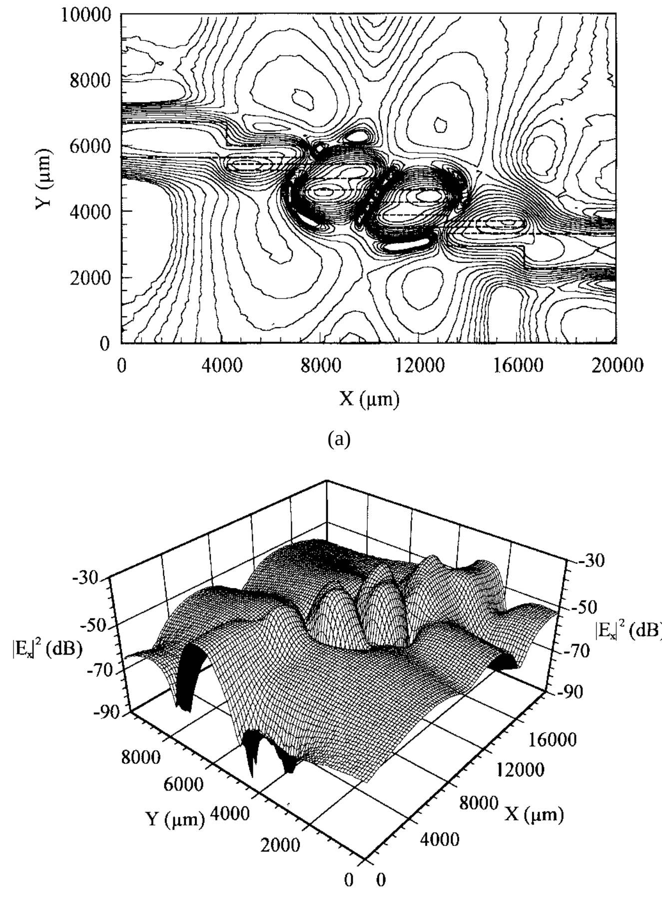


Fig. 9. $|E_x|^2$ distribution for a bandpass filter at 12.8 GHz. (a) Measured lines of constant field strength. (b) 3-D representation of the measured squared field strength $|E_x|^2$.

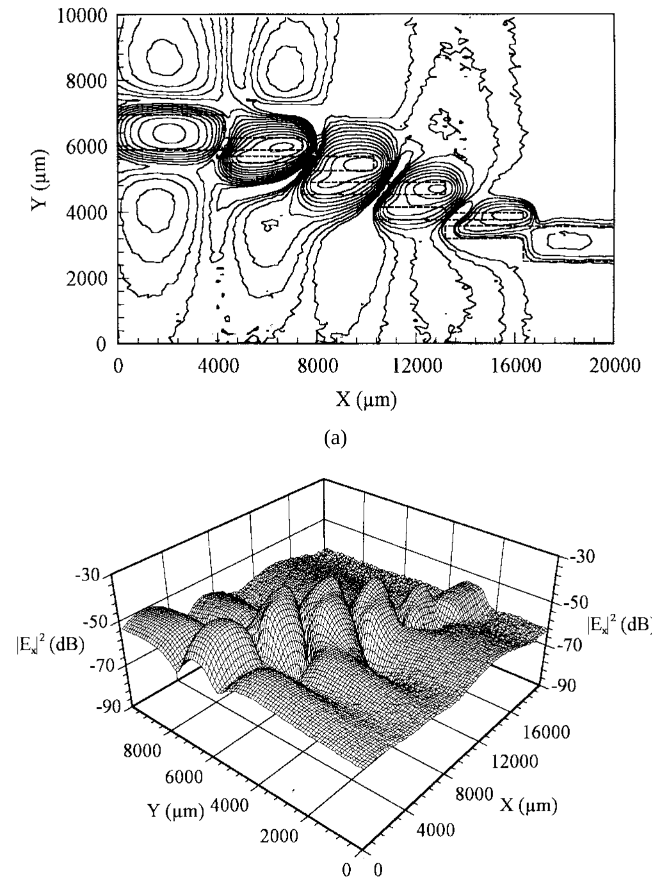


Fig. 10. $|E_x|^2$ distribution for a bandpass filter at 14 GHz. (a) Measured lines of constant field strength. (b) 3-D representation of the measured squared field strength $|E_x|^2$.

the stopband are about 7.0 and 0.4 dB, respectively. It means that the measurement error is larger if the DUT has a smaller reflections coefficient, e.g., as in the passband. In order to improve the accuracy of the measurement, a smaller probe is needed. For example, it can be tried to cut the substrate of the probe EPXY, so that the substrate in the top of the probe has the same size as the dipole (220 μm). Another way to improve the accuracy is to set the probe in a higher position, but this will reduce the sensitivity and the resolution of the measurement.

IV. Conclusions

In this paper, investigations using electric-field probes on passive and active MIC's are presented. The electric-field probe constructions and the measurement setup have been discussed. The potential of the field probe measurements for circuit diagnostics are described using some examples. These probes are very useful for magnitude and phase measurements of the electric fields at interior points of planar microwave circuits. They help in the design and manufacturing process of microstrip and other printed antenna. In order to quantitatively measure the electric field of microwave circuits, the probes must be calibrated using a known field. Relative measurements can be made by calibrating the probe in a special position inside the circuit, e.g., at the input port. The accuracy of the measurement is then approximately 0.5 dB.

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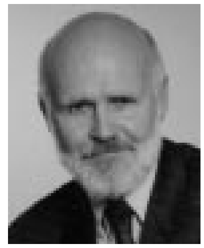

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