A New Miniature Magnetic Field Probe for Measuring Three-Dimensional Fields in Planar High-Frequency Circuits

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***Abstract*—A new noncontacting miniature magnetic field probe for measuring the surface current distribution on high-frequency planar circuits in x-, y-, z-directions in the 1–20 GHz band has been designed, fabricated and tested. The field probes have very small dimensions and do not need any connection to the operating circuit under test, therefore there is almost no perturbation of the circuit properties. This simple and practical magnetic field probes can be used to assist the design of microwave circuits, antenna diagnostics and to test products in industry. This paper describes the producing procedure of the magnetic field probes, a scanning diagnostic system, measurement examples and comparisons between measurements and calculations. The measurement results agree very well with theoretically expected field distributions.**

I. Introduction

WITH the growing complexity of circuit-integration techniques, especially in microwave integrated circuits (MIC's), there exist many problems in circuit design, for example in fault location and test procedures. Conventional network analyzer techniques can only be applied to the device ports, therefore no information on the internal circuit elements is given. One early method of measuring the dispersive properties of a microstrip field with the inner conductor of a coaxial cable was reported in [1], [2]. However, this probe is not applicable in the case of dimensional small circuits. Another electro-optical probing system provides a very wide bandwidth and good resolution [3], [4], but such system is normally complicated, expensive, and applicable only for special substrates. To measure detailed field distributions, a miniature magnetic field probe has been developed here. This simple and practical field probe can be used in circuit design, antenna diagnostics and production tests. It is an important advantage for this probe that it does not have galvanic contact with the circuit during the measurement procedure, hence the disturbance of the circuits under test is very small. At least two authors have described magnetic field probes, which were used in similar applications [5]–[7]. Osofsky and Schwarz constructed probes, which consist of two loops and have the form of a magnetic quadrupole and which were used in the 26.5–40 GHz range [5], and from 0.1 to 0.3 GHz [6]. The described configuration however has an electric asymmetry of the probe central conductor, which therefore also works as an electric field probe in the perpendicular direction. This asymmetry disturbs the magnetic measurements, especially in the position of the magnetic field minimum, where the electrical field is maximum. In the work of Grzybowski and Bansal [7], a half-loop magnetic field probe has been discussed in which a 1 mil gold bond wire was connected to a Cascade Microtech WPH-102-250 wafer probe test head. Because the fabrication procedure is very complicated and additionally the wafer probe test head is expensive, it seems not to be suitable for practical applications. In order to solve all these problems

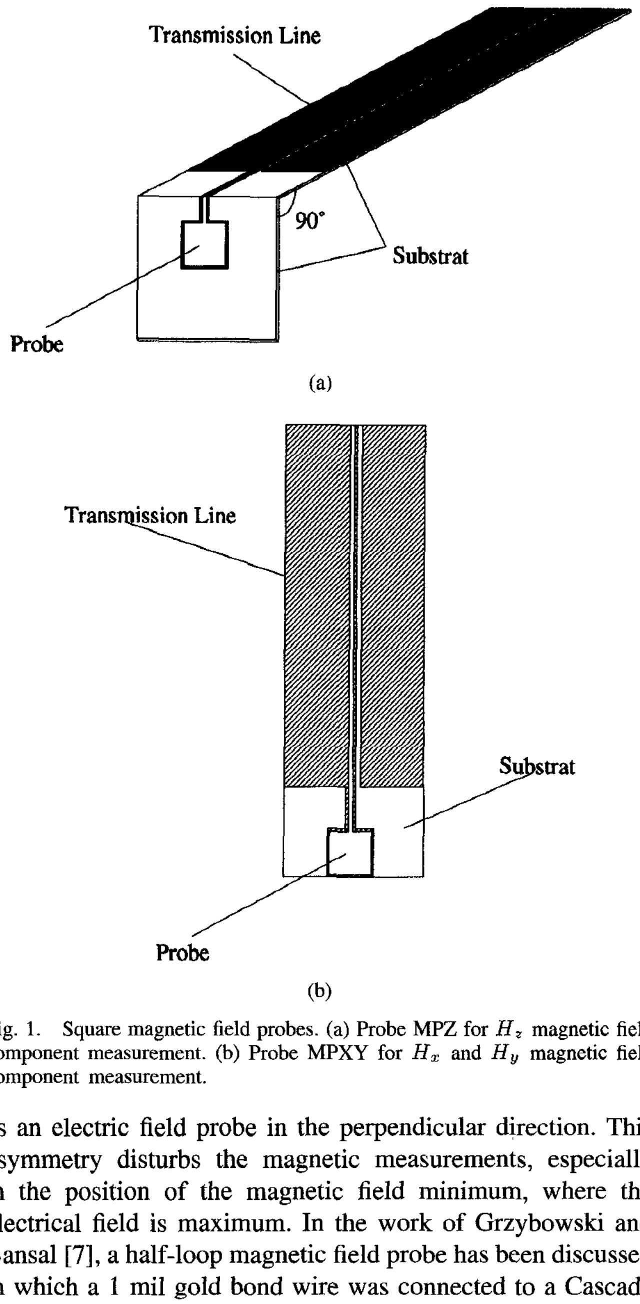

Fig. 1. Square magnetic field probes. (a) Probe MPZ for H_z magnetic field component measurement. (b) Probe MPXY for H_x and H_y magnetic field component measurement.

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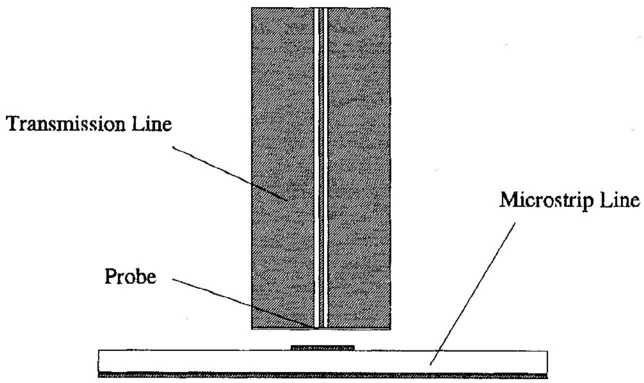


Fig. 2. Probe position over the microstrip line.

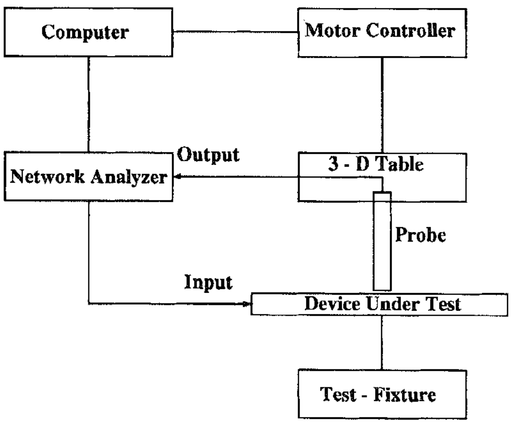


Fig. 3. Block diagramm of the field measurement system.

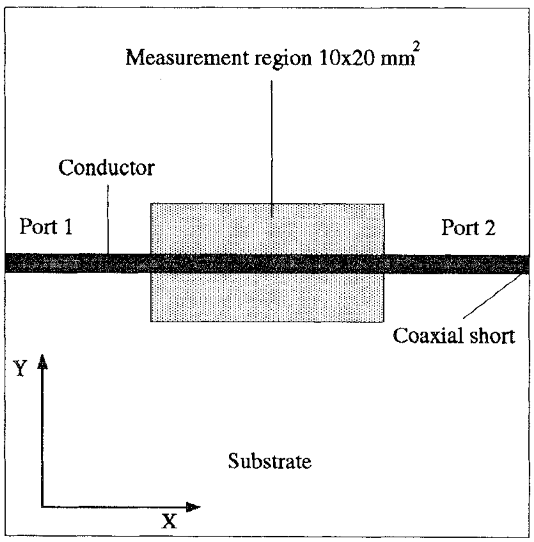


Fig. 4. A short-circuited microstripline.

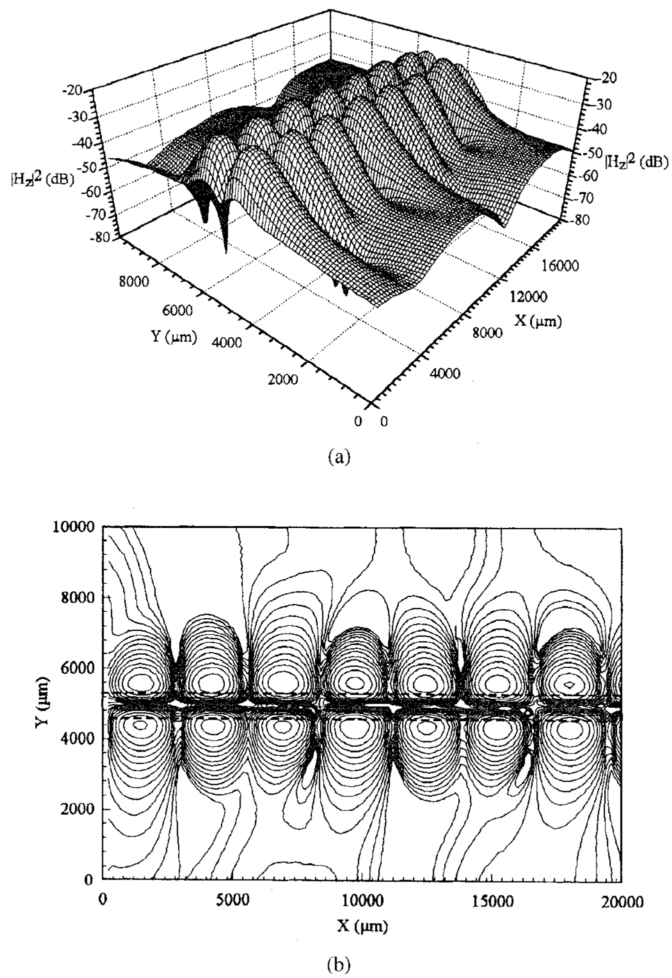


Fig. 5. Measured H_z field distribution of a short-circuited microstripline at 20 GHz. (a) Three-dimensional (3-D) representation of the measured squared field strength $|H_z|^2$. (b) Measured lines of constant field strength.

connected with the available magnetic field probes, a kind of new square magnetic field probes has been designed. Some measurements on shorted microstrip lines and a stub antenna using these probes are presented and compared with theoretical calculations.

II. Probe and Instrumentation

In the high frequency regime the dimensions of circuits are very small. In order to accurately measure the amplitude and phase of fields at points inside a circuit, a field probe must be as small as possible, so that the perturbation of the operating circuits by the probe can be ignored approximately. The design of the magnetic field current probes started using a conducting loop. It was assumed that the loop is immersed into a plane linearly polarized electromagnetic wave in free space and is placed in the x-y, x-z or y-z plane, perpendicular to the magnetic field H_z-, H_y- or H_x-components, which are considered to be constant over the area of the loop. Because the dimensions of the loop probe are much smaller than the wavelength and the form of the loop is square, the induced electrical field is compensated in the loop. Under these conditions the current I induced in the loop is only proportional to the magnetic field radiated from the Device Under Test (DUT). Measuring the magnetic field distributions on a microstrip line, the probe signal A has the form

$$A = KI(l) \tag{1}$$

where K is the coupling coefficient, which is associated with the properties of the probes and can be obtained by calibration, and l is the relative distance between the DUT and the probe plane. Because of the small size, the probe can be placed very

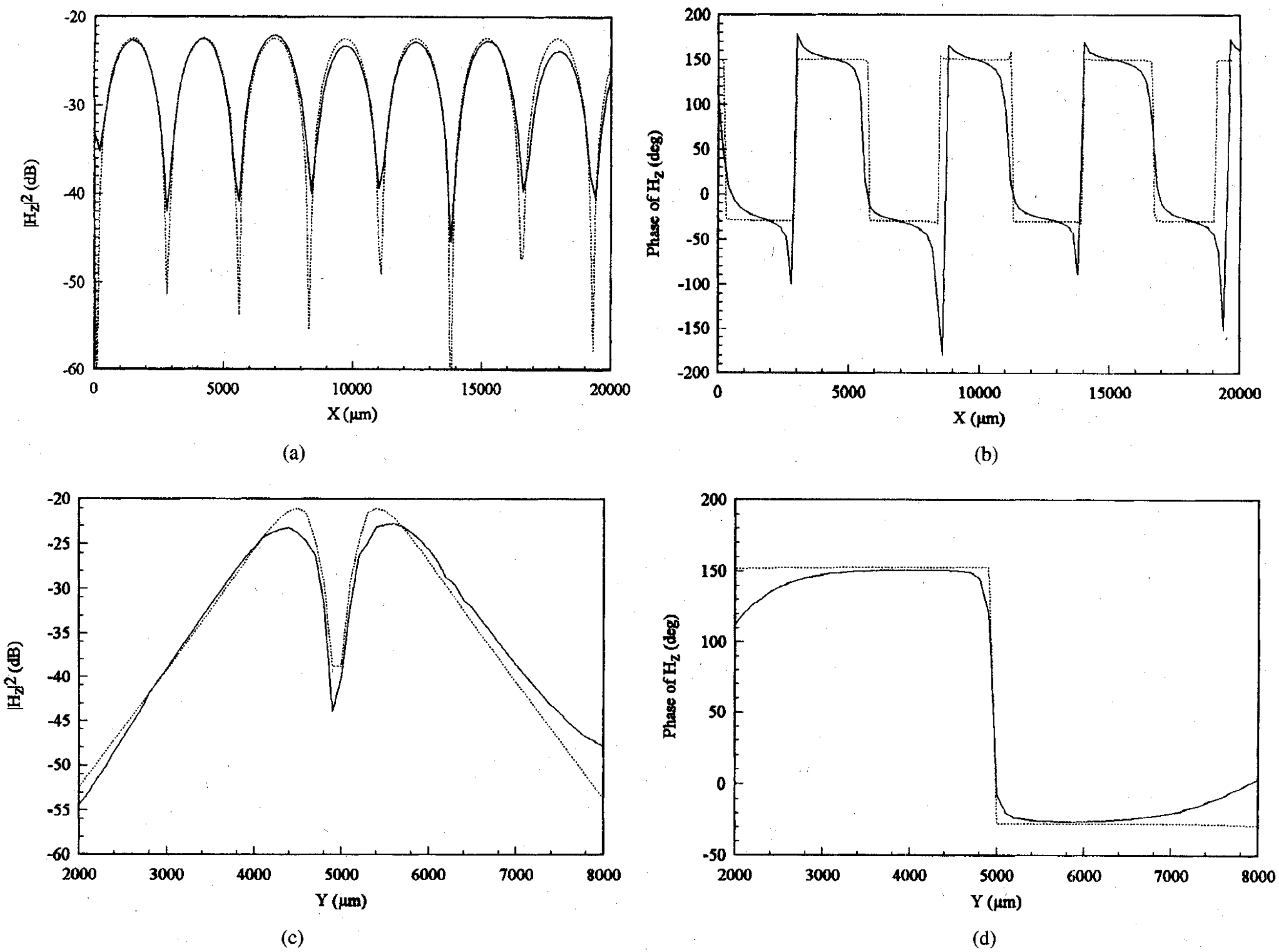


Fig. 6. Comparison of measured and calculated squared-amplitude $|H_z|^2$; (a) and phase (b) of H_z along a shorted microstripline, (c) the squared-amplitude $|H_z|^2$, and (d) the phase of H_z perpendicular to the shorted microstripline at current maximum. (—— measured, ········ calculated).

near to the DUT with a very small influence on the DUT and an increased sensitivity of the measurement.

The size of the fabricated probes is in a first approach $710 \times 710\,\mu$m. Each probe and a short transmission line are etched on a $3 \times 20\,\text{mm}^2$ RT Duroid substrate ($\epsilon_r = 2.2, h = 0.5\,\text{mm}$). The central conductor of the transmission line is insulated with a non conducting adhesive, and then the two ground planes are electrically connected with silver adhesive (not shown in figures), 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 DUT and the measurements. The substrate was then bent by 90° between the probe and the transmission line in order to measure the magnetic field H_z-component (probe MPZ) as shown in Fig. 1(a). The transmission line is connected to a semirigid coaxial cable, which links to a network analyzer through a SMA plug.

The square loop probe is $710\,\mu\text{m} \times 710\,\mu\text{m}$ in size and its conductor width is $55\,\mu$m after production. This width of the conductor is a very important factor for such a probe. The smaller the width of the conductor is, the smaller the influence of the probe on the circuit will be, and hence it can be used for higher frequency bands. With the available technology, the width of the transmitting conductor must be larger than $50\,\mu$m, otherwise the conductor may break during the above mentioned bending procedure. The probe has a geometrically symmetrical form and is a one-loop square magnetic field probe, hence the results of the measurements can be directly interpreted. Using this simple form of the probe, also the two other components of the magnetic field (x-, y-directions) can be measured, if the substrate of the probe is not bent by 90° (probe MPXY), as shown in Fig. 1(b). These two probes have the same loop size and the same transmission lines, but the loop of the probe MPXY is placed to the edge of the substrate. Because of the tolerances in fabrication, it is very difficult to produce probes with equal properties, for example equal electrical impedances. It means that it is improper to compare measurements from different probes without calibrating the probes. Using a thin film technology, the production costs for the magnetic field probes are very small and a very stable field probe can be fabricated, i.e., it is suitable for industrial applications.

The probe position over the circuit is shown in Fig. 2. For the measurements the distance between the probe and the circuit is an important factor. If the probe is too near to the circuit, it may obtain a large signal, but it then disturbs the operation of the circuit. For the measurements shown later, it was an aim to hold the probes in a constant plane during

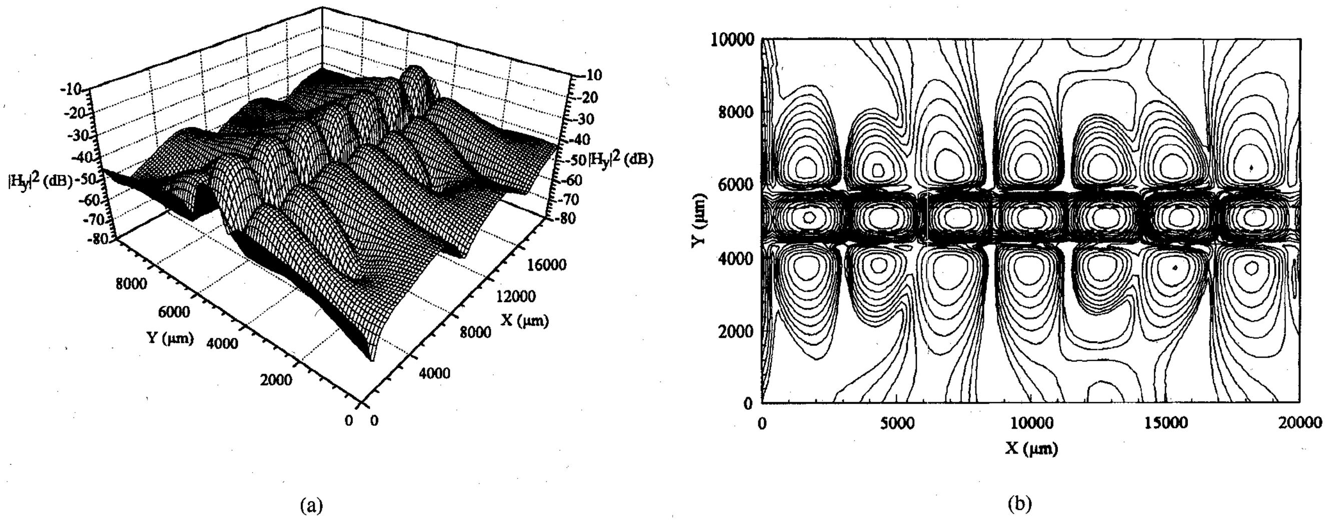


Fig. 7. Measured H_y field distribution of a short-circuited microstripline at 20 GHz. (a) 3-D representation of the measured squared field strength $|H_y|^2$, and (b) measured lines of constant field strength.

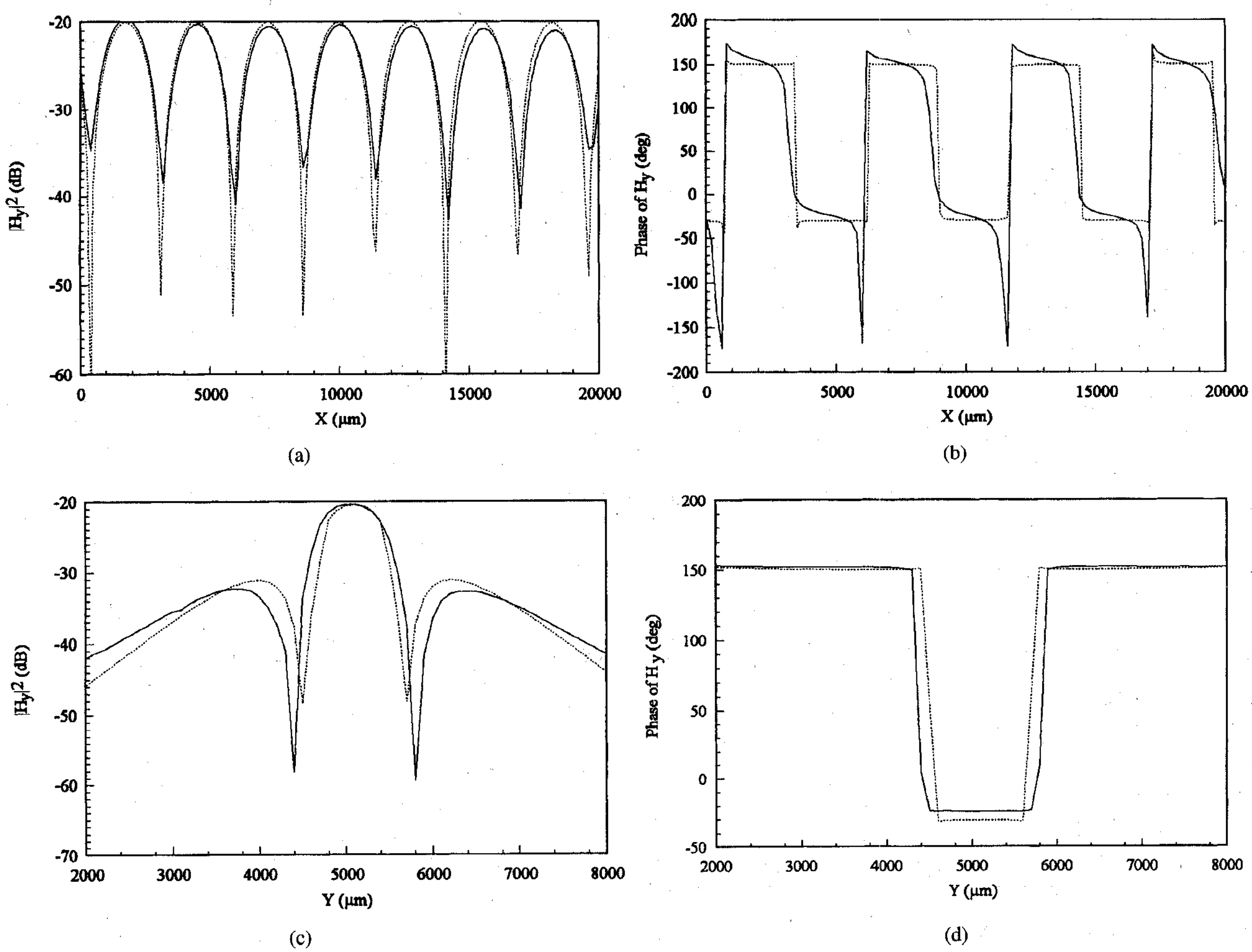


Fig. 8. Comparison of measured and calculated squared-amplitude $|H_y|^2$; (a) and phase (b) of H_y along a shorted microstripline, (c) the squared-amplitude $|H_y|^2$, and (d) the phase of H_y across a shorted microstripline at current maximum. (—— measured, ········ calculated).

the measurements in three directions, so that the results finally can be compared with each other. The probe MPZ is placed in a height of 400 μm and the probe MPXY 100 μm above the circuit, in order to have the central points of the probes at the same level. It is also important that the substrate height variations of the DUT must be kept to a minimum, if the probe is placed near to the circuit.

A block diagram of the field measurement system is shown in Fig. 3. This is a three-dimensional (3-D) microwave circuit diagnostic system. It consists of one PC computer, three

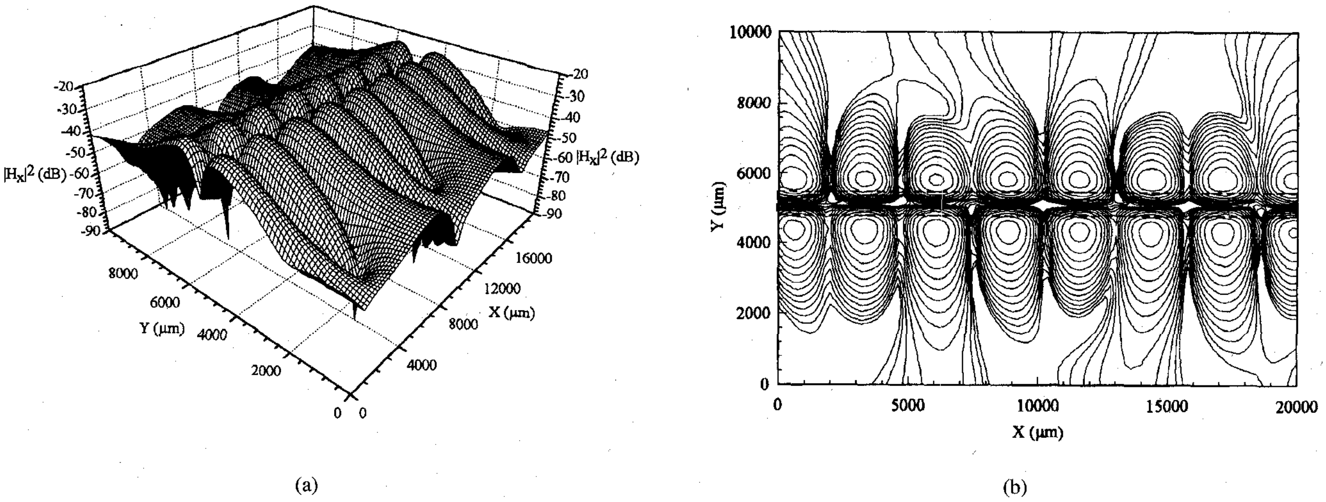


Fig. 9. Measured H_x field distribution of a short-circuited microstripline at 20 GHz. (a) 3-D representation of the measured squared field strength $|H_x|^2$. (b) Measured lines of constant field strength.

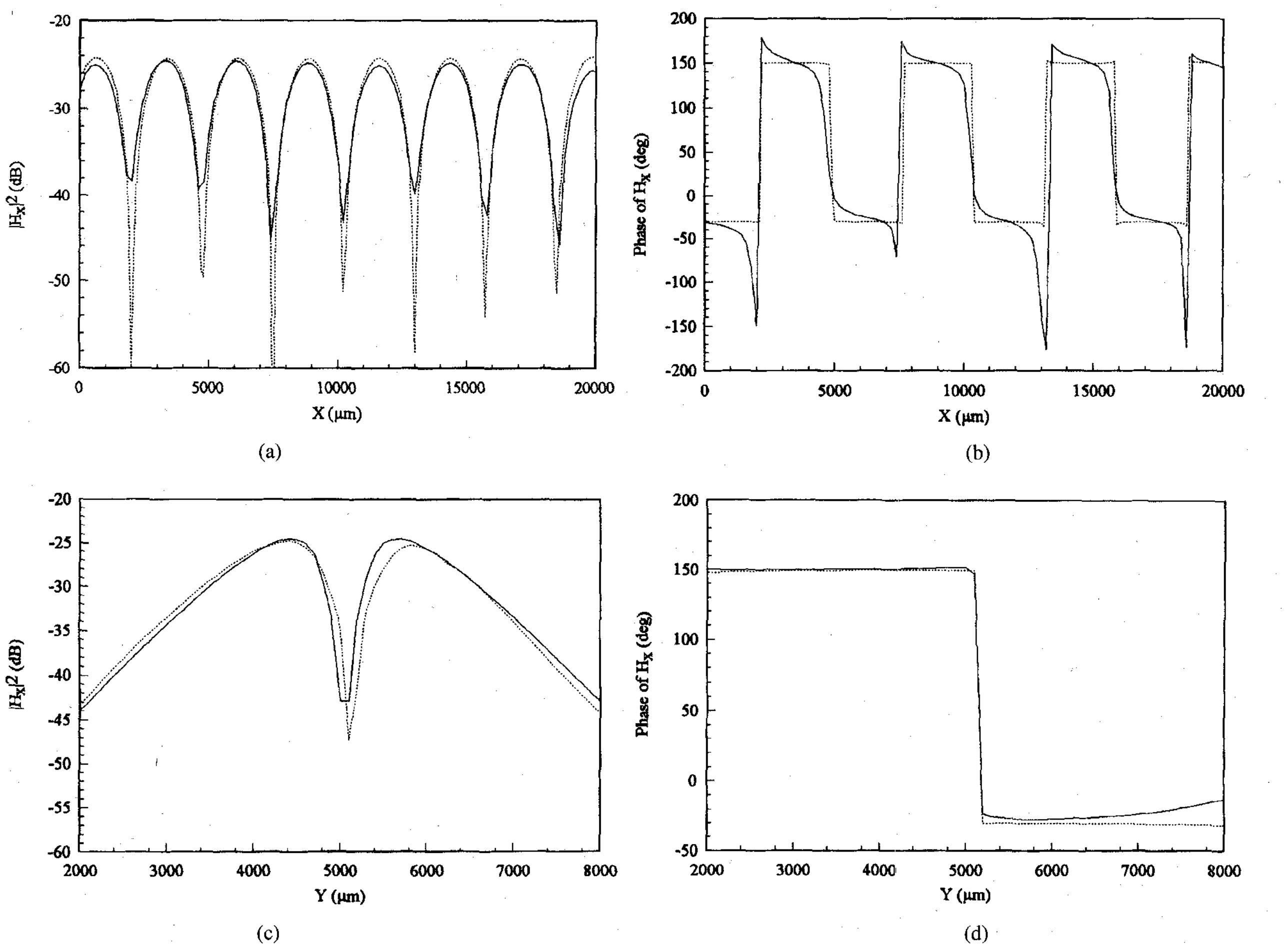


Fig. 10. Comparison of measured and calculated squared-amplitude $|H_x|^2$; (a) and phase (b) of H_x along a shorted microstripline, (c) the squared-amplitude $|H_x|^2$, and (d) the phase of H_x across a shorted microstripline at current maximum. (—— measured, ········ calculated).

motors and motor controllers, a 3-D table, a network analyzer, and an AH 1300 test-fixture from ArguMens GmbH. The magnetic field probe is mounted on a table, movable in three dimensions, 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 open loop positions with 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 receivers can be used for cases where no network analyzer is available for this application. For the measurements here a Hewlett Packard 8510 vector network analyzer is used

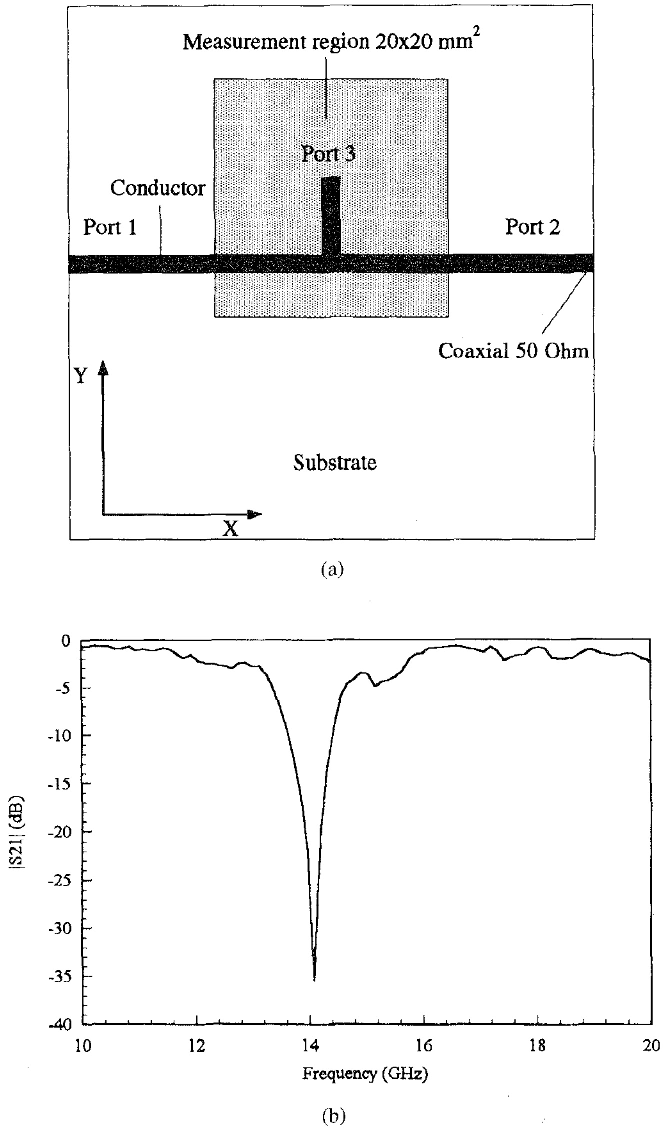


Fig. 11. (a) 14 GHz microstrip stop band filter geometry, and (b) value of the S_{21}.

to excite the circuit input with $-10\,\mathrm{dBm}$ input power and to receive the S_{21}-signal. The movement of the field probe is controlled by a computer program that also overtakes the evaluation of the measurements.

III. Measurements

A. Measurements on Microstrip Lines

In order to check the magnetic field probe, a 685 μm shorted microstrip line was constructed on a ceramic substrate with a size of $50.8 \times 50.8\,\mathrm{mm}^2$, a height of 635 μm and a relative permittivity $\epsilon_r = 9.8$, shown in Fig. 4. The measurements shown here have been taken over a region of $20 \times 10\,\mathrm{mm}^2$ of the microstrip lines. Scanning steps of 200 μm in the x- and 100 μm in the y-direction were employed, so that 10 000 field values were measured in each measurement cycle. The stepper widths depend on the structure of the circuit, the frequency, and the size of the probe. If the circuit components are closely spaced, the steps must be smaller, which may lead to a long measurement time. It is possible that the minimum step of the measurements is set to 1 μm and the maximum range is set to $50 \times 50\,\mathrm{mm}^2$ for this measurement system.

1) Measurement of z-Directed Magnetic Field Strength Using MPZ-Probe: The measurement result of the H_z-component in a standing wave at 20 GHz is shown in Fig. 5. Shown are the lines of constant magnetic field strength in the plane 400 μm above the circuit. The maximum signal can be measured near the edge of the conductor. From this measurement the wavelength λ and the effective dielectric constant of the microstrip line $\epsilon_{r,\mathrm{eff}}$ can be obtained

$$\epsilon_{r\mathrm{eff}} = \left(\frac{\lambda_0}{\lambda}\right)^2. \tag{2}$$

In Fig. 5(a) a three dimensional representation of the field is shown, where the measured signal S_{21} corresponding to $|H_z|^2$ from the network analyzer is between -20 and $-80\,\mathrm{dB}$, but it is possible that a probe signal under $-60\,\mathrm{dB}, \mathrm{SWR} > 4$, may be inaccurate. It will also be observed that the periodic shifts of the SWR maxima are different in positions near the conductor and on the ground plane. The boundary of the conductor is shown in the contour picture Fig. 5(b) by the broken line. From this figure $\lambda = 5.5\,\mathrm{mm}$ can be measured and $\epsilon_{r,\mathrm{eff}} = 7.4$ can be calculated using (2).

Comparison of measured and calculated amplitude and phase signals along and across the shorted microstrip line in the probe signal maxima are shown in Fig. 6. In x-direction the amplitude is shown only in the range $\mathrm{SWR} < 4$, because it was not possible to consider the real measurement conditions in the calculations. In y-direction only a measurement range from 2000 μm to 8000 μm, e.g., about 4000 μm far from the microstrip line is shown. Outside this range the magnetic field strength of the conductor may be smaller than other disturbing signals, as for example the signals radiated from the coaxial conductor and the transmission line of the probe. The current distribution on the shorted microstrip line can be assumed in the form [6]

$$I(l) = M_0(e^{-jk_g l} - e^{jk_g l}) \tag{3}$$

with a real wave propagation constant k_g. The current magnitude M on the microstrip line is given by

$$M(l) = [1 + |\rho|^2 - 2|\rho| \cos(2k_g l + \phi_\rho)], \tag{4}$$

if the wave propagation constant k_g is complex, then the current magnitude M has the form

$$M(l) = [1 + |\rho|^2 - 2|\rho| \cosh(2k_g l + \phi_\rho)]. \tag{4a}$$

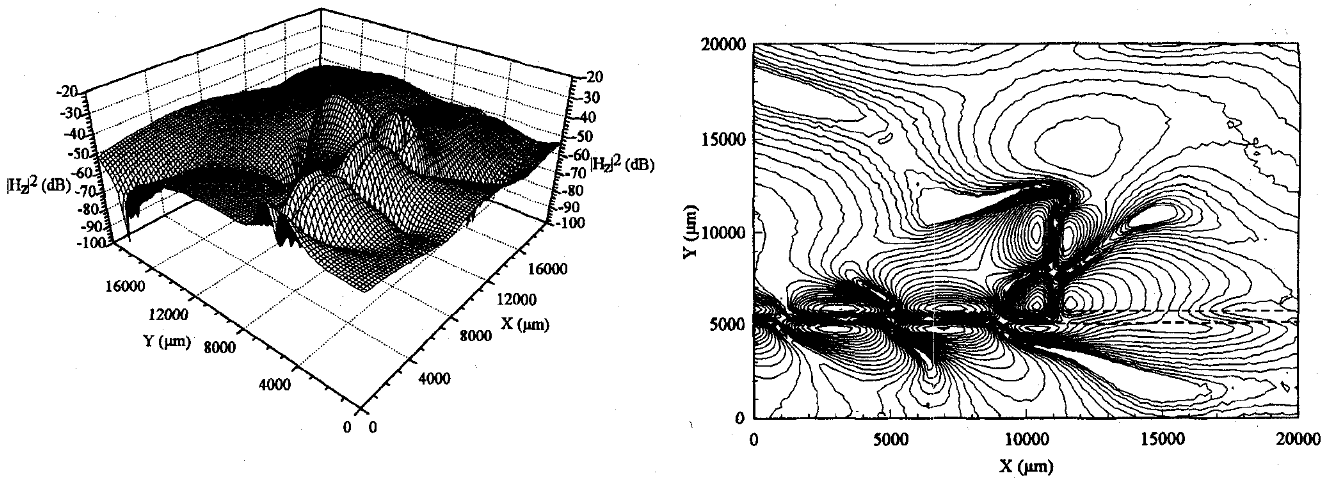
The phase Φ on the microstrip line is given by

$$\phi(l) = \phi_0 + \arctan[-(\mathrm{SWR})\tan(k_g l + \phi_\rho/2)], \tag{5}$$

here SWR is the standing wave ratio, given by

$$\mathrm{SWR} = \frac{1 + |\rho|}{1 - |\rho|}. \tag{6}$$

Using (3) and (4), the amplitude and phase of the current distribution can be calculated, which then can be used for comparison with measurements. However it is not easy to



(a) (b)

Fig. 12. Measured magnetic field distribution of the stop band filter at 14 GHz. (a) 3-D representation of the measured $|H_z|^2$ values. (b) Measured lines of constant magnetic field strength.

determine all the parameters, $k_g, M_0, \rho(= |\rho|e^{j\Phi_\rho})$, and Φ_0 especially at high frequencies. Therefore an analysis based on a numerical field calculation is applied for comparison. The analytical expressions (3)–(6) finally can be used to analyze the occurring errors.

The theoretical results used here for comparison are based on the work [9] and a program which uses the finite difference time domain method (FDTD) with perfectly matched layer (PLM) absorbing boundary conditions. For comparison the calculated results are normalized to the maximum probe signal. It is reasonable that the magnetic H_z-field distribution along the shorted microstrip line is about a standing wave and across the shorted microstrip line has a dual-lobe pattern. It may be recognized that the cycles of the measured and calculated magnetic fields agree very well, Fig. 6(a). In the positions of the signal minima the measured and calculated amplitudes deviate, this is due to that the step width (Δx) of the measurement is not small enough and the size of the probe is too large compared to the size of the microstrip line to exactly measure the minimum signal. Another reason is the influence of the electrical field, because the electrostatic coupling between the microstrip line and the field probe rises errors in these positions. That is to say, in order to exactly measure the minimum signal of the microstrip line at frequencies as high as 20 GHz, the size of the probe must still be smaller. Nevertheless, even for the numerical calculations it is also difficult to keep a high accuracy for SWR > 4. The phase distribution along the transmission line is shown in Fig. 6(b). For an ideally shorted microstrip line the distribution of the phase along the conductor must be $+90°$ in one half cycle and $-90°$ in the other half cycle without considering the initial phase angle in (5). The phase distribution of the measurements is not constant in a half cycle, because the measured microstrip line is not an ideal $50\,\Omega$ line and it is shorted by a coaxial termination, that means, the current distribution is not an ideal standing wave $(\rho < 1)$. This phenomenon influences weakly the amplitude distribution, but strongly the phase. There is a strong negative overshooting pulse of the phase in the position changing from one cycle to the other. This error results from the phase calculations using the function

$$\phi - \phi_0 = \arctan\frac{\mathrm{Im}(z)}{\mathrm{Re}(z)}. \quad (7)$$

In these positions the magnitude of the real parts are much larger than that of the imaginary parts and $\Phi - \Phi_0 \cong \pm 90°$.

In the cross section, Fig. 6(c), the calculation shows that the maximum field value occurs very near to the conductor, but the measured signal is about $100\,\mu$m shifted compared to the calculations and it is a little bit flatter. This is due to that the size of the probe is not small compared to the conductor width of the microstrip line. However it is seen that the measured and calculated amplitudes and phases agree very well in the range from $2000\,\mu$m to $8000\,\mu$m.

2) Measurements in x-, y-Directions with the Probe-MPXY: The area scan of the shorted microstrip line at 20 GHz in y-, x-directions as given in Figs. 7 and 8 show the overall field distribution. The maximum signals of the H_y- and H_x-components are measured at the center of the conductor and at the edge of the conductor. The measured and calculated maximum signals along and across the conductor of the two measurements are shown in Figs. 8 and 10. The same wavelength and effective dielectric constant ϵ_r, eff as those from the H_z measurement are obtained from these measurements. This observation demonstrates that the results of the measurements are well reproducable. The magnetic field distribution in the y-direction is a tri-lobe pattern and the maxima lie in the center conductor of the shorted microstrip line. The agreement between the measured and calculated H_y minima is good, because the probe now is placed along the conductor of the microstrip line, where an electric field disturbance can be avoided. The phase distributions of the H_y- and H_x-measurements in the longitudinal section have the same problems as those of the H_z-measurement, but in the cross section the agreement of the measured and calculated phase distribution is very good, as can be seen in Figs. 8(d) and 10(d).

In these measurements the probes are set to 100 μm above the DUT. It was tried to place the probes MPZ and MPXY in correctly the same plane for the measurements in the three-directions, so that the results of the measurements really can be compared to each other. It is seen that the maximum of the H_y-component is about 5 dB larger than that of the H_x-component, as it is expected from theory. In the calculations the H_z maximum is equal to the H_y maximum, but this is not in measurements, even though the centers of the probes are nearly in the same plane. This is due to that the probes may have different physical properties, for example resulting from different electrical impedances and the 90° bend of the probe MPZ. That means the probes must be calibrated if a quantitative comparison between the different probes and their signals are needed. It is possible that the total magnetic field H in one plane above the DUT is investigated using the results of the measurements in all three-directions and two calibrated magnetic field probes.

B. Measurement on a Stop Band Filter Using MPZ-Probe

The next structure under test is a microstrip stop band filter. This filter uses a $\lambda/2$ stub with a 685 μm conductor shown in Fig. 11(a). The same substrate was used here as in the case of the microstrip line. The measurement has been taken over a region of $20 \times 20\,\text{mm}^2$ of the stub filter. The scanning steps in x- and y-directions are 200 μm.

Fig. 11(b) shows the measured results for the amplitude of the transmission coefficient S_{21}. It can be seen, that there is a minimal transmission between port1 and port2 at 14.0 GHz. The signal will be transmitted from port1 to port3 at such frequency, but it is not easy to measure the transmission coefficient S_{31}. The near field distribution of the filter gives very clearly the path of the signal transmission as shown in Fig. 12. From this measurement it can be seen that the magnetic field probe measurement is a valuable qualitative technique for printed filter diagnostics and is capable of providing essential physical insight into the problem areas of the design geometry.

IV. Conclusion

A new square magnetic field probe for measuring the field distribution in planar high frequency circuits in the 1–20 GHz band and in three dimensions has been presented. A scanning diagnostic system is described, which is useful for the amplitude and phase measurement of magnetic fields at interior points of planar microwave circuits, and in the design and manufacturing process of microstrip and other printed filters and also antennas. Various measurement examples are given to demonstrate the capability of these probes and the measurement equipment. The objective of this work is to measure quantitatively the field distribution in planar high frequency circuits. Therefore it is necessary to calibrate the probes using some known fields. The technology of probe fabrication still can be improved to reduce the size of the probes for application in higher frequency regions.

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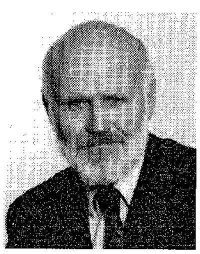

Ingo Wolff (M'75–SM'85–F'88) was born in Köslin, Germany, in 1938. He studied electrical engineering at the Technical University of Aachen and received the Dipl.-Ing. degree in 1964. In 1967, he received the doctoral degree, and in 1970 the habilitation degree, also from the Technical University of Aachen.

From 1970 to 1974, he was a Lecturer and Associate Professor for high-frequency techniques in Aachen. Since 1974, he has been a Full Professor of electromagnetic field theory, University of Duisburg. His main areas of research are electromagnetic field theory applied to the computer-aided design of MIC's and MMIC's, millimeter-wave components and circuits, and the field theory of anisotropic materials. Since 1992 he leads the Institute of Mobile and Satellite Communication Techniques, Kamp-Lintfort, in parallel to his university position. This institute intensively works in the area of mobile communication techniques, microwave and millimeter wave techniques, antenna techniques and electromagnetic compatibility techniques.