High Resolution Near-Field Measurements of Microwave Circuits

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ABSTRACT

In this paper we report on measurements of electric field intensities of microwave field above surface of microwave circuits using miniaturized coaxial antennas. During the scanning process the antenna is driven at various distances above the sample surface according to topographic data acquired prior to the field measurement. A position/signal difference method is used to increase the spatial resolution of the antenna to about $20\,\mu$m ($\lambda/10^4$) - one order of magnitude better than contemporary microwave scanning systems. For measurement of the tangential field components parallel to the sample surface the antenna is tilted by about 45° relative to the sample surface. By its rotation about the vertical axis various components of the field are measured, vertical and horizontal electric field intensities are recalculated. Performance of our scanning system utilizing these methods is tested using a PCB surface capacitor, a microstrip filter and a microstrip transmission line.

Keywords: Microwave near-field measurements, scanning near-field microscopy, coaxial antennas

1. INTRODUCTION

Scanning near-field measurements become an attractive method for testing circuit performance and failure analysis. By analyzing the electric and magnetic field distribution above the circuit surface [1] one can evaluate quantitatively the field sources or explain the signal coupling between the circuit components. For acquisition of microwave electric intensities in a near-field region short coaxial antennas [1, 2] are commonly used. In such antennas a central conductor protrudes for a defined length from the shielding. The antennas are sensitive to vertical component of the electric field intensity and their spatial resolution corresponds to the length of the protruding conductor.

2. POSITION/SIGNAL DIFFERENCE METHOD

It appears that only by decreasing the antenna dimensions along with the coaxial shielding its spatial resolution capability can be improved. Unfortunately, miniaturization of the antenna to the micrometer range makes its fabrication rather difficult, especially forming a short protruding central conductor. Our Position/Signal Difference (PSD) method overcomes the resolution limit, determined by the antenna's dimensions, and allows increasing its resolution capability without the need for further miniaturization of the antenna. The method is based on comparing results of two subsequent scans with the antenna displaced by a small distance Δl along its axis (see Fig.1). It can be shown [3], that for planar microwave circuits, where the strength of the field is greatest close to the circuit surface and decays with increasing distance from the surface, the difference between two signals measured for two different antenna/circuit separation depends only on the field strengthin the region A surrounding the displaced apex of the protruding conductor. In this way the spatial resolution R of the microwave field mapping can be improved with particular value depending on displacement Δl. The effect of resolution enhancement is demonstrated in the figure 2. The analysis of the field images would suggest that in this case the resolution is about $R = 20\mu$m which gives the ratio of the the resolution to the wavelength R/λ of some $2.5 \cdot 10^{-4}$, one order of magnitude better than contemporary microwave scanning systems utilizing coaxial antennas.

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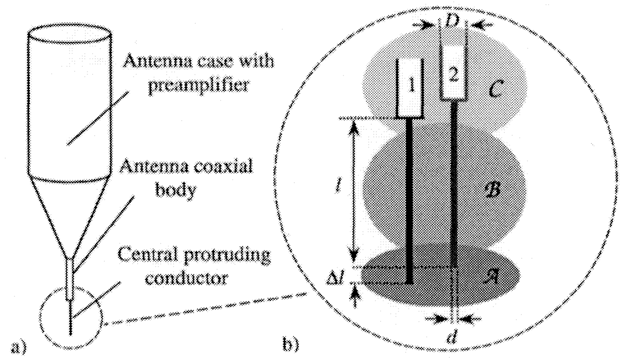


Figure 1. Electric field probe and principle of position/signal difference method: a) outline, b) central protruding conductor. The two positions of the antenna corresponding to different heights above the surface of the device under test are indicated in figure (b) by numbers 1 and 2. Our antennas have a shield with an outer diameter of $D = 230\mu\mathrm{m}$ and thin, relatively long ($l \gg d$) central protruding conductor: a copper wire of length $l \simeq 0.3 - 1\mathrm{mm}$, $d = 8\mu\mathrm{m}$.

3. SCANNING OF NON-FLAT SURFACES

To obtain the field map with high resolution, the antenna must be driven very close to the circuit surface and its movement has to be accurately controlled. Conventional horizontal plane scanning [1, 2, 4] can not be implemented with sufficient precision if the small separation has to be kept constant over a large scanning area.

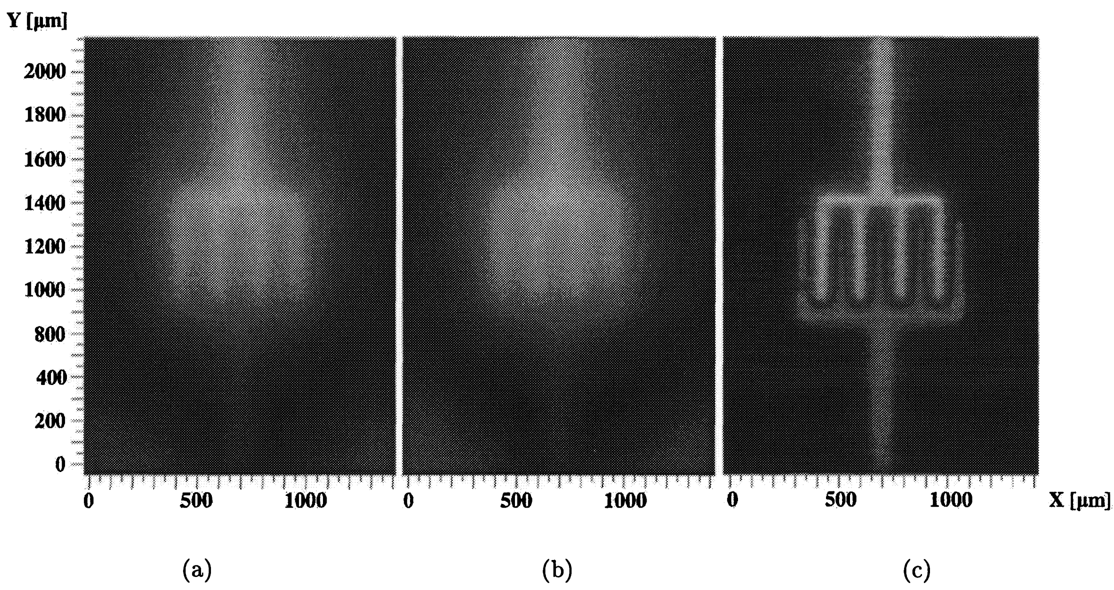


Figure 2. Increase in spatial resolution using PSD method. A PCB surface capacitor with small separation gap (60 μm) between its fingers was prepared using standard lithographic methods. The capacitor was excited from the source of a Vector Network Analyzer (VNA) at frequency f =3.84 GHz. Figures (a), (b) represent the signals acquired for antenna/sample separation 5 μm and 12 μm respectively. The difference signal (c) significantly increases spatial resolution of the field mapping.

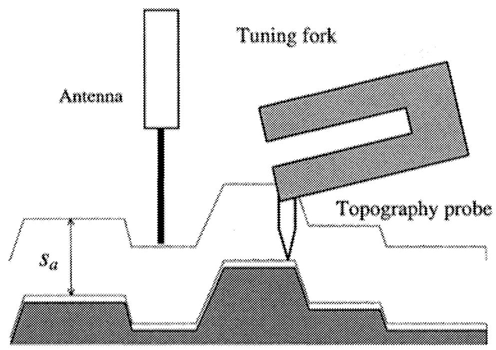
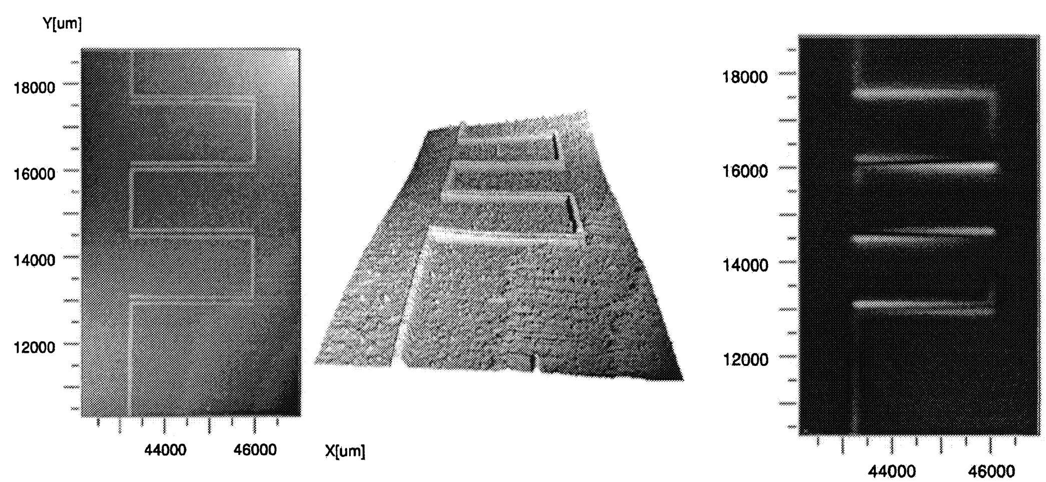


Figure 3. Separate topography and field acquisition during the scanning process.

This is due to the fact that most circuits are not flat and the sample tilt and bending of its surface would cause unacceptable variation in the separation. Additionally, step-like profile of the transmission lines and various surface features like air bondings, signal contacts or shunt elements are typically comparable or else exceed the required working distance and may cause collision of the antenna with the surface.

Our measurement process consists of two separate steps: sample topography acquisition and field probe scanning (see Fig. 3). During the first step the topography acquisition is performed using an AFM-like (Atomic Force Microscopy) technique where a glass probe is dithered perpendicular to the surface and the dependency of the amplitude and the phase of the mechanical oscillation of the probe on the probe/sample separation is used to keep the separation constant in the range of several tens of nm. A quartz tuning fork [5, 6] in a single oscillating arm configuration [7] is utilized for probe frequency stabilization and amplitude detection. The technique can be employed with all types of materials used in circuit fabrication to include various metals, dielectrics and semiconductors. After the topography acquisition, the probe is exchanged for the field antenna A static reference tip is used when the topography probe is exchanged for the antenna, the probes are aligned



(a) Topography of the microstrip filter

(b) Normal elecric field intensity

Figure 4. Acquisition of topography and electric fields of a microstrip filter.

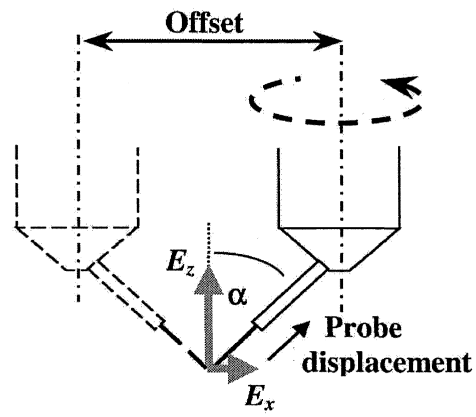


Figure 5. Antenna configuration for measurement of normal and tangential components of the electric field intensity. After each rotation the antenna is aligned using a static reference tip so that its apex is placed at the same location. The offset, resulting from such an alignment, is then used during scanning process for correct antenna placement.

by means of an optical control using a long-focal length microscope. During the second step the electric field intensity is measured with the antenna driven according to previously acquired topographic data. An arbitrary separations between the front end of the antenna and the surface can be chosen and it is kept constant during the field scanning.

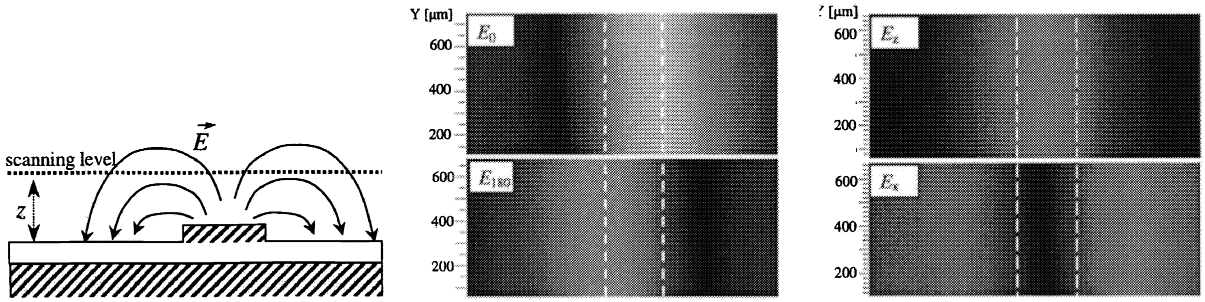
Figure 4 (a) shows a topography image of a 3-stage distributed microstrip filter. In 3D representation the zooming ratio for the vertical z axis is greater than for horizontal x and y ones to highlight bending of the surface.The interval of the surface elevation exceeds 80μm and normally would not allow planar scanning with small probe/sample separation. Using acquired topographic data, the antenna was driven with much smaller separation - only 20μm and 40μm. Figure 4 (b) represents the field distribution above the circuit obtained as a signal difference for two scans at these separations. The field was measured for frequency 7.45 GHz for which the circuit functions as a narrow by-pass filter. At this frequency the length of the strips corresponds to $\lambda/2$ of guided waves and the ends of the strips are excited to maximum potentials and induce relatively strong surrounding electric field.

4. ACQUISITION OF TANGENTIAL COMPONENTS OF THE ELECTRIC FIELD

Although in many cases measurement of the vertical electric intensity E_z is the most appropriate method for the investigation of the circuit signals, some situations may require examination of other spatial components of the field. Knowledge of the tangential field components E_x, E_y can be useful i.e. for the description of fields of coplanar transmission lines and other structures with strong fields parallel to the circuit surface or for measurements of the field coupling between different parts of a device. The antennas for acquisition of normal and tangential components of the electric field are usually different: in most cases for the later small dipoles are used [8, 9]. Simultaneous mapping of the various spatial field components using an alternative approach with electro-optical detection was also reported [10].

The PSD method gives us an opportunity to measure all spatial components with a single probe. To accomplish this goal we have modified the configuration of our probes by placing the coaxial antenna with an inclination of about $\alpha = 45°$ relative to the vertical axis (see Fig. 5). By rotating such an antenna about that axis, different spatial components can be measured. Standard Cartesian intensities, perpendicular and parallel relative to the circuit surface plane, can be further recalculated. In the case of two measurements with the probe rotated by 180° around the normal axis, a vertical and one tangential field intensity can be obtained:

$$E_z = \frac{1}{2\cos\alpha}\left(E_{0°} + E_{180°}\right)$$



(a) (b) (c)

Figure 6. Measurement of normal and tangential spatial components of the electric field for separation $z = 600\mu$m above area B of the microstrip transmission line. Schematics (a) shows the distribution of the electric field across the line. In figure (b) the intensities for the inclined antenna were measured for two directions with antenna rotated by 180° , for each direction position/signal difference method was used to limit measured electric field intensity to the antenna apex. Normal E_z and tangential E_x field intensities in figure (c) were calculated according to (1) as a sum and difference of those signals. The position of the strip edges is highlighted by dashed lines.

$$E_t = \frac{1}{2\sin\alpha}\left(E_{0^\circ} - E_{180^\circ}\right) \quad (1)$$

Here E_{0°, E_{180° are the electric field intensities detected by the antenna before and after the rotation. For three measurements with the antenna rotated by angles 0°, 120° and 240° all three components can be calculated,

$$\begin{aligned} E_x &= \frac{1}{\sin\alpha}\left(2E_{0^\circ} - E_{120^\circ} - E_{240^\circ}\right) \\ E_y &= \frac{1}{\sqrt{3}\sin\alpha}\left(E_{120^\circ} - E_{240^\circ}\right) \\ E_z &= \frac{1}{3\cos\alpha}\left(E_{0^\circ} + E_{120^\circ} + E_{240^\circ}\right) \end{aligned} \quad (2)$$

In general the field can be elliptically polarized and the phase of the electric intensities may vary for different spatial directions. Therefore both the amplitude and the phase of the signal must be acquired by a VNA and the intensities of the electric fields in (1), (2) represent complex amplitudes of the signal.

As the rotation about the vertical axis changes the probe's position above the sample surface, the probe position is offset so that the displaced apex of the central protruding conductor is located at the same point before and after the antenna rotation. This position is adjusted using a reference tip following to procedure similar to the one used in for alignment of the topography probe and the antenna for high resolution measurements. It is also important to to keep the rotation axis vertical so that the declination angle α remains constant for all antenna positions. Constant declination angle is crucial for calculation of tangential electric field to remove the influence of normal field component. This is especially important for measurements of microstrip transmission lines, where normal fields components are typically several times stronger than tangential ones.

The tangential components in figure 6 were acquired using a 45^O inclined antenna. The measurements were performed above a microstrip transmission line (Fig. 6 a) with antennas aligned in two opposite directions perpendicular to the strip. In this experiment the distance from the circuit surface was chosen to be larger ($600\,\mu$m) as the tangential components are negligible close to the circuit surface and vanish at the conductive boundaries of the strip or grounding. For each direction two scans were performed with antenna displaced along the inclined protruding conductor, their difference represent the field intensities at the antenna apex (Fig. 6 b). Normal E_z and tangential E_x electric field components, (Fig. 6 c) were obtained using equation (1). As expected, the tangential component E_x vanishes at the very center of the microstrip where the vector of electric intensity is perpendicular to the sample surface.

5. CONCLUSION

High spatial resolution and low distortion of the measured field are key considerations for the adoption of near-field measurements as a non-invasive technique for the testing of microwave devices. Utilization of PSD method and combined of topography and field scanning appears to be an effective approach to measure the electric field intensity in the deep near-field region ($\lambda/10^4$) and allows one to achieve exceptional resolution with low distortion of the measured field and good quantitative field characterization. Although we have focused our attention on acquisition of the electric field components, the scanning set-up and many of the described techniques may be used for magnetic field measurements utilizing a small loop antenna which would give complementary information about distribution of currents in devices under test. We believe that high resolution near-field measurements can become an attractive method for non-invasive investigation of functionality of microwave devices, especially during their development and testing phase when maximum information about devices and subsystems is desired.

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