Near Electric Field Mapping Above X-Band MMICs Using Modulated Scattering

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Abstract

This paper presents near electric field measurements above a directional coupler at 10 GHz and a Texas Instruments 2-20 GHz TGA8310-SCC distributed low noise amplifier at 14.5 GHz. The measurements are performed with a low cost modulated scattering system using 100 μm long monopole probes with monolithically integrated Schottky diodes on a 40 μm thick high resistivity silicon substrate. Normal electric field intensity and phase maps are presented and demonstrates the possibility of using this mapping technique for low cost MMIC diagnostics.

Introduction

Most standard testing techniques for characterizing monolithic microwave integrated circuits (MMIC) involve S-parameter on-wafer probing systems where the device under test (DUT) is contacted at several ports outside the circuit. However, during microwave circuit design and development, circuit resonances may occur that oftentimes go unexplained by network analyzer measurements. The mapping of the electromagnetic fields above a microwave circuit can be of great importance in viewing directly the internal performance of a microwave circuit, thereby gaining a greater understanding of the microwave circuit's operation. Tighter control over line lengths, coupling and losses may also be achieved that could save valuable chip real-estate. Near electric field information above an active microwave circuit may help improve future MMIC designs and could possibly eliminate unnecessary redesigns of a MMIC.

Electromagnetic field mapping of microwave circuits is possible with electro-optic sampling, photo-emission sampling, electron-beam sampling, scanning force microscopy, passive detection schemes and modulated scattering [1]-[8]. Of all the electromagnetic near-field detection methods at present for microwave circuits on any substrate, the easiest to implement and least expensive system below 60 GHz is the modulated scattering method proposed and developed in the 1950's [1]-[3] and applied to planar microwave circuits in 1992 [5]. In this paper, the near electric field measurements obtained using the modulated scattering technique over a 10 GHz directional coupler and a Texas Instruments Inc. 2-20 GHz TGA8310-SCC distributed amplifier at 14.5 GHz are presented. By using monolithically integrated monopole scatterers, the uncorrected true electric field resolution of the system has been pushed to below 100 μm while the probe's interaction with the microwave circuit has been minimized. This system is capable of completely characterizing all electric field components with monopole and dipole probes and it is believed that the resolution can be pushed to 25 μm with smaller and thinner probes before the system becomes noise limited. The systems developed at The University of Michigan currently operate from 500 MHz to 18 GHz.

Modulated Scattering System

Figure 1 displays the modulated scattering RF system used for the amplifier measurements. The system for measuring the scattered reflected signal is described previously in [6]. The power from an RF source is first divided by a wideband Wilkinson power divider. Half of the RF power is used as the local oscillator for the quadrature mixer and the other half is sent to the DUT through two circulators and an attenuator. An attenuation of 10 dB is chosen for this particular amplifier test to prevent oscillations.

A 100 μm long monopole probe with a low resistance, low capacitance Schottky diode is scanned over the DUT. The Schottky diode is switched on and off at a low video frequency (typically 10 KHz). The switching of the diode modulates the coupling of the probe with the DUT and a weakly modulated RF signal is scattered back into the DUT. Because the power scattered to the input/output port by the probe is very small (orders of magnitude less than the input power to the DUT), homodyne mixing is used to detect the weakly modulated signal. The transmitted scattered signal is diverted to a wideband homodyne quadrature mixer by two wideband circulators after travelling through the output port. The in-phase and quadrature intermediate frequency (typically 10 KHz to 100 KHz) voltages are detected by a lock-in amplifier. Unlike the modulated scattering techniques previously presented by other authors [1]-[5], this modulated scattering technique allows for the testing of amplifiers, circulators, mixers and other nonreciprocal devices by also measuring the scattered signal from the output port.

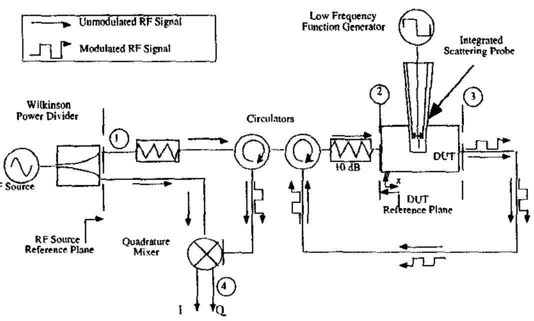

Figure 1. Modulated scattering experiment used for measuring the electric field over non-reciprocal devices.

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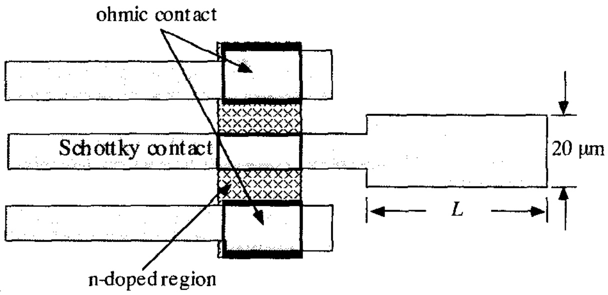

Figure 2. Monolithically integrated monopole probe fabricated on 40 micron thick high resistivity silicon.

The scattering probes are mounted on a computer controlled submicron translational stage. By moving the probe over a region of interest, a complete two dimensional electric field intensity image and phase image from the normal and tangential electric fields is collected and stored in the computer. The entire system is controlled via a personal computer with software written in "C". The system fits on an optical bench with optical rails and manual micrometers to align the probe with the microwave circuit (±10 μm for each 10.0 mm of travel). The automated positioning of the probe is accomplished by the use of an X-Y submicron translational stage. The range of travel is limited to 25.4 mm and the positioning accuracy is better than 0.5 μm. Because the resolution of the system is limited by diode feature size and antenna size, a translational stage with a positioning accuracy of 5 μm is adequate for most systems.

Monolithic Probe Description

In this paper, monolithic probes on a 40 μm thick high resistivity silicon substrate (0.1 λ_d at 200 GHz) are used with an integrated Schottky diode as the modulating element. Hybrid probes on 125 μm quartz wafers were initially fabricated and are described in [6]. The diodes are highly doped, low capacitance Schottky diodes with resistive bias lines to minimize coupling of the bias lines with the DUT. The series resistance of a single diode is measured to be 12 Ω. The junction and parasitic capacitance (C_j+C_p) of the dipole diode is measured to be 2.0 pF which yields a cutoff frequency of 40 GHz.

Figure 2 displays a diagram of the 100 μm long integrated monopole used in this work before dicing. Individual probes have an overall length of 5 mm and a width of 0.5 mm. The resistive feeding transmission lines are chosen to have a characteristic impedance of 120 Ω and rapidly attenuate any RF signal that may propagate along the bias lines. The probe is mounted in a rectangular groove on an anisotropically etched low resistivity silicon wafer probe holder. After the probe is mounted in the groove, wire bonds complete the connection to gold bias lines on the holder wafer. A low frequency connector is then attached with conductive epoxy on an acrylic mount that can then be attached to the translational stage.

Theory of Operation

The theory of operation and calibration techniques are discussed in [8]. To summarize, the voltage amplitude of the reflected scattered wave in a linear and reciprocal circuit is

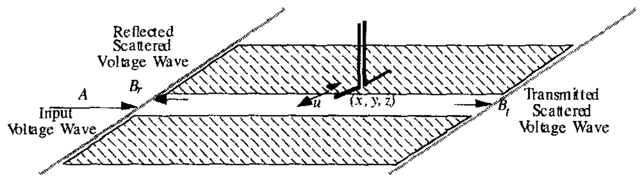

Figure 3. A simplified modulated scattering experiment over a slotline transmission line with a dipole probe at point *(x, y, z)*.

proportional to the square of the *normalized* electric field distribution at the position of the scattering probe. However, the measured voltage of the scattered wave varies linearly with the input voltage amplitude. This has been proven using the reciprocity theorem in [2]. In this paper, the square of the electric field ($|E(x, y, z)|^2$) is referred to as the *electric field intensity.* The form is the reflected scattered voltage, B_r, at the output of the quadrature mixer is given by:

$$B_r = Ak(\bar{u} \bullet \bar{F}(x, y, z))^2 \qquad (1)$$

Where A is the complex input voltage amplitude to the DUT, k is a unitless scaling constant that is dependent on the losses of the measurement system, the strength of the probe's coupling to the DUT and other system parameters, $\bar{u}$ is the unit vector in the direction of the probe's dipole or monopole moment and $\bar{F}(x, y, z)$ is the normalized electric field distribution [2]. Figure 3 displays a hypothetical experiment with a dipole scatterer over a slotline transmission line at the position (x, y, z). To facilitate comparison of the reflected scattered voltage wave, B_r, with the transmitted scattered voltage wave, B_t, equation (1) is rewritten as:

$$B_r = Ak(L_i(x, y, z))^2 \qquad (2)$$

where $L_i(x, y, z)$ is the normalized complex amplitude of the electric field in the direction of the moment vector, $\bar{u}$.

If the circuit is nonreciprocal, the form for the reflected scattered voltage is given by:

$$B_r = AkL_i(x, y, z)L'_i(x, y, z) \qquad (3)$$

where $L'_i(x, y, z)$ is the normalized complex amplitude of the voltage at the input port excited by the probe at the position (x, y, z) with a moment of $\bar{u}$. For reciprocal circuits: $L_i(x, y, z)=L'_i(x, y, z)$. If the DUT is reciprocal, then the measured reflected scattered voltage, B_r, is proportional to the square of the electric field over the entire circuit. For nonreciprocal devices, $L'_i(x, y, z)$ must be de-embedded from B_r to obtain a measurement of the electric field above the DUT. If the nonreciprocal element is localized and the region being tested is located beyond the reciprocal device, then $L'_i(x, y, z)$ is proportional to S_{12} and the region beyond the device may be scaled by the inverse of S_{12} to give a true measure of the electric field. More sophisticated calibration techniques must be employed if there are more than one nonreciprocal device within a MMIC.

The transmitted scattered voltage wave, B_t, can be given in a similar manner to be:

$$B_t = Ak'L_i(x, y, z)L_o(x, y, z) \qquad (4)$$

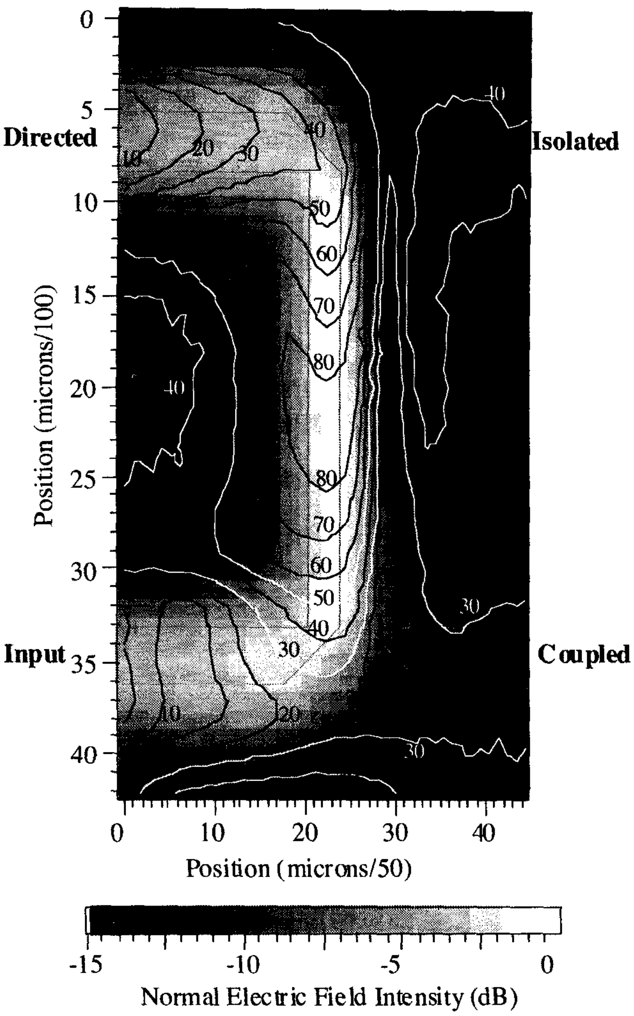

Figure 4. Normal electric field intensity and round trip phase delay over a -12 dB directional coupler fabricated on a high resistivity silicon

where k' is a unitless scaling constant that is dependent on the losses of the measurement system, the strength of the probe's coupling to the DUT and other system parameters, $L_o(x, y, z)$ is the normalized complex amplitude of the voltage at the DUT's output port excited by the probe at the position (x, y, z) with a moment of $\bar{u}$. Equation (4) demonstrates that the scattered transmitted voltage does not vary simply as the square of the electric field but varies as a product of the normalized electric field with a spatially dependent voltage loss or gain factor, $L_o(x, y, z)$, of the scattered RF voltage wave as it travels from the point (x, y, z) to the output port.

For simple microwave circuits such as a lossy transmission line or a single stage amplifier, the product of $L_i(x, y, z)$ and $L_o(x, y, z)$ is a constant magnitude along the main RF path and is analogous to S_{21}. As the probe is moved away from the main RF path such as along a cross section of a transmission line, the product is no longer a constant and yields information of the strength of the electric field away from the main RF path and of the loss involved in travelling to the output port. The same statements hold true for the phase. The phase information of the scattering process is contained within these two terms because $L_i(x, y, z)$ and $L_o(x, y, z)$ are complex functions. Along the main RF path, the measured phase of B_t is a constant value. As the probe moves away from the main RF path, the phase will deviate from a constant value and the electric field phase delay map will yield contours of constant phase for example along lines parallel to a transmission line. This type of information may be useful in designing power dividers/combiners and will be shown to be helpful in studying the operation of distributed amplifiers.

Microstrip Directional Coupler

A single stage microstrip coupled line directional coupler is fabricated on a 380 μm thick high resistivity (2000 Ω-cm) silicon substrate (ε_r=11.7). The layout of the directional coupler used for this experiment is superimposed over the normal electric field and round trip phase delay map presented in figure 4. The device is tested at 10 GHz where the measured input reflection coefficient (S_{11}) is -14 dB, the transmission to the direct port (S_{21}) is -3 dB, the coupling (S_{31}) is -15 dB and the isolation (S_{41}) is not measured because the isolated port was terminated with a 50 Ω thin film resistor. It is estimated that each SMA connector used contributes 0.4-0.5 dB of loss at 10 GHz and that the 1 cm long microstrip line on either side of the coupler contributes 0.8 dB of loss as well. After taking these initial losses into account, the directional coupler is expected to provide an internal coupling ratio of nearly -12 dB of coupling at 10 GHz.

Figure 4 displays the measured normal electric field intensity and round trip phase delay at 10 GHz using a 100 μm long integrated monopole. The measurement is performed by measuring the scattered voltage wave through the input port and because the directional coupler is reciprocal, the results are truly proportional to the normal electric field intensity. The important features of these figures are that the normal electric field is nearly constant between the input and directed port microstrip line and that the isolated port does not appear to have a normal electric field intensity within the dynamic range of the measurements. However, the coupled port does have a normal electric field intensity that is approximately -12 dB lower than the peak normal electric field component over the input microstrip line, which agrees well with measured S-parameter values.

Distributed Amplifier Measurement

The Texas Instruments TGA8310-SCC distributed amplifier is a 2-20 GHz nine transistor amplifier on a 100 μm thick gallium arsenide substrate. The S-parameters of the amplifier are measured from 2-20 GHz. Over this band, the gain ranges between 5-6 dB with a return loss better than 15 dB and with S_{12} between -40 dB and -25 dB making a measurement of the scattered reflected wave impractical due to the high level of attenuation from the scattering points beyond the amplifier to the input port.

Figure 5 displays the measured normal electric field intensity (grayscale) and the phase (contours) of the scattered transmitted signal with the layout of the amplifier's metal layer superimposed over the test region. As the theory predicts, it is seen that the peak electric field over the input meander line is nearly the same level as the peak electric field over the output meander line.

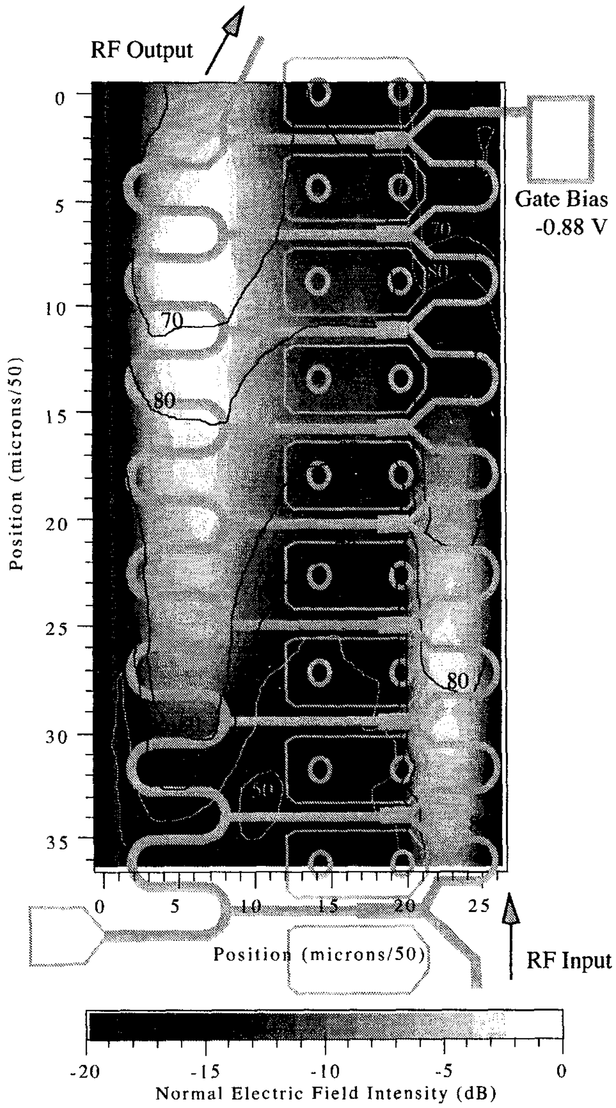

Figure 5. Normal electric field intensity and phase at 14.5 GHz (S_{21}=6.0 dB) measured with a 100 μm long monopole.

In a distributed amplifier, a portion of the incoming RF power is coupled into each transistor, thereby reducing the electric field intensity along the input meander line. Similarly, the electric field strength along the output meander line should increase with intensity as each amplifier stage adds RF power in phase to yield a maximum electric field intensity at the output of the distributed amplifier. The measured peak electric field at the output meander line occurs near the seventh and eighth transistor in figure 5. The location of this peak is seen to vary at other frequencies and indicates a small standing wave along the output line. For an ideal distributed amplifier, the phase along the main RF path that is measured with this modulated scattering technique should be constant. From figure 5, the phase contours vary from 65° to 80° over the main RF path indicating nearly ideal operation.

Conclusions

The modulated scattering technique is easily adaptable to a wide variety of microwave circuits. In situations where knowledge of the internal operation of a MMIC is desired, a map of the electric field intensity and phase delay provide valuable design information. Unlike other modulated scattering systems previously used over reciprocal devices, for nonreciprocal devices such as amplifiers, the RF system presented in this paper is capable of mapping the electric field intensity and transmitted phase of the scattered signal at the probe position. Even though the measured phase from the scattered *transmitted* signal is not the true phase of the electric field at the probe position, the phase does give important information regarding the operation of the DUT. A phase map over a power amplifier would give net phase deviations of the main RF signal and may lead to more efficient power combining network designs.

The modulated scattering technique is a very flexible method for testing microwave circuits fabricated on any dielectric substrate. Because the system is modular with an RF detector system, probes, a translational stage, a frequency source and a lock-in amplifier, any component of the system may be replaced or improved without affecting the operation of the other components of the modulated scattering system. This attribute facilitates the optimization of a modulated scattering system to test microwave circuits at the wafer level or mounted in a module while changing only a few components of the system.

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