FIELD-TUNABLE PROBE FOR COMBINED ELECTRIC AND MAGNETIC FIELD MEASUREMENTS

Ronald M. Reano, John F. Whitaker, and Linda P. B. Katehi

Radiation Laboratory and Center for Ultrafast Optical Science, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109, USA

Abstract — **A method to measure the magnitude and phase of electric and magnetic fields with a single probe is presented. The optically-based probe, consisting of a hybrid combination of gallium arsenide followed by terbium gallium garnet, employs the Pockels effect to measure electric fields and the Faraday effect to measure magnetic fields. Isolation between the two effects is achieved via external polarization optics, allowing the probe to be toggled between electric field and magnetic field sensitivity by switching the input optical polarization between two states. A demonstrated isolation of 22 dB is observed using a shorted microstrip transmission line as a test bed.**

I. INTRODUCTION

Field mapping of microwave/millimeter-wave circuits provides valuable insight into their internal electromagnetic operation. In the last decade, a myriad of creative techniques have been developed to obtain electric and magnetic field distributions, each design trading off different aspects of sensitivity, spatial resolution, accuracy, bandwidth, invasiveness, complexity, and cost. Methods to measure electric fields have included coaxial and dipole antenna based probes, modulated scattering probes, scanning-force-microscopy based probes, and electro-optic based probes [1]-[4]. Techniques to measure magnetic fields utilized conducting loop-based probes, as well as magneto-optic based probes [5]-[6].

Electric and magnetic field probes are complementary inasmuch as the fields, which they measure, are coupled via Maxwell's equations. In the far-field, the intrinsic impedance of the medium relates electric and magnetic field intensities. In the near-field, however, the electric and magnetic field distributions approach their quasi-static solutions. The ability to probe both electric and magnetic fields allows for a complete diagnosis of electromagnetic behavior and provides the means to obtain point-wise characterizations of field distributions in terms of point-impedance.

In this paper, a method to measure the magnitude and phase of electric and magnetic fields with a single probe is presented. The theory behind the approach is first detailed using Jones calculus. Next, the physical implementation of the technique is described including a description of the choice of materials employed. Finally, a shorted microstrip transmission line is examined in order to investigate the sensitivity isolation between electric and magnetic fields and to demonstrate the accuracy of the measurement technique.

II. THEORY

The two physical phenomena used to measure microwave/millimeter wave electric and magnetic fields in this work are the Pockels effect and the Faraday effect. The Pockels effect is an electric-field induced *linear* birefringence, and the Faraday effect is a magnetic-field induced *circular* birefringence [7]. Both effects change the polarization state of an optical beam. By abutting an electro-optic material against a magneto-optic material, as shown in Fig. 1, and using external polarization controls, the probe can be toggled between electric field sensitivity and magnetic field sensitivity by switching the polarization optics between two states.

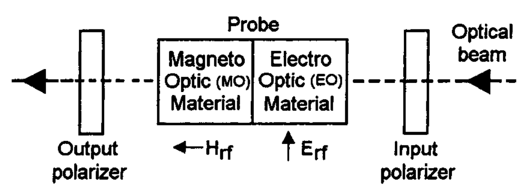

Fig. 1. Conceptual schematic of combined electro/magneto-optical probe with external polarization controls.

The change in polarization state as the optical beam propagates through the system can be described via the following cascade of matrices

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\frac{\Gamma}{2} & -i\sin\frac{\Gamma}{2} \\ -i\sin\frac{\Gamma}{2} & \cos\frac{\Gamma}{2} \end{bmatrix} \begin{bmatrix} \cos^2\theta & \frac{1}{2}\sin 2\theta \\ \frac{1}{2}\sin 2\theta & \sin^2\theta \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (1)$$

In this equation from right to left, the first vector represents the input optical field, which is set to be polarized along the y-direction. The following matrix

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represents the input polarizer, where θ is the orientation angle of the polarizer relative to the x-axis. The next matrix represents the optical retardance between two orthogonal eigenwaves polarized at ±45° with respect to the y-axis. The retardance, Γ, is modulated by the presence of an RF electric field due to the electro-optic effect. The following matrix represents a vector rotation through an angle α. The magnitude of this angle is modulated by the presence of an RF magnetic field due to the Faraday effect. The final matrix represents the output polarizer, which is aligned along the x-axis.

For θ equal to 90° the output optical transmission intensity, T_1, of this cascade of matrices is found to be

$$T_1 = \left(\sin^2\alpha\right)\cos^2\frac{\Gamma}{2} + \left(\cos^2\alpha\right)\sin^2\frac{\Gamma}{2} \approx \sin^2\frac{\Gamma}{2}, \quad \alpha << 1^\circ. \quad (2)$$

This equation shows that a sin-squared modulation curve for pure electro-optic sensitivity ensues for small angles of Faraday rotation. The transmission is plotted as a function of retardance, Γ, for several values of rotation, α, in Fig. 2.

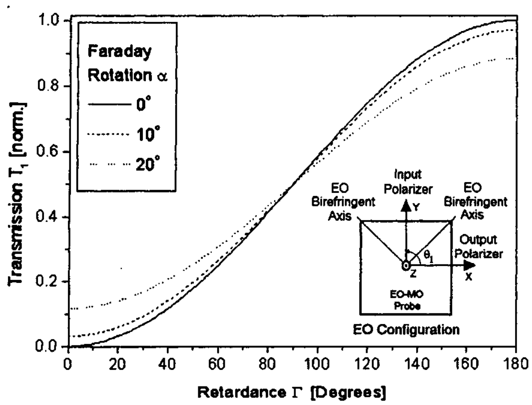

Fig. 2. Calculation of the change in polarization state through the system shows that the combined probe is insensitive to the Faraday effect when the input polarizer is oriented at θ = 90° and the retardance is biased at π/2.

This figure shows that electro-optic modulation about an optical retardance of 90° is unaffected by the effects of Faraday rotation for rotation angles much less than 1°. The expected Faraday rotation due to typical RF magnetic fields of interest is expected to much less than one milli-degree. Thus, in this configuration, to an excellent approximation, the combined probe exhibits only electro-optic sensitivity.

For θ equal to 3π/8, the output optical transmission intensity, T_2, of the cascade of matrices is found to be

$$T_2 \approx \sin^2\left(\frac{3\pi}{8}\right)\left(\frac{1}{2}+\frac{1}{2}\cos 2\left(\alpha+\frac{3\pi}{8}\right)\right), \quad \Gamma<<1^\circ. \quad (3)$$

This equation shows that the output transmission depends only on the Faraday rotation angle for small values of the optical retardance. As discussed in section IV, an input polarization angle of ~3π/8 minimizes the electro-optic contribution to the overall detected signal. Fig. 3 graphically conveys that a magneto-optic modulation about α=0° is unaffected by the optical retardance for values of Γ much less than one degree. Typical RF electric fields of interest are expected to induce optical retardations much less than one milli-degree. Therefore, to a good approximation, this second input polarization configuration adjusts the combined probe to exhibit only magnetic-field sensitivity.

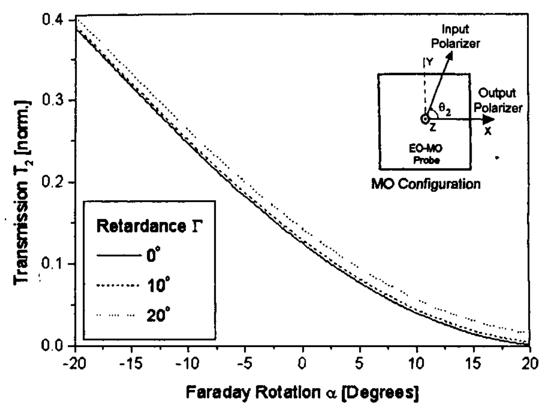

Fig. 3. The combined probe is essentially insensitive to the electro-optic effect when the input polarization angle is θ = 3π/8 and the optical retardation is << 1°.

III. IMPLEMENTATION

The electro-optic material used in this study is gallium arsenide (GaAs) and the magneto-optic material is terbium gallium garnet (TGG). A 1.5 mm^2 portion of GaAs was cleaved from a 100 μm <110> semi-insulating wafer and attached to one face of a 2-mm diameter, 2-mm long TGG circular cylinder using UV-cured optical adhesive. RF reflections at the boundary are minimal due to their similar material parameters (GaAs: ε_r = 13.2, TGG: ε_r = 12.4). Electro-optic sensitivity in GaAs and magneto-optic sensitivity in TGG have demonstrated pico-second response times and therefore they are expected to serve as a broadband spectral domain sensors extending to frequencies greater than 100 GHz [8], [9]. The completed probe, supported by a thin quartz tube, is shown in Fig. 4.

Each material is primarily sensitive to one component of each respective field-type. The directional sensitivity of <110> GaAs favors the electric-field component that is transverse to the direction of optical beam propagation and oriented in the <110> direction [10]. On the other hand, a Faraday effect magneto-optic material such as TGG is sensitive to the magnetic field component collinear with the direction of optical beam propagation [7].

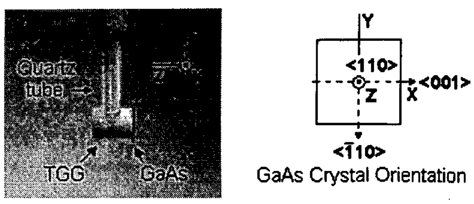

Fig. 4. The probe consists of a series combination of GaAs (100 um thick) and TGG (2 mm thick). A quartz tube is used for support.

The experimental setup is shown in Fig. 5. A Ti:Sapphire mode-locked laser tuned to 905 nm is used to generate a linearly polarized sampling beam (80 MHz repetition rate, 80 fs pulse duration) that is directed through the probe and the polarization controls via free-space optics. The device under test is fed via an RF synthesizer configured for harmonic mixing in order to down-convert the sampled electric fields to IF frequencies allowing envelope detection with a MHz bandwidth photodiode [9]. For electric-field measurements, the quarter-waveplate provides the required 90° of optical bias. For magnetic-field measurements, the quarter-waveplate is removed.

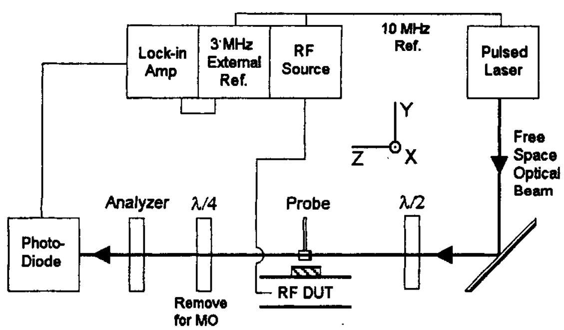

Fig. 5. The experimental set-up.

IV. CHARACTERIZATION

The isolation between electric and magnetic field sensitivity, and vice-versa, was the primary focus regarding probe characterization in this study. A shorted microstrip transmission line was selected as the test bed. The advantage of this structure is that the electric and magnetic fields form standing waves with maxima that are displaced by a quarter-wavelength. The RF frequency was 4.003 GHz at 17.0 dBm and the probe height was 2.0 mm above the surface.

A pure sample of GaAs (no TGG) was used to determine the degree to which the relative electro-optic signal could be minimized. As shown in Fig. 6, as the input polarization is decreased from $\theta=90°$ (vertical polarization), the electro-optic signal is a minimum at $\theta\approx67.5°$. The quarter-waveplate is absent and the output polarizer is aligned along the x-axis ($\theta=0°$). Since the result is a cusp, the isolation between electric and magnetic field sensitivity is strongly determined by the tuning precision of the input polarization. An important note is that the electro-optic signal is significant at $\theta=45°$ thereby preventing the use of this ideal angle for magneto-optic sensitivity.

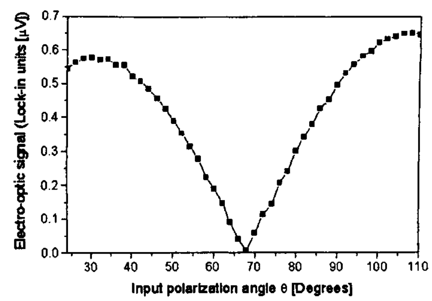

Fig. 6. Minimization of the electro-optic signal in a pure GaAs sample is achieved with external polarization control.

Fig. 7 shows line scans of the magnitude and phase of the electric and magnetic field standing waves using the

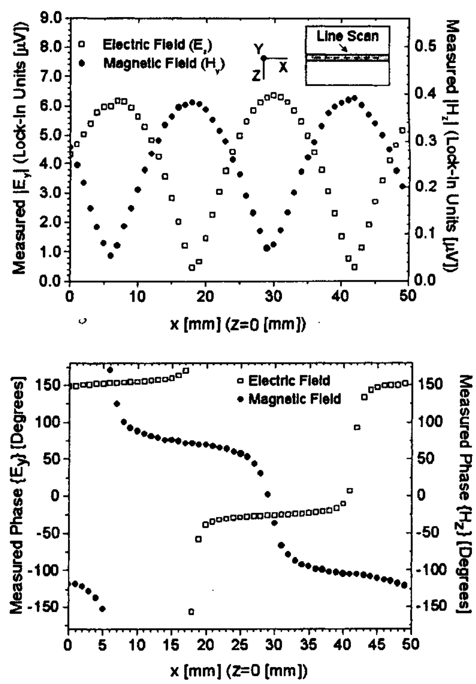

Fig. 7. The magnitude (top figure) and phase (bottom figure) of the standing waves on a shorted microstrip transmission line measured with the combined probe at a height of 2.0 mm above the surface.

combined probe. At x = 6 mm, the electric field is a maximum and the magnetic field is a minimum. The isolation at this point is 22 dB.

V. MEASUREMENT VS SIMULATION

In order to determine the accuracy of the measurement technique, measured line scans across the microstrip transmission line were compared with simulation results from full-wave finite-element-method simulations [11]. The width of the microstrip was 3.76 mm. Fig. 8 shows simulated and measured results when the combined probe was tuned for electric-field sensitivity and scanned for the z-component of the electric field. The measurement is in excellent agreement with the simulation results. Using the combined probe tuned for magnetic-field sensitivity, the probe was scanned for the z-component of the magnetic field. As shown in Fig. 9, the measurement is also in excellent agreement with the simulation.

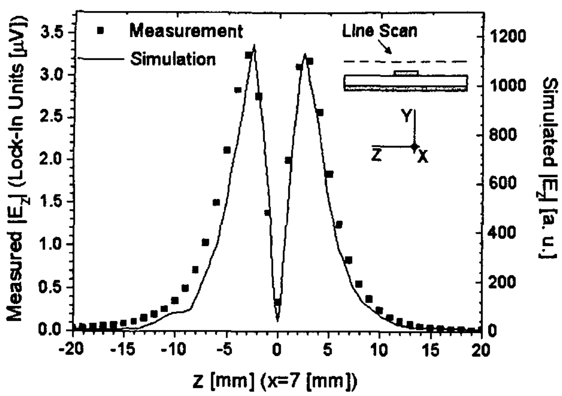

Fig. 8. Measured and simulated results of the z-component of the electric-field 2.0 mm above a microstrip line.

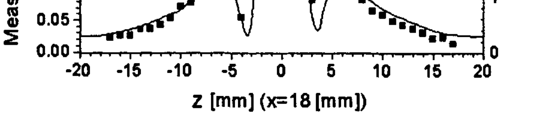

Fig. 9. Measured and simulated results of the z-component of the magnetic-field 2.0 mm above a microstrip line.

VI. CONCLUSION

A field-tunable probe capable of combined measurements of electric and magnetic fields is presented. Experimental observations of the response of the probe to electric and magnetic fields are shown to be consistent with theoretical expectations. The picosecond response times of the materials involved suggest the ability for broadband frequency-domain measurements in excess of 100 GHz. This novel measurement technique can provide a complete electromagnetic diagnosis of the field behavior of microwave and millimeter-wave structures.

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