Electro-optic field mapping system utilizing external gallium arsenide probes

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(Received 23 March 2000; accepted for publication 30 May 2000)

External electro-optic probes fabricated from two different crystal orientations of GaAs have been implemented in an electro-optic sampling system that is capable of mapping three independent orthogonal components of free-space electric fields. The results obtained for the radiated field from a microstrip patch antenna by the GaAs probes are compared with results on the same antenna obtained using bismuth silicate and lithium tantalate probes. An 8 μm spatial resolution has also been demonstrated for the electro-optic field-mapping system, and the capability for the system to measure field patterns at frequencies up to 100 GHz has been shown. © *2000 American Institute of Physics.* [S0003-6951(00)04529-0]

Electro-optic field mapping systems that utilize bismuth silicate (BSO) and lithium tantalate ($LiTaO_3$) probes have provided a great deal of important information on many different types of microwave and millimeter wave structures, including integrated circuits,[1] antennas,[2] and arrays.[3] While conventional measurement techniques, such as open-waveguide, near-field scanning, or far-field detection, either introduce metal into the near-field region and/or have poor spatial resolution, electro-optic sampling[4] can be used to obtain high-resolution, two-dimensional or even three-dimensional results from the near field of a device under test.

Even though the BSO and $LiTaO_3$ crystals typically used have been miniaturized to a footprint area as small as 20 $\mu m \times 10$ μm,[1] the fact still remains that the microwave permittivities of these electro-optic crystals are very large (43 for $LiTaO_3$, 50 for BSO). It is known that this property could lead to distortion of the local electric field distribution near the probe,[5] and thus electro-optic crystals that might be considered replacements for BSO or $LiTaO_3$ would need to have a small dielectric constant. It would also be convenient if one was not limited by the mechanical constraints of the polishing processes required to reduce the size of the BSO and $LiTaO_3$ crystals.

Gallium arsenide is one material that is recognized as an alternative electro-optic crystal.[6] Not only can standard solid-state fabrication processes, such as photolithography and various wet and dry etching techniques, be used for GaAs,[7] but it also has a relatively small dielectric constant ($\epsilon_r \approx 12.5$). While a number of groups have reported the use of GaAs as an electro-optic sensor crystal,[8–10] its application has been limited to normal-field-component detection up to now.

In this work, complete maps of three orthogonal field components have been obtained using two different GaAs electro-optic probes with appropriate crystal orientations. Measurements have been performed on microwave integrated circuits and a patch antenna, and the capability of electro-optic field mapping for frequencies up to *W* band (specifically, 100 GHz) has been demonstrated.

It is well known that the index of refraction of (100)-orientated GaAs is sensitive to the component of the electric field that is polarized perpendicular to the (100) surface.[8] However, in spite of the advantages in using GaAs, the (100) orientation of the crystal is not sufficient to replace BSO and $LiTaO_3$ electro-optic crystals that were used to detect three orthogonal field components. That is, it is also important to achieve tangential-field sensitivity with GaAs for the implementation of a GaAs probe in an electro-optic measurement system.

GaAs has a zincblend lattice crystal structure,[11] so that it has an identical crystal structure for (100), (010), and (001) directions. All three orientations have normal-field sensitivity (i.e., sensitivity to the field component that is polarized perpendicular to the plane). For these orientations, in order to maximize sensitivity in the electro-optic modulation, it is desirable to have both the incident laser probe-beam direction and rf polarization normal to the plane in each case. On the other hand, when the incident laser beam is aligned normal to the (110) plane, the GaAs crystal shows sensitivity to the rf field component that is parallel to the plane. This al-

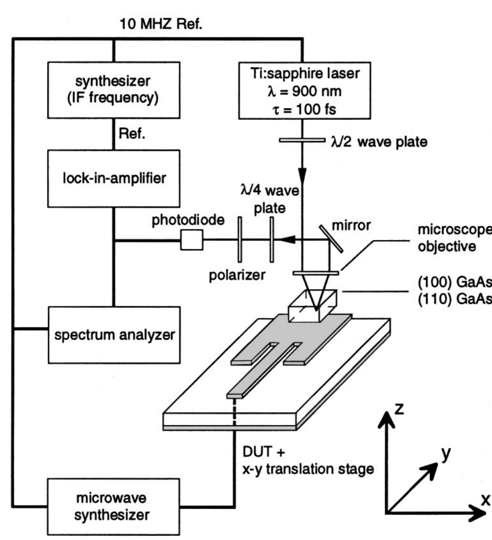

FIG. 1. System block diagram for electro-optic field mapping measurement.

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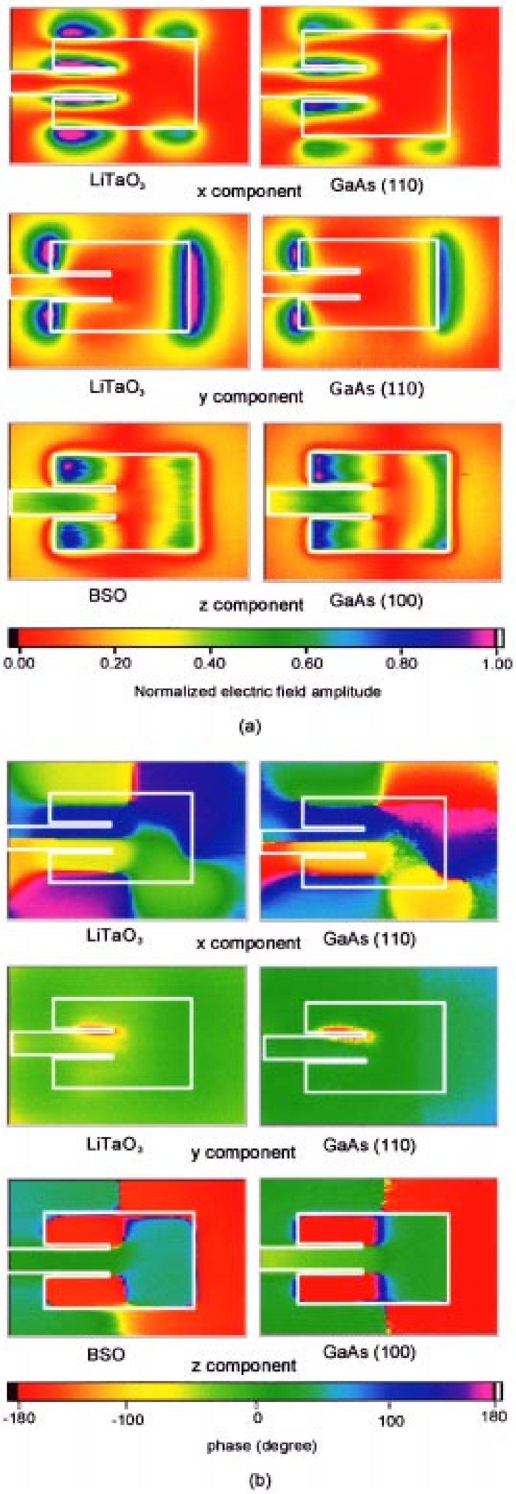

FIG. 2. (Color) Comparison of electro-optic mapping results obtained using BSO/LiTaO$_3$ and (100)/(110) GaAs probes: (a) normalized amplitude; (b) phase in degrees.

lows the GaAs crystal to be used for the detection of the tangential field components.

Based on these characteristics, two different GaAs electro-optic probes are fabricated. Since our main goal is to demonstrate that field mapping of three orthogonal components can be accomplished with GaAs, a simple mechanical cleaving process is used to fabricate the GaAs probe tips. For the detection of the field that is perpendicular to the surface of the devices under test (DUTs) (i.e., the normal compo-

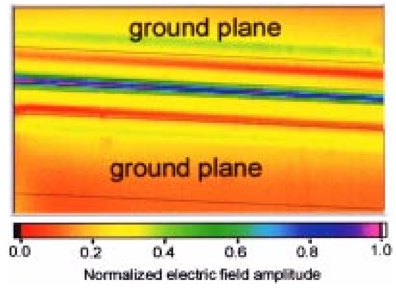

FIG. 3. (Color) Electro-optic mapping result from coplanar waveguide structure for normal field component (normalized amplitude). A (110) GaAs probe was used for the measurement. The boundaries of the center conductor and ground planes are denoted by the solid lines.

nent), a wafer that has (100) orientation and a 600 μm thickness is cleaved into a cube so that it has 1 mm$\times$1 mm facets on the bottom and top. For the fabrication of the probe that has tangential field sensitivity, a (110) wafer with 400 μm thickness is also cleaved so that it has 1 mm$\times$1 mm facets.

A 4 GHz microstrip patch antenna is selected for the GaAs electro-optic field-mapping test. The measurement setup is displayed in Fig. 1. A model locked Ti:sapphire laser emitting 100 fs duration pulses with an 80 MHz repetition rate and a 900 nm wavelength is used to produce the probe beam. The laser pulse train, modulated by the field radiated from the patch antenna via the Pockels effect, is downconverted after detection in a harmonic mixing scheme at an intermediate frequency of several megahertz and measured in a rf lock-in amplifier. Using a phase-locked loop that also stabilizes the cavity length of the laser, it is possible to synchronize the cw signals from the microwave synthesizer with the laser pulse train so that measurements in amplitude and phase can be performed.[1] The DUT is raster-scanned under

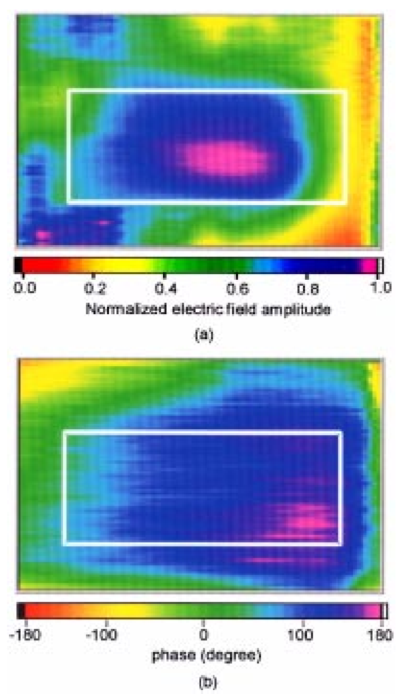

FIG. 4. (Color) Electro-optic field mapping result for the dominant electric field at the aperture area of a 6$\times$ frequency multiplier. Input frequency: 16.7025 GHz; output frequency: 100.323 GHz. (a) Normalized amplitude; (b) phase in degrees. The aperture area is outlined in white.

the electro-optic probe using a computer-controlled $x-y$ motorized translation stage.

In order to evaluate the two GaAs field probes, a comparison is made between field maps made with the GaAs and those obtained using the established BSO and $LiTaO_3$ electro-optic crystals. The principal difference for the GaAs-based system as compared to the BSO/$LiTaO_3$-based system is that a longer laser wavelength is required to keep the probe-beam photon energy below the GaAs band gap. Figure 2(a) shows a comparison of the two-dimensional maps of the electric-field amplitudes acquired by the BSO/$LiTaO_3$-based systems and the GaAs-based systems, while Fig. 2(b) compares the phase measurements. For the scanning, a 250 μm $\times$200 μm unit step size is used, and 80$\times$80 total steps are taken. The total scanning time is about 30 min.

An excellent agreement between the results for all three orthogonal fields is obtained with the two systems, as observed in Fig. 2. The (110) GaAs probe captures the tangential electric fields, so it is found that the amplitudes are very low directly over the metal patch, and high at positions just off the patch where the field is parallel to the plane of the patch. The (110) GaAs probe and $LiTaO_3$ probe are rotated 90° to alternate between measurements on the x and y components, and a cross polarization isolation in excess of 20 dB is found for both probes. In addition, for the y-component field maps, results from both probes show very low amplitude within the patch antenna slots, which are used for impedance matching. However, the phase measurement results obtained on both systems display identical abnormal phase distributions around the upper slot, an effect that is possibly caused by some small defect. As expected, the x component of the field is found by both GaAs (110) and $LiTaO_3$ probes to be large within the slots. For the z component of the field, which is highest when it is normal to the metal patch in the near field, the GaAs (100) probe yields superior results to the BSO crystal probe in terms of high definition for both amplitude and phase mapping. This is likely due to the four times lower permittivity of the GaAs as compared to BSO.

In addition to the comparison with the BSO and $LiTaO_3$ probes, the GaAs probe system has also been used to investigate the spatial resolution of the electro-optic field mapping technique. Figure 3 shows an electro-optic measurement from a coplanar waveguide transmission line for the normal component of the guided field. The widths of the center conductor, the gaps, and the ground planes are 16, 35, and 106 μm, respectively. The normalized amplitude mapping result clearly shows that, as expected, the peak amplitude occurs on the center conductor. A good symmetric amplitude distribution can also be observed on the center conductor, which implies that the resolution of the measurement is at least 8 μm (the half width of the center conductor). The phase result (not shown) indicates a 180° phase difference on the center conductor and ground plane due to the direction change of the normal field component.

Finally, in order to investigate the capability of the field mapping technique at very high, millimeter-wave frequencies, the GaAs-based electro-optic field sensors were used to probe the output of a frequency multiplier with a six times multiplication factor. The input frequency for the multiplier is 16.7205 GHz. The resultant output signal has a frequency of 100.323 GHz at the output waveguide opening. This output signal includes a 3 MHz IF signal. Figure 4 displays the two-dimensional field-mapping result of the output aperture of the multiplier for the dominant field component. The actual scanning area is 3 mm$\times$2 mm, which includes the 2.3 mm$\times$1 mm output waveguide opening. Because the dominant component should be parallel to the aperture plane of the waveguide, the (110) GaAs probe is used to detect it. The result shows a reasonable amplitude shape in the output opening. However, the phase distribution is slightly asymmetric. This asymmetric phase distribution can be explained by the proximity of the measured output aperture to the actual output source. In spite of an asymmetric distribution of phase, the result does show only a small amount of variation over the central part of the aperture.

GaAs electro-optic probes have been developed as an alternative to high-permittivity BSO and $LiTaO_3$ crystals for performing field mapping of three orthogonal components in the near field of radiating structures. The results obtained by (100)- and (110)-oriented GaAs probes show excellent agreement with those obtained using BSO and $LiTaO_3$ probes and also highlight the accuracy and repeatability of electro-optic field mapping.

This work was supported by the MURI program on ''Spatial and Quasi-Optic Power Combining'' monitored by U.S. Army Research Office Grant No. DAAG 55-97-0132 under subcontract to Clemson University and by the National Science Foundation through the Center for Ultrafast Optical Science under STC PHY 8920108.

[1] K. Yang, G. David, S. Robertson, J. F. Whitaker, and L. P. B. Katehi, IEEE Trans. Microwave Theory Tech. **46**, 2338 (1998).

[2] K. Yang, G. David, J.-G. Yook, I. Papapolymerou, L. P. B. Katehi, and J. F. Whitaker, IEEE Trans. Microwave Theory Tech. **48**, 288 (2000).

[3] K. Yang, G. David, W. Wang, T. Marshall, L. W. Pearson, Z. Popovic, L. P. B. Katehi, and J. F. Whitaker, Ultrafast Electronics and Optoelectronics Conference Technical Digest 1999, p. 30.

[4] J. A. Valdmanis and G. Mourou, IEEE J. Quantum Electron. **QE-22**, 69 (1986).

[5] H.-J. Cheng, J. F. Whitaker, K. J. Herrick, N. Dib, L. P. B. Katehi, and J. L. Coutaz, in *Ultrafast Electronics and Optoelectronics*, 1995 OSA Technical Digest Series (Optical Society of America, Washington, DC, 1995), Vol. 13, p. 128.

[6] A. Yariv and P. Yeh, *Optical Waves in Crystals-Propagation and Control of Laser Radiation* (Wiley-Interscience, New York, 1984).

[7] R. E. Williams, *Gallium Arsenide Processing Techniques* (Artech House, Dedham, MA, 1984).

[8] B. H. Kolner and D. M. Bloom, IEEE J. Quantum Electron. **QE-22**, 79 (1986).

[9] M. Shinagawa and T. Nagatsuma, Electron. Lett. **26**, 1341 (1990).

[10] M. S. Heutmaker, G. T. Harvey, D. G. Cruickshank, and P. E. Bechtold, Digest of the 17th International Conference on Quantum Electronics, IQEC 90, pp. 50 and 52.

[11] S. M. Sze, *Semiconductor Devices Physics and Technology* (Wiley, New York, 1985).