Electric-Field Observation of Pico-pulse Propagation on Right-angle Bends By Miniature Photoconductive Near-Field Probe

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***Abstract* — The picosecond electric-pulse propagation characteristics on microstrip and coplanar waveguide right-angle bends have been successfully measured by mapping the time-dependent spatial electric near-field distributions. The measurement was performed using a 2-dimensional photoconductive (PC) electric near-field mapping system incorporating a new miniature PC electric-field probe, which was implemented on an optical fiber by coupling a PC switch on 1-μm-thick LT-GaAs epilayer to the end-facet of a 45° bevel-edge optical fiber. The probe could measure the three orthogonal picosecond electric-field components separately with minimal loading effects. The measured field-images showed quite remarkable transient picosecond electric-pulse propagation phenomena at the right-angle bends, which cannot be measured using conventional test instruments.**

I. Introduction

With increasing operating frequencies and integration densities of chips, packages, and boards, the reliable transmission of high-frequency signals [signal integrity] has become more important than ever. In such current situation, in-circuit diagnostic ultrafast measurement techniques incorporating optical techniques [1][2] have attracted a great deal of attention because of their high temporal and spatial resolutions and high sensitivity based on time-equivalent sampling measurement. However, their application was limited to the voltage distribution measurements by electrical contact method. Recently, the rise of high-frequency electromagnetic problems such as unwanted crosstalk and EMI in high-frequency (digital) systems enlarges the demand for high-performance near-field diagnostic system, which can observe the time-evolution of ultrafast signal propagation.

In general, near-field measurements involve the use of probes whose electromagnetic performances are devoted to minimize the distortions introduced by the probe itself and by associated equipment in the field under measurement. Besides a near-field probe must be small enough to measure the field at a point, it must have the desired polarization and finally it must deliver a measurement signal large enough to permit accurate measurements.

Recently, we developed a photoconductive near-field probe (PCNFP) [3] by coupling a photoconductive switch (PCS) implemented on 1-μm-thick LT-GaAs epilayer and three optical fibers (one for probe pulse guiding and two for electric connections), and have showed usefulness of the PCNFP to investigate how ultrafast electrical signals propagate in the real world [4][5]. However, the use of the previous PCNFP was actually limited to the measurement of in-plane tangential electric-field components. That is, the normal electric-field component could be measured by using the PCS with 90°-rotated direction and by positioning the probe vertically, so that an additional PCNF was required to measure the normal electric-field component. In addition, the previous PCNFP was easily breakable to the external influences. To overcome these drawbacks, in this paper, a miniature and practical PCNFP was implemented by attaching a PCS implemented on 1-μm-thick epitaxial lifted-off LT-GaAs to the end facet of an optical fiber with 45° bevel-edge. The new PCNFP is capable of measuring/mapping independent three orthogonal components of free-space electric fields separately with uniform sensitivity (~ $\mu V/(Hz)^{1/2}$) by positioning the probe with a 45° inclination from normal to the surface.

In this paper, we apply the developed new PCNFP to observation of spatial electric near-field distribution images of picosecond electric pulse propagating on both microstrip and coplanar waveguide (CPW) right-angle bends and its time evolutions.

II. System Setup

Figure 1 shows the experimental setup. Ultra-short optical pulse train from a mode-locked Ti:Sapphire laser with a 120 fs pulse duration and a 80 MHz repetition rate at a wavelength of λ = 830 nm was split into two parts, pump beam and probe beam, by an optical beam splitter. The pump beam, modulated by a mechanical chopper, was used to generate a picosecond electric pulse by focusing it onto a DC-biased PCS of DUT. The probe laser pulses, delayed relative to the pump pulse via an optical delay-line, were focused onto the PCS of the

PCNFP through an optical fiber to sample the electric-field component of DUT with uniform sensitivity.

To obtain time-resolved 2-D electric near-field images by scanning the PCNFP above an arbitrary DUT, the PCNFP was controlled by a computer-controlled *XY*-translation stage with 1-μm moving resolution, and positioned at a height of 100 μm over DUT.

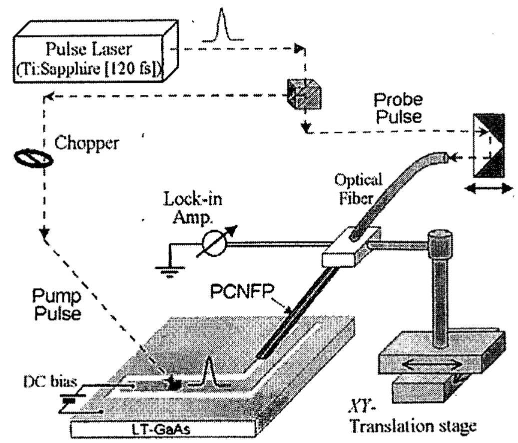
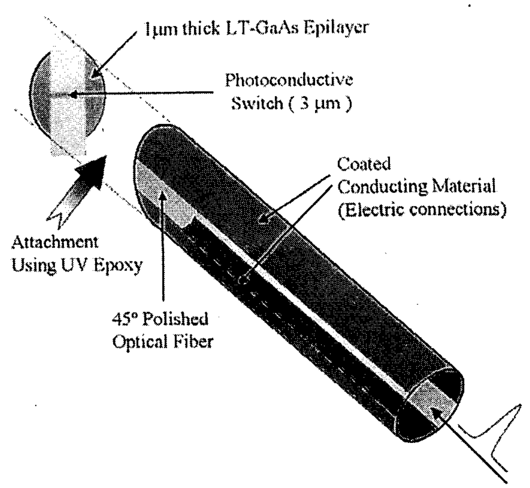


Fig. 1. Schematic of system setup for 2-D electric near-field scanning. Pump laser beam generates electrical pulse train and probe laser beam turns on the PCS on the PCNFP.

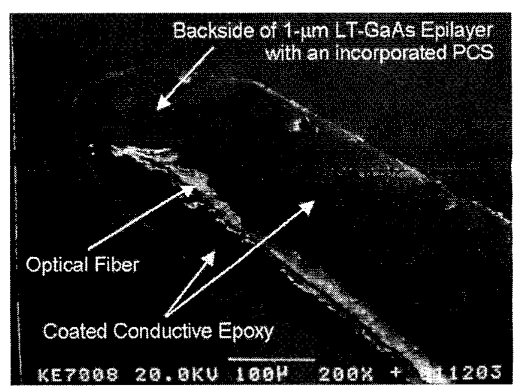
III. Miniature Photoconductive E-fiedl Probe

Schematic drawing of the new miniature PCNFP fabrication is shown in Fig. 2(a). The operation principle and the fabrication procedure are similar to those of the previous three-fiber based PCNFP [3]. To minimize the loading and the substrate effects of the probe, the probe head with a PCS was fabricated on 1-μm-thick LT-GaAs epilayer, which was lifted-off from growing substrate by preferentially etching a sandwiched AlAs layer in hydrofluoric acid solution. The PCS with 3-μm gap consisted of 40 nm/250 nm Cr/Au. The LT-GaAs was grown by molecular beam epitaxial technique at 200°C and annealed in the chamber at 600 °C for 10 min to obtain a subpicosecond switching time [6].

The elliptical probe head was attached to the 45°-polished facet of an optical fiber. The 45°-polished optical fiber serves to measure the tangential and the normal electric-field components at the same condition by changing the probe direction. Conductive epoxy was coated as a parallel line on the fiber to connect electrically the PCS electrodes of the probe and the external data acquisition apparatus such as lock-in amplifier. The Resulting PCNFP was constructed on a single optical fiber so that the probe size was minimal and could be positioned any measuring points with minimal invasiveness. Also, the single-fiber-based probe system is strong to use for practical application, because the LT-GaAs epilayer probe head is attached to the end facet of the fiber without margin. Figure 2(b) is a SEM photograph of the resulting PCNFP.



(a)



(b)

Fig. 2. (a) Schematic design of new miniature PCNFP. Probe head and electrical connecting lines are implemented on an optical fiber. (b) SEM picture.

Figure 3 shows the normal electric near-field distribution of electric-pulse propagating on a 50-μm-wide short-terminated CPW transmission line. The image was measured by scanning the PCNFP in transverse direction of the CPW. The positive electric-field amplitude in Fig. 3 means the up-going electric-field component. The opposite field profile around 80 ps to the main transient around 12 ps implies the normal electric-field property of short reflection. Although the normal electric field at the center of signal line must approach zero, Fig. 3 is not the case. This is understood due to the spatial-resolution degradation of the PCNFP, because we used multi-mode optical fiber with 50-μm core diameter. We convince the spatial resolution will be enhanced with single-mode optical fiber.

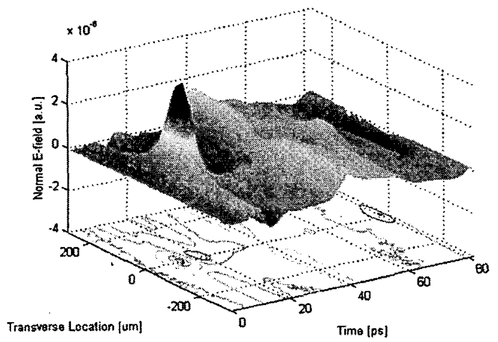


Fig. 3. Normal E-field distribution measured over a short-terminated CPW transmission line by scanning the PCNFP in transverse direction.

IV. Measurement Results

Figure 4 shows top views of sample devices with right-angle bends on microstrip [Fig. 4(a)] and CPW [Fig. 4(b)]. Right-angle bend is widely used structure especially in high-density integrated circuits. The DUTs were fabricated on the LT-GaAs with an incorporated PCS using photolithographic micro-fabrication processes. We generated picosecond electric-pulses by illuminating the pump pulses onto the interdigit PCS with 3-V DC-bias, and measured electric near-field distributions in the areas around the bends shown in Fig. 4 by rectangles.

The resulting time-dependent 2-D spatial near-field images of propagating picosecond electric pulse are shown in Fig.'s 5 and 6 for the microstrip and CPW right-angle bends respectively. The sequential images are depicted every 4.1 ps. The negative amplitude of E-field indicates the opposite field direction to the reference.

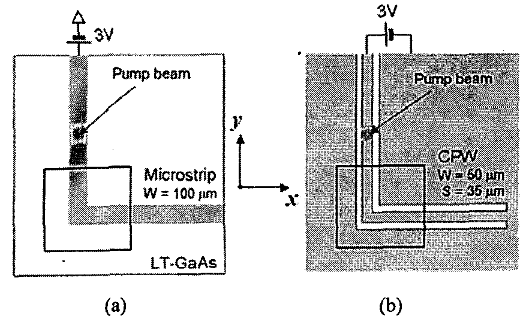


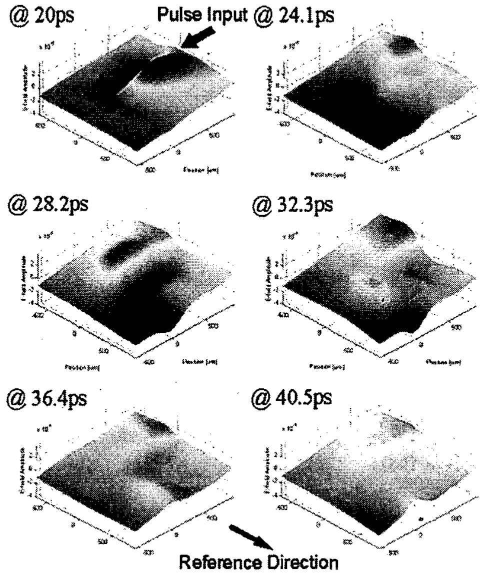
Fig. 4. Top views of sample devices. (a) microstrip right-angle bend, (b) coplanar waveguide right-angle bend. The rectangles indicate the areas observed by the PCNFP.

Following pulse propagation phenomena on right-angle bends can be extracted form the images, and the phenomena become apparent when they are animated.

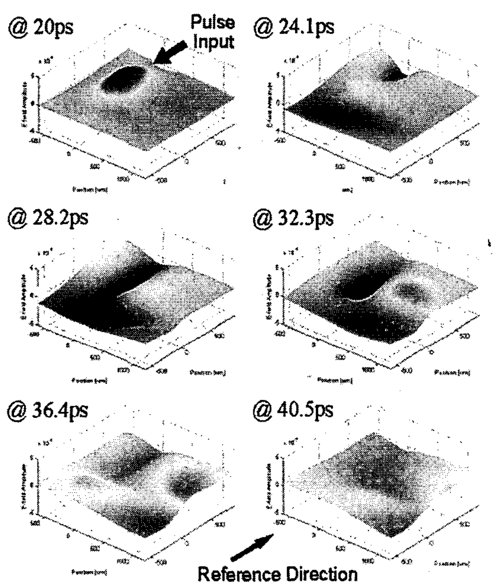
- Figure 5 shows that there are much leaky electric fields around microstrip right-angle bends and that the leaky fields are outward components.
- Reflection property of transverse electric-field component from the microstrip right-angle bend shown around 30 ps in Fig. 5(a) is similar to that from short structure. This phenomenon was also observed in CPW right-angle bends, but it existed only inner portion of the bend [5]. In that case, the reflected component radiated out rather than guided in reverse direction and bend-smoothing techniques reduced the phenomena.
- Comparing the *Y*-directional electric-field distributions shown in Fig. 5(b) and Fig. 6, we can see that the transverse electric-field component over the microstrip bent line propagates without time difference, but there is a flight-time difference of guided transverse electric-field components in the two slots of the CPW bent line. This time difference was removed by using air-bridges as expected.

V. Conclusion

We succeeded in visualizing instantaneous electric near-field distributions of picosecond electric-pulse propagating on both microstrip and CPW right-angle bends using the new miniature PCNFP. The PCNFP is able to measure time evolution of ultrafast signals at any internal areas of devices and circuits with uniform sensitivity. The obtained images showed quite remarkable reflection and transmission phenomena of picosecond electric-pulse on right-angle bends. The result means that the PCNFP can give very important means for ultrafast signal propagation diagnosis.



(a)



(b)

Fig. 5. Time-dependent 2-D spatial near-field images of picosecond electric-pulse propagating on the microstrip right-angle bend shown in Fig. 4(a). (a) *X*-directional electric-field components (b) *Y*-directional electric-field components.

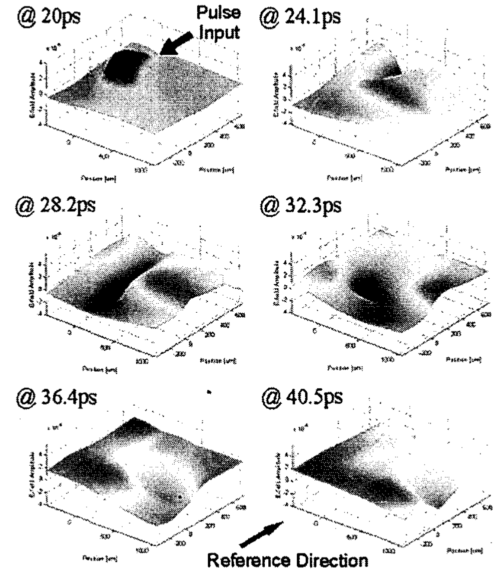


Fig. 6. Time-dependent 2-D spatial near-field images of the *Y*-directional electric-field components propagating on the CPW right-angle bend shown in Fig. 4(b).

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