Pulse-Coupling Measurement of Coupled Microstrip Lines Using a Micromachined Picosecond Optical Near-Field Probe

Jongjoo Lee, *Student Member, IEEE*, Heeseok Lee, Seungyong Baek, You Chul Jeong, and Joungho Kim, *Member, IEEE*

***Abstract*—By measuring the transverse electric-field distributions using a newly developed micromachined optical near-field mapping probe, pulse-coupling phenomena on coupled microstrip lines are reported for the first time. The measured field distribution of the propagating coupled pulse provides useful information to aid understanding of the coupling phenomena; this cannot be obtained by conventional external-port access test instruments. The measurement is performed based on the picosecond photoconductivity of low-temperature-grown GaAs (LT-GaAs). A system for the measurement of the internal electric field distribution using the optical near-field probe is described and characterized. It is capable of measuring independent orthogonal components of free-space electric fields with less than 2-ps temporal resolution and with minimal loading effects. The loading effects of the probe are minimized by adopting a micromachining technique for the use of a 1-μm-thick LT-GaAs epilayer as a substrate, and by using silver-paint-coated optical fibers for electrical connections.**

***Index Terms*—Crosstalk, electric-field measurement, internal circuit testing, near-field probe, photoconductive measurement, pulse-coupling measurement, time-domain technique.**

I. Introduction

In RECENT years, the rapid progress in operating speed and integration density of high-performance monolithic microwave integrated circuits (MMICs) and digital circuits/systems has given rise to a number of unwanted interconnection problems. As the interline spacing of the interconnections becomes even smaller, among the unwanted electromagnetic (EM) phenomena in interconnection lines, the effect of signal coupling between adjacent interconnection lines becomes one of the most important interconnection problems, not only at the on-chip level and on-package level, but also at the on-board level. For transmission of pulses with ultrashort pulse duration, the existence of closely located conductors introduces coupling distortion to the signal pulse, in addition to the intrinsic frequency dispersion and propagation attenuation, and causes unexpected crosstalk to the neighboring lines. This signal coupling produces additional delays and false logic switching, degrading the system's speed and noise margins.

To date, studies of pulse coupling and crosstalk have been conducted based on the measurement of voltages at the external ports of the device-under-test (DUT) or based on numerical simulation [1]–[4]. However, numerical simulation has potential errors associated with the approximations inherent in a computational algorithm and with available resources such as memory capacity and calculation time. Voltage measurement at the external ports by conventional test instruments yields insufficient information to thoroughly understand the coupling phenomena because it measures only one of the macroscopic quantities that are available at the external ports. That is, the physics of the EM wave phenomena, such as details of the internal field distribution within coupled-line structures, cannot be obtained. Therefore, a new transient measurement technique capable of measuring the internal circuit information including the EM field distribution is required. Scanning probe microscopes [5] and EM probing techniques using dipole- or monopole-type probes [6], [7] have shown potential for the high-frequency in-circuit measurement. However, a scanning microscope [5] detects voltage waveforms based on the small deflection of a cantilever by the Coulomb force, thus, its sensitivity is very low. EM probing techniques, based on modulated scattering [6] and antenna response [7], also suffer from poor sensitivity and the techniques have limited application for digital circuit testing because they cannot detect the original shape of the propagating digital pulse that contains the broad-band frequency spectrum, including dc. In this paper, we introduce a new measurement technique capable of measuring picosecond electric-field components for internal circuit testing. The measurement is based on an optical sampling technique, the so-called photoconductive (PC) sampling, using short laser pulses and ultrafast PC switching of a photodetector. One of the most important properties of this technique is that it detects the original shape of the electric-field waveform, and this property was demonstrated in [8].

The PC sampling technique, as an ultrafast optical sampling technique, has been used in the past for characterization of devices and circuits by on-wafer external port measurements [9], [10] or by internal-node conductive contact measurements [11]–[13]. This technique utilizes picosecond electrical pulse signals generated by PC switches and measures the time-domain characteristics of integrated DUTs. It has the advantages

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of a measurement bandwidth of several hundreds of gigahertz and a very high signal-to-noise ratio for room-temperature measurements. The on-wafer measurement methods [10], [11] have provided an alternative to on-wafer network analyzer measurement, but are limited to measurements at the point of the intentionally integrated probing structure. Miniaturized PC probes [11]–[13] have provided free access to arbitrary internal ports of circuits. Nevertheless, the probes have been also used for voltage measurement, draining charges directly from the DUT in a conductive-contact embodiment. Therefore, they suffer from unavoidable large loading effects (invasiveness) due to the T-connected probe line structure acting as a high-frequency electrical stub. On the other hand, electrooptic (EO) sampling, which is another ultrafast optical sampling technique and is operated by coupling fringing fields into EO crystals, measures electric fields and has much larger measurement bandwidth of a few tens of terahertz [14], [15]. However, EO probing suffers from poor sensitivity and invasiveness due to the very high dielectric constant of the EO crystals (43 for $LiTaO_3$ and 50 for BSO) with comparable thickness.

In the probe developed for this paper, we have successfully adopted a PC switch and sampling to the measurement of picosecond transient electric-field components. In this paper, the structure and performance of the novel picosecond optical near-field probe are introduced. The probe was fabricated using a semiconductor micromachining process based on low-temperature-grown GaAs (LT-GaAs) liftoff thin-film technology. The picosecond temporal resolution was achieved by combining the 120-fs width of a triggering laser pulse and the picosecond switching time of a metal–semiconductor–metal (MSM) PC switch made on the LT-GaAs liftoff thin film [16]. The probe has a dipole switch structure to measure both the electric-field intensity and the field direction. The performance of the near-field probe is demonstrated by measuring the picosecond electric-field component of an optically excited coplanar stripline (CPS), where the measured pulse has a 2.7-ps duration, and the field direction change is detected as a polarity change of the measured waveforms. As a highlight, the pulse-coupling phenomena of coupled microstrip lines (MCLINs) fabricated on a printed-circuit-board (PCB) substrate are investigated by measuring the transverse electric-field component distribution. Detailed electric-field waveforms that vary in shape and direction at different positions of the MCLIN are presented, and the propagation delays within the DUT are also shown.

II. System Description

A. Measurement Principle

The developed near-field probe operation is based on PC sampling, and the principal experimental setup is shown in Fig. 1. Time-resolved measurement is performed with a short pulse laser system in a pump-probe setup. In this paper, a passively mode-locked Ti : sapphire laser with 120-fs pulse duration and 76-MHz repetition rate at 810-nm wavelength is used as a laser source. The laser beam is split into two, i.e., the pump beam and probe beam, by an optical beam splitter. The pump beam, modulated by a mechanical chopper at an intermediate frequency (2 kHz), is used to generate electrical pulses by being focused

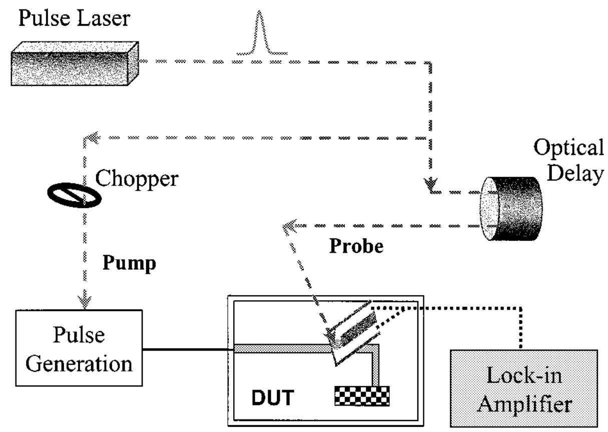


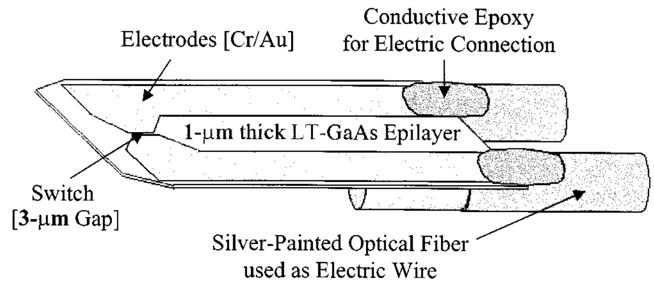
Fig. 1. Schematic experimental setup for transverse picosecond electric-field component measurement of interconnection lines using the optical near-field probe. The measurement is performed using a PC pump-probe principle.

onto a biased ultrafast photodetector. Probe laser pulses, time-delayed relative to the pump pulses via a translation stage (optical delay), are focused onto the PC switch of the near-field probe to sample the electric-field component at that time. A lock-in detection scheme is used to increase the signal-to-noise ratio. The operation of the probe is understood to be that the free carriers (electron–hole pairs) generated in the semiconductor region of the PC switch by the short laser pulses are swept by the instantaneous electric field at the measurement position, and their movement is determined by the magnitude and direction of the instantaneous electric field. The measurement action and the characteristics of the near-field probe were simulated using a finite-difference-time-domain method, as described in [8]. A brief summary of the simulation results is: *the measurement is dominated by the switching action of the generated carriers in the PC switch of the probe*. The probe detects the original shape of the incident EM field pulse with picosecond temporal resolution and detects only the electric-field component with the same direction as that of the PC switch of the probe.

B. Optical Near-Field Probe

The designed and fabricated optical near-field probe is shown in Fig. 2. Fig. 2(a) shows a schematic design of the probe. To minimize the loading effect (invasiveness) of the probe, we adopted a micromachining process of epitaxial liftoff (ELO) [17] to use a 1-μm-thick LT-GaAs epilayer as a substrate. The LT-GaAs epilayer 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 [16]. It is lifted from the growing SI-GaAs substrate by preferentially etching a sandwiched AlAs epilayer in diluted hydrofluoric acid ($HF : H_2O = 1 : 10$). While the probe head size is 420 μm $\times$ 500 μm, it has an MSM dipole switch structure with a 3-μm-wide PC gap determining spatial resolution. The switch consists of 40-nm/210-nm Cr/Au to withstand the HF solution during the ELO process. The shape of the probe was defined by an ammonium hydroxide acid mesa wet etch through the LT-GaAs layer. Fig. 2(b) shows the scanning electron microscope image of the fabricated near-field probe.

The fabricated probes are preserved in isopropyl alcohol, and when needed, they are picked up and mounted on two silver-



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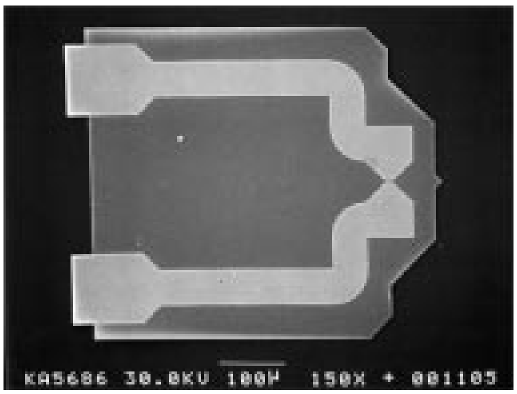

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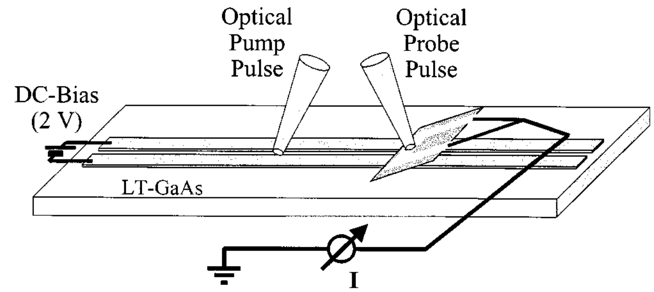
Fig. 2. (a) Schematic of the devised micromachined PC near-field probe. The probe is 500 μm × 420 μm by 1 μm and consists of a Cr/Au MSM PC switch with a 3-μm switch gap. It is mounted on optical fibers serving as electric wires between the probe electrodes and external electronic apparatus. (b) Scanning electron microscope picture of the fabricated near-field probe before assembly.



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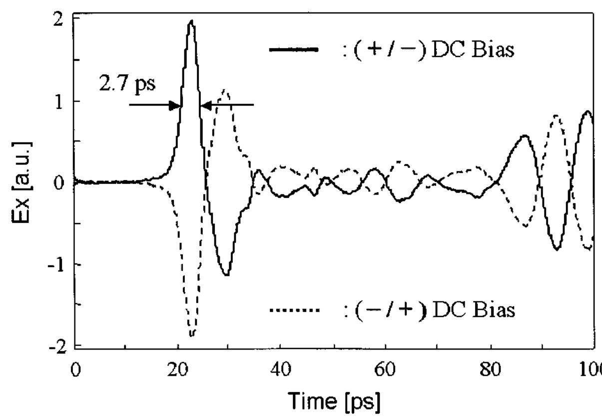


(b)

Fig. 3. (a) Schematic experimental diagram showing a picosecond electric-pulse generation on a CPS made on an LT-GaAs substrate and the probe positioning to measure the transverse electric-field component of the electric pulse. (b) Two measured transverse electric-field component waveforms demonstrating the electric-field polarity discrimination ability of the probe.

paint-coated optical fibers using optical ultraviolet cement. The silver-paint-coated optical fibers are connected to a supporting module on a PCB substrate and serve as electric wires between the probe and supporting module. Finally, conductive epoxy is applied and cured to provide strong adhesion between the probe electrodes and silver-paint-coated optical fibers.

C. System Performance

To demonstrate the picosecond electric-field detection ability of the developed near-field probe, the transverse electric-field component of the optically excited CPS was measured. Fig. 3(a) shows the schematic diagram of experimental method in the pump-probe. The CPS pattern was defined on an LT-GaAs substrate by standard photolithography of image reversal and acetone liftoff process, and consisted of 50-nm-thick Ti for Schottky contact adhesion and 250-nm-thick Au, with 100-μm strip widths, 15-μm interline space (slot), and 10-mm line length. Picosecond electrical pulses were generated by illumination of the pump laser pulse to the slot of the 2-V dc-biased CPS. To measure the transverse electric-field component, the probe was positioned with a 60° inclination from normal to the surface, with 100-μm spacing between the switch of the probe and the slot of the CPS. Fig. 3(b) shows the measured results using the probe positioned at 300 μm apart from the electrical-pulse generation point. The solid waveform is the transverse electric-field component measured at the dc-bias condition shown in Fig. 3(a). The dotted waveform is that measured when the polarity of the dc bias is exchanged. Therefore, it can be said that the probe can efficiently measure the change of the electric-field direction as a polarity change, as well as electric-field intensity. The measured main pulse has 2.7-ps full-width at half maximum. It demonstrates that the probe has <2-ps temporal resolution, considering the correlation detection between the measuring pulse and the PC switch sampling pulse of the probe. An interesting feature shown in Fig. 3(b) is the large measured undershoot. Although more analysis is required to fully understand the origin of the undershoot, more experimental results also performed for different guiding structures revealed that the signal is not the spurious response of the developed probe, but the real undershoot of the main pulse.

To evaluate the invasiveness of the probe, S-parameters of a microstrip line were measured using a vector network analyzer (HP8722C). The microstrip line was fabricated on a PCB substrate (FR4 ($\varepsilon_r \sim 4.3$, $h = 400$ μm): the same PCB used in Section III) and had 760-μm-wide signal line. Fig. 4 is the magnitude plot of the S_{21}s measured without (solid line) and with (dotted line) the probe positioned at 100 μm over the DUT. It clearly shows that the probe has negligible invasiveness up to 10 GHz.

III. Pulse-Coupling Measurement on a Coupled Microstrip Line

A. DUT

The DUT examined for the pulse-coupling measurement is an MCLIN fabricated on a 400-μm-thick PCB substrate (FR4: $\varepsilon_r \sim 4.3$). It was specially designed for measuring the signal-

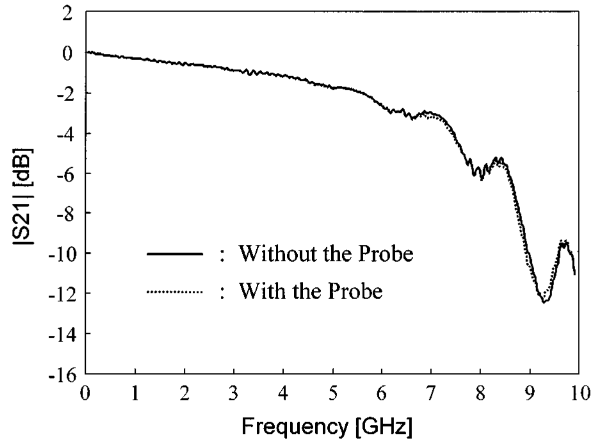
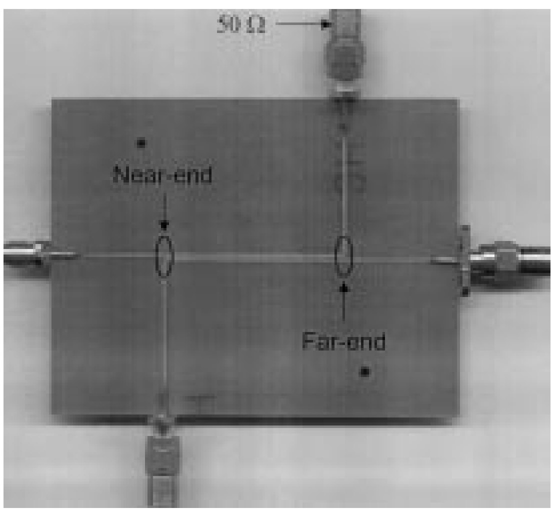


Fig. 4. S_{21}'s measured by vector network analyzer (HP8722C) with and without the probe positioned at a height of 100 μm over a microstrip line fabricated on a PCB. It demonstrates that the developed probe has negligible invasiveness.



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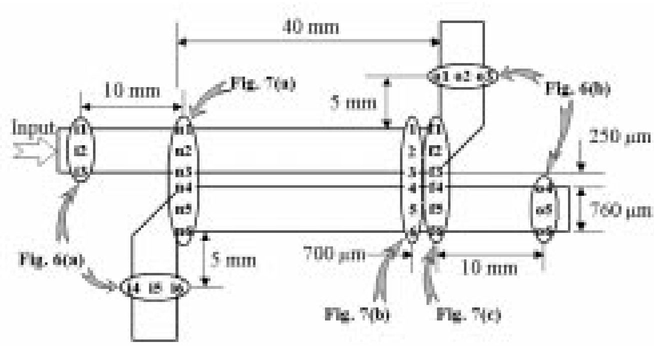
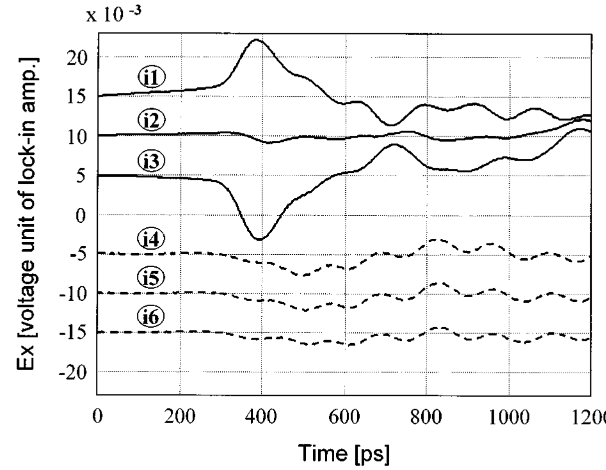


(b)

Fig. 5. (a) Photograph of tested MCLIN structure fabricated on an FR4 ($\varepsilon_r \sim 4.3$) substrate for pulse-coupling (crosstalk) phenomena measurement. The MCLIN has 760-μm-wide signal lines, 250-μm-wide interline spaces, and a 40-mm-long coupled region. In addition, the MCLIN has orthogonal feed lines to confine pulse-coupling phenomena to the coupled region only. (b) Schematic drawing of the MCLIN to indicate the measurement positions.



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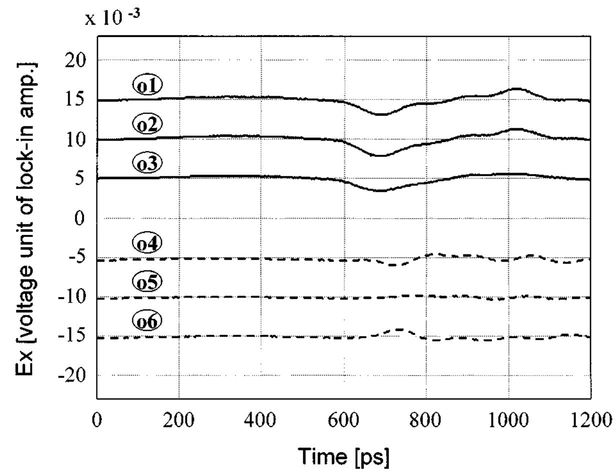

(b)

Fig. 6. Transverse electric-field waveforms measured over feed lines. (a) Outside of near end. (b) Outside of far end. Upper solid-line: three waveforms are measured at the upper edge, center, and lower edge of the signal line, respectively. Lower three dot-lines: those for the adjacent microstrip line [refer to Fig. 5(b)]. The amplitude of the lower dotted-line three waveforms in (a) was magnified three times to clearly show the peaks.

coupling (crosstalk) phenomena directly over the DUT using the developed probe. That is, the feed lines are connected to the MCLIN in an orthogonal direction, as shown in Fig. 5(a). In the previous crosstalk measurements, most test patterns have been made with open-end terminations and/or with transition regions to the contact probing pads for the use of conventional test instruments such as a network analyzer or a time-domain reflectometry (TDR)/time-domain transmission (TDT). Deembedding procedures in these cases can seriously affect the measurement accuracy. Since the characteristics of the open termination vary with frequency and the transition region of the line for the pad probing hinders the correct definition of the coupled region, it is very difficult to correctly consider the capacitive coupling and the inductive coupling effects in the coupled lines. However, in our case, the orthogonal direction of feed lines eliminates coupling between the feed lines, and confines coupling to the parallel-coupled region. The probe measures the electric-field distribution waveforms directly at the arbitrary measurement points in the DUT. Deembedding is performed by a time windowing method [9]–[15].

The fabricated MCLIN has 760-μm-wide signal lines, 250-μm-wide interline spaces, and a 40-mm-long coupled region. Signal input to the DUT was given from a conventional photodetector (Model: Newport 818-BB-21) activated by the

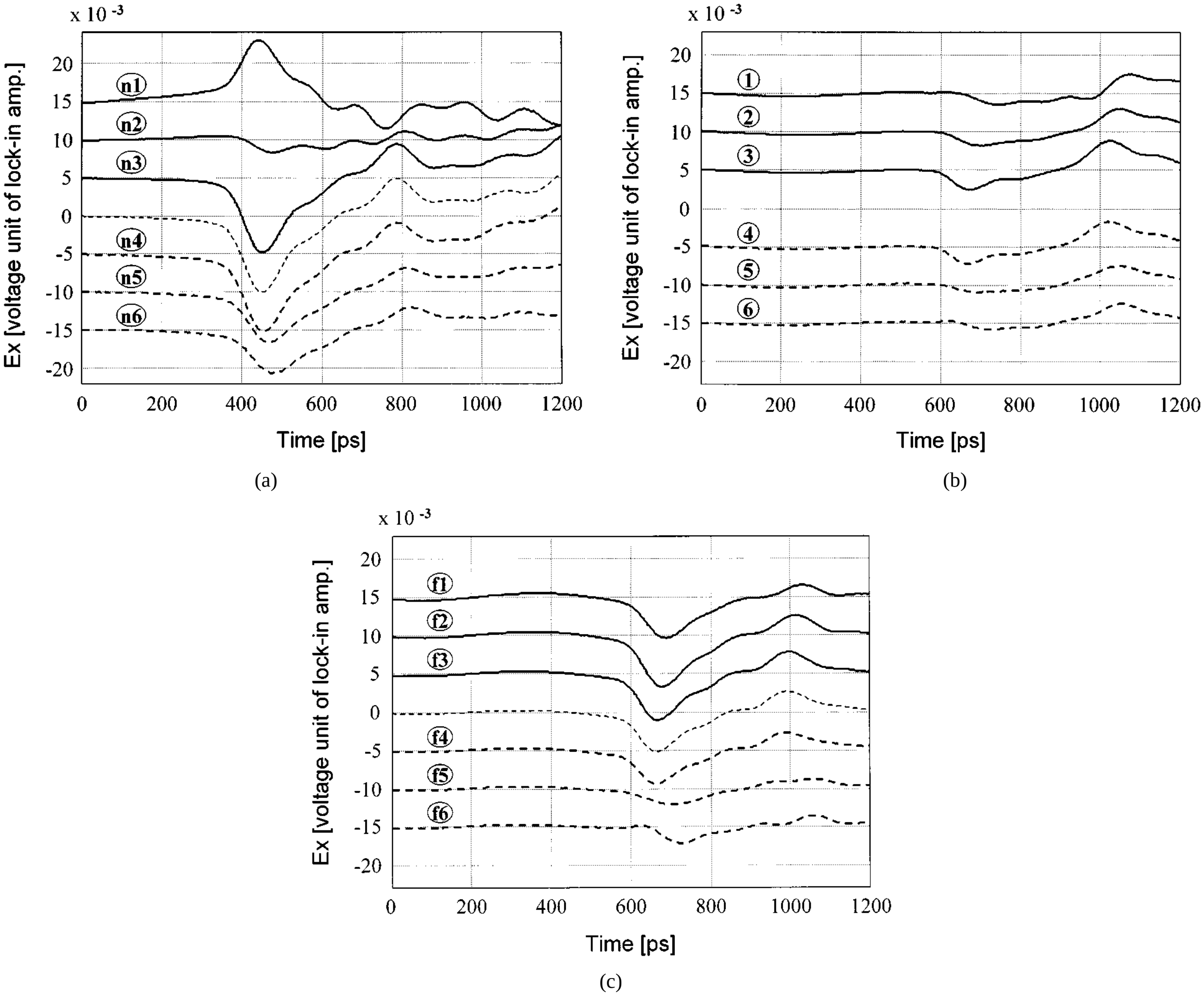

Fig. 7. Transverse electric-field waveforms measured over the coupled region shown in Fig. 5. (a) At the near end. (b) At 700 μm before the far end. (c) At the far end. They show the previously unknown electric-field phenomena related to the propagating modes and the time delay in the coupled region.

laser pulses, and three other ports are terminated by 50-Ω coaxial terminations to reduce signal reflections from the termination. In the bend region of the MCLIN, an optimum right-angle miter ($M = 0.57$) was adopted to minimize bend effects [18], [19]. For convenience, the bend position near the input port is defined as the "near end" of the coupled region, and the other bend position as the "far end" as shown in Fig. 5(a). The probe is positioned at a fixed height of 100 μm over the DUT, and then the DUT is moved using an XY-translation stage to measure the electric-field component at different positions. Fig. 5(b) is a schematic drawing of the DUT illustrating the measurement positions, and the measurement points are numbered to facilitate identification.

B. Measurement Results

Fig. 6(a) and (b) shows the transverse electric-field waveforms measured over the feed lines of the MCLIN, i.e., (a) for outside of the near end and (b) for outside of the far end. The upper solid-line three waveforms are the transverse electric-field component measured at the upper edge, center, and lower edge of the active signal line, respectively. On the other hand, the lower three dotted lines are those measured at the adjacent line, and their amplitude was magnified three times to clearly show the peak. In Fig. 6(a), the upper three waveforms are measured at 10 mm before the near end, but the lower three waveforms are measured at 5 mm from the bend structure, as shown in Fig. 5(b). The time delay between the upper three waveforms and the lower three in Fig. 6(a) is approximately 100 ps. When the effective dielectric constant of the microstrip line on the FR4 substrate is taken to be 3.3 [20], the lower three waveforms originate from the parallel-coupled line region. This also demonstrates the time-discrimination ability of the probe measurement.

The upper three waveforms shown in Fig. 6(a) prove that the DUT is correctly activated in microstrip line mode. The reverse polarity of the waveforms measured at the upper and lower edges of the signal line identifies the microstrip line mode. However, the dotted three waveforms in Fig. 6(a), which are the near-end crosstalk output of the DUT, all have the same polarity, meaning an even field direction. On the other hand, for the signals that have gone through the coupling region shown in Fig. 6(b), the three waveforms measured over the active signal line show the same field direction, while the adjacent coupled line (far-end crosstalk output) is in microstrip line mode with the shape of negative derivative of the incident field [solid-line three waveforms in Fig. 6(a)]. To our knowledge, this is the first measurement of this phenomenon. Another interesting feature observed in Fig. 6 is that the near-end crosstalk pulse signal [three dotted waveforms in Fig. 6(a)] is broader than the far-end crosstalk pulse [three dotted waveforms in Fig. 6(b)] [21].

As a next step, in order to see what happens in the coupled region, the same field measurements were performed in the parallel-coupled region. Fig. 7 shows the measurement results. Fig. 7(a) is measured at the near end of the coupled region, (b) at 700 μm before the far end, and (c) at the far end. From Fig. 7, it is observed that a large signal delay exists at the outer edge of the adjacent line. Fig. 7 also clearly shows that the adjacent line strongly acts as a ground line with respect to the active signal line in the coupled region as it nears the far end. In particular, Fig. 7(b) shows a transverse-field distribution similar to that of the symmetric CPS. This has been understood as the strong odd mode of in-plane E-field between coupled lines, although Fig. 7(b) shows a slightly different field distribution at the outer edges compared to that of the MCLIN influenced by the ground plane. Fig. 7(b) and (c) shows the time delay between the waveforms measured over the inner edges of the MCLIN and those measured over the outer edges. As a reference, there is no time delay over the feed metal strips, as shown in Fig. 6. This time delay may be understood from the faster odd mode phase velocity compared to that of even mode [21]. It can also be said that the odd-mode effect of the MCLIN becomes dominant as a signal propagates to the far end in the coupled region. This phenomenon becomes apparent when the same measurement is performed at the far end of MCLINs with wider interline spacing. In the measurement, it was found that, as the interline spacing of MCLINs became wider, the time delay and amplitude difference between the waveforms measured at the interline space of MCLINs and those at the outer edge of each signal line of MCLINs became larger.

IV. Conclusion

A picosecond micromachined electric-field probe was successfully developed based on the picosecond photoconductivity of LT-GaAs. A surface micromachining technique of the ELO process was adopted to remove the thick growing substrate from the LT-GaAs epilayer so that a thin and minuscule probe was fabricated. The probe minimizes the substrate effects of the probe and gives freedom in positioning to an arbitrary measuring point. In addition, the use of the silver-paint-coated optical fibers for the electrical connection between the probe and external apparatus also contributes to minimize the loading effect of the probe. By measuring the transverse electric-field component of an optically excited CPS, it was demonstrated that the probe could efficiently detect an electric-field component with the same polarization as the direction of the probe switch, with less than 2-ps temporal resolution. Finally, the pulse-coupling phenomena of the MCLIN fabricated on a PCB substrate were measured using the new probe for the first time. The measurement showed the time delay due to the parallel-coupled region, as well as the propagation delay. In addition, for the first time, the change of transverse electric-field direction over the feed lines and parallel-coupled region was measured, showing previously unknown electric-field distribution properties. Although the developed probe can measure the in-plane E-field components practically, the vertical E-field component can be measured efficiently by defining the PC switch of the probe to have a 90°-rotated direction. The near-field probe could also find application in the measurement of transient phenomena in passivated digital and millimeter-wave integrated circuits (ICs), which can never be observed using conventional external-port test instruments.

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