Picosecond Time-Domain Characterization of CPW Bends Using a Photoconductive Near-Field Mapping Probe

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***Abstract*—Propagation and reflection characteristics of right-angle coplanar waveguide (CPW) bends were measured using a novel photoconductive near-field probe with picosecond temporal resolution and μm spatial resolution. The probe can measure the transverse electric-field components existing over devices under test. Time-varying transverse electric field maps for different CPW bending structures were acquired by varying the probe position. The CSL mode generation and a difference in flight time of propagating pulses on two slots of the CPW bends were observed. Further, it was found that there exists a considerable unexpected pulse caused by the bent line structure, which has opposite polarity to the input pulse and exists only at the inner ground plane. The undesirable phenomena originated from the bend discontinuity were adequately reduced by bend smoothing techniques.**

***Index Terms*—Bend, coplanar waveguide, mapping, near-field, photoconductive, picosecond, probe, pulse measurement.**

I. Introduction

THE coplanar waveguide (CPW) is one of the most advantageous guiding structures for high frequency interconnects at the chip, package, or PCB level. Co-existence of the signal and ground lines on the same plane enables easy integration of active and passive devices on a substrate without any drilling or thinning processes [1]. Moreover, the CPW has very good noise immunity by virtue of the inherent shielding effect of the ground planes. Further, the number of metal layers can be reduced by adopting the CPW interconnection line structure. As the operating frequency and the integration density of chips, packages, and PCBs increase, however, the transmission and reflection characteristics of interconnection lines are becoming the crucial part of system performance. Hence, it is quite valuable to study the principles of electromagnetic wave propagation in CPWs. The characteristics of CPW bends attract special interest, because the system complexity of high-speed and very large-scale integrated circuitry and devices forces the use of many bend structures.

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CPW bends have been studied, mainly in the frequency domain, using electromagnetic CAD simulation. Equivalent circuit [2], coupled-slotline (CSL) mode generation by CPW bends [3], and optimization of chamfering [4] have been treated. In time domain analysis, Alexandrou et al. [5] demonstrated some basic measurement results applying an electro-optic sampling technique to the study of CPW bends with finite-grounds using a step-like input signal. However, we believe that the measurement of time-varying near-field distribution over CPW bends will enhance further understanding of the bend effects on propagation, reflection, and radiation of high-frequency signals traveling on the CPW.

In this letter, we successfully demonstrate the measurement of time-varying electric near-field distributions over CPW right-angle bends. A novel photoconductive near-field mapping probe [6] was used for the measurements, based on a photoconductive pump-probe measurement technique with picosecond temporal resolution and μm spatial resolution. The probe can measure two orthogonal free-space near-fields by changing the direction of the probe. From the measured time-varying field maps, we found, to our knowledge for the first time, that there exists an unknown pulse only at the inner ground plane of CPW bends. The reflection originated from the bent line structure, and it was significantly reduced by bend smoothing techniques.

II. Experiment

Fig. 1 is a schematic diagram of the test device showing the short-terminated right-angle CPW bend structure (we call it a "corner bend"), an integrated photoconductive switch for picosecond electric pulse generation, and the photoconductive near-field probe. The three figures shown in the lower section of Fig. 1 are the smoothed bend structures created using 0.5 miters, curvature, and double-chamfer consisted of two series-connected 45° bends. The CPW bend structure with 50-μm wide center signal-line and 30-μm wide slots was deposited on a low-temperature-grown GaAs (LT-GaAs) epilayer of 1-μm thickness. The LT-GaAs was grown on a 625-μm-thick SI-GaAs substrate by molecular beam epitaxial technique at 200°C to ensure a subpicosecond carrier lifetime. The photoconductive sampling principle reported previously in [7] was applied. Bold dotted-line arrows shown in Fig. 1 are the scanning directions of the probe to measure the incident/reflected and the transmitted transverse electric-field components, respectively.

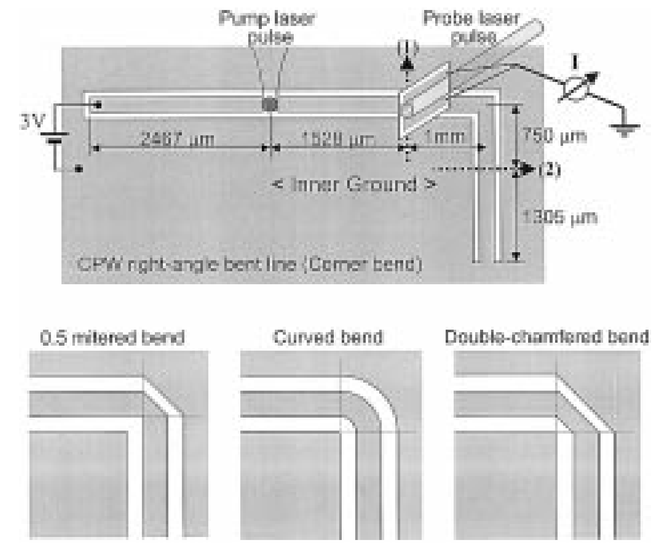


Fig. 1. Schematic diagram of the test device containing the short-terminated CPW bend structure, a photoconductive switch for picosecond electric-pulse generation, and the photoconductive near-field probe for transverse electric-field measurement. Bold dotted arrows indicate the scanning direction of the probe. The lower three drawings are smoothed bend structures being tested.

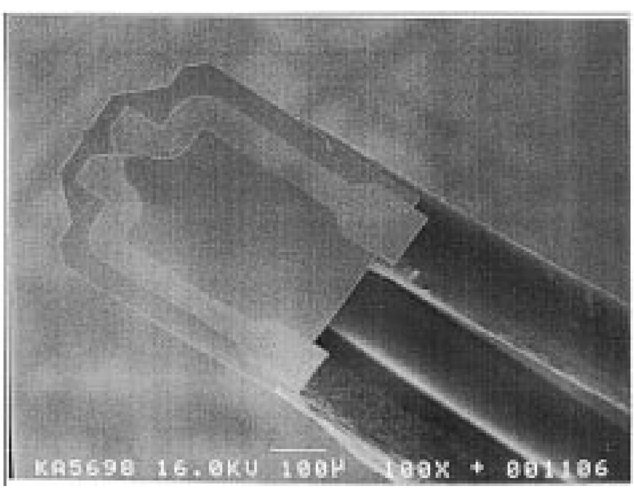
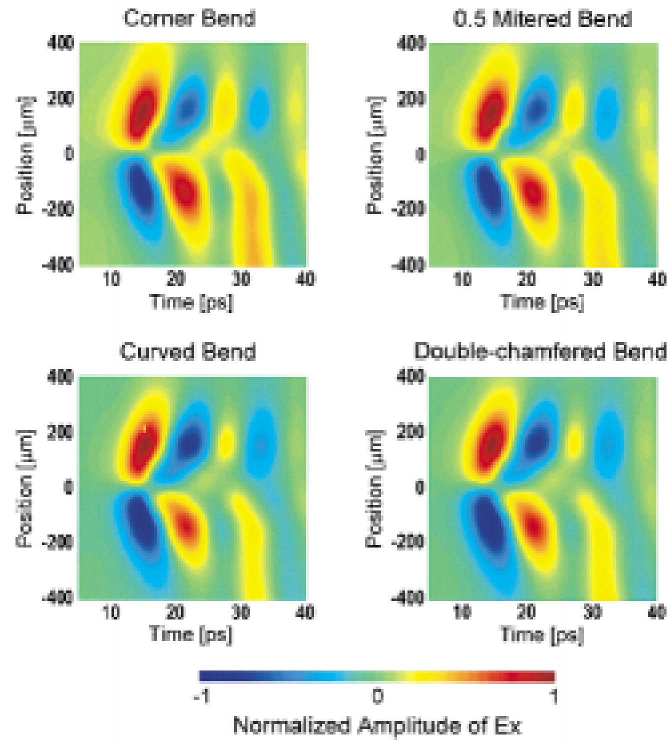


Fig. 2. SEM photograph of the photoconductive near-field mapping probe developed using a micromachining process (500-μm $\times$ 420-μm $\times$ 1-μm).

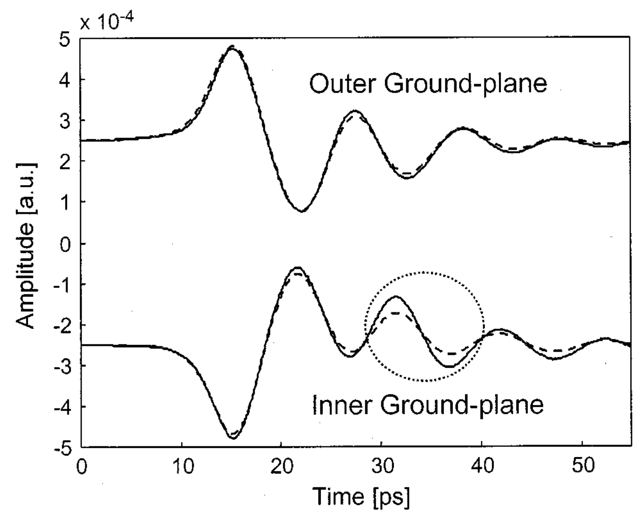
A SEM photograph of the photoconductive near-field mapping probe is shown in Fig. 2. It was operated by the switching action of the integrated photoconductive switch fabricated on a 1-μm-thick LT-GaAs epilayer. The switch was activated by probe laser pulses of 120-fs pulse duration, and the probe laser pulse was guided to the switch by a 45° polished bevel-edge multi-mode optical fiber with 50-μm-core diameter. This ensured that the sensitivity of the probe in each measurement at different positions was unchanged. The probe was fixed to a computer-controlled XY-translation stage with 1-μm scanning resolution, and it scanned over the devices under test to acquire the near-field distribution image.

III. Results and Discussion

Fig. 3 shows the scanned transient images of the propagating transverse electric-field component. Fig. 3(a) shows the field images measured at 1 mm before the centers of bends [Bold-dotted arrow in Fig. 1 numbered (1)] showing the incident and reflected signals from the four different types of CPW bend. The waveforms in Fig. 3(b) were measured above the ground planes at a position 200 μm from the center signal-line. As shown in Fig. 3, at about 14 ps, the anti-symmetry of the main incident pulses measured over the outer ground plane and the inner ground plane indicates that the CPW mode is correctly propagating on the CPW structures. The pulse at about 21 ps is the undershoot of the incident main pulse [6].



(a)



(b)

Fig. 3. Transient transverse electric-field component distributions of incident and reflected pulses scanned at 1 mm distance before the bend structures. [Bold-dotted arrow in Fig. 1 numbered (1)] (a) Transient images; (b) waveforms measured on the ground planes of the corner bend (solid-line) and the double-chamfered bend (dashed-line).

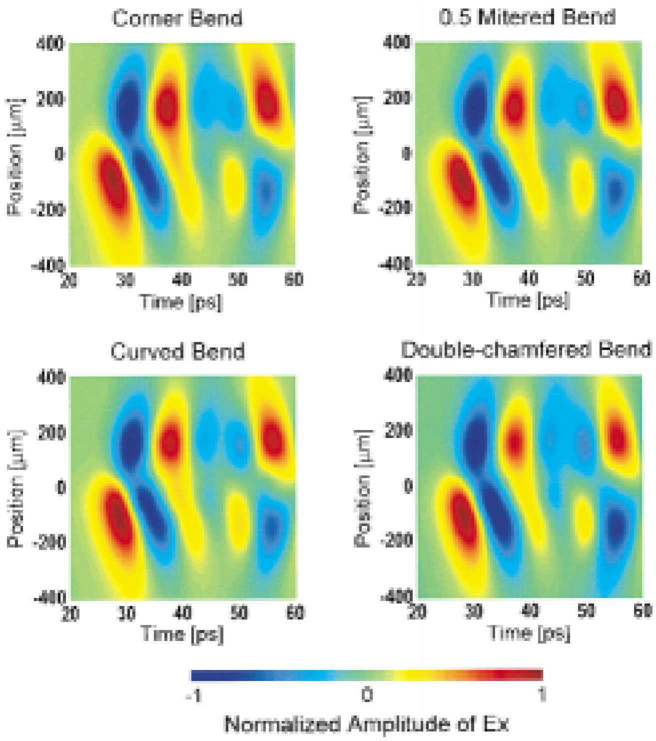


Fig. 4. Transmitted images of transient transverse electric-field component distributions scanned at 750-μm after the short-terminated bend structures [Bold-dotted arrow in Fig. 1 numbered (2)].

The propagating signals that destroy the anti-symmetry of the guided transverse electric field of the CPW appear at around 32 ps [dotted-circle region in Fig. 3(b)]. They have the opposite polarity to the main incident pulse and exist only at the inner ground plane of the bend structures. The amplitude of the signal does not decrease exponentially as it moves away from the signal line over the inner ground plane. In addition, it is reduced adequately by using bend-smoothing techniques, as also shown in the circle region of Fig. 3(b). Additional experiments (two-dimensional spatiotemporal image) revealed that the signal is generated at the inner portion of the bent line and propagates like a radiated wave only at the inner ground plane. Therefore, although more analysis is required, the signal is understood as a leaky wave originating from the transient electric-field component when the field is changing direction at the bend. When a transverse electric field component suddenly meets the 90° bent line, it becomes a longitudinal component of the CPW after the bend. However, there is little longitudinal electric-field component in a common CPW. Therefore, the longitudinal component on the CPW after the bend should be removed instantly, so an opposite polarity field component is generated and radiated in the bend. Smoothed bends make the change more gradual, resulting in less reflected signal of the longitudinal component.

Fig. 4 shows the transmitted transverse electric-field images through the bend structures measured at 750 μm after the center of the bend structure [Bold-dotted arrow in Fig. 1 numbered (2)]. It clearly shows the flight-time difference of the two incident pulses traveling in the two slots of a CPW. The flight-time difference matches to the path difference of the two slots as described in [5]. Figure 4 also clearly shows the existence of the CSL mode of the CPW in the 30-ps to 40-ps region. It is depicted as the same-color component (meaning the same field direction) extending to the opposite side of the CPW, and it is found that the bend smoothing techniques used also contribute to the reduction of the mode conversion. Another interesting phenomenon is related to the reflected signals from the short-circuit-termination at about 56 ps in Fig. 4. At 56 ps, it is shown that the reflected signals measured over the two slots of the CPW arrive at the same time. Although more analysis is required, we consider that most of the energy of the high-order CSL-mode component is radiated at the short termination. However, most of the CPW mode field component guided well is reflected from the structural short termination and travels back.

IV. Conclusion

The propagating picosecond electric-field phenomena on CPW bends were investigated by measuring the transverse electric-field distributions using a novel photoconductive near-field mapping probe. It was demonstrated that not only the CSL-mode but also an unknown signal with 180° phase shift of the incident pulse are generated when a guided pulse meets the CPW bends. The unknown signal was measured only at the inner ground portion of the CPW. The undesirable phenomena by the bend discontinuity were adequately reduced by using bend-smoothing techniques. The probe proved to be able to characterize the high frequency interconnection problems of advanced interconnects.

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