Section 2
ADVANCED TECHNOLOGY DEVELOPMENTS

2.A Picosecond Characterization of Bent Coplanar Waveguides

Many of today's experimental electronic devices can successfully operate at frequencies far above 100 GHz. However, at these frequencies, characteristics of the interconnecting medium often become the limiting factor in the overall performance of high-speed circuits, restricting their maximum operating bandwidth. Speed limitations imposed by the interconnects will be even more severe in future high-speed, very-large-scale integrated (VLSI) circuitry, where the system complexity will force the designers to widely implement bent interconnects.

The studies of straight, coplanar transmission-line structures, suitable for high-speed interconnects, have been the subject of intensive research in the past.[1–7] Both room temperature[1–4] and superconducting (low-T_c[5] and high-T_c[6,7]) lines have been investigated. On the other hand, the previous studies of bent coplanar transmission lines were primarily limited to the low-frequency regime, where the bends were treated as point discontinuities.[8]

In this article we present the first sub-THz, time-domain characterization of bent transmission lines. For our studies we selected the coplanar waveguide (CPW) because it is a planar structure with comparatively low dispersion, low inductance, and low substrate sensitivity. Thus, it can be successfully implemented in a high-frequency regime.[9] We show that at sub-THz frequencies, bends in the CPW cannot be treated as point discontinuities and signal propagation along the bend must be included in the analysis. Nevertheless, we demonstrate that bent CPW's, especially those with curved or chamfered bends, can sustain low-distortion propagation up to about 100 GHz.

Experiment

The CPW's studied in this work are schematically shown in Fig. 47.22. In each case the transmission line formed a meander-like structure in order to measure cumulative distortion of the signal as it propagated along many bends. The CPW's were made of Au on undoped (semi-insulated) 500-μm-thick GaAs substrates, using a standard lift-off technique. The metal lines were 50 μm wide and 250 nm thick. The line separation was also 50 μm. Seven bent CPW's with different degrees of bend smoothing were fabricated in the same run. Each CPW was about 10 mm long and incorporated 20 bends over this distance, as well as the photoconductive switch (see Fig. 47.22). For comparison, a straight CPW of the same dimensions was also fabricated and tested. Figure 47.22 presents only the extreme cases and shows the right-angle-bent line (No. 1) and the lines with the bends smoothed by chamfering (No. 3) or curving (No. 6).

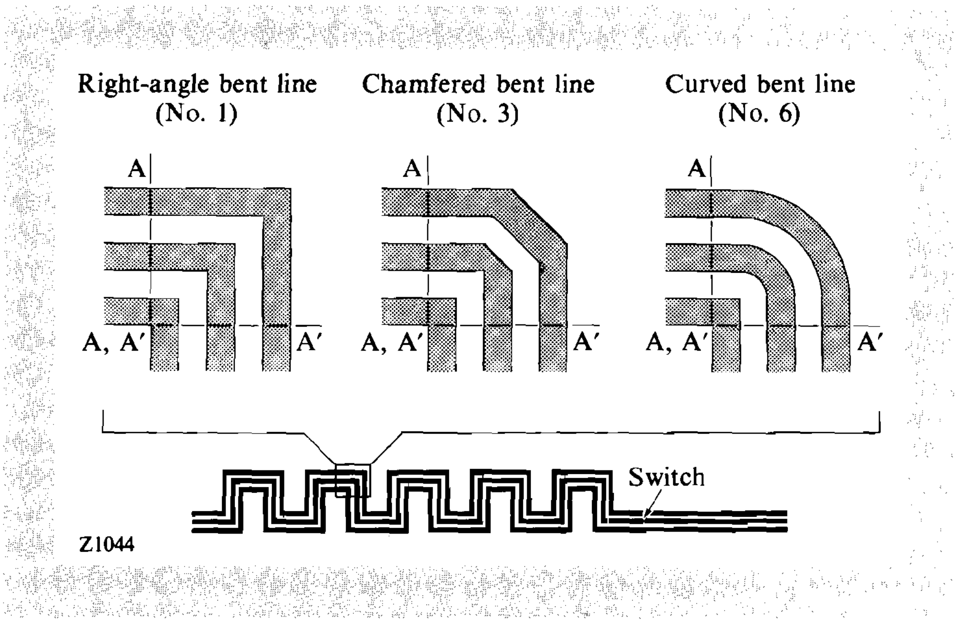

Fig. 47.22
Geometries of the bent CPW's studied in this work.

The measurements were performed with the aid of an electro-optic sampling system, similar to that described in Ref. 10. The CPW's were biased with a 10-V peak-to-peak square wave at a frequency of 3.5 MHz and terminated by a 50 Ω load. A colliding pulse, mode-locked dye laser was used to provide two trains of ~100-fs optical pulses (λ = 620 nm) at 100-MHz repetition rate. The first train of pulses (excitation train) was directed, via a short piece of an optical fiber, to the photoconductive switch (see Fig. 47.22) and used to launch a step-like electrical transient in the CPW. The implementation of the fiber enabled us to speed up the beam-alignment procedure and substantially improved reproducibility of the measured electrical transients. The second (probing) beam was fed to a small, movable electro-optic $LiTaO_3$

crystal (so-called "finger tip"), which was used to probe propagating electrical waveforms at different points along the transmission line.[10]

Results

Figure 47.23 shows the measured step-like electrical transients as they propagate along the bent CPW No. 6. The waveform (a) shows the input signal, while the waveforms (b), (c), and (d) show the same signal after it propagated through 2, 4, and 10 bends, respectively. Only the rising parts of the transients are shown for better clarity. The transients of the type presented in Fig. 47.23 enabled us to precisely determine both the signal arrival time (taken as the midpoint of the transient) and the 10%–90% rise time. As expected, the transient's rise time became longer as it propagated along the line. At the same time we did not observe any significant attenuation of our signals.

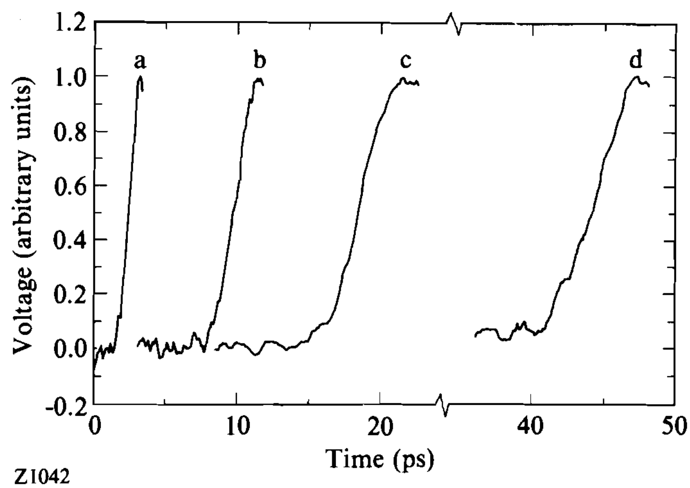

Fig. 47.23
Experimentally measured waveforms of the signal propagating on the curved-bent CPW (No. 6). (a) – the input transient; (b), (c), and (d) – the propagated signals after 2, 4, and 10 bends, respectively. The waveforms are normalized with respect to the amplitude of the input pulse, in order to eliminate spurious, measurement-to-measurement fluctuations.

The signal-propagation velocity v along the bent CPW's can be determined from a plot of propagation distance versus time as presented in Fig. 47.24. The propagation distance represents the full physical length of the CPW, defined as the path along the center of the CPW signal line. The bent CPW's exhibit the same propagation velocity as the straight CPW. Further, it is practically constant over the entire distance. All of the data points (including the ones for the CPW's not presented in Fig. 47.24) lie on the same straight line, which corresponds to the value of v given by the quasi-static approximation:

$$v = \frac{c}{\sqrt{\frac{\varepsilon_{air} + \varepsilon_{GaAs}}{2}}} = 0.38\,c\,, \quad (1)$$

where $\varepsilon_{GaAs} = 12.9$, $\varepsilon_{air} = 1$, and c stands for the light velocity in vacuum. The result is in excellent agreement with Ref. 1 and suggests that, within our frequency range, the propagation velocity (or equivalently signal dispersion) depends very weakly on the number of bends, or their shape.

The fact that the propagation distance represents the full physical length of the CPW supports an intuitive expectation that at the sub-THz frequency range the effect of propagation of the electrical signal along the bend must be fully taken into account. Thus, at these frequencies, one cannot follow the analysis given by Simons *et al.* (Ref. 8), where the bend (defined as the region of the CPW between A–A and A′–A′ cross sections in Fig. 47.22) was treated as the point discontinuity with a small, frequency-dependent length correction.

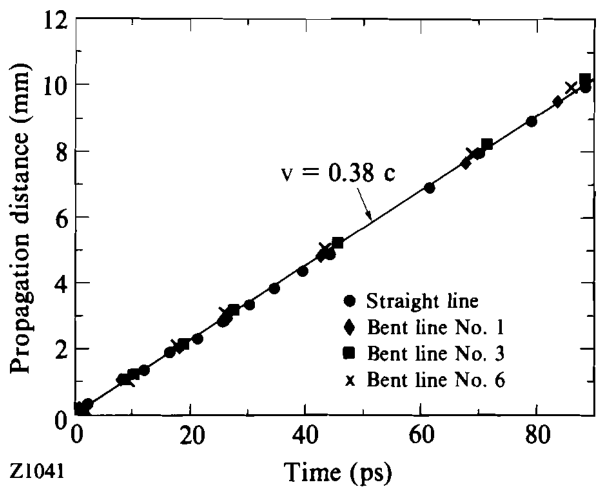

Fig. 47.24
Propagation distance versus time for the picosecond transients propagating on the straight and bent Au-on-GaAs CPW's. The straight line corresponds to the signal velocity within the quasi-static limit.

The variation of the rise times as the transients traveled along the bent and straight CPW's is shown in Fig. 47.25. As expected, the rise times were shortest for the straight line and they initially increased linearly with the propagation distance (see also Ref. 1). The bent CPW's exhibited considerably longer rise times in the initial propagation distance (0–3 mm), as compared to the straight line. We associate this effect with high-frequency reflections of the signal from the bends. For longer distances, the rise times continued to increase only for the right-angle-bent line (No. 1), while for the chamfered-bent line (No. 3) and the curved-bent line (No. 6), the values of the rise times leveled off to ~5 ps after 4 mm of propagation. At this frequency regime, the bent CPW's behaved almost like the straight line.

The observed difference in the rise times between the bent and the straight CPW's shows that the bend-induced distortion depends on the bend geometry and is significantly reduced for the smooth bends, which, apparently, cause less reflection. The distortion is also frequency dependent. However, for the curved- and chamfered-bent lines, it practically vanishes for transients longer than 5 ps. The previous observations show that high-frequency reflections from the bends are the leading mechanism of signal distortion in the bent CPW's operating in the sub-THz frequency range.

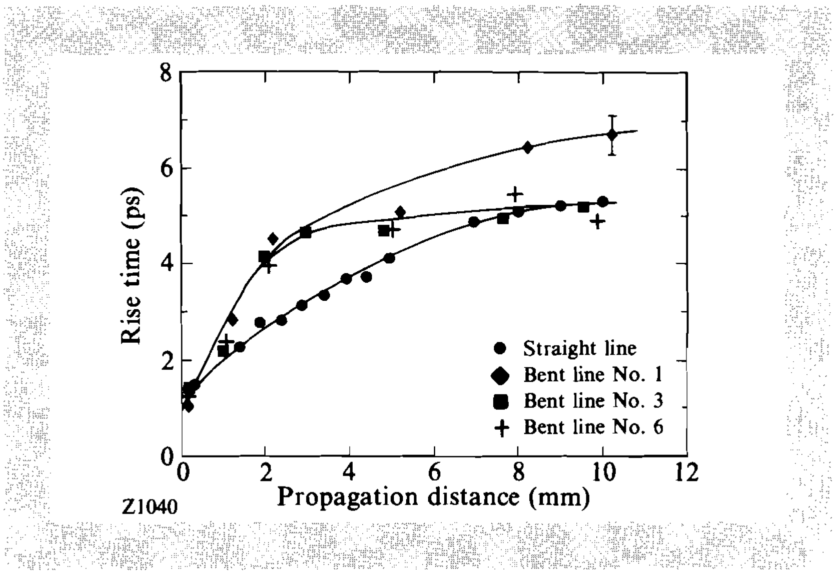

Fig. 47.25
Rise time versus the propagation distance comparison between the right-angle bent, smooth-bent, and straight CPW's. The error bar on the line No. 1 data point represents the maximal error of our measurements. The solid lines are only to guide the eye.

Conclusions

We have measured the propagation characteristics of the 20-bend CPW's over a distance of about 10 mm. Our results demonstrate that picosecond transients, having the bandwidth in excess of 100 GHz, can propagate over a large number of bends with a limited signal distortion. We have found that the physical length of the bent CPW must be taken into account in order to correctly evaluate the signal propagation velocity. Finally, we showed that smoothing of the bends considerably improves the very-high-frequency performance of the bent CPW's.

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