Mode-discriminating photoconductor and coplanar waveguide circuit for picosecond sampling

N. Zamdmer, Qing Hu, S. Verghese, and A. Förster

Citation: Appl. Phys. Lett. **74**, 1039 (1999);
View online: https://doi.org/10.1063/1.123448
View Table of Contents: http://aip.scitation.org/toc/apl/74/7
Published by the American Institute of Physics

APPLIED PHYSICS LETTERS VOLUME 74, NUMBER 7 15 FEBRUARY 1999

Mode-discriminating photoconductor and coplanar waveguide circuit for picosecond sampling

N. Zamdmer[a] and Qing Hu
Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

S. Verghese
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts 02173-9108

A. Förster
Institut für Schicht- und Ionentechnik (ISI), Forschungszentrum Jülich, Jülich D-52428, Germany

(Received 12 August 1998; accepted for publication 15 December 1998)

We introduce a circuit for ultrafast measurements with coplanar waveguide transmission lines. The circuit contains photoconductive switches that allow tunable generation and reception of a coplanar waveguide's two propagating modes. The circuit has fewer discontinuities than other circuits with similar capabilities and does not require airbridges. We show how the photoconductive switch can be biased to compensate for pump laser beam misalignment, and that a circuit composed of two chips making up a hybrid has only 4% broader temporal resolution than a circuit integrated on a single chip. We measured a minimum temporal resolution of 2.4 ps. © *1999 American Institute of Physics.* [S0003-6951(99)02807-7]

The coplanar waveguide (CPW), which consists of a strip centered between two ground planes, is perhaps the most useful type of transmission line for picosecond sampling. It shares certain advantages over microstrip with other coplanar transmission lines: it can be made with micron precision using photolithography, which pushes the cutoff frequency of parasitic modes far above 1 THz; and it can be easily integrated with planar active devices. Experiments have shown CPWs with narrow ground planes to be less attenuative and dispersive than microstrip and coplanar strips at subterahertz frequencies.[1,2] Signals traveling on CPWs are less susceptible to distortion by freely propagating radiation than signals on coplanar strips, because a CPW's signal-carrying center conductor is shielded on both sides by its ground planes, while coplanar strips are unshielded.[3]

The main disadvantage of CPWs is that they allow two quasi-transverse-electromagnetic (TEM) propagating modes, compared to the single quasi-TEM propagating mode of coplanar strips. The modes are called even and odd according to the symmetry of each mode's electric field with respect to the CPW's center conductor. The even mode is wider than the odd mode in the direction transverse to the CPW, because its characteristic dimension is the distance between the two ground planes, while the odd mode's characteristic dimension is the distance between each ground plane and the center conductor. The even mode's extra width makes it more dispersive and attenuative than the odd mode in the subterahertz frequency range, because dispersion occurs when a mode's width is comparable to the wavelength, and radiative attenuation increases with the square of the width.[2,4] Since the two modes have different propagation characteristics, any asymmetry or discontinuity in a circuit that mixes the modes causes distortion. Every useful circuit must contain some discontinuities, usually at active devices or at photoconductive switches, and at breaks in the CPW's ground plane which allow access to its center conductor. Even if these discontinuities have mirror symmetry with respect to the center conductor, the unwanted even mode of the CPW can still be generated if the pump laser beam of a sampling experiment is misaligned.

Modal distortion must be controlled if CPWs are to be useful. Airbridges have been used to connect the two ground planes of a CPW and suppress the even mode.[3,5] Several authors have optoelectronically sensed the electric field on either side of the center conductor and thereby discriminated between the odd and even modes, allowing the meaningful and spurious parts of signals to be distinguished.[3,6] We propose a simple single-layer CPW circuit that makes airbridges unnecessary and allows mode discrimination and selective mode generation without requiring optoelectronic sampling. The circuit includes a photoconductive pulser and sampler for fiber-coupled measurements of active devices inside a cryostat,[7] where optoelectronic sampling is difficult.[8]

Figure 1 shows a schematic diagram of the circuit. There are photoconductive switches at the pump and probe spots. Each switch has two active regions, grounded by and located on either side of the CPW's center conductor. The active regions are 10-μm wide with 3-μm gaps, and are separated by the center conductor at a point where it narrows to 3 μm. They are close enough to be illuminated by the same laser spot, yet can be biased independently on the pump side, or collect independent samples on the probe side. Thus the type of mode generated at the pump can be adjusted by V_1 and V_2,[2] and the even and odd modes can be distinguished by comparing the two probe currents.

Our circuit is "device ready" in that a device can be embedded between the pump and probe spots in common-gate configuration without having to create any other discon-

[a]Electronic mail: nzam@mit.edu

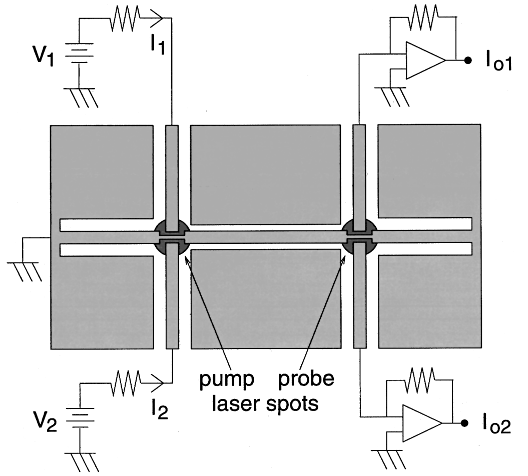

FIG. 1. Schematic diagram of our coplanar waveguide circuit. The pump and probe regions are drawn to scale, though the entire circuit is not. V_1 and V_2 are voltage supplies for the pump photoconductor, and I_1 and I_2 are the supplied dc photocurrents (dark current is negligible). I_{o1} and I_{o2} are the dc outputs of the transimpedance amplifiers collecting the two probe currents. I_{o1} and I_{o2} depend on the time delay between the arrivals of the pump and probe laser pulses.

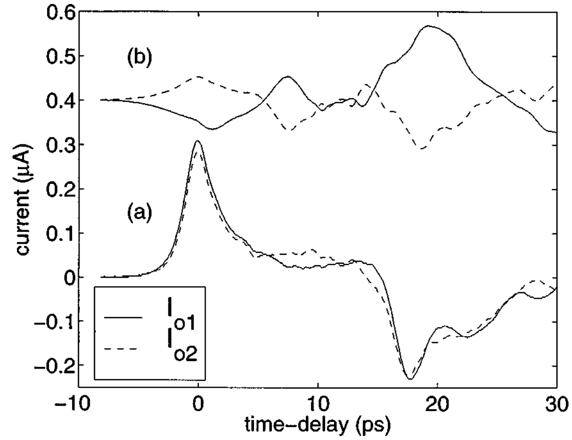

FIG. 2. Pump–probe transients under symmetric bias (a) and antisymmetric bias (b). (a) $V_1 = V_2 = 20$ V, $I_1 = 8.8$ μA, $I_2 = 8.7$ μA, pulse width (FWHM)=2.4 ps. (b) $V_1 = -20$ V, $V_2 = 20$ V, $I_1 = -14.4$ μA, $I_2 = 14.8$ μA (shifted by 0.4 μA).

tinuity than the device itself. To embed a device, the center conductor of the CPW must be split halfway between pump and probe and the device placed in between. The two portions of the center conductor become source and drain contacts, and the two ground planes become independent gate contacts. The dual-photoconductor design has two important capabilities: generation of a pure odd mode, and access to the source and drain. Previous designs had either one or the other.[3,5]

One disadvantage of dual photoconductors compared with a single photoconductor is the added loss in coupling between the photocurrent and the current excited in the propagating modes. We calculated the coupling constants of a few configurations of photoconductors and CPWs using a FD–TD electromagnetic simulator.[9] The least loss (−0.4 dB at 1 THz) occurs when a single switch, formed by a gap in the center conductor of a CPW, excites the odd propagating mode. The small loss is due to radiation into the substrate and free space. Heavier loss (−1.4 dB at 1 THz) occurs when dual photoconductors are symmetrically biased to excite the odd mode. The dual photoconductors radiate more than an embedded photoconductor because they are not as well shielded by the ground planes. Even greater loss (−2.8 dB at 1 THz) occurs when dual photoconductors are asymmetrically biased to excite the even mode. This coupling rolls off at a lower frequency than the coupling from an symmetric excitation to the odd mode because, as explained above, the even mode has a greater width than the odd mode.

The circuits used in our experiments were fabricated on a 1-μm-thick layer of low-temperature-grown (LTG) GaAs grown by molecular beam epitaxy on a semi-insulating GaAs wafer at 250 °C and annealed at 540 °C for 10 min inside the chamber in As-rich conditions. This is the same material we used earlier,[7,10] though now we measure a carrier lifetime of 1.1 ps by measuring the effect of autocorrelating two 100 fs optical pulses on the dc photocurrent of a single photoconductive switch.[10] The circuits were patterned from an evaporated 250-nm-thick Au film with a 50-nm-thick Ti adhesion layer. Each circuit contains six parasitic CPWs which provide contact to the photoconductive switches. They are 1-mm long so that spurious electrical transients traveling along them arrive at the probe substantially later than the main pulse. The main CPW has a 10-μm-wide center conductor and a 5-μm gap between the center conductor and each ground plane (characteristic impedance $Z_0 = 44\,\Omega$). The parasitic CPWs have 10-μm-wide center conductors and 10-μm gaps ($Z_0 = 55\,\Omega$).

Picosecond sampling measurements were performed using a mode-locked Ti:sapphire laser coupled to our circuits in the standard pump–probe configuration. The laser was operated at 760 nm, emitting pulses of 100 fs width (as inferred from the spectral width) at a rate of 80 MHz. The pulse train was split into pump and probe beams with a variable time delay scanned at 15 Hz. They were focused onto their respective photoconductive switches by a single 5× microscope objective. The spot diameters were approximately 12 μm. The average power in the pump beam was 8 mW and the power in the probe beam was 11 mW. The two probe currents were measured by low-noise transimpedance amplifiers whose outputs were displayed and averaged on a digital oscilloscope triggered at 15 Hz. The two traces were averaged simultaneously for 90 s.

Figure 2 shows the averaged traces for two different pump biases. Both traces were measured with the two active regions of the pump and probe switches equally illuminated. Trace (a) was measured with equal pump biases, and trace (b) was measured with equal pump biases of opposite sign. In trace (a), I_{o1} is nearly equal to I_{o2}, indicating that a pure odd mode was generated and received. In trace (b), I_{o1} and I_{o2} are approximately equal and of opposite sign, indicating that a pure even mode was generated and received. There is a portion of trace (a) for which I_{o1} and I_{o2} are significantly different at a time delay of 10 ps. This is evidence that the even mode was received at the probe a substantial time after the arrival of the odd mode's main peak. The even mode was probably generated by stray radiation coupling to the main line after a pulse on a parasitic CPW reflected from a bond wire. This is an example of how the mode-discriminating photoconductors can distinguish the main features of a signal

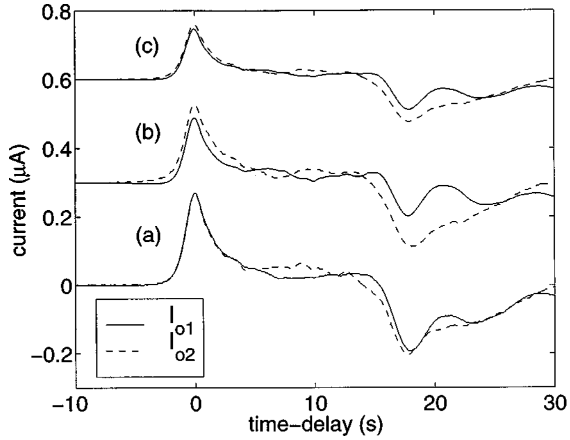

FIG. 3. Compensation of pump beam misalignment. (a) Pump and probe beams aligned, $V_1=V_2=20$ V, $I_1=I_2=8.0$ μA. (b) Pump beam misaligned, $V_1=V_2=20$ V, $I_1=1.9$ μA, $I_2=11.3$ μA (shifted by 0.3 μA). (c) Pump beam still misaligned, $V_1=30$ V, $V_2=13$ V, $I_1=I_2=5.0$ μA (shifted by 0.6 μA).

from the spurious ones. The main peaks of trace (a) are six times higher than the main peaks of trace (b). This is because, as explained earlier, the odd mode attenuates and disperses less than the even mode does, and the coupling between a symmetric excitation and the odd mode is more efficient than the coupling between an asymmetric excitation and the even mode. The large negative peaks in both traces at 18 ps are due to reflections at the shorts that terminate the parasitic CPWs that contact the main center conductor.

The two contacts to the pump photoconductor can be used to generate a pure odd mode even when the two active regions of the pump are not equally illuminated. This is particularly useful with fiber-optic coupling since unavoidable fiber misalignment can then be compensated.[7] Figure 3 shows an example of such compensation. Trace (a) was measured with balanced illumination of both the pump and probe switches, and equal pump biases. It shows that the propagating pulse was almost purely in the odd mode. Trace (b) was measured at the same bias, after the pump beam was slightly misaligned, as evidenced by the inequality of I_1 and I_2. This trace contains some asymmetric features that are visible in trace (b) of Fig. 2, such as the asymmetric peak at 7 ps. Obviously, this pulse contained both even and odd modes. Trace (c) was measured after V_1 and V_2 had been adjusted to equalize I_1 and I_2, without further adjustment of the pump beam. It shows that mode purity was recovered, since trace (c) is approximately a scaled version of trace (a). Interdigitation of the two active regions of each photoconductor using e-beam lithography would have made the switches less sensitive to optical misalignment, and more responsive as well.

All the advantages of our circuit, as well as its large bandwidth, are maintained even when it is used in a hybrid experiment, in which the device to be tested is on a separate chip from the photoconductive switches. Thus impulse response measurements with picosecond resolution can be done without monolithically integrating the device of interest with a fast photoconductor such as LTG GaAs. We tested a hybrid circuit by first scribing then breaking a chip like the one shown in Fig. 1 in half vertically. The two pieces were then fixed in place abutting each other, and the corresponding parts of the main CPW were contacted by applying silver epoxy to the gap between those parts with a needle tip. The circuit used had a large main CPW to make alignment and contact easier. The center conductor was 30-μm wide and the gaps were 15-μm wide. The traces measured on an integrated circuit and on a hybrid circuit are nearly identical to each other and to trace (a) of Fig. 2. The integrated circuit's trace has a pulse width [full width at half maximum (FWHM)] of 2.5 ps, and the hybrid circuit's pulse width is only 0.1 ps greater.

The authors thank K. M. Molvar and L. J. Mahoney for processing the samples. This work was supported in part by the MRSEC Program of the National Science Foundation under Award No. DMR-9400334, and by the National Aeronautics and Space Administration, Office of Space Access and Technology, through the Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology.

[1] S. Alexandrou, C.-C. Wang, M. Currie, R. Sobolewski, and T. Y. Hsiang, Proc. SPIE **2149**, 108 (1994).
[2] R. W. McGowan, D. Grischkowsky, and J. A. Misewich, Appl. Phys. Lett. **71**, 2842 (1997).
[3] J. Allam, N. de B. Baynes, J. R. A. Cleaver, K. Ogawa, T. Mishima, and I. Ohbu, Opt. Quantum Electron. **28**, 875 (1996).
[4] M. Frankel, S. Gupta, J. A. Valdmanis, and G. A. Mourou, IEEE Trans. Microwave Theory Tech. **39**, 910 (1991).
[5] N. G. Paulter, D. N. Sinha, A. J. Gibbs, and W. R. Eisenstadt, IEEE Trans. Microwave Theory Tech. **37**, 1612 (1989).
[6] H.-J. Cheng, J. F. Whitaker, T. M. Weller, and L. P. B. Katehi, IEEE Trans. Microwave Theory Tech. **42**, 2399 (1994).
[7] S. Verghese, N. Zamdmer, Q. Hu, and A. Förster, Appl. Phys. Lett. **70**, 2644 (1997).
[8] D. R. Dykaar, R. Sobolewski, J. M. Chwalek, T. Y. Hsiang, and G. A. Mourou, Adv. Cryog. Eng. **33**, 1097 (1988).
[9] http://www.cray.com/lc
[10] S. Verghese, N. Zamdmer, Q. Hu, E. R. Brown, and A. Förster, Appl. Phys. Lett. **69**, 842 (1996).