Ultrafast coplanar air-transmission lines

D. R. Dykaar, A. F. J. Levi, and M. Anzlowar
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974-2070

(Received 12 April 1990; accepted for publication 22 June 1990)

We demonstrate subpicosecond electrical pulse propagation using coplanar air-transmission lines. Rise times of 0.8 ps after 2.8 mm of propagation are achieved with a velocity of propagation which is 86% of the speed of light in vacuum. Our results suggest that intrachip communication in digital circuits with rise times as short as 1 ps is readily achievable using electrical signals.

A limit to ultrafast electronics with single picosecond switching time is the ability to rapidly propagate undistorted electrical signals from one transistor to another. For example, a 100 Gbit/s data rate requires a 100 GHz clock and its complement which can be distributed less than 1 mm (using metal lines on GaAs) before timing errors between devices become important. The choice of an appropriate technique to distribute the clock and data on length scales greater than this has been the subject of some discussion.[1] We demonstrate experimentally that ultrafast coplanar air-transmission (CAT) lines may be used to propagate subpicosecond electrical signals across typical chip dimensions of a few mm, at very high speeds, and with little distortion. Our results suggest that electrical propagation (as opposed to optical interconnects) is a practical method of intrachip (~mm) communication in digital circuits requiring rise times as short as 1 ps.

Subpicosecond electrical transients can be propagated for short distances ($\lesssim 100\ \mu m$) without significant loss in fidelity (rise time).[2,3] However, there has been little attempt to propagate subpicosecond electrical signals large distances (e.g., a few mm) because of dispersion mechanisms involving dielectric discontinuities and materials-related losses.[2-4] We show that a practical solution to this problem is the formation of CAT lines in which the bulk of the substrate dielectric is removed around the conductors.

Gold coplanar transmission lines 1 μm thick by 5 μm wide with a 5 μm gap are fabricated on a 200 nm layer of SiO_2 on semi-insulating GaAs substrates. The layer of SiO_2 acts both as an etch mask and as a physical cantilevered support for the lines. In addition, the electrically insulating SiO_2 layer reduces leakage and dark currents in the system. As shown in Fig. 1(a), islands of unetched material form the photoconductive switches which are connected to the conductors through openings in the SiO_2 layer. This region is protected with a layer of photoresist while the substrate is etched for a few minutes in a 10 H_2O_2:2H_2SO_4:40 H_2O solution. A scanning electron micrograph showing a cross section of a completed CAT line is shown in Fig. 1(b). Note that the electrodes overhang the SiO_2 layer by about 2 μm, so the region of highest field strength experiences a uniform air dielectric. This is a robust design, not affected by the wet processing or ultrasonic wire bonding.

Electrical transients about 0.1 V in magnitude are generated at the voltage-biased photoconductive switch using the sub 100 fs full width at half maximum optical pulses from a colliding pulse mode locked (CPM) laser. The CPM laser operates at a wavelength $\lambda = 620$ nm and a 100 MHz repetition rate. An optical fiber is used to deliver the excitation pulse thereby guaranteeing that the laser timing delays remain fixed. Electrical signals are detected using electro-optic sampling[2] with a sampling geometry similar to that shown in Fig. 1(a) and submillivolt detection electronics.[5] A $LiTaO_3$ sampling crystal with a high-reflectivity dielectric coating is used to reflect the sampling laser beam which detects the transient electric fields. The

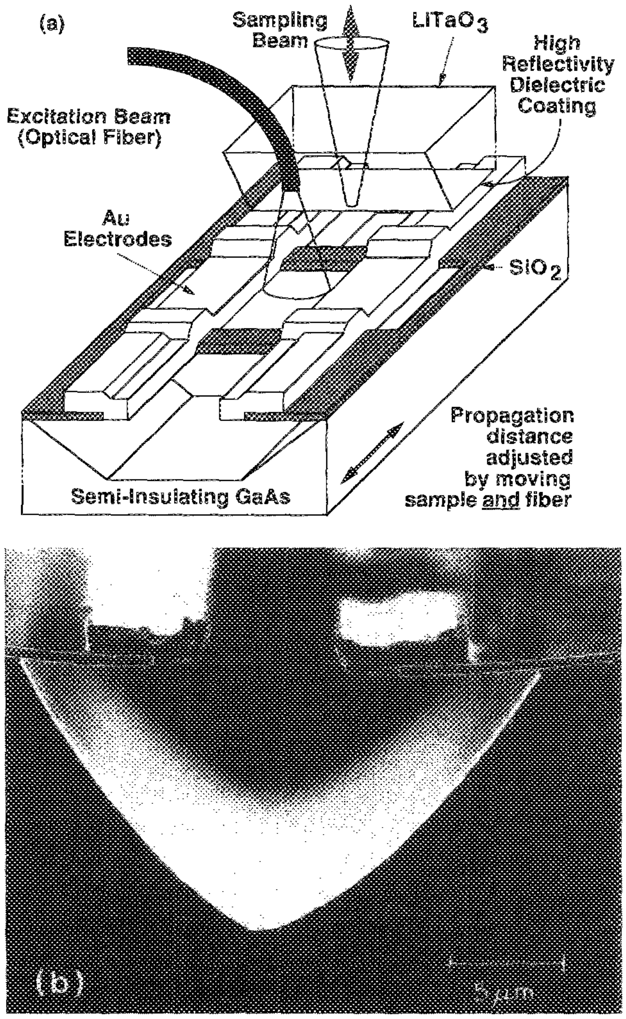

FIG. 1. (a) Sampling geometry of the CAT line. Central window area defines the photoconductive switch. A single mode optical fiber is used to deliver the excitation beam for the delay time measurement. The propagation distance is adjusted by moving the fiber and GaAs chip relative to the sampling crystal. (b) Scanning electron micrograph of the etched CAT line. Linewidth and spacing is 5 μm. The front edge of the SiO_2 layer has been highlighted for clarity.

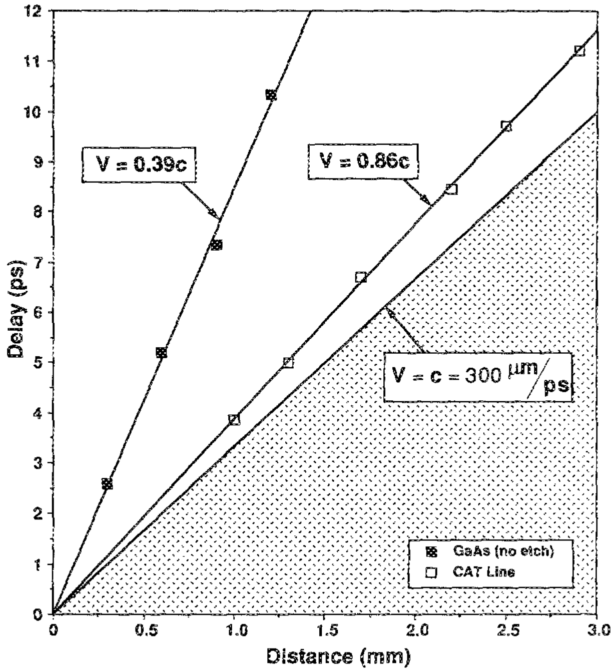

FIG. 2. Plot of delay (as measured by midpoint of linear fit to rise time) vs propagation distance. Velocity V is found from a linear fit to the data. Shaded area is bordered by $V=c$.

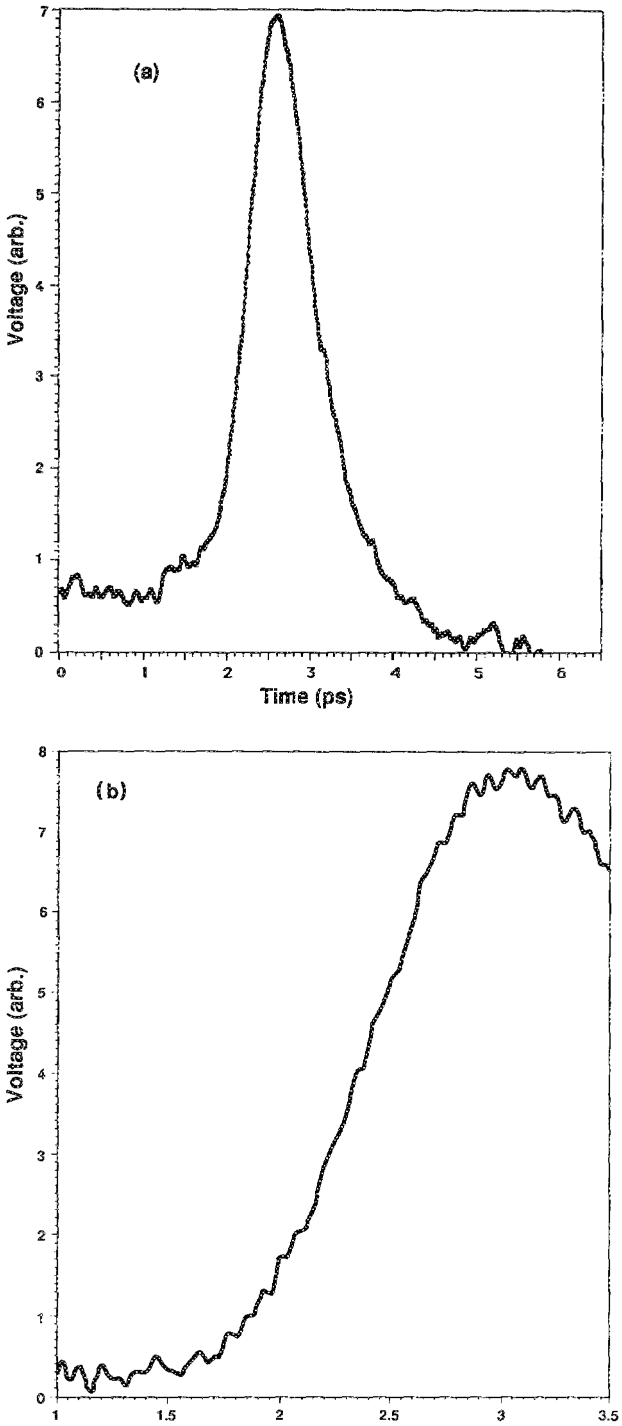

FIG. 3. (a) Measured signal on CAT line after 75 μm of propagation. (b) Measured signal on CAT line after 2.8 mm of propagation showing rise time of 0.8 ps.

dielectric coating also allows the crystal to be placed on the surface of the device while ensuring the high dielectric constant of $LiTaO_3$ does not adversely load the lines. The beveled edge of the crystal enables the sampling spot to be located at the very edge of the lower surface of the crystal without clipping the beam at the upper surface. This minimizes the distance that the electrical signal must travel inside the very dispersive $LiTaO_3$ crystal before being sampled.

Propagation times are measured for distances from 200 μm to 2.9 mm. The results are shown in Fig. 2 for both the CAT line and a conventional (unetched) transmission line. The solid lines are least-squares linear fits to the data.

A naive calculation of the velocity V, which uses an average value of the dielectric constant, gives

$$V=\frac{c}{\sqrt{\epsilon_{av}}}=\frac{c}{\sqrt{(\epsilon+\epsilon_{air})/2}}=0.38c, \qquad (1)$$

where $\epsilon=12.85$ ($\epsilon_{air}=1$) is the static dielectric constant of GaAs[6] (air) and c is the speed of light in vacuum. This is in good agreement ($<3\%$) with the measured value of $0.39c$ for the unetched sample. In contrast, a CAT line with an etch depth of 12 μm and an etched width of 20 μm gives a velocity of propagation (see Fig. 2) of $0.86c$. This is more than a factor of 2 faster than the unetched transmission line. Using Eq. (1) to calculate the effective dielectric of the etched substrate yields $\epsilon=1.7$ and an average dielectric $\epsilon_{av}=1.35$. This value is so close to a uniform air dielectric that electrical signals should propagate with little dispersion entirely in a TEM mode having a cutoff frequency $f_{TE}=c/4h\sqrt{\epsilon-1}$, where h is the dielectric thickness.[7] For a conventional coplanar transmission line $h\rightarrow\infty$, f_{TE} is small and other modes will propagate. In the CAT line $h\rightarrow 0$, f_{TE} is large and propagation is mainly in the TEM mode with little modal dispersion. The effect of dispersion was investigated by measuring the rise time as a function of distance propagated along the CAT line.

In order to measure the rise time, the optical fiber was removed to prevent dispersion of the fs excitation pulse. Figure 3(a) shows a representative rise time measurement after 75 μm of propagation. Note that despite the long carrier recombination time in semi-insulating GaAs, a short pulse is produced. This pulse is the result of a reflec-

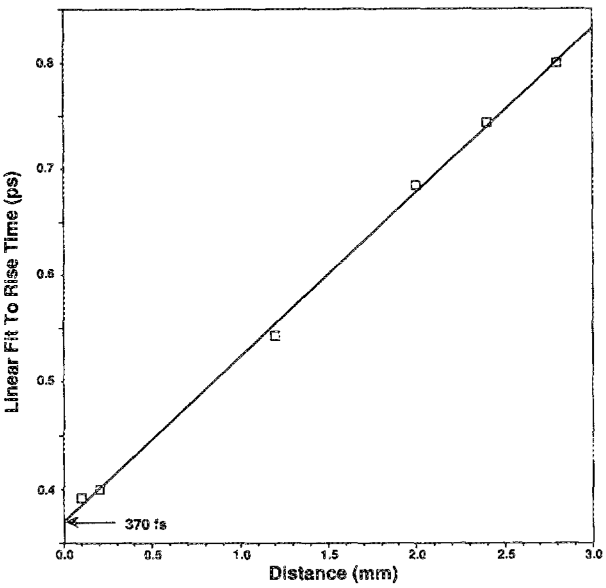

FIG. 4. Plot of rise time (as measured by midpoint of linear fit to rise time) vs propagation distance. The zero distance intercept gives a system response rise time of 370 fs. Measured rise time after 2.8 mm of propagation is 0.8 ps.

tion, from either the backside of the substrate or as a result of pulse shaping due to the islands or contact pads. Figure 3(b) shows the measured rise time of 0.8 ps after 2.8 mm of propagation. A summary of rise time measurements versus distance from 100 μm to 2.8 mm is given in Fig. 4. The zero distance intercept of 370 fs gives a measure of the overall system response which includes the effects of the sampling crystal, velocity mismatch between the electric and optical waves inside the $LiTaO_3$, etc. Removing the system response τ_s of 370 fs from the measured rise time τ_m at 2.8 mm using a sum of squares technique $\tau_m^2 = \tau_s^2 + \tau_c^2$ gives a corrected rise time τ_c of 0.7 ps. The same correction at 100 μm($\tau_m = 0.4$ ps) of propagation gives a corrected rise time of 150 fs.

In addition to long distance propagation of subpicosecond electrical signals, CAT lines also result in reduced charging energies compared to unetched transmission lines. If we model the transmission line electrodes as cylinders of diameter, d, separated by a center to center distance, s, then the characteristic impedance Z_0 in a uniform dielectric is given by[8]

$$Z_0(\eta/\pi)\cosh^{-1}(s/d), \quad (2)$$

where the intrinsic impedance is $\eta = \sqrt{\mu_0/(\epsilon_{av}\epsilon_0)}$ and $\sqrt{\mu_0/\epsilon_0} = 377\ \Omega$. Using the average value of $\epsilon_{av} = 6.92$ for the dielectric of the unetched line with $s = 10\ \mu$m and $d = 5\mu$m, Eq. (2) yields $Z_0 = 60\ \Omega$. The characteristic impedance for the CAT line is *increased* by a factor of more than 2.2 to 136 Ω since Z_0 scales as $1/\sqrt{\epsilon_{av}}$. Thus, a CAT line with the measured ϵ_{av} of 1.35, but with $d = 2\ \mu$m and $s = 2.24\ \mu$m has an impedance of $\sim 50\ \Omega$.

Using the same model[8] of two cylindrical conductors in a uniform dielectric, the capacitance C is

$$C = \frac{\pi\epsilon_0\epsilon_{av}}{\cosh^{-1}(s/d)}. \quad (3)$$

The capacitance scales as the dielectric constant ϵ_{av} and so is reduced by 4.8 times in the etched line to 28.5 fF/mm. For a line resistivity of 2 $\mu\Omega$ cm with $1 \times 5\ \mu$m lines the characteristic RC time constant is 1.1 ps for a 1- mm-long line (for a digital circuit, the entire line is driven).

The energy required to charge the line, (1/2) CV^2, scales as ϵ_{av}, and so is reduced by a factor of 4.8. For a load resistor R matched to Z_0 the energy dissipated is (1/2) V^2/R and scales as $1/\sqrt{\epsilon_{av}}$ so the total energy required to drive the CAT line is reduced by a factor of more than 7 (4.8 from the reduction in C plus a little more than 2.2 from the reduction in the required load resistor) compared to the unetched case.

The simple analysis of Eqs. (1)–(3) does not take into account effects such as electrode absorption and radiation, fringing electric fields in the remaining dielectric (necessary to model the propagation[7]), or losses and resonances present in the dielectric [important in the conventional (unetched) transmission line at frequencies of 1 THz and above[2,4]]. In addition, it is likely that further improvements could be achieved by operating a CAT line at low temperature, or by using superconducting electrodes).[9]

In conclusion, we have developed a practical technique for fabricating ultrafast transmission lines with a demonstrated velocity of propagation of 0.86c and a measured rise time of 0.8 ps after 2.8 mm of propagation. Using a simple model assuming a uniform dielectric gives beneficial reductions in the line capacitance and an increase in the required load resistor, both of which reduce the required energy to drive the line, as compared to the unetched case. Ease of fabrication and the practicality of our approach suggests that CAT lines are the most convenient way to implement intrachip communication over distances of a few mm in digital electronic circuits with rise times as short as 1 ps.

[1] D. A. B. Miller, Opt. Lett. **14**, 146 (1989); M. R. Feldman, S. C. Esener, C. C. Guest, and C. H. Lee, Appl. Opt. **27**, 1742 (1988).
[2] J. A. Valdmanis and G. A. Mourou, IEEE J. Quantum Electron. **QE-22**, 69 (1986); D. R. Dykaar, J. Chwalek, J. F. Whitaker, R. Sobolewski, S. Gupta, T. Y. Hsiang, and G. A. Mourou, IEEE Trans. Magn. **MAG-25**, 814, (1989).
[3] D. H. Auston, in *Picosecond Optoelectronic Devices*, edited by C. H. Lee (Academic, London, 1984), pp. 73–116; W. H. Knox, J. E. Henry, K. W. Goossen, K. D. Lee, B. Tell, D. A. B. Miller, D. S. Chemla, A. C. Gossard, J. English, and S. Schmitt-Rink, IEEE J. Quantum Electron. **25**, 2586 (1989).
[4] G. Hasnain, K. W. Goossen, and W. H. Knox, Appl. Phys. Lett. **56**, 515 (1990).
[5] J. M. Chwalek and D. R. Dykaar, Rev. Sci. Instrum. **61**, 1273 (1990).
[6] J. S. Blakemore, J. Appl. Phys. **53**, R123 (1982).
[7] J. F. Whitaker, R. Sobolewski, D. R. Dykaar, T. Y. Hsiang, and G. A. Mourou, IEEE MTT **36**, No. 2, 277 (1988).
[8] S. Ramo, J. R. Whinnery, and T. Van Duzer, *Fields and Waves in Communication Electronics* (Wiley, New York, 1965), Table 8.09, p. 444.
[9] D. R. Dykaar, J. Chwalek, J. F. Whitaker, R. Sobolewski, T. Y. Hsiang, G. A. Mourou, D. K. Lathrop, S. E. Russek, and R. A. Buhrman, Appl. Phys. Lett. **52**, 1444 (1988); D. R. Dykaar, R. Sobolewski, and T. Y. Hsiang, IEEE Trans. Magn. **MAG-25**, 1392, (1989); M. C. Nuss, P. M. Mankiewich, R. E. Howard, B. L. Straughn, T. E. Harvey, C. D. Brandle, G. W. Berkstresser, K. W. Goossen, and P. R. Smith, Appl. Phys. Lett. **54**, 2265 (1989); C-C. Chi, W. J. Gallagher, I. N. Duling III, D. Grischkowski, N. J. Halas, M. B. Ketchen, and A. W. Kleinsasser, IEEE Trans. Magn. **MAG-23**, 1666 (1987).