Generation of subpicosecond electrical pulses on coplanar transmission lines

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Electrical pulses shorter than 0.6 ps were generated by photoconductively shorting a charged coplanar transmission line with 80 fs laser pulses. After propagating 8 mm on the line the electrical pulses broadened to only 2.6 ps.

It has been demonstrated that by using fast photoconductive switches driven by short laser pulses, very short electrical pulses can be produced and measured.[1] The shape of the electrical pulse depends on the laser pulse shape, the material properties of the semiconductor, the nature of the charge source, and the characteristics of the associated electrical transmission line onto which it is coupled. The standard microstrip line configuration suffers from reflections (ringing) at the generation site[1] and from strong frequency dispersion.[1,2] Due to structural factors it is difficult to eliminate these problems by shrinking the microstrip line geometry to dimensions below 0.1 mm while maintaining 50 Ω impedance. However, these problems can be bypassed by eliminating the line altogether, as was demonstrated by Auston *et al.*[3] They used a Hertzian dipole configuration of fast photoconductive switches to generate and detect freely propagating 1.6 ps (FWHM) electrical pulses. An alternative measurement approach has been to use the electro-optic effect in a nonlinear crystal. In this case, the field of the electrical pulse is sampled through the rotation of the polarization of the optical sampling pulse.[4] Recent work using this approach has shown a temporal resolution of less than 500 fs by measuring the fast rising edge of a longer pulse propagating on a 100-μm coplanar transmission line.[5]

In this letter we report the generation of subpicosecond electrical pulses obtained by photoconductively shorting a charged 5-μm coplanar transmission line with 80 fs laser pulses. The electrical pulses were measured by a fast photoconductive switch (gap), driven by a time delayed beam of the same 80 fs laser pulses, which connected the transmission line to an electrical sampling probe. This method of excitation seems to be especially well matched to the propagating mode of the transmission line in that shorter pulses are obtained and they broaden less with propagation than their counterparts generated via photoconductive gaps. After 8 mm of propagation on this line, the pulses broadened to only 2.6 ps.

The geometry of the experiment is illustrated in Fig. 1. The 20-mm-long transmission line with a design impedance of 100 Ω is made of three parallel 5-μm-wide aluminum lines separated from each other by 10 μm. The dc resistance of a single 5-μm line is 200 Ω. Because of the small dimensions, the geometrical dispersion of this line is much less than an equivalent microstrip line. The laser spot diameters are both 10 μm. It is important to note that we can continuously move the excitation beam and that no special lithographic features are required for the pulse generation. We thus have the equivalent of a "sliding contact" for the excitation beam.

The transmission line together with its pads and sampling gaps was fabricated on an undoped commercial (Union Carbide UCC-O) silicon on sapphire (SOS) wafer. The transmission line pattern was defined by conventional photolithographic lift-off techniques. The wafer with the photoresist stencil in place was precleaned with buffered HF before it was loaded into an electron beam evaporation system. The surface of the sample was further cleaned with an Ar plasma just prior to the deposition of a 0.5-μm-thick Al film. A clean Al-SOS interface is required to prevent an excessive interface resistance due to oxides. To ensure the required short carrier lifetime, the wafer with the Al transmission line pattern was implanted with two doses of O^+ ions, $1.0\times10^{15}/\text{cm}^2$ at 200 keV and $1.0\times10^{15}/\text{cm}^2$ at 100 keV.

The laser source is a compensated, colliding pulse, passively mode-locked dye laser producing 80 fs pulses at a 100-MHz repetition rate.[6,7] The average power was 2 mW (20 pJ/pulse) in the excitation beam and 4 mW in the sampling beam. The measurements were made with the standard excite and sample arrangement for the beams of optical pulses.[1–7] The time delay between the exciting and sampling beams was mechanically scanned by moving an air-spaced retroreflector with a computer-controlled stepping motor, which was synchronized with a multichannel analyzer (MCA) used in the signal averaging mode. The exciting beam was chopped at 2.5 kHz, and a lock-in amplifier was

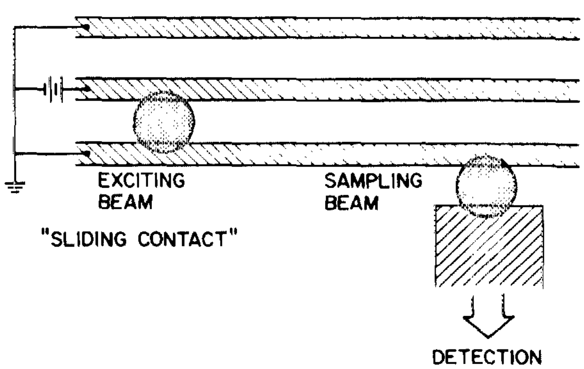

FIG. 1. Coplanar transmission line consisting of three parallel 5-μm-wide Al lines separated by 10 μm. Also shown is the 25-μm-wide sampling probe separated by a 10-μm gap from the transmission line. The exciting and sampling laser beams are indicated by the circles. The dc bias was 20 V.

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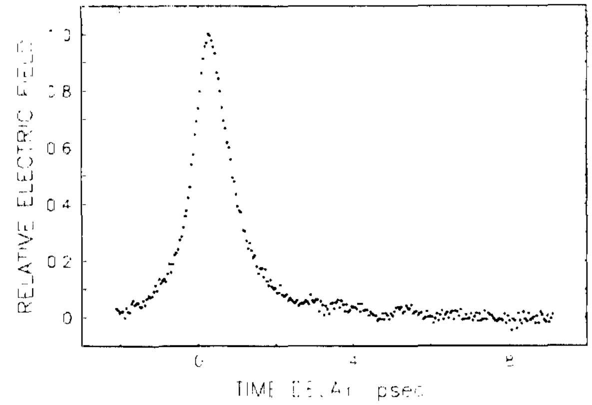

FIG. 2. Measured cross-correlation electrical pulse with less than 50 μm separation between the exciting and sampling beams. Zero delay corresponds to the exciting and sampling pulses hitting the sample simultaneously.

connected to the electrical probe switched by the sampling beam. The output of the lock-in was connected to the MCA, and repetitive scans were acquired.

The cross-correlation measurement of our subpicosecond electrical pulse is shown in Fig. 2. The magnitude of 10 mV was determined from sampling oscilloscope measurements and estimates based on the measured photocurrent. Here the spatial separation between the exciting and sampling beams was approximately 50 μm. As can be seen, the measured pulse has an excellent signal to noise ratio. The observed noise is a sum of laser oscillations which occur within the detection bandwidth of the lock-in amplifier and amplitude modulation on the laser slower than the averaging time (0.1 s) but faster than the scan duration of 50 s. Only four scans were averaged to obtain this figure.

We will now describe our procedure for determining that the actual pulse width was less than 0.6 ps. We follow the theory presented by Auston[1] and use his notation throughout. An important experimental observation was that when, instead of using the sliding contact, we generated the electrical pulse with a photoconductive gap of the same type as shown in Fig. 1, the pulse width of the autocorrelation measurement broadened by 1.5 times to 1.7 ps. This measurement had the characteristic asymmetric shape (Fig. 10, Ref. 1) of a gap generated and detected pulse for which the carrier lifetimes and the driving laser pulses were short compared to the measured autocorrelation pulse.

This result will now be explained, and the sampling gap capacitance C_s and the sliding contact capacitance C_{sc} will be calculated in the short pulse limit of Ref. 1. For this, the photoconductances $g_1(t)$ and $g_2(t)$ for the excitation and sampling gaps, respectively, are assumed to be delta functions, thereby implying infinitely short laser pulses and carrier lifetimes. For this limiting case with similar gaps we can estimate C_s from the relationship $\Delta\tau = 3.67 Z_0 C_s$, where $\Delta\tau$ is the autocorrelation pulse width and $Z_0 = 100\ \Omega$ is the characteristic impedance of the transmission line. With $\Delta\tau = 1.7$ ps, we obtain $C_s = 4.6$ fF. The actual pulse width Δt is given approximately by $\Delta t \approx Z_0 C_s \approx 0.5$ ps, corresponding to the unphysical shape of an infinitely sharp rising edge decaying exponentially with the time constant $(3/2) Z_0 C_s$. Now the fact that with the sliding contact excitation we measure the shorter cross-correlation pulse width $\Delta\tau = 1.1$ ps implies that the effective capacitance C_{sc} of the sliding contact is less than $C_s/2.4$. This result is obtained from Eq. (32) of Ref. 1. For this simple limiting case, reducing the generation capacitance by 2.4 reduces the generated pulse width by 2.4. However, if this limit was valid the measured cross correlation would remain strongly asymmetric, in disagreement with experiment.

We then made the more reasonable assumption that $g_1(t)$ and $g_2(t)$ were given by the convolution of the laser pulse (allowing for its spatial extent) with an exponential response function describing the carrier lifetime τ_c. It should be clear that the value of $C_s = 4.6$ fF obtained above in the delta function limit is only an upper limit for C_s obtained from a numerical fit to the measured cross correlation using the realistic $g_1(t)$ and $g_2(t)$, i.e., the inclusion of other broadening mechanisms only broadens the observed pulse width and thereby less capacitance is required for a fit. The same reasoning holds for C_{sc}. With these $g_1(t)$ and $g_2(t)$, we numerically calculated [via Eq. (32) of Ref. 1] the predicted cross-correlation pulse shape, using the parameters $\tau_c = 250$ fs, $C_{sc} = 1$ fF, and $C_s = 4$ fF. The result agrees well with the slightly asymmetric cross-correlation measurement in Fig. 2 and corresponds to an electrical pulse duration of less than 0.6 ps. An additional point is that this value of C_{sc} compares well with that obtained from the calculated capacitance per unit length of the transmission line (0.7 pF per cm) multiplied by the laser spot size.

In Fig. 2 the measured delay of 0.25 ps is consistent with the group velocity for the pulse and indicates a rapid response of the sampling gap. By changing the separation between the exciting and sampling beams, we measured the pulse as it propagated down the line. When the separation was increased to 0.3 mm the cross-correlation pulse only slightly broadened to 1.2 ps. At 8 mm separation the pulse changed as shown in Fig. 3. The 65.4 ps delay indicates a group velocity of $v_g = c/2.45$. The low-frequency dielectric constant of sapphire is 9.95,[2] and neglecting the small frequency dispersion, v_g would be $v_g = c/3.15$. However, for our case the field is partially in air so that the pulse should

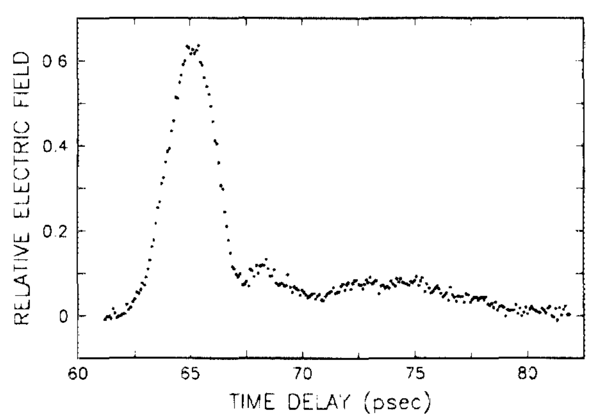

FIG. 3. Measured cross-correlation electrical pulse with 8 mm separation between the exciting and sampling beams. Zero delay corresponds to the exciting and sampling pulses hitting the sample simultaneously.

travel faster. The energy of this pulse is 0.5 of that of the pulse shown in Fig. 2, indicating an absorption length of 12 mm for our line. The measured pulse width of 2.6 ps is surprisingly short and illustrates the advantages of the small dimension coplanar transmission line compared to the microstrip line.[8]

In conclusion, we have generated electrical pulses shorter than 0.6 ps on a coplanar transmission line by using a new method of pulse generation, "the sliding contact." This method does not require any special lithographic features, allows pulse generation anywhere on the transmission line, and generates shorter pulses than the standard photoconductive gaps. We have also measured the exceptionally small dispersion of the 5-μm-wide coplanar transmission lines.

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