Generation of subpicosecond electrical pulses by optical rectification

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We describe the generation of subpicosecond electrical pulses by optical rectification of ultrashort optical pulses. The electrical pulses are generated by the second-order nonlinear response of a $LiTaO_3$ crystal bonded to a coplanar transmission line. A bipolar temporal waveform with a width of 875 fs was measured after a propagation distance of 175 μm. This pulse width was limited by the response time of the photoconductive sampler. We observed both broadening and amplitude reduction in the temporal waveform owing to propagation. © 1998 Optical Society of America

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The use of ultrashort electrical pulses is becoming increasingly important for applications ranging from high-speed electronics to wideband spectroscopy. With respect to the latter application, the analysis of pulse propagation characteristics on transmission lines offers a powerful approach for spectroscopic studies of materials.[1] In this geometry, long interaction lengths are possible, which is of particular value for probing thin films. Thus there is considerable incentive to increase the bandwidth of the generated electrical pulses. The established approach to producing electrical transients relies on the optical excitation of photoconductors by femtosecond optical pulses.[2,3] Other techniques for generating ultrashort electrical pulses include the use of exciton ionization in quantum-well structures[4] and the use of nonlinear transmission lines.[5] Although these techniques have significant utility, they exhibit a fundamental limitation in response time related to the transient dynamics of the photoexcited carriers or propagation characteristics of the device.

The use of nonlinear optical approaches seems well suited for circumventing these fundamental temporal limitations. Specifically, rectification of optical pulses is an attractive technique for generating ultrashort electrical pulses. Bass and co-workers[6] first observed optical rectification in the form of an induced dc voltage across a KDP crystal irradiated by an intense ruby laser. Generation of nanosecond electrical pulses was later demonstrated with an ADP crystal as the nonlinear medium.[7] Two additional techniques involving the absorption of the optical pump beam by impurities in polar crystals were found to be capable of generating intense picosecond electrical pulses.[8] However, the electrical pulses were limited to durations well in excess of 1 ps. Although optical rectification in nonlinear optical media has been suggested as a means of generating electrical pulses of picosecond duration on transmission lines,[2,9] there has not, to our knowledge, been any experimental demonstration of this effect.

In this Letter we describe the generation of subpicosecond electrical pulses by optical rectification, using the nonresonant second-order susceptibility of a nonlinear medium. The demonstration employs a coplanar strip-line geometry, shown schematically in Fig. 1, with a $LiTaO_3$ crystal superstrate acting as the nonlinear medium. Because of the nature of the generation process, we are able to vary the generation-to-detection distance. Detection of the electrical pulses on the transmission line is accomplished by use of a gated photoconductive switch integrated into the device.

We begin by examining the behavior of current produced on a transmission line through optical rectification. For this purpose we adapt the classic analysis of Ward.[7] For simplicity we neglect all finite response times and retardation effects in the system. We begin by considering the charge induced on the transmission line, $q(t)$, by a photogenerated dipole. The nonlinear polarization, $\mathbf{P}_{NL}$ ($= P_{NL}\hat{z}$), is given (in MKS units) by

$$P_{NL}(t) = -\frac{n^3 r_{33}}{2c} I_{opt}(t) , \qquad (1)$$

where n denotes the optical refractive index of the nonlinear medium; c, the speed of light in vacuum; r_{33}, the relevant electro-optic coefficient, and $I_{opt}(t)$, the intensity profile of the pump pulse. Here we have

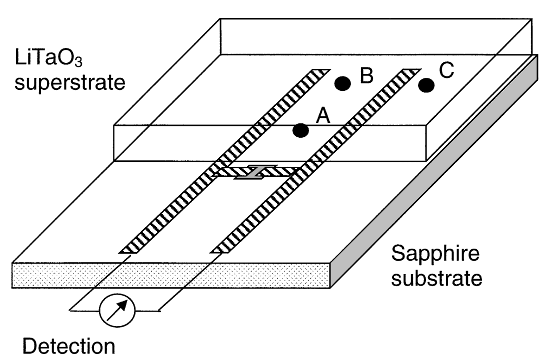

Fig. 1. Schematic drawing of the device with a coplanar strip-line transmission line and an integrated photoconductive switch. A $LiTaO_3$ crystal is bonded onto the device. Points A–C represent the positions of the pump beam used in the experiment.

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assumed that the optical pump field is polarized along the $\hat{z}$ crystallographic axis and that the important component of the induced nonlinear polarization also lies along the $\hat{z}$ axis.

We now suppose that the transmission line structure consists of two electrodes separated by a spacing d and that the nonlinear polarization $\mathbf{P}_{\mathrm{NL}}$ is perpendicular to the axis of the transmission line. In this case we expect that polarization P_{NL} will induce a time-dependent charge, $\pm q(t)$, on each side of the line. For the case of a coplanar transmission line we can approximate this charge by $q(t) = \alpha P_{\mathrm{NL}}(t) t_m l$. Here t_m is the effective thickness of the nonlinear medium, l is the length along the transmission line over which the polarization is present, and the dimensionless parameter α accounts for the efficiency with which the photogenerated charge generated in the nonlinear medium couples to the transmission line. The induced current, $i(t)$, is the first derivative of the induced charge on the transmission line. Thus the temporal waveform is expected to vary as the first derivative of the optical intensity envelope, yielding a bipolar electrical pulse. The corresponding voltage, generated in two counterpropagating electrical pulses, is given by

$$V(t) = Z_0 i(t) = Z_0 \frac{\mathrm{d}q(t)}{\mathrm{d}t} = -\alpha Z_0 \frac{n^3 r_{33}}{2c} \frac{\mathrm{d}I_{\mathrm{opt}}(t)}{\mathrm{d}t} t_m l\,, \tag{2}$$

where Z_0 is the characteristic impedance of the transmission line.

We now discuss the experimental procedure and results. The device structure and excitation scheme are shown schematically in Fig. 1. A coplanar strip-line transmission line consisting of two parallel 10-μm-wide lines separated by 30 μm was fabricated upon a silicon-on-sapphire substrate. A photoconductive switch was defined by coplanar strips separated by a 5-μm electrode gap.[10] The structure was formed by aluminum metallization and then ion implanted to reduce the carrier lifetime.[11] After implantation, the silicon was removed everywhere except in the electrode gap of the switch. We bonded a 1-mm thick y-cut $LiTaO_3$ crystal to the device, such that the crystallographic c axis of the nonlinear medium was perpendicular to the transmission line axis. The edge of the crystal was approximately 50 μm from the photoconductive gap.

A mode-locked Ti:sapphire laser producing 160-fs pulses at 800 nm with a 76-MHz repetition rate was used as the optical source. We performed the measurements by focusing both the excitation and the sampling beams through a common objective onto the device. The pump beam, which produced the ultrafast electrical pulses on the transmission line by optical rectification, had an average optical power of as much as 100 mW (pulse energy to 1.3 nJ). This beam was directed onto the $LiTaO_3$ crystal at normal incidence and focused onto the center of the transmission line (Fig. 1, point A) with a spot size of ~10 μm. The pump beam was polarized parallel to the crystallographic c axis of the $LiTaO_3$ crystal. The probe beam, with an average optical power of 20 mW, was focused directly onto the photoconductive gap. We obtained temporal information regarding the electrical pulses by varying the time delay between the pump and the probe beams and using standard photoconductive sampling techniques.

The pump beam, with an optical pulse energy of 0.65 nJ, was initially positioned at point A on the transmission line. This spot was 175 μm from the sampling gap. Curve (a) of Fig. 2 shows the observed bipolar temporal waveform of the subpicosecond electrical pulse generated by optical rectification. The FWHM of the positive lobe of the temporal waveform is 875 fs. We calibrated the transient voltage on the transmission line by determining the dc voltage that would yield the same average current obtained at optimum delay. From this information we estimate that the peak in the waveform [Fig. 2, curve (a)] corresponds to a voltage of ~450 μV, although this value is believed to represent the lower limit of the maximum voltage.[10] We observed the effects of propagation by translating the pump beam to point B, which is 1050 μm from the sampling gap. The corresponding temporal waveform is shown as curve (b). Here the width of the positive lobe of the temporal waveform is 1.6 ps (FWHM). Figure 3 shows an expanded view of the waveforms in Fig. 2, demonstrating the broadening

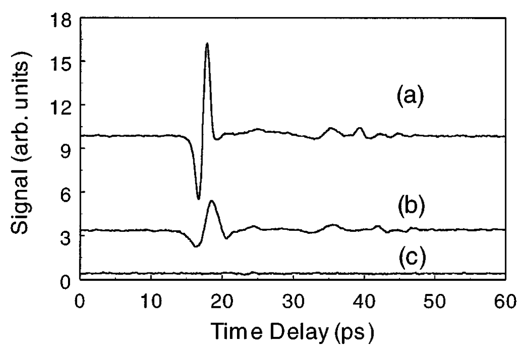

Fig. 2. Temporal waveform observed with the excitation beam at (a) point A (175 μm from the sampling gap), (b) point B (1050 μm from the sampling gap), and (c) point C (outside the transmission line structure). The waveforms are offset from the origin for clarity. Additionally, the relative time delay between the waveforms is arbitrary.

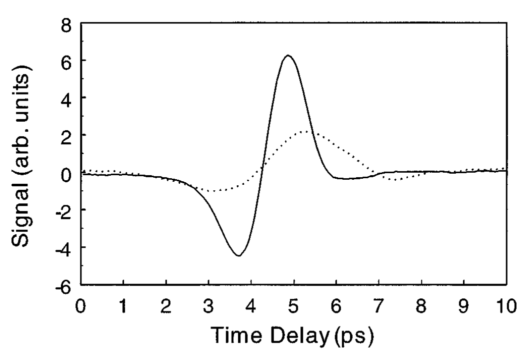

Fig. 3. Expanded view of the waveforms from curves (a) (solid trace) and (b) (dashed trace) of Fig. 2. The width of the positive lobe of curve (a) is 875 fs and that of curve (b) is 1.6 ps. The relative time delay between the waveforms is arbitrary.

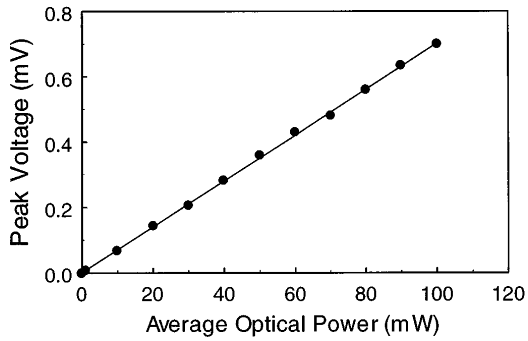

Fig. 4. Peak voltage versus average optical power in the pump beam. The distance from the electrical generation site to the sampling gap is 350 μm. The solid line represents the best linear fit.

of the electrical pulse. No signal was observed in the absence of the $LiTaO_3$ crystal.

We demonstrated that the observed response was due to a transient electrical pulse coupled to the transmission line, rather than to freely propagating terahertz radiation generated in the nonlinear medium,[12] by moving the pump beam to point C. This spot was located 50 μm outside the transmission line structure. The nominal distance from point C to the sampling gap was ~350 μm. Curve (c) of Fig. 2 shows the corresponding temporal waveform, demonstrating that guided-wave electrical pulses were the dominant contribution to the observed waveforms.

To verify further that the electrical pulses were indeed generated by means of optical rectification we examined both the linearity and the polarization dependence of the electrical pulse generation process. Figure 4 shows the peak transient voltage versus pulse energy of the pump beam for a generation-to-sampling distance of 350 μm. The dependence was found to be linear over a power range of 1–100 mW (energy range 0.013–1.3 nJ). We also examined the polarization dependence of the pump beam on the electrical pulse amplitude and found that it followed the predicted angular dependence.[13]

As we mentioned above, the minimum width of the temporal waveform is 875 fs (for a generation-to-sampling distance of 175 μm), which is considerably longer than the optical pulse duration. In our current experimental arrangement the carrier lifetime of the photoconductive gate determines the minimum response time of the device. For the ion implantation dose used in this study the carrier lifetime is ~600 fs[14]. Initial simulations suggest that by including the effects of propagation we can account for the additional broadening. Detailed modeling of this behavior is beyond the scope of this Letter, and we intend to present it in a future publication.

A substantial improvement in both the bandwidth and the amplitude can be expected from use of a phase-matched geometry in which both the optical and the electrical pulses copropagate down a transmission line. We recently showed that long coherence lengths are possible for the optical rectification process in ZnTe (Ref. 15) and in organic media.[16] Use of electro-optic sampling would also be necessary to reduce the detection response time. The generation scheme described in this Letter can be used to inject electrical pulses at arbitrary points into a device or circuit. The combination of this scheme with electro-optic sampling would allow for a design of a compact (circuit) spectroscopy system. We are currently investigating these ideas.

In conclusion, we have demonstrated the generation of subpicosecond electrical pulses by optical rectification of ultrashort laser pulses. This process utilizes the nonresonant second-order susceptibility of a $LiTaO_3$ crystal bonded to a coplanar transmission line. Bipolar electrical pulses of millivolt amplitude are detected by photoconductive sampling. Significant enhancement of the voltage amplitude and bandwidth should be possible with refinements in the device design.

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