

Nonlinear Transfer of Intense Few Cycle Terahertz Pulse Through Opaque Semiconductors

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An ultra-strong terahertz (THz) electric field has become available for experiments recently and this opened feasibility of nonlinear terahertz optics. Record-breaking results have been obtained using synchrotron radiation sources (pulse energy $W_{\text{THz}} > 100 \mu\text{J}$, electric field strength E_{THz} up to 20 MV/cm in the frequency range > 10 THz) or using optical rectification in nonlinear organic crystals ($W_{\text{THz}} \sim 900 \mu\text{J}$, $E_{\text{THz}} \sim 50$ MV/cm in the frequency range ~ 1 THz).

Self-induced transparency of a medium under the action of terahertz radiation (or bleaching) was previously observed in semiconductors irradiated with a THz field of relatively low strength and increase in transmission was of a few percent only.

We studied the interaction of an intense THz pulse with the n-doped Si sample under the conditions inaccessible to quasi-stationary electric fields. In this work we observed that transmission by energy of the 700 fs THz pulse through n-doped Si sample amounts to as high as $\sim 8\%$ with field strength up to 5–7 MV/cm and then gradually decreases nearly twofold at higher electric fields of 10–20 MV/cm [1,2]. Analysis of the transmitted pulse waveform demonstrated its strong distortions and generation of higher frequency spectral components at 7–10 MV/cm, and finally a 300-fs single-cycle pulse was observed at a maximum field. Simulations showed that with $E_{\text{THz}} \sim 5\text{--}7$ MV/cm saturation of the electron-phonon collision rate occurs, and THz transmission saturates. Generation of a single-cycle pulse at even higher fields was associated with formation of a thin ionized layer at the front sample's surface during the first intense oscillation of the THz field cutting out subsequent field oscillations and decreasing total transmission.

We used the open-aperture Z-scan technique, based on gradual varying of the THz radiation intensity on the surface of the sample moved along the beam line by a stepping motor, to study nonlinear effects. THz radiation was generated by the optical rectification in the nonlinear organic crystal 4-N,N-dimethylamino-4'-N-methyl-stilbazolium 2,4,6-trimethylbenzenesulfonate (DSTMS), pumped by 100-fs femtosecond laser pulses at a central wavelength of 1240 nm delivered by a Cr:forsterite laser system [3,4]. A broadband THz filter (LPF8.8-47, Tydex) with a cutoff wavelength of 34 μm was placed after the crystal. Two off-axis parabolic

mirrors were used as a 5:1 telescope to expand the THz beam. Finally, THz pulses with energy of 6.3 μJ were focused with an off-axis parabolic mirror with a 2" diameter and a focal length of 2" onto the sample to a spot with a radius of $w_0 \approx 200 \mu\text{m}$ at $1/e^2$, measured using the knife edge technique. The duration τ_{FWHM} of the THz pulse measured with a first order autocorrelator (a THz Michelson-type interferometer) was 700 fs at full width at half-maximum (FWHM).

The Golay Cell GC-1D (Tydex) was used to measure THz pulse energy transmitted through the sample. The THz electric field in the time domain after the sample was measured using electro-optical (EO) sampling in a nonlinear bilayer 2.1-mm-thick GaP crystal with a 2-mm-thick GaP (100) and a 0.1-mm-thick GaP (110). Fields strengths at the crystal were low enough to ensure linearity of measurements. This scheme was placed instead of the Golay cell.

Maximal THz field strength reached at $z=0$ was estimated in two ways. First, we employed the well-known time-averaged Poynting vector approach using data on the energy, spot size and duration of the THz pulse. Second, we fulfilled EOS with a 100- μm thick GaP crystal placed at $z=0$ with femtosecond laser radiation at 1240 nm as a probe. The both measurements gave an estimate of the maximal THz field strength $E_{\text{THz}} \approx 21 \pm 1$ MV/cm at $W_{\text{THz}} \approx 105 \mu\text{J}$.

The sample used was a commercially available n-doped silicon wafer of 245 μm thickness with carrier concentration and mobility of $8.7 \times 10^{16} \text{ cm}^{-3}$ and 800 $\text{cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, respectively, obtained from Hall effect measurements.

Transmittance of the THz radiation was assessed as the ration of the THz pulse energy passed through the sample to the THz pulse energy without the sample (Fig.1). With increasing maximum electric-field strength above 1 MV/cm a complex nonlinear dynamic of transmission of the 245- μm thick n-doped Si with carrier concentration of $9 \times 10^{16} \text{ cm}^{-3}$ was observed. An increase of electron-phonon collision rate (due to an increase of "instantaneous" electron energy) results in the bleaching at electric fields below 5 MV/cm. The maximum transmission by energy was found out $\sim 8\%$ that is more than two orders of magnitude higher than with a low-intensity THz pulse. Saturation of the transmission is attributed to saturation of the collision rate at electron energies above 1.5 eV.

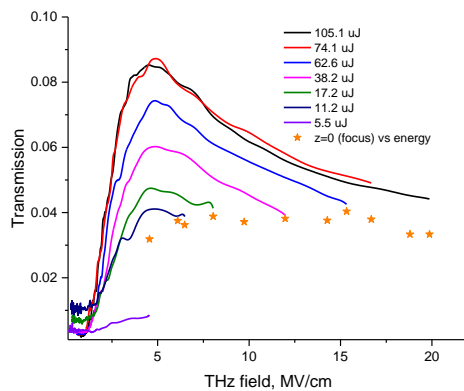


Fig.1. Experimental dependencies of the transmission η on the strength E_{THz} at different pulse energies.

The transmission gradually decreases at higher fields above 7 MV/cm that is related to the onset of ionization by electron impact. Ionization occurs in a thin surface layer during the first intense oscillation of the THz field. This results in efficient reflection and attenuation of subsequent field oscillations leading to formation of a single-cycle THz pulse with sharp rising edge and broad spectrum (Fig.2). This pulse propagates deeper into the sample under the bleaching conditions. The observed effect strongly depends on the spatial energy distribution over the THz beam cross section and, in our experiments, the maximum transmittance was observed out of the focal plane.

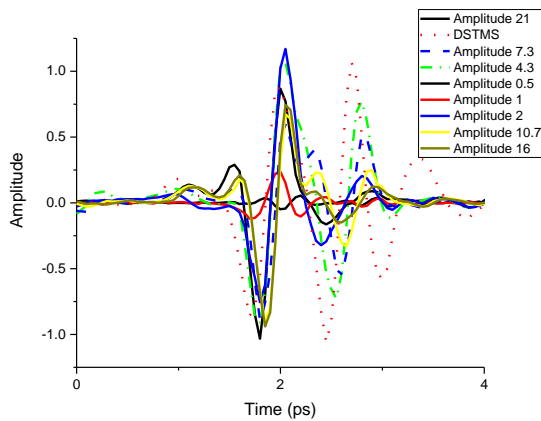


Fig.2. Waveforms of THz pulses without (DSTMS) and with the sample at different THz field strengths.

To make deeper insight into the spectral-temporal changes of the THz pulse, preliminary numerical simulations of nonlinear propagation of an intense THz pulse through a silicon plate were performed. The Finite Difference Time Domain method was used to solve numerically the 1D Maxwell's equations for the electromagnetic field together with equations for

plasma currents and carrier concentration. Dependencies of both the collision and impact ionization rates in Si on the E_{THz} were taken into account when calculating the current.

We also studied the nonlinear carrier dynamics in n-doped semiconductor InGaAs [5]. Intense THz pulses have pushed the nonlinear responses of doped InGaAs semiconductor into a new regime that involves interband carrier dynamics. Intraband heating dominates the overall THz responses and therefore doped semiconductor can still be a good candidate for the applications of saturable absorber.

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