Terahertz Nonlinear Optics in Semiconductors

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Published in:
Proceedings of the 38th International Conference on Infrared, Millimeter and Terahertz Waves IRMMW-THz 2013

Link to article, DOI:
10.1109/IRMMW-THz.2013.6665865

Publication date:
2013

Citation (APA):

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Abstract—We demonstrate the nonlinear optical effects – self-phase modulation and saturable absorption of a single-cycle THz pulse in a semiconductor. Resulting from THz-induced modulation of Drude plasma, these nonlinear optical effects, in particular, lead to self-shortening and nonlinear spectral breathing of a single-cycle THz pulse in a semiconductor.

I. INTRODUCTION AND BACKGROUND

We present the nonlinear optical effects such as saturable absorption (SA) and self-phase modulation (SPM) of a single-cycle THz pulse in a doped semiconductor. The nonlinearity arises from the electron plasma response to the ponderomotive potential of the strong-field THz pulse, which leads to electron heating and intervalley electron scattering. This produces ultrafast modification of electron plasma frequency via increase of average electron effective mass (see Fig. 1). The complex-valued dielectric function \( \hat{\varepsilon}(\omega) \) of a semiconductor in the presence of free carriers is described by a well-known Drude model:

\[
\hat{\varepsilon} = (n + \frac{ic\omega}{2\omega_p})^2 = \varepsilon_{dc} - \frac{\omega_p^2}{\omega^2 - \omega_0^2/\tau}
\]  

where \( n \) and \( \sigma \) are frequency-dependent refractive index and power absorption coefficient, \( \omega_p \) – plasma frequency, and \( \tau \) is electron momentum scattering rate. Plasma frequency

\[
\omega_p = (Ne^2/\varepsilon_0 m)^{1/2}
\]

where \( N \) is free carrier density, \( e \) is elementary charge, \( \varepsilon_0 \) is the vacuum permittivity, and \( m \) is the effective mass.

II. RESULTS

In our studies we have used the nonlinear THz time-domain spectroscopy (NL THz-TDS) based on the strong-field THz emitter - the tilted pulse front pumped lithium niobate [1]. Our experiments were performed in a traditional transmission configuration, and for each measurement two THz waveforms – reference (THz propagation through vacuum) and sample (THz propagation through vacuum and sample) were measured. The THz peak field strength was controllably attenuated in the range 9 – 292 kV/cm using crossed wire-grid polarizers.
The optical nonlinearities are observed directly in the time domain (see Fig. 2), and characterized in the frequency domain (Fig. 3). In particular, we present the effects of self-shortening of a single-cycle THz pulse [2], and THz self-phase modulation (SPM) observed on a single-cycle waveform, with sub-cycle time resolution [3], as shown in Fig. 2. The THz SPM, similar to the nonlinear optics demonstrated in the infrared and visible spectral ranges, results in nonlinear spectral breathing of the THz waveform. Further, we have found that the sign of the THz-range refractive index nonlinearity in doped semiconductor can be both positive and negative. In fact, we have discovered the co-existence of positive and negative refractive index nonlinearity within the spectral bandwidth of a single-cycle THz waveform [3]. This is quite a unique situation in nonlinear optics, though hardly unexpected given an inherently ultrabroadband nature of any single-cycle waveform.

All our findings, including the co-existence of index nonlinearity of different signs within the spectrum of the same THz waveform, can be well described within the Drude plasma model. For example, we have found that the point of zero THz refractive index nonlinearity is defined by (but is not equal to) the electron momentum relaxation rate $\tau$ in the semiconductor, as a result of the transition between low-frequency Hagen-Rubens regime featuring a larger refractive index, and higher frequency conductivity featuring a reduced values of $n$ in the presence of free carriers.

In summary, the effects of saturable absorption, self-phase modulation, pulse self-shortening, and nonlinear spectral breathing were demonstrated in nonlinear propagation of a single-cycle THz waveform through a doped semiconductor. The THz nonlinearity is caused by the nonlinear response of the free carriers to the strong THz fields, leading in particular to inter-valley scattering.

REFERENCES