Cross-Phase modulation of laser pulses by strong single-cycle terahertz pulse

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(Received January 17, 2013)

Abstract: Laser pulses cross-phase modulated by strong single-cycle THz pulse is investigated numerically. It is found that the cross-phase modulation is mainly induced by Pockels effect and Kerr effect. These effects can make the laser pulses spectral shift, including red-shift and blue-shift, and broadening. And the duration of the THz pulse affects the cross-phase modulation greatly.

Keywords: Cross-phase modulation, THz pulse

doi: 10.11906/TST.206-211.2013.09.14

1. Introduction

Linear electro-optic effect (Pockels effect) has been used to detect terahertz (THz) wave electric field widely [1, 2], which is called free space THz electro-optical sampling method. However, when the intense single-cycle THz pulse and an ultrafast laser pulse propagate in an elect-optical crystal simultaneously, the laser pulses can be modulated by the THz pulse linear and nonlinear effect. Because of the change of the refractive index induced by the THz field, the laser pulse phase undergoes phase modulation, including self-phase modulation and cross-phase modulation (XPM) [3, 4]. When the THz field is very high, the XPM will induce the laser pulse change greatly, and its spectral can be blue-shift or red-shift [5, 6]. When THz pulse is single-cycle and bipolar, it can play a function as an optical switch. Therefore crest and trough of THz pulse have different modulation effect on laser pulses.

Yuzhen Shen *et al* have researched the THz modulation when the THz field is several $10^7 V/m$ [5, 6]. In their experiment, the Pockels effect is included but the Kerr effect is omitted. In fact three-order nonlinear effect and second-order nonlinear effect have different influences according to the THz field strength. And when the THz field varies greatly, Kerr effect and Pockels effect on cross-phase modulation will be different. Here we investigate the modulation of laser pulses by an intense, single-cycle THz pulse numerically.

The paper is organized as follow. The second part introduces the theory of laser pulses modulated by the THz pulse through Pockels effect and Kerr effect. In fact both effects should be included when the intense THz pulse and laser pulse co-propagate in the electro-optic crystal. The third part is the simulation results and discussion. The influence of amplitude and the duration of THz pulse to the modulation are explored. The conclusion is given in the last part of the paper.

2. The theory of laser pulses cross-phase modulated by THz pulse

When the laser pulses and the THz pulses propagate in nonlinear media, the laser pulses can be modulated by nonlinear effects induced by THz field. In an electric-optic crystal, the main nonlinear effects include second-order effect (Pockels effect) and third-order effect (Kerr effect). But when the field of THz pulse varies from 10^6 to $10^8 V/m$, the Kerr effect and Pockels effect are different because the former is the second order effect and the latter is the third effect. Depending upon the interval of time between THz pulse and laser pulses, the modulation will be different. Ignoring the high order nonlinear effect, the refractive index for laser pulses in media can be described as:

$$n = n_0 + n_1 + n_2 , \tag{1}$$

where n_0 is the linear index, $n_1 = \frac{\chi^{(2)} E_{THz}}{n_0}$ is the second order index induced by Pockels effect, and $n_2 = \frac{3\chi^{(3)} \left| E_{THz}^2 \right|}{2n_0}$ is the third order index by Kerr effect. So ignoring the group velocity dispersion and self-phase modulation of the laser pulses, the total phase shift can be written as:

$$\Delta\varphi(t) = \frac{2\pi}{\lambda_0} \int_0^L \Delta n[E_{THz}(t - \beta z)] dz , \tag{2}$$

Where λ_0 is the central wavelength of laser pulses, L is the thickness of nonlinear media, and β is the walk-off parameter defined by $\beta = 1/v_{laser} - 1/v_{THz}$. Therefore the frequency shift is given by:

$$\Delta\omega = -\frac{d\varphi(t)}{dt} . \tag{3}$$

Equations (1)-(3) have described the cross-phase modulation of laser pulses by the THz field and the spectral shift can be known from the solution. With the strong single-cycle the THz pulse, the modulation will be different from that by laser pulses. Some tunable THz sources have a tunable duration so the application of THz wave in modulation can choose different duration of THz pulses.

Although the modulation of THz pulse to laser pulses has no limitation, there is a half-wave voltage for the electro-optic crystal, which means when the THz field is too high, the rotation phase will not be the linear function of the field. So half-wave voltage of electro-optic crystal decides the limitation of THz field strength.

3. Simulation and discussion

Here we solve the equation (1)-(3) numerically, and get the wavelength shift as the function of THz amplitude and duration. The THz pulse is used as the form defined by Peng [7]:

$$E_{THz}(t) = -A\frac{t}{T}e^{-\frac{t^2}{T^2}} \tag{4}$$

Here A is the amplitude of THz pulse, and the parameter T is related to the pulse duration. The Figure 1 is the THz waveform and the wavelength shift of laser pulses induced in a 0.5 *mm* thick, <110> ZnTe crystal. The other parameters of ZnTe crystal are the same to that in reference [8]. The THz amplitude is 1.0×10^7 *V/m*; the duration T is 0.25 *ps*; the frequency bandwidth is 1.3 *THz* (Full Width at Half Maximum). Here the central wavelength of the laser is 800 *nm*. The spectral shift is the function of time delay between laser pulses and the THz pulse. When the THz field gets its maximum gradient, the modulation gets its maximum, as shown in Figure 1.

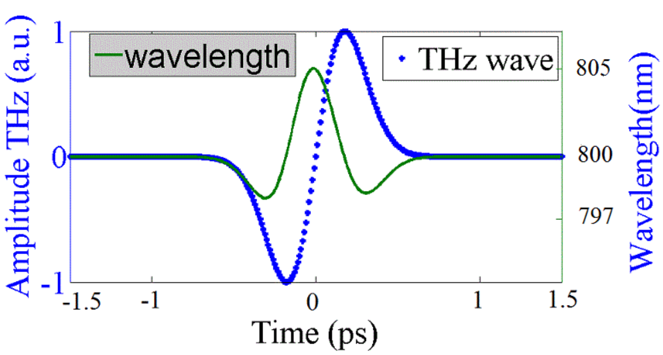

Fig. 1 The THz time waveform and its modulation to the laser pulses. The THz amplitude is 1.0×10^7 *V/m*, its T is 0.25 *ps*, frequency bandwidth is 1.3 *THz* (FWHM). (Both Pockels and Kerr effect are included, the walk-off parameter β is 0).

Because the THz pulse and laser pulses have different velocity, they will induce phase match and walk-off effect [9]. In <110> zinc blende crystal the phase match between them is well. However, the wake-off parameter decreases the spectral shift. When the walk-off parameter β is 0, 0.5 *ps/mm* and 1 *ps/mm*, the modulated laser spectral is given in Figure 2. It is found that walk-off effect decreases the modulation induced by THz pulse. The Pockels effect is a second nonlinear effect while the Kerr effect is a third one. So if the THz field is very small, the Kerr effect inducing the modulation is also small. The Kerr effect and Pockels effect induced spectral shift is shown in Figure 3(a). The parameters used are the same to as previous with β=0. The shift by Pockels is symmetrical while when both interactions in the crystal, the shift will be asymmetry. While increasing the strength of the THz wave, the maximum of the wavelength shift increases too, but it is obvious that two effects will generate a bigger shift, which is shown in Figure 3(b). The simulations indicate that when the THz amplitude is higher than 8×10^7 *V/m*, Kerr effect will not be ignored and will contribute to the cross-phase modulation.

Using a tunable THz pulse source, the THz pulse duration can be changed, therefore, the cross phase modulation from it should vary. Here the maximum wavelength shift of laser pulses modulated by THz pulse with different duration is shown in Figure 4. When the duration increases, the modulation is becoming weaker and the spectral shift is an inverse proportion function of the THz pulse duration.

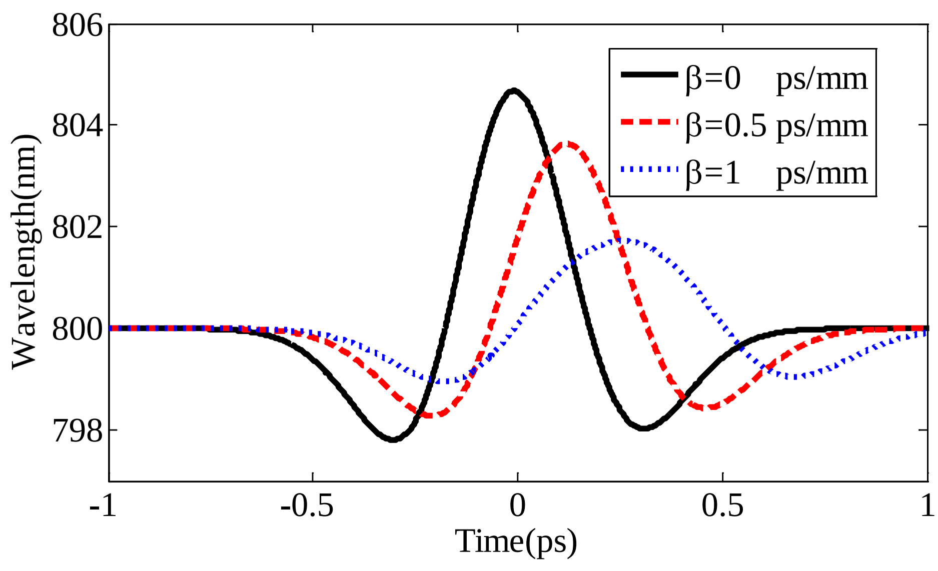

Fig. 2 The beta affects the modulation directly. It makes the wavelength shift less, and also leads it delay. Other parameters are the same to that used in Fig. 1. Both Pockels effect and Kerr effect are included.

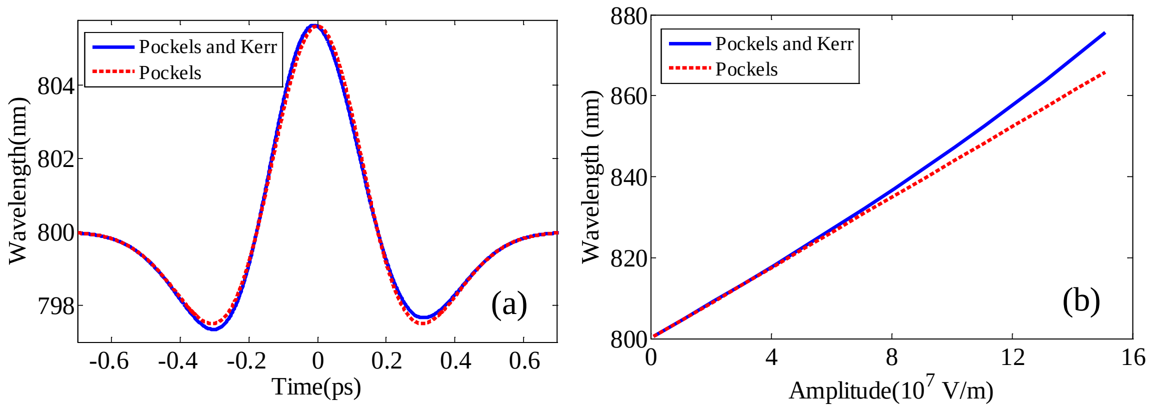

Fig. 3 (a) THz pulse spectral shift induced by Pockels effect (red) and by Pockels effect with Kerr effect together (blue). (b) The maximum of THz pulse spectral shift as the function of the THz amplitude. The parameters used are the same to that in Fig.1.

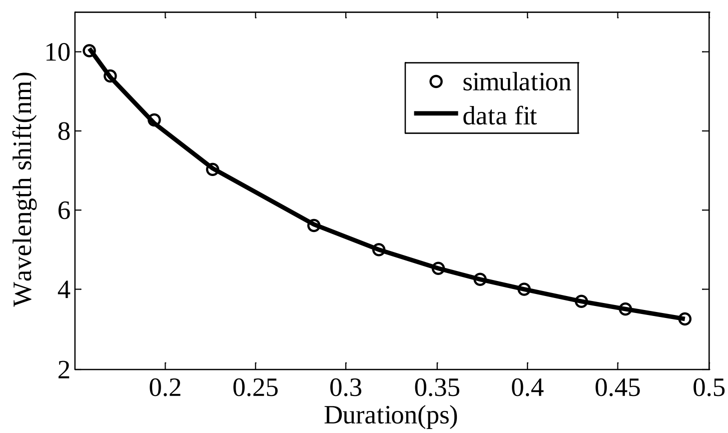

Fig.4 The maximum of laser pulses spectral shift is the function of the THz pulse duration. Here the circle is from the solution of the equations (1)-(3) . The line is from the data fit as an inverse proportion function of THz pulse duration.

4. Conclusion

The intense single-circle THz pulse can modulate the laser phase through Pockels effect and Kerr effect when they propagate in the nonlinear media. The simulation uses <110> cut ZnTe crystal as nonlinear media, and it is found that when the THz field is small, the modulation is mainly deduced by Pockels effect. The time delay between the THz pulse and the laser pulses decides the spectral shift. The modulation also is the function of the THz pulse duration. When the THz pulse is shorter, the spectral shift is larger.

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