Detection of the spatiotemporal field of a single-shot terahertz pulse based on spectral holography*

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According to electro-optical sampling theory, we propose a new method to detect the spatiotemporal field of a single-shot terahertz pulse by spectral holography for the first time. The single-shot terahertz pulse is coupled into a broadened chirped femtosecond pulse according to electro-optical sampling theory in the detecting system. Then the reference wave and the signal wave are split by Dammann grating and spread into the interference band-pass filter. The filtered sub-waves are at different central-frequencies because of the different incident angles. These sub-waves at different central-frequencies interfere to form sub-holograms, which are recorded in a single frame of a charge coupled device (CCD). The sub-holograms are numerically processed, and the spatiotemporal field distribution of the original terahertz pulse is reconstructed. The computer simulations verify the feasibility of the proposed method.

Keywords: spatiotemporal field of single-shot terahertz pulse, Dammann grating, interference band-pass filter, spectral holography

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1. Introduction

In recent years, the rapid development of ultrafast pulse laser technology has promoted the basic and application research of terahertz waves. Some methods of measuring the time domain waveform of terahertz pulses have been proposed,[1–6] for example, terahertz pulses of free space propagation are measured by optical antenna or electro–optic sampling (EOS). Although these methods possess very high signal-to-noise ratios and temporal resolutions, a single-shot terahertz pulse cannot be directly measured by these methods. However, the measurement of a single-shot terahertz pulse is necessary in the research of the transient diagnosis or structural phase transition. A spectrum coding method of a chirped pulse,[7] a streak camera method,[8] a chirp pulse cross-correlation method,[9] and a coaxial holographic spectrum restoration method[10] have been proposed to measure the electric field distribution of a single-shot terahertz pulse. Even so, the distribution of a detected single-shot terahertz pulse is expressed only in one-dimensional (1D) or two-dimensional (2D) form such as $E(t)$ or $E(x,t)$, $E(x,y)$.

Up to now, there have been few methods that can measure the spatiotemporal field of a single-shot terahertz pulse $E(x,y,t)$. Li *et al.*[11] proposed a detection method of the 3D distribution of the full spatiotemporal field of a single-shot terahertz pulse based on digital holography with angle multiplexing. It involves crossing the reference beams of different incident angles with signal beams of a certain time interval and generating multiple image holograms, which are used to reconstruct the spatiotemporal field of a single-shot terahertz pulse. This method realized 3D measurement of a single-shot terahertz pulse, but the complex splitting devices for signal beams and reference beams should be provided. In addition, the delay line is also required for synchronous calibration.

Pablo and Rick[12,13] proposed a method of measuring the full spatiotemporal field of a single-shot ultrashort pulse, in which an experimental apparatus with a simple structure is used to obtain a composite hologram containing sub-holograms of different central frequencies, and the 3D spatiotemporal field of an ultrashort pulse could be obtained from the composite hologram. Because the terahertz wave can be loaded into an ultrashort probe pulse by the electro–optic sampling principle, if we can characterize the ultrashort probe pulse containing the spatiotemporal distribution information of a terahertz pulse, the terahertz information of interest can be obtained. Therefore, we propose a method of measuring the full spatiotemporal field of a single-shot terahertz pulse based on spectral holography. The method mainly takes advantage of the ingenious combination of Dammann grating and interference filter, and reconstructs the full spatiotemporal field of a single-shot terahertz pulse from a single frame image without time-delayed scanning. Computer simulations confirm the feasibility of the proposal.

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2. Basic principle and method

In the detection of terahertz wave electro–optic sampling, the detecting chirped pulse, the measured terahertz pulse collinearly spread to the electro–optic crystal, and the different frequency components of the detecting chirped pulse are modulated by different terahertz electric field components, therefore, the terahertz pulse is coupled to the detecting chirped pulse. The coupling process can be expressed as[14]

$$\begin{aligned} E_{\mathrm{f}}(t) &= aE_{\mathrm{pr}}(t)\left[1+bE_{\mathrm{THz}}(t)\right] \\ &= aE_{\mathrm{pr}}(t)+abE_{\mathrm{pr}}(t)E_{\mathrm{THz}}(t), \end{aligned} \tag{1}$$

where coefficients a and b are the constants, the first item on the right-hand side, $E_1 = \alpha E_{\mathrm{pr}}(t)$, is regarded as the background signal beam without terahertz pulse information, $E_{\mathrm{f}}(t)$ is regarded as the signal beam with terahertz pulse information. The single-shot terahertz pulse can be reconstructed by measuring the background signal beam without terahertz pulse information and the signal beam with terahertz pulse information. The schematic diagram of this method is shown in Fig. 1.

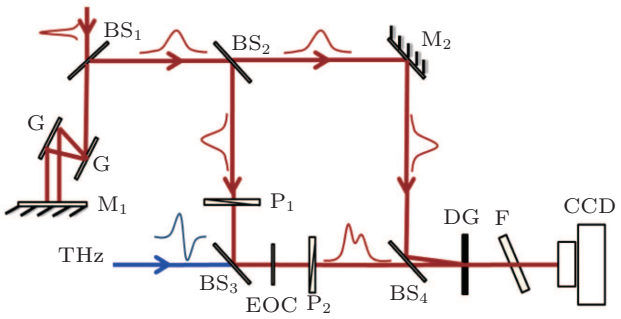


Fig. 1. (color online) Schematic diagram of spatiotemporal field detection of a single-shot terahertz pulse based on spectral holography.

In Fig. 1, a single femtosecond pulse is broadened by the grating group G–G and then is divided into a reference pulse and a signal pulse by the beam splitter BS_2. The reference pulse is transmitted to the beam splitter BS_4 after the reflection of a totally reflecting mirror M_2. The signal pulse is sent into the signal arm and coupled with a single-shot terahertz pulse in electro–optic crystal EOC. Therefore, the signal pulse and reference pulse are recombined at the beam splitter BS_4. Between the beam splitter BS_4 and the CCD camera, we insert 2D Dammann grating DG and the tilted band-pass interference filter to generate the array of sub-holograms with different frequency spectra.[15] This recombination is quasi-collinear. A small vertical angle α is introduced in order to generate horizontal fringes on the CCD camera, where both pulses are temporally and spatially overlapped.

In Fig. 2, the Dammann grating DG is rotated by an angle φ about the z axis in the x–z plane and the interference band-pass filter is rotated by an angle β about the y axis in the x–z plane, which ensure each hologram involves pairs of beams of a (uniformly spaced) different wavelength. The central wavelength of the filtered beam depends on the propagation angle θ, expressed as $\lambda_i = \lambda_0\left(1-\theta^2/2n^{*2}\right)$,[16] where n^* is the effective index of refraction. Therefore, the frequency distribution is related to the parameters of the interference band-pass filter and arrangement angle in Fig. 2. The bandwidth of the input beam is small compared with its central wavelength, so the sub-holograms are quasi-monochromatic. The resulting quasi-monochromatic holograms, each at a different color, yield the complete spatial field for each color in the pulse and can be combined to yield the complete spatiotemporal field of the signal pulse, $E(x,y,t)$. In this paper, we can obtain the field distribution $E(x,y)$ of central frequency ω_k spaced by $\delta\omega$ through the Fourier transform and digital filtering of nine sub-holograms, as shown in Fig. 3.

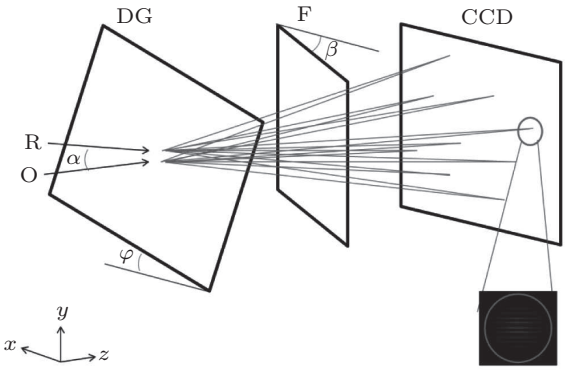


Fig. 2. Orientation diagram of Dammann grating and interference filter.

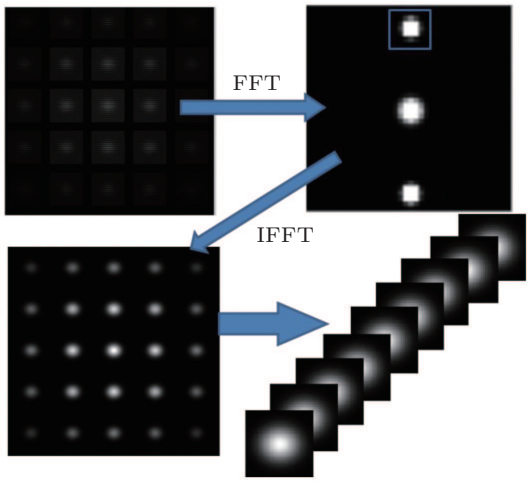


Fig. 3. (color online) Diagram of the inverse solution of terahertz pulse information from the sub-holograms.

3. Numerical simulation and measurement results

We conducted our computer simulation using MATLAB. The simulation process is divided into two parts: the first part is to simulate the relevant physical process, targeting to simulate the sub-hologram array containing terahertz pulse information and background sub-hologram array; the second part

is to digitally process the sub-holograms, which means that the full spatiotemporal field of a terahertz pulse $E(x,y,t_i)$ is numerically reconstructed from sub-holograms.

In the numerical simulation, the basic physical parameters are as follows.

(i) We assume that the central wavelength of a femtosecond pulse is 800 nm, and the pulse width is 100 fs. The width of the chirped pulse broadened by the double gratings is 2 ps. The terahertz pulse to be measured is of a single-period in the time-domain, and the pulse width is 1 ps. The specific function expression of the spatiotemporal field of the terahertz pulse is as follows:[11]

$$E_i(x,y,t_i) = A\exp\left\{-\frac{1}{2a^2}\cdot\left[x^2+\frac{y^2}{0.7\,(t_i/T)^2+0.75}\right]\right\} \times\left[-\frac{t_i}{T}\cdot\exp\left(-\frac{t_i^2}{T^2}\right)\right], \quad (2)$$

where $[-(t_i/T)\cdot\exp(-t_i^2/T^2)]$ indicates the time characteristic of the terahertz pulse, and

$$\exp\left\{-\frac{1}{2a^2}\cdot\left[x^2+\frac{y^2}{0.7\,(t_i/T)^2+0.75}\right]\right\}$$

indicates the transverse distribution of the electric field, which is a Gaussian distribution at one point in time.[1] The peak value of the electric field intensity of the pulse is chosen as $A=10^5$ V/m, with parameter $a=2$ mm (space).

(ii) The splitting ratio of Dammann grating is chosen as 5×5, and the coordinates of the catastrophe point are ($a_1=0$, $b_1=0.03859$) and ($a_2=0.38588$, $b_2=0.65056$) during a period. The grating size is 1 cm$\times$1 cm, the pixel number is 1000×1000, and the grating period is 1/50 cm. The Dammann grating can generate 25 sub-beams, but a central nine sub-beams with homogeneous intensity distribution as shown in Fig. 3 are chosen in our simulation for a higher signal-noise-ration. The 9 sub-holograms represent nine sampling points in the frequency, and the sampling rate is not high. The interference band-pass filter is symmetrical in structure, and high in refractive index ($n_{\rm H}=2.1$) but low in refractive index ($n_{\rm L}=1.0$).

(iii) We suppose that the maximum energy transmission position of the interference filter is at $\lambda_{\rm f}=850$ nm. In Fig. 1, the distance between BS_4 and Dammann grating is $z_1=2f=20$ cm, and the distance between CCD and Dammann grating is $z_2=2f=20$ cm. The angle between the reference beam and the object beam is $a=1.5^\circ$, the rotation angle of the Dammann grating is $\varphi=17^\circ$, and the rotation angle of the interference band-pass filter is $\beta=31^\circ$.

The spatial resolution of the proposed method is restricted because the nine sub-holograms are spatially multiplexed and recorded in a single frame of the charge coupled device (CCD), therefore, the 2D size of the terahertz pulse is small. On the other hand, sub-holograms are recorded by CCD, so the spatial resolution is also restricted by the size of a single pixel of the CCD. Using a larger-area CCD with a higher pixel count is helpful for enhancing the spatial resolution. It is noticed that the trade-off between frequency resolution and spatial resolution should be considered in the method.

In view of the parameters above, we simulate the measuring process of a single THz pulse and the generated nine sub-holograms containing the THz pulse information. Each sub-hologram is used to reconstruct the object beam of different center wavelengths, as shown in Fig. 3. According to formula (1), the amplitude of the reconstructed terahertz pulse at the central point of the transverse section is shown in the timer shaft according to the corresponding point in time, compared with the time distribution of the original terahertz pulse, as shown in Fig. 4.

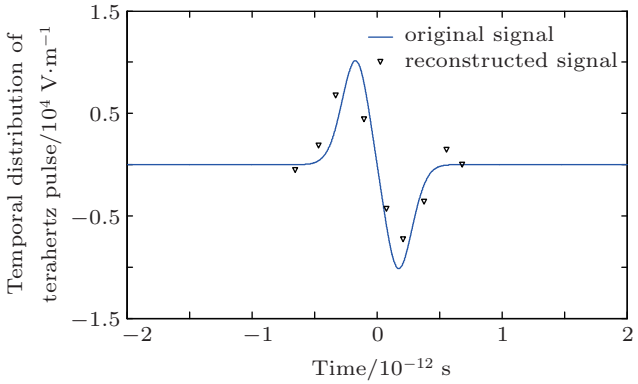


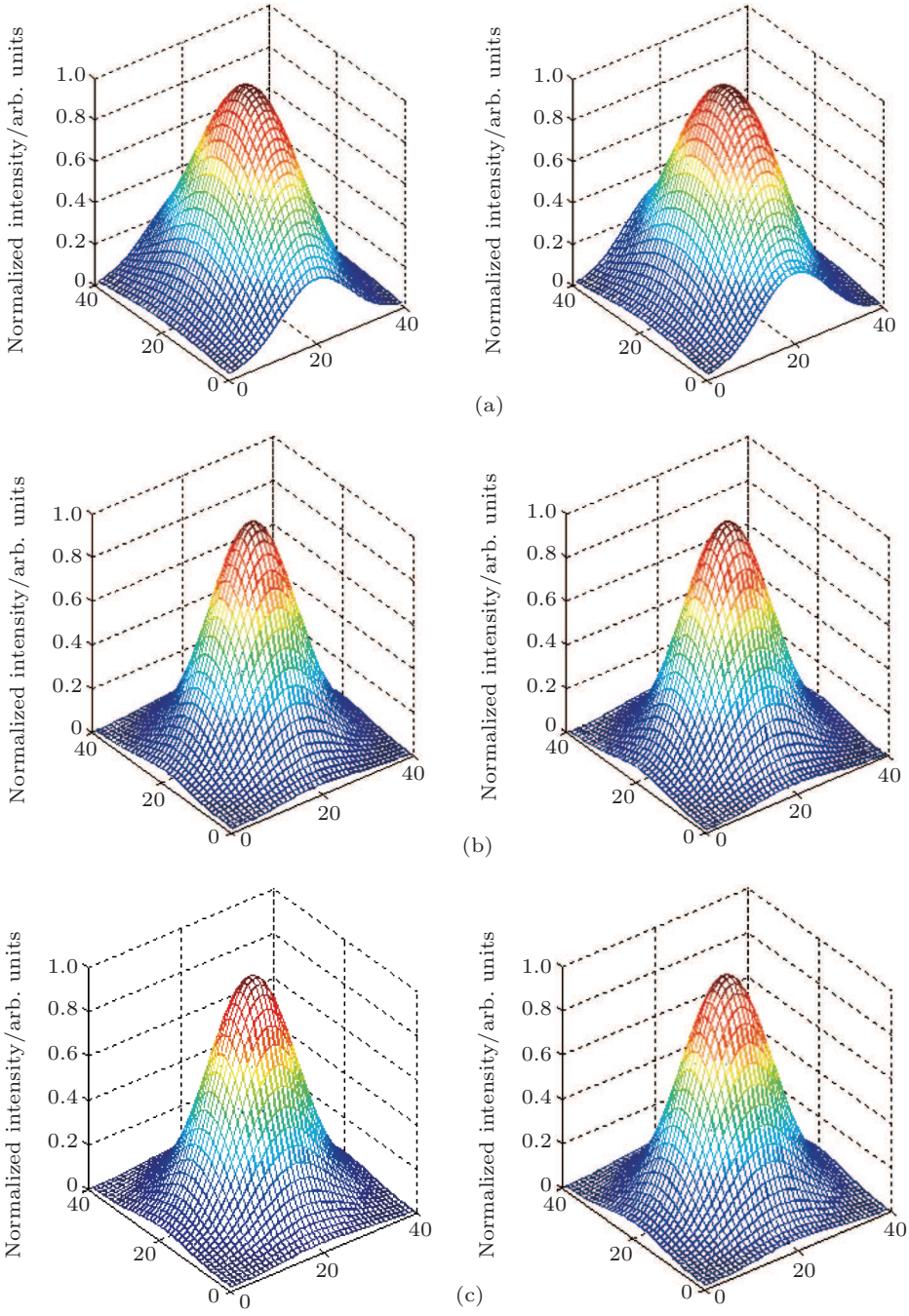
Fig. 4. (color online) Temporal distribution of the reconstructed terahertz pulse.

From Fig. 4 we can see that the reconstructed temporal distribution of the terahertz pulse at nine time points is generally consistent with that of the original terahertz pulse, which proves the feasibility of this method in the time dimension. However, some errors can be seen from Fig. 4, which are caused by the low sampling rate. The spatiotemporal field $E(x,y,t)$ is reconstructed based on $E(x,y,\omega)$, so the accurate $E(x,y,t)$ is obtained by integral operation to $E(x,y,\omega)$ at each continuous frequency theoretically. In our simulations, only nine frequency sampling points are used and the sampling rate is low, therefore the reconstructed signal is broadened and distorted. Besides, in the reconstruction of sub-holograms, the window filter operation in Fourier space is used, which also induces information loss.

In the aspect of the spatial distribution of the reconstructed THz pulse, the reconstruction of the spatial distribution of a terahertz pulse is based on the 2D phase distribution retrieved from the sub-holograms. In simulations, the background phase distribution in sub-holograms without a THz signal is subtracted from that with a THz signal. The reconstructed spatial distribution of the THz pulse is normalized. As

an example, we provide the comparison diagram of the spatial distribution of reconstructed terahertz pulses at the representative five points located in the middle of the nine time points and that of an original terahertz pulse corresponding to the same time points. These results are shown in Figs. 5(a)–5(e), and the original spatial distributions corresponding to the time points are on the left and the reconstructed spatial distributions are on the right, respectively.

From Fig. 5 we can see that the spatial distributions of reconstructed terahertz pulses accord with those of the original signals in general. We calculate the relative errors between the spatial distribution of reconstructed terahertz pulses and those of original terahertz pulses, which are shown in Table 1. In Table 1, the selected nine time points are given in the second line, and the relative errors between the spatial distribution of the reconstructed terahertz pulses and those of the original terahertz pulses are shown in the third line correspondingly. From Table 1 it follows that the maximum relative error is 8.48% at the time point −96.4 fs and the minimum relative error is 0.04% at the time point 84.8 fs, showing that the differences in spatial distribution between the reconstructed terahertz pulses and the original terahertz pulses are small.



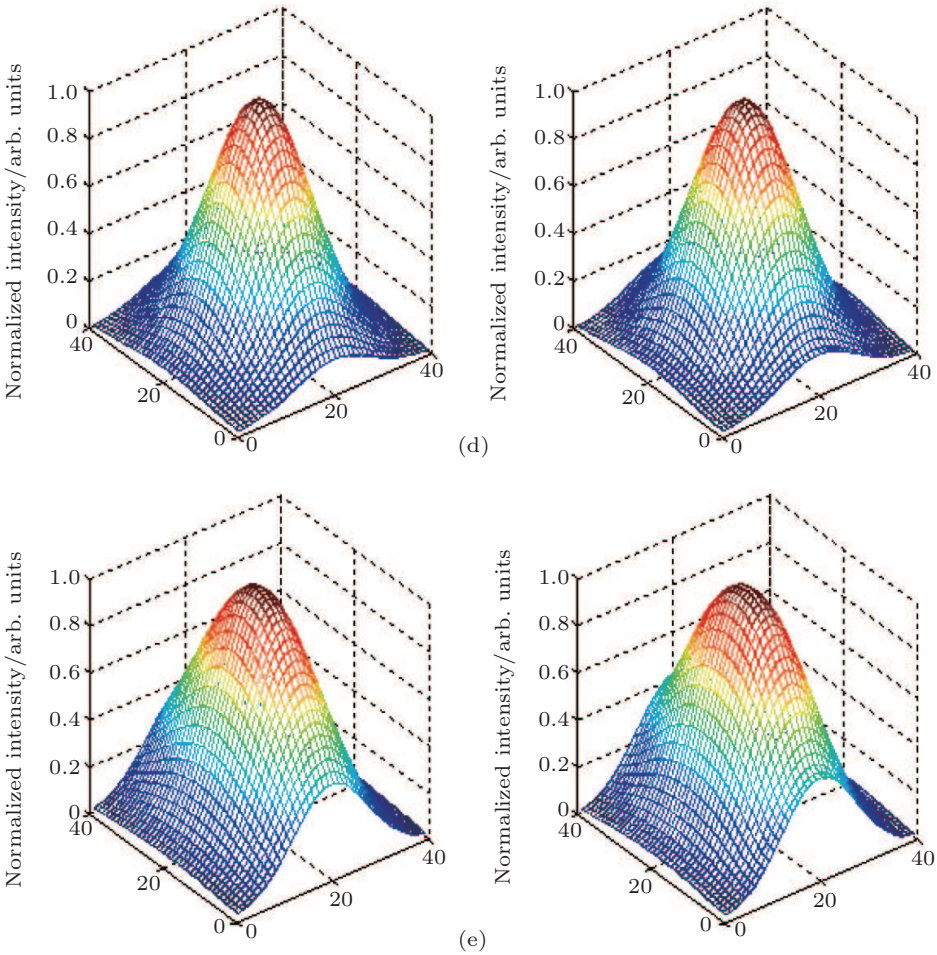


Fig. 5. (color online) Comparisons of the spatial distribution between a reconstructed terahertz pulse and the original terahertz pulse at $t = -323.0$ fs (a), -96.4 fs (b), 84.8 fs (c), 214.9 fs (d), and 385.0 fs (e).

Table 1. Relative errors between the spatial distributions of reconstructed THz pulses and those of original THz pulses.

Sequence number	1	2	3	4	5	6	7	8	9
Time/fs	–645.6	–457.7	–323.0	–96.4	84.8	214.9	385.0	560.6	686.5
Relative error/%	2.79	3.08	2.27	8.48	0.04	0.19	3.59	1.67	4.85

4. Conclusions

In this paper, we combine the principle of electro–optic sampling and spectral holographic technology, and propose a new method of measuring the full spatiotemporal field of a single-shot terahertz pulse. We generate sub-holograms containing the spatiotemporal field of a single-shot terahertz pulse by the ingenious combination of Dammam grating and an interference filter. The reconstructed spatiotemporal distribution of the terahertz pulse is generally consistent with the spatiotemporal distribution of the original terahertz pulse, which shows the feasibility of the proposed method. The instrument structure is simple and the optical delay line is not necessary in our method. This method has great potential applications in the spatiotemporal characterization of a single-shot terahertz pulse.

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