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The study of numerical character for femtosecond pulse shaping

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This paper describes the generation of shaped femtosecond multiple pulses by using the phase-only Dammann filters in 4f femtosecond shaper and gives the experimental result of femtosecond pulse characterization by the frequency-resolved optical gating (FROG) technique. With the theoretical simulation, it concludes that the quality of the generated output array is relevant to the number of pixels and the spacing between the components.

Keywords: space–time conversion, femtosecond pulse shaping, Dammann, frequency-resolved optical gating

PACC: 4280W, 7847, 4225F, 6110D

1. Introduction

As is well known, the ultrafast laser is the shortest artificial event that cannot be manipulated by resorting to other faster controllable physical effects. Space–time conversion technique is the unique and the most-efficient method to manipulate the femtosecond pulse. The ability of producing temporally ultrashort laser pulses has long been considered as a topic of particular interest in different fields of science, such as the generation of pulse trains for optical fibre communication systems including en- and decrypting of information,[1] the generation of complex pulse structures for the coherent control of atomic systems,[2] femtosecond chemistry[3−6] and so on. Femtosecond pulse shaping[7,8] is in close analogy with traditional spatial-domain Fourier processing techniques, and commonly achieved by placing a phase or intensity modulator such as a liquid-crystal display (LCD) array, moving mirror, deformable mirror, diffractive optical element[9,10] and so on. One well-known example of a phase-only filter is the Dammann grating[11−13] which is used to generate large, highly uniform beam arrays for femtosecond pulse shaping systems.[14] Recently, interest in Dammann gratings has been restimulated by new development in optical digital computing, in which arrays of spots have to be generated to provide optical power supply beams for arrays of logic device, and in ultrashort laser pulse characterization with Dammann grating for splitting beam.[15] Zou *et al* have reported femtosecond pattern generation with a time-to-space conversion technique in detail and give one pulse experimental result for femtosecond pattern recognition with frequency-resolved optical gating (FROG) technique.[16] In this work, we extend the previous research by analysing the different quality of the generated output array with the influence of the number of pixels and the spacing between the components, and give two pulse experimental result for femtosecond characterization with FROG technique. With the most commonly used new pulse-measurement method, FROG is now possible to measure pulses over a wide range of wavelengths, pulse lengths, and complexities.

2. The theory of the femtosecond pulse shaping

The theory of the femtosecond pulse shaping described in this paper is based on the linear and time-invariant filter. The apparatus of femtosecond pulse shaping consists of an identical pair of diffraction gratings placed at the outside focal planes of an unit-magnification confocal lens pair, as depicted in Fig.1. Spatially patterned masks are inserted midway between the lenses at the point where the optical spectral components experience maximal spatial separation. The second lens and grating reassemble the various spectral components into a single collimated beam.

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When no mask is presented inside the apparatus, the incident femtosecond pulse $e_{\rm in}(t)$ is transmitted without distortion. When patterned mask is presented, the output pulse shape $e_{\rm out}(t)$ is given by the Fourier transform of the pattern modified by the masks onto the spectrum.

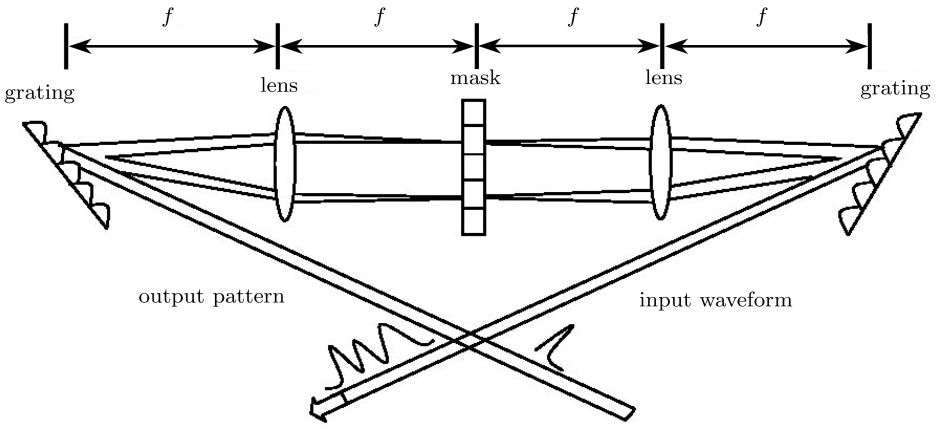


Fig.1. Apparatus of the femtosecond pulse shaping.

The theory of femtosecond pulse shaping can be written as

$$e_{\rm out}(t) = e_{\rm in}(t) * h(t) = \int {\rm d}t' e_{\rm in}(t') h(t - t'), \quad (1)$$

$$E_{\rm out}(\omega) = E_{\rm in}(\omega) H(\omega). \quad (2)$$

Here

$$H(\omega) = \int {\rm d}t h(t) {\rm e}^{-{\rm i}\omega t} \quad (3)$$

and

$$h(t) = \frac{1}{2\pi} \int {\rm d}\omega H(\omega) {\rm e}^{{\rm i}\omega t}. \quad (4)$$

Where $*$ denotes convolution. $h(t)$ is impulse response function of filter in the time frequency, $H(\omega)$ is the effective frequency filter implemented by the mask within the femtosecond pulse shaper. Where $e_{\rm in}(t)$, $e_{\rm out}(t)$, and $h(t)$ and $E_{\rm in}(\omega)$, $E_{\rm out}(\omega)$, and $H(\omega)$, respectively, are Fourier transform pairs.

Therefore, due to the Fourier transform relations, generation of a desired output waveform can be accomplished by implementing a filter with the required frequency response.

3. Gaussian spectral optimization for Dammann grating

We consider the output pulses is relevant to the pixel number further.[16] We used a phase mask based on periodic repetition of the so-called a_n sequences. Each period of the mask is divided into N pixels of width, as determined by a particular a_n sequences $\{\cdots 1 - 1 \cdots 1 - 1 \cdots\}$. In the example considered here, we used a 1×12 phase mask pattern consisting of 1200 pixels that are more accurate than Weiner's 128 pixels.[14] The calculated output intensity profiles that were produced from Dammann grating designed to transform a Gaussian-like input pulse with the different pixel numbers of 132 and 1200, are shown in Figs.2(a) and 2(b), respectively. From Figs.2(a) and

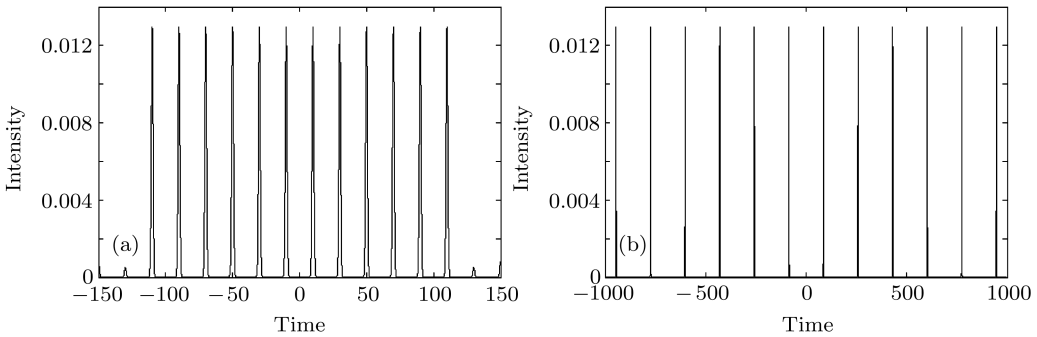


Fig.2. Temporal output pulses of a 1×12 array (a) with 132 pixels mask, and (b) with 1200 pixels mask plane in Fig.1.

2(b), we find that the trains of output pulses for 1200 pixels are more precise than those of 132 pixels. The spacing of the diffraction peaks becomes larger than that of 132 pixels in the time domain, in the other words, the resolution of the output spectra grows higher than that in 132 pixels mask. Our current results occupy a broader time window and exhibit a finer temporal structure because of the larger number of pixels in the phase mask, in fact, the duration of each pulse does not change with the pixel number. We can conclude that the uniformity of generated multiple ultrafast temporal pulse is relevant to the pixel number.

4. The effect of spacing between the components

As is well known, the femtosecond pulse shaping setup consists of an identical pair of diffraction gratings placed at the outside focal planes of an unit-magnification confocal lens pair. However, if the spacing of the every two components is longer or shorter than the focal length, the output pulse will not be regular. Here we consider that the spacing between the components had little effect to disturb the spectral phase but had a strong effect on the output pulse.

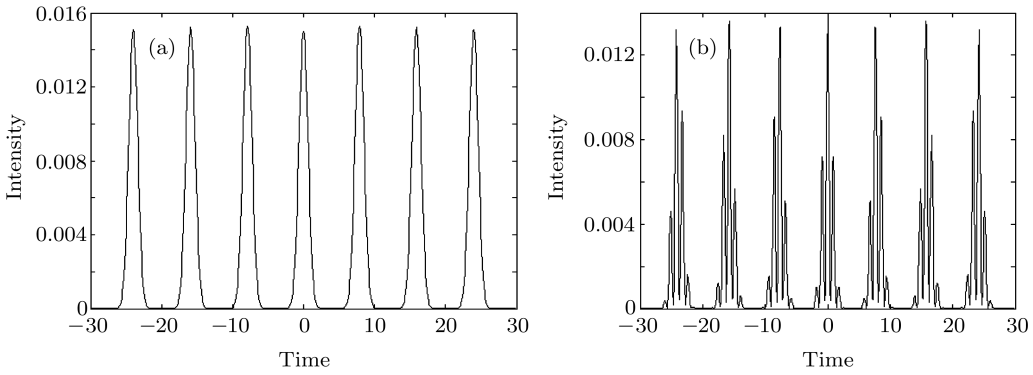


Fig.3. Temporal output pulses of a 1×7 array: (a) without consideration of the change of the spacing between the components, (b) with consideration of the change of spacing between the components. As a consequence, the output pulses in (b) become unorderly.

The spacing between the components is not equal to focal length, which will impose a phase modulation on the output spectrum. We use a 1×7 array to simulate such effect, which is shown in Fig.3. Figure 3(a) gives the temporal output pulses without consideration of the change of the spacing between the components. From Fig.3(b) we can get that the output pulses have been disturbed for the accessional modulated phase. The output pulses have the great side wings.

5. Characterization of two femtosecond pulse trains

The desired multiple pulse trains can be accomplished by implementing the corresponding Dammann grating with the required frequency response. In this work, one example that we discussed is the realization of 1×2 Dammann grating for creating specially two pulses shaped femtosecond pulse sequences, this method is also applied for synthesizing arbitrarily desired multiple shaped femtosecond pulse. In this femtosecond shaper, the assumed input spectrum is shown in Fig.4. Figure 5 shows the theoretical target pulse trains for 1×2 Dammann grating as mask in the space–time conversion shaper.

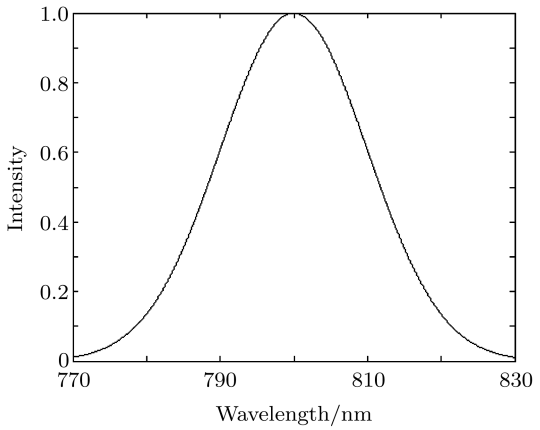


Fig.4. Input power spectrum assumed.

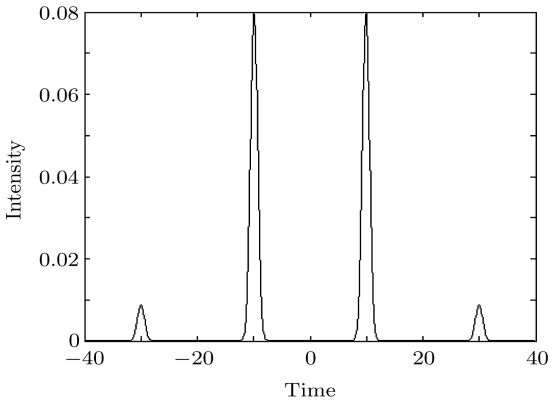


Fig.5. The theoretical target output pulse trains for 1×2 Dammann grating as mask in the space–time conversion shaper.

Figure 6 shows the frequency-resolved optical gating (FROG) which can determine the intensity and phase evolution of an arbitrary ultrashort pulse on a single-shot or multishot basis,[17,18] it consists of two main parts: first, an experimental apparatus in which two replicas of the pulse to be measured are mixed in a nonlinear-optical medium, and one spectrally resolves the resulting mixing signal as a function of the time delay between the two replicas to create a so-called FROG trace, and second, a phase-retrieval-based algorithm that extracts the complete intensity and phase evolution from the experimentally generated FROG trace.

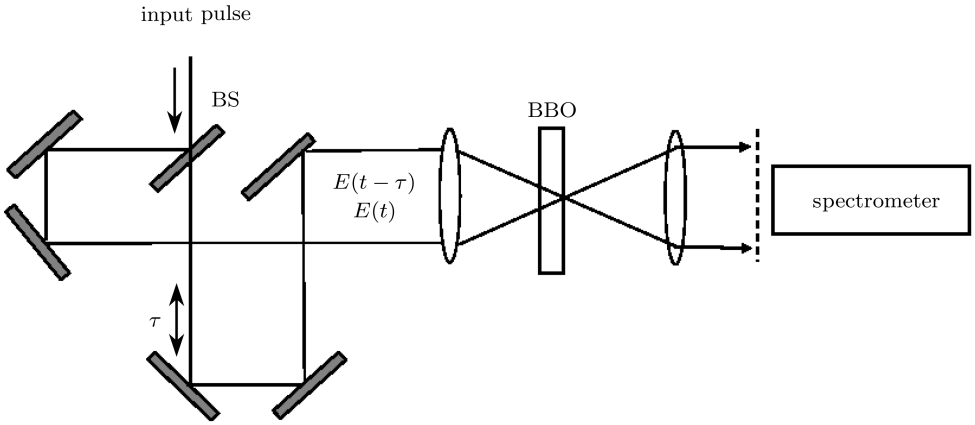


Fig.6. Schematic illustration of experimental setup for implementation of the FROG technique.

With the FROG technique, the two femtosecond pulses can be measured. Here we record the beam profile of 72 fs Ti:sapphire laser pulse (Coherent Mira SEED) with a wavelength of 800 nm at the target plane. The laser pulse was split into two pulses, the distance that two pulses travel can be changed by moving a micro-motor stage. The two pulses are focused on the nonlinear beta-barium metaborate (BBO) of the thick 100 μm for crystal by a lens, thus producing a second harmonic beam. The resulting output frequency versus time delay of the pulse trace is acquired with a spectrometer (In Spectrum Acton). The FROG trace for this experiment is shown in Fig.7. We can find that these three traces are symmetric. Then applying commercial software to this data to determine the complete complex envelope, we should retrieve the intensity and phase of the input pulse, shown in Fig.8. The generated two pulse trains profile [Fig.8(a)] matches the desired pulse one [Fig.5] closely. However, the dispersion, nonlinear optical effects and the misalignment between the components may alter the output profile of ultrashort laser pulses, and the pulse duration time expanded is 140 fs. The pulse intensity and phase can be estimated simply by looking at the experimental trace, or the iterative algorithm may be used to retrieve the precise intensity and phase versus time or frequency.

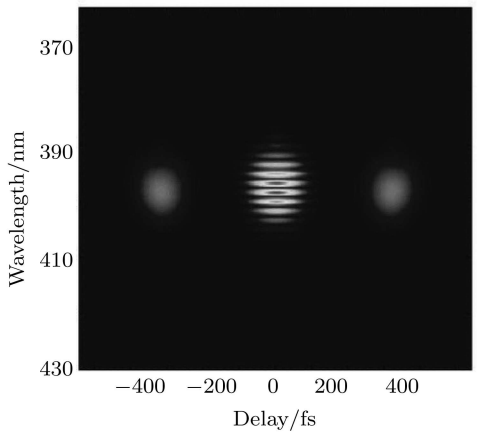


Fig.7. Experimental FROG trace for two pulses.

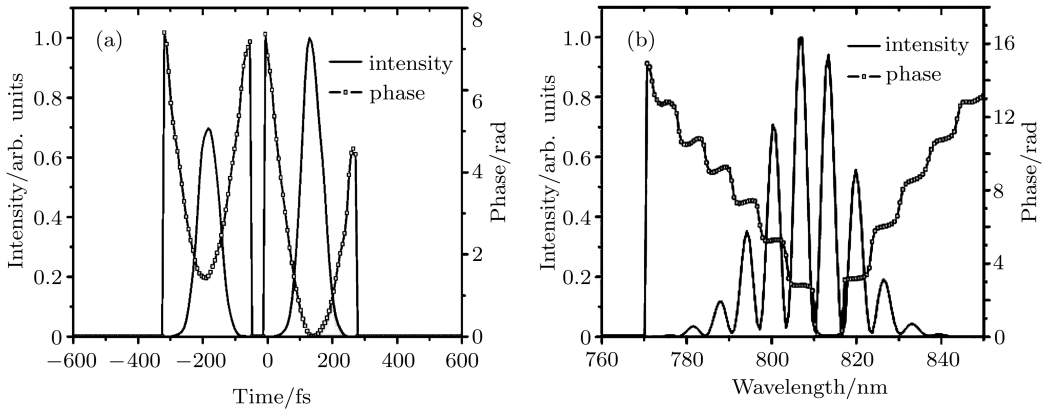


Fig.8. (a) Intensity and phase of the pulse retrieved from the FROG trace, (b) the intensity and phase of the spectrum.

6. Summary

In summary (this work), we have reported the generation of shaped femtosecond multiple pulses by using the phase-only Dammann filters and give the experimental result of femtosecond pulse characterization by the FROG technique. With the theoretical simulation of the Gaussian spectral distribution, we conclude that the uniformity of generated multiple ultrafast temporal pulse is relevant to the pixel number, and the spacing between the components. Femtosecond pulse shaping has been applied in many fields, so the subject of femtosecond pulse shaping is a hot topic in recent years. The character of shaped pulses becomes quite indispensable to its efficient applications. We also give the femtosecond pulse characterization applying FROG technique. It seems that there is no doubt that the femtosecond pulse shaper reflects the trend of ultrafast optics field that should benefit wide applications in the near future.

References

[1] Weiner A M, Heritage J P and Salehi J A 1998 *Opt. Lett.* **13** 300
[2] Meshulach D and Siberberg Y 2002 *Nature* **418** 512
[3] Feurer T, Vaughan J C and Nelson K A 2003 *Science* **299** 374
[4] Rabitz H 2003 *Science* **299** 525
[5] Tian P, Keusters D and Suzaki Y 2003 *Science* **300** 1553
[6] Zhao Q Z, Qiu J R, Zhao C J, Jiang X W and Zhu C S 2005 *Chin. Phys.* **14** 1181
[7] Weiner A M 2000 *Rev. Sci. Instrum.* **71** 1929
[8] Frumker E, Oron D and Silberberg Y 2004 *Opt. Lett.* **29** 90
[9] Zhou C H, Jia J and Liu L R 2003 *Opt. Lett.* **28** 2174
[10] Dai E W, Zhou C H, Xi P and Liu L R 2003 *Opt. Lett.* **28** 1513
[11] Dammann H and Gortler K 1971 *Opt. Commun.* **3** 312
[12] Jahns J, Downs M M and Prise M E 1989 *Opt. Eng.* **28** 1267
[13] Zhou C H and Liu L R1995 *Appl. Opt.* **26** 5961
[14] Weiner A M, Oudin S and Leaird D E 1993 *J. Opt. Soc. Am.* A **5** 1112
[15] Dai E W, Zhou C H, and Li G W 2005 *Opt. Exp.* **13** 6145
[16] Zou H, Dai E W and Zhou C H 2004 *Opt. Eng.* **43** 1874
[17] Trebino R 2000 *Frequency-Resolved Optical Gating, the Measurement of Ultrashort Laser Pulses* (Norwell, MA: Kluwer)
[18] Wang P, Wang Z H, Wei Z Y, Zheng J A, Sun J H and Zhang J 2004 *Acta Phys. Sin.* **53** 3004 (in Chinese)