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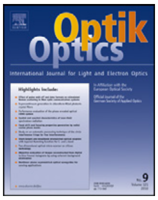

# Generation of multiple femtosecond pulses by step gratings

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ABSTRACT

A simple method for generating multiple isolated femtosecond pulses by step gratings is presented, and a criterion for judging whether or not an incident pulse is just split into multiple independent pulses is obtained. The dependences of multiple pulses on the structural parameters of the step gratings are explored. The results show that an incident pulse can split into multiple isolated similar diffraction pulses for enough step height, and the pulse repetition interval increases with the increasing of the step height.

## 1. Introduction

The femtosecond laser pulse has already demonstrated a strong impact as an experimental tool providing unprecedented control in the field such as physics, chemistry, biology, especially in micro-machining [1]. Multiple pulses, with controllable time delay and shape, are an important class of optical waveforms. They are well suited for ultrasort pulse measurement [2,3], multiple pulses micro-machining [4–6], coherent control experiment, multidimensional and nonlinear spectroscopy. There has been amount of work on pulse train generation using a pulse shaper. Those efforts either utilize both phase and amplitude shaping [7–9], mimic phase-and-amplitude modulation by means of diffraction in a phase-only shaper [10–12], or report on phase-only generation of pulse trains with fairly limited properties [13,14].

In this paper, we present a simple method for generating multiple isolated femtosecond pulses by step gratings, obtain a criterion for judging whether or not an incident pulse is just split into multiple independent pulses, and explore the dependences of multiple pulses on the structural parameters of the step gratings. When the step height is a critical value, an incident pulse can just split into multiple isolated similar diffraction pulses. If the step height is bigger than the critical value, the pulse repetition interval increases with the increasing of the step height. This work is beneficial to the investigation of the ultrashort pulse in the propagation and diffraction property, and the control of laser beam waveforms.

## 2. Model and theoretical analysis

The schematic of multiple femtosecond pulses generated by step gratings is shown in Fig. 1. The step width is $d$, the step height is $h$, and the step level number is $n$. The collimated femtosecond laser pulse is oblique incidence to the step grating reflective surface with an incident angle $\alpha$, and it is diffracted with a diffractive angle $\theta$.

The reflective function of the step gratings can be expressed as:

$$r(x) = \sum_{m=1}^{n} \left\{ \exp\left[ j\frac{2\pi}{\lambda}(m-1)h(\cos\alpha + \cos\theta) \right] \times \mathrm{rect}\left[ \frac{x-(m-1/2)d}{d} \right] \right\} \tag{1}$$

where rect is the rectangle function.

We consider the femtosecond laser pulse with an incident angle $\alpha$ is a Gaussian-shaped temporal pulse, as given by:

$$E_{in-t}(x, z=0, t) = \exp\left[ j\frac{2\pi}{\lambda}x\sin\alpha \right] \exp\left[ -\frac{t^2}{2\tau^2} + j\omega_c t \right] \tag{2}$$

where $\tau = 1/2\sqrt{\ln 2}\tau_{FWHM}$, $\tau_{FWHM}$ is full width of the pulse at half maximum. $\omega_c$ is the pulse central frequency, $\omega_c = 2\pi c/\lambda_c$, $\lambda_c$ is the pulse central wavelength, $c$ is the light speed. After Fourier transform, the spectrum of the incident pulse can be written as

$$E_{in-s}(x, z=0, \omega) = \int_{-\infty}^{\infty} E_{in-t}(x, z=0, t) \exp[-j\omega t]\, dt \tag{3}$$

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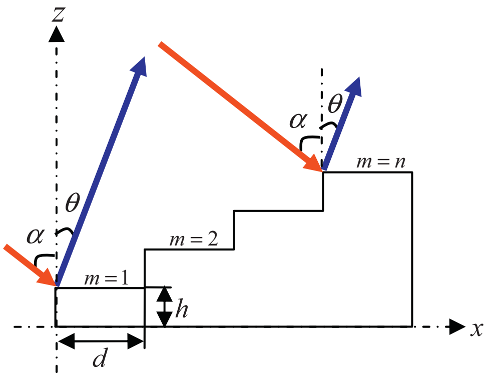

**Fig. 1.** Schematic of multiple femtosecond pulses generated by step gratings.

The spectral distribution in the Fraunhofer diffraction field can be expressed as:

$$E_F(x,z,\omega)=\frac{1}{j\lambda z}\exp\left[j\frac{2\pi}{\lambda}\left(z+\frac{x^2}{2z}\right)\right]\mathrm{F}\{E_{in-s}(x,z=0,\omega)r(x)\} \quad (4)$$

where F is about $x$ Fourier transform.

By Fourier transform, the temporal distribution in the Fraunhofer diffraction field can be represented as:

$$E_F(x,z,t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}E_F(x,z,\omega)\exp[j\omega t]d\omega \quad (5)$$

By inserting the variable $\lambda = 2\pi c/\omega$, Eqs. (1) and (3) into Eq. (4), and substituting its result into Eq. (5), we can obtain the temporal distribution.

The temporal intensity in the Fraunhofer diffraction field can be expressed as:

$$I_F(x,z,t)=E_F(x,z,t)E_F^*(x,z,t)=\left[\frac{1}{2\pi z(\sin\alpha-\sin\theta)}\right]^2 \times\left|\sum_{m=1}^{n}\left\{\exp\left[-\frac{{t_1}^2}{2\tau^2}+j\omega_c t_1\right]-\exp\left[-\frac{{t_2}^2}{2\tau^2}+j\omega_c t_2\right]\right\}\right|^2 \quad (6)$$

where the asterisk denotes complex conjugate,

$$t_1=t'+\frac{m-1}{c}[h(\cos\alpha+\cos\theta)+d(\sin\alpha-\sin\theta)],$$

$$t_2=t'+\frac{1}{c}[h(m-1)(\cos\alpha+\cos\theta)+md(\sin\alpha-\sin\theta)],$$

$$t'=t+\frac{z}{c}+\frac{x^2}{2cz}$$

## 3. Design and analysis of step gratings

On the basis of previous theoretical analysis and Eq. (6), we explore the dependence of multiple femtosecond pulses on the structural parameters of the step gratings. In the following simulations, unless specially specified, otherwise $\tau = 3$ fs, $\lambda_c = 800$ nm, $\alpha = 5°$, $d = 30$ μm, and $h = 14\lambda_c/4$.

The spatial and temporal diffractive pulses intensities for different $n$ are shown in Fig. 2. We can easily find that the pulse number changes obviously with $n$, and the incident pulse can split into $n$ similar diffraction pulses on the temporal axis under certain conditions. The diffractive pulses intensity is mainly concentrated on the principal maximum.

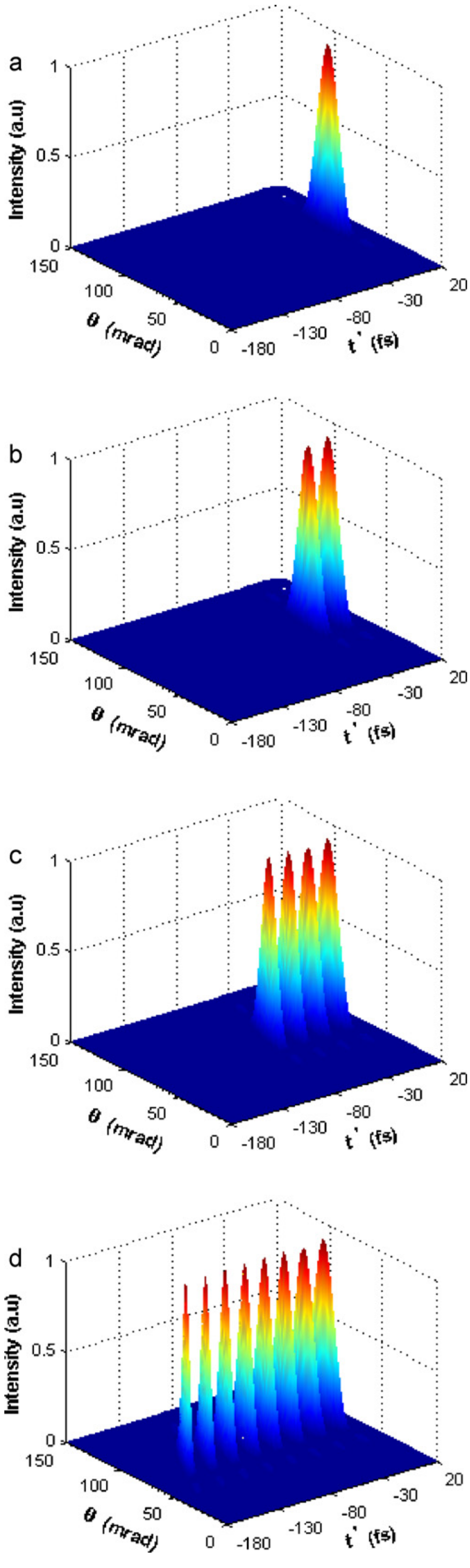

**Fig. 2.** Spatial and temporal diffractive pulses intensity for (a) $n = 1$, (b) $n = 2$, (c) $n = 4$, and (d) $n = 8$.

The spatial and temporal diffractive pulses intensities for different $d$ are shown in Fig. 3. The spatial pulse width of the diffractive pulses narrows with the increasing of $d$.

The spatial and temporal diffractive pulses intensities for different $h$ are shown in Fig. 4. We find that the incident pulse can