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Investigations of the Talbot effects for a grating illuminated by the ultrashort optical pulses

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ABSTRACT

Based on the theories of the Fresnel diffraction and the signal processing, the Talbot effects for a grating illuminated by a train of ultrashort optical pulses are investigated numerically. Influences of the input pulse parameters and the grating structure on the Talbot images are discussed detailedly. Results demonstrate that the contrast of the high/low field boundary becomes obscure for the optical pulse with shorter temporal duration and chirp. And a grating with smaller duty cycle (DC) is easier to the formation of constructive interference field. In addition, although the high/low field distribution resembles as the image of grating period at the integer Talbot detecting planes, it repeats k-times at the fractional Talbot detecting plane, which can be exploited for obtaining higher pulse repetition rate multiplication.

1. Introduction

The Talbot effect is a near-field diffraction and interference phenomenon when a plane wave is reflected or transmitted through a periodic amplitude or phase grating [1]. Due to its promising application in lithography [2], optical array illumination [3], and optical pulse rate multiplication [4], the Talbot effect has been intensively studied both theoretically and experimentally[5]. In the past, most of the investigations relied on the use of monochromatic continuous wave (CW). As the generation of ultrashort optical pulses with high repetition rates has attracted considerable attention in recent years, some new Talbot phenomena are observed for the ultrashort optical pulses with wider wavelength bandwidth. In this paper, our goal is to theoretically investigate the Talbot effect for a grating illuminated by a train of ultrashort optical pulses. Influences of the input pulse chirp, temporal duration, and the grating's duty cycle are discussed in detail.

2. Theoretical background

Let us assume that a grating with one-dimensional x-direction period (Λ) and the rectangular amplitude is employed [6]:

$$g(x) = \sum_{m=-\infty}^{+\infty} rect\left(\frac{x - m\Lambda}{\Lambda/M}\right) \quad (1)$$

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here M is the ratio of the grating period to the transparency window width (defined as grating duty cycle (DC = 1/M)).

A train of transform-limited Gaussian ultrashort optical pulses are injected to illuminate the grating, and each individual pulse is expressed as [7]:

$$E_0(0,t)=\exp(-i\omega_0 t+iCt^2-\frac{t^2}{2T^2}) \tag{2}$$

where $\omega_0=\frac{2\pi c}{\lambda_0}$ is the angular frequency, λ_0 is carrier central wavelength, $c=3\times 10^8$ m/s is light speed. Cis the pulse chirp, T is the pulse's temporal duration.

Based on the signal processing theory, the Fresnel diffraction field of ultrashort optical pulse with a wider wavelength bandwidth can be calculated as the product of the Fresnel diffraction field of monochromatic continuous light and the Fourier-transformed spectrum of input ultrashort optical pulse:

$$\Phi(x,z,\omega)=E_0(0,\omega)U(x,z,\omega) \tag{3}$$

here $E_0(0,\omega)$ is the Fourier-transform ($F(\cdot)$) of the input pulse:

$$\begin{aligned} E_0(0,\omega)&=F(E_0(0,t)) \\ &=\frac{1}{2\pi}\int_{-\infty}^{+\infty}E_0(0,t)\exp(i\omega t)dt \\ &=\sqrt{\frac{T^2}{2\pi(1-i2CT^2)}}\exp\left(-\frac{(T^2+i2CT^4)(\omega-\omega_0)^2}{2+8C^2T^4}\right) \end{aligned} \tag{4}$$

$U(x,z,\omega)$ is the Fresnel diffraction field when the grating is illuminated by a beam of monochromatic continuous light:

$$\begin{aligned} U(x,z,\omega)&=\frac{\exp\left(i\frac{2\pi z}{\lambda}\right)}{\sqrt{i\lambda z}}\int_{-\infty}^{+\infty}F(g(x))\exp\left(-\frac{i\pi}{\lambda z}(x-x_1)^2\right)dx \\ &=\exp\left(i\frac{2\pi z}{\lambda}\right)\sum_{l=-\infty}^{+\infty}A_l\exp\left(i\frac{2\pi lx}{\Lambda}\right)\exp\left(i\frac{2\pi l^2 z}{2\Lambda^2/\lambda}\right) \end{aligned} \tag{5}$$

As can be seen from Eq. (5), in the lateral direction, the second exponential factor is eliminated every spacing of $x=\Lambda$. That is the field intensity distribution reappears as the image of grating period. At a periodic axial distance $z_T=2\Lambda^2/\lambda$ (defined as the "Talbot distance"), the third exponential factors are eliminated and the interference field intensity behind the grating also repeats itself. At the detecting plane, the high-resolution interference microscopy can record the average optical intensity as:

$$I(x,z)=2\pi\int_{-\infty}^{+\infty}|\Phi(x,z,\omega)|^2d\omega \tag{6}$$

3. Numerical results and discussions

Based on the theoretical analyses above, the Talbot image characteristics for a grating illuminated by a train of ultrashort optical pulses are numerically calculated. The input pulse's temporal duration is $T=20$ fs and its carrier central wavelength is 800 nm. A grating with period $\Lambda=200$ μm and duty cycle $DC=1/4$ is used. As shown in Fig. 1, the normalized high or low amplitude denotes the grating's transparency or opaque region, respectively.

Firstly, Fig. 2 compares the interference field intensity distributions when the grating illuminated by different ultrashort optical pulses or the ideal monochromatic continuous light. All the intensities are normalized with respect to the maximum field intensity of ultrashort pulse at the Talbot plane ($z=z_T=10$ cm). As can be seen, although the field at the Talbot plane still shows a periodicity in the lateral direction as the illuminated grating (Fig. 1), the field intensity distributions of ultrashort pulses don't have such steep boundary as the monochromatic continuous light. And as the pulse temporal duration decreases, the field intensity becomes smaller and the high/low boundary becomes smoother. This can be explained as: the spectrum of ultrashort optical pulse is constituted by several monochromatic lights with different wavelengths, which lead to some slight difference of their Talbot distances. When the image is detected at the Talbot distance calculated by the central wavelength, the fields at other wavelengths overlap destructively [8]. Therefore, the contrast between the "bright spot" (for high field intensity) and "dark spot" (for low field intensity) becomes obscure and image resolution reduces.

Secondly, influence of the input pulse chirp on the Talbot effect is discussed. Fig. 3 shows the intensity distribution of the Talbot images under the illumination of ultrashort optical pulses with or without chirp. As can be anticipated, the Talbot field distribution is indistinct further due to the pulse with chirp having a wider wavelength bandwidth than the pulse without chirp.

Next, the impact of grating's duty cycle on the Talbot image is discussed. As can be seen from Fig. 4, the Talbot field distribution for grating with smaller duty cycle is steeper and the ripple at the region of low field intensity is smaller. The