Experimental study of the FemtoTalbot effect

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Experimental investigation of Talbot self-imaging effect of an amplitude grating under illumination of femtosecond laser pulse — the FemtoTalbot effect is reported. Theoretical analyzed results show that Talbot images under illumination of femtosecond laser pulses are not the same as that under continuous wave illumination. Experimental results are in good agreement with the theoretical analysis. We believe that the experimental investigation of the FemtoTalbot effect is highly interesting for the enormous potential applications of Talbot effect.

OCIS codes: 050.1950, 070.6760, 320.2250.

If a periodic object is illuminated by a monochromatic continuous wave (CW), images of the object will appear at certain distances behind the object, which is so-called the Talbot effect. Talbot distances are $z=nZ_T$, where $Z_T=2d^2/\lambda$, λ is the wavelength of the incident light, d is the period of the grating, and n is a positive integer. The Talbot effect is one of the most basic optical phenomena that has been received extensive investigations[1−4]. During the past decade, the technology of femtosecond pulse laser has been developed rapidly[5,6]. It becomes worthful to study the Talbot effect under illumination of femtosecond laser pulse, which is defined as the Femto-Talbot effect in this paper for the sake of brevity. Wang *et al.* theoretically studied the Talbot effect under illumination of a femtosecond pulse laser and pointed out the FemtoTalbot effect exhibits different behaviors from the Talbot effect under CW illumination[7]. Xi *et al.* have presented a method for measurement of the femtosecond laser pulse-width based on the differences of the FemtoTalbot effect from the Talbot effect under CW illumination[8]. In this paper, we report experimental verifications of the differences between the FemtoTalbot images and the Talbot images under illumination of CW. A rectangular amplitude grating can be expanded into a Fourier series as

$$g(x)=\sum_{l=-\infty}^{+\infty}A_l\exp(i\frac{2\pi l}{d}x),\ A_l=\frac{1}{M}\mathrm{sinc}(\frac{l}{M}),\qquad(1)$$

where M is a positive integer, d is the period of the amplitude grating. By using of the Fresnel diffraction formula, it is easy to obtain the field of light waves under the paraxial approximation behind the rectangular amplitude grating. It can be expressed in the frequency domain as

$$U\left(x,z,\omega\right)=\exp(i\frac{2\pi}{\lambda}z)\sum_{l=-\infty}^{+\infty}A_l\exp(i\frac{2\pi lx}{d})\exp(i\frac{2\pi l^2z}{2d^2/\lambda}),\qquad(2)$$

where ω is the frequency of the incident light wave, $\lambda=2\pi c/\omega$ is the wavelength of the incident light, z is the distance behind the input amplitude grating. Considering that the incident light is femtosecond laser pulse and supposing that the femtosecond pulse beam has a Gaussian shape in the time domain, the femtosecond pulse light can be described as[7−9]

$$U_0(t,\Delta\tau)=\exp[-i\omega_0t-4\ln2(t/\Delta\tau)^2],\qquad(3)$$

where ω_0 represents the central frequency of the femtosecond laser pulse and $\Delta\tau$ denotes the full-width at half-maximum (FWHM) of the pulse. With Fourier transform, the pulse can be described in the frequency domain

$$V_0(\omega,\Delta\tau)=\frac{\Delta\tau}{4\sqrt{\pi\ln2}}\exp\left[-\frac{\Delta\tau^2(\omega-\omega_0)^2}{8\ln2}\right],\qquad(4)$$

A femtosecond pulse laser can be treated as a summation of coherent monochromatic beams, with the central frequency ω_0. In this sense, the diffraction pattern can be regarded as the summation of a series of monochromatic components, a femtosecond pulse laser in the frequency domain can be expressed as

$$U_{\mathrm{femto}}(x,z,\omega,\Delta\tau)=V_0(\omega,\Delta\tau)U(x,z,\omega),\qquad(5)$$

The intensity distribution of a femtosecond laser is

$$I_{\mathrm{femto}}(x,z,\Delta\tau)=2\pi\int_{-\infty}^{+\infty}|V_0(\omega,\Delta\tau)U(x,z,\omega)|^2\mathrm{d}\omega,\qquad(6)$$

Then for $z=nZ_T=2nd^2/\lambda_0$, where $\lambda_0=2\pi c/\omega_0$ is the central wavelength and n is a positive integer, we can have the intensity distribution behind the input grating as[8]

$$\begin{aligned}I_{\mathrm{femto}}(x,z,\Delta\tau)=&\frac{\Delta\tau^2}{8\ln2}\int_{-\infty}^{+\infty}\exp\left[-\frac{\Delta\tau^2(\omega-\omega_0)^2}{8\ln2}\right]\\&\times\sum_{l=-\infty}^{+\infty}\sum_{l'=-\infty}^{+\infty}A_lA_{l'}\exp\left[i\frac{2\pi(l-l')}{d}x\right]\\&\exp\left\{i\frac{2\pi[l^2-(l')^2]n\omega_0}{\omega}\right\}\mathrm{d}\omega,\end{aligned}\qquad(7)$$

Generally speaking, a Ti:sapphire laser oscillator is used to generate the femtosecond laser pulse with a central wavelength of λ_0=780 nm. Assuming that the FWHM of incident femtosecond laser pulse is 60 fs, with computer numerical simulation, we can obtain the distribution of $I_{\mathrm{femto}}(x,\ z,\ \Delta\tau)$ at one and two Talbot distances, which is shown in Fig. 1. In Fig. 1, we also present the distribution of intensity under illumination of CW. From Fig. 1, we can know that there are some differences between the FemtoTalbot self-images and the Talbot self-images of CW. The differences exist mainly on maximum intensity area and minimum intensity area. The contrasts of the FemtoTalbot images are remarkably decreased. In addition, increasing the Talbot distances can decrease the

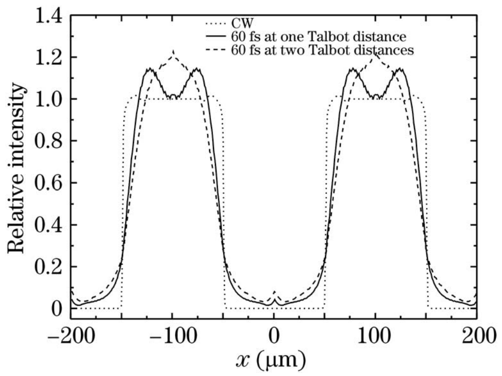

Fig. 1. Comparison of numerical simulation results of the FemtoTalbot self-images ($\Delta\tau$=60 fs) at different Talbot distances and Talbot self-image of CW. A grating with the period of 200 μm and the opening ration of 1/2 is used as the input grating.

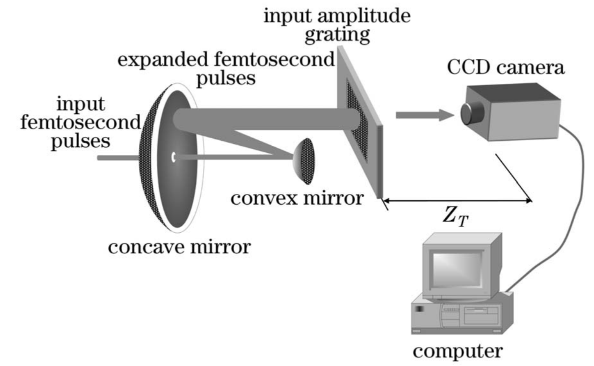

Fig. 2. Scheme of the optical setup.

contrast of the FemtoTalbot images. In another word, the FemtoTalbot images are destroyed because of the illumination of femtosecond laser pulses.

For experimental verification, we employ an optical setup shown in Fig. 2. In our experiment, femtosecond laser pulses come from a Coherent Mira Ti:sapphire oscillator with the central light wavelength of 780 nm and the FWHM of 60 fs. This oscillator is pumped by a Coherent Verdi 6 diode-pumped laser. Adjusted the operation mode and pump energy, this femtolaser can generate femtosecond pulse with the FWHM width of 60 fs and CW with a frequency of 780 nm. After expande by an expanded system, the femtosecond laser pulse or CW illuminate an amplitude grating. A reflective expanded system which includes a concave mirror and a convex mirror are used to expand the femtosecond laser in order to not change the information of femtosecond laser pulses in the time-domain and frequency-domain. A charge-coupled device (CCD) camera is put at Talbot distances behind of the grating to record the Talbot self-images. In our experiment, an amplitude grating with the opening ratio of 1/2, and periods of 200 μm is used as the input grating. Talbot images of CW at one Talbot image and the FemtoTalbot images at one and two Talbot distances are obtained. By using image processing tools, intensity profiles of the Talbot images are presented in Fig. 3. From Fig. 3, we can find that femtosecond laser can cause a large distortion of the FemtoTalbot images. Compared with self-images of CW, the intensity in dark area and bright area of the FemtoTalbot images are not uniformly distributed respectively. The main differences between the Talbot self-images and the FemtoTalbot images exist on the top and bottom of the profiles of intensity. The intensity profiles of the FemtoTalbot images are not flat top. And in dark area, there is also not flat bottom and is a small peak, which causes a brighter fringe. Considering from energy aspect, we can know that the energy in the dark area of the FemtoTalbot images is higher than that of the Talbot images of CW. So the contrast of the FemtoTalbot images and diffraction efficiency are obviously decreased compared with that of CW. In addition, it is well known that Talbot images of CW at different integral Talbot distances are almost completely same, which can be easily proved by experiments. But for the FemtoTalbot self-images, increasing of the Talbot distance can also result in the distortion of a Talbot image, including the decrease of contrast and diffraction efficiency of the FemtoTalbot images, which can be seen from the intensity profiles of the FemtoTalbot images in Fig. 3. Experimental results are in good agreement with the theoretical analysis above.

In conclusion, experimental verification of the differences between the FemtoTalbot effect and the Talbot effect under illumination of CW is presented in this paper. Compared with CW, Femtosecond laser pulse can cause a large distortion of the Talbot self-images, and the increasing of the Talbot distances can also result in the distortion of a FemtoTalbot image. Experimental results are in good agreement with the theoretical analysis. We believe that it is important to carry out further investigation in this field, because diffractive optical elements and femtosecond laser pulses both have a variety of practical applications, and their combination must have enormous potential applications.

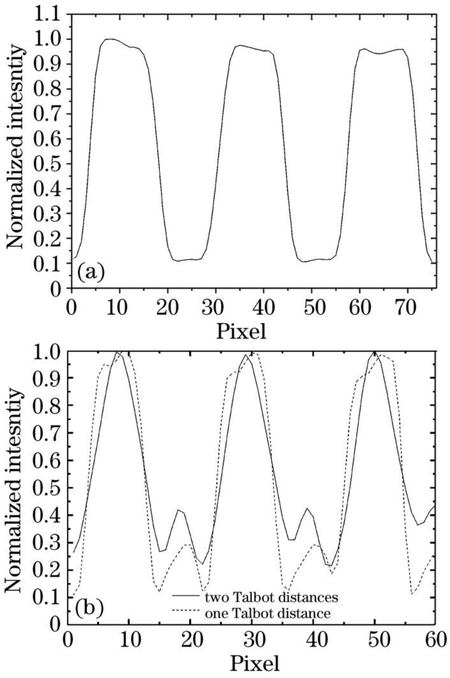

Fig. 3. Comparison of the intensity profiles of measured Talbot image of CW (a) and FemtoTalbot images at one Talbot distance and two Talbot distances (b).

This work was supported by the National Outstanding Youth Foundation of China (No. 60125512), and Shanghai Science and Technology Committee (No. 036105013) under Program of Shanghai Subject Chief Scientist (No. 03XD140). C. Zhou is the author to whom the correspondence should be addressed (chazhou@mail.shcnc.ac.cn).

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