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Experimental study about the diffraction of high-density grating in deep Fresnel field

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ABSTRACT

The experimental study about the diffraction of high-density grating in deep Fresnel region is performed in this paper. A microscope-magnification method is advanced, and the diffraction intensity distributions of high-density grating in deep Fresnel region are measured. The quasi-Talbot image of grating is also obtained in experiment. The corresponding theoretic results are also provided for convenient comparison with the experimental ones. The coincidence of experimental and theoretical results verifies the reliability of microscope-magnification method. This method can be used in the measurement of the diffraction of sub-wavelength structure in near field and deep Fresnel region.

1. Introduction

As an important diffraction optical element, grating has been applied in many fields such as the wave modulation, the compression of high power laser pulse and the excitation of surface plasmons [1–3]. Talbot effect of grating is a self-imaging phenomenon of grating in Fresnel diffraction region [4]. This phenomenon has been used in the information storage, the laser array illumination, the digital holography and the laser phase locking [5–7]. In Fresnel diffraction region, the point spread function of the optical system can be simplified by the second function of spatial coordinates, and the analytical formula of the diffraction intensity of grating can be easily expressed. For a one-dimensional grating in series form $\sum C_m \exp(i2m\pi x_0/d)$, the diffraction intensity in Fresnel region can be written as $|\sum C_m \exp(i2\pi mx/d)\ \exp(-i\pi\lambda m^2 z/d^2)|^2$ [8]. Where d is the period of grating, λ is the incident wavelength and m is an integer. Obviously, at the propagation $z_N = 2Nd^2/\lambda$ (N is also an integer), the second phase factor in the above sum is just equal to 1. Thus the diffraction intensity distribution has the same structure as the grating structure, and this is so-called Talbot image of grating. These characteristic positions are Talbot distances, and they change with the period of grating.

As we know the propagation distance in Fresnel diffraction region should satisfy the Fresnel approximate condition $z^3 \gg (x-x_0)^4_{\max}/8\lambda$. While the propagation distance is very small and it does not satisfy this above condition, the observation plane goes into the region between the Fresnel region and the near field with the propagating distance less than or comparable with the incident wavelength. We call this region as the deep Fresnel region [8]. In this region, the diffraction intensity cannot be denoted by the analytical solution but only expressed as the integral form, and the diffraction of grating shows some other properties different from those in Fresnel region, such as the polarization dependence [9,10]. In our former work, we find the exact Talbot image of grating does not exist, and only the similar structure to the grating appears. We call the most similar structure to the grating as the quasi-Talbot image. In this paper, we aim to study experimentally the diffraction of high-density grating in deep Fresnel region, and measure the quasi-Talbot image of grating.

For the grating with larger period, Talbot image of grating in the far Fresnel diffraction region appears at the distance larger than decimeters, and the experiment measurement is easily operated by use of the common photoelectric detector. But for the diffraction in the deep Fresnel region within several or tens of micrometers away from grating, the direct measurement gets difficult since the photoelectric detector can not reach easily, and some specific high-precision instruments often need to be used, such as the optical probe or the near-field optical microscope. In this paper, we present a microscope-magnification method to measure the deep Fresnel diffraction of high-density grating. This method only includes the micro-objective and the imaging lens. The micro-objective magnifies the spatial distribution on its objective plane, and then the lens combination images the magnified spatial distribution onto the detector plane of CCD. Thus, the diffraction distribution of grating at one propagation distance just locating on the objective plane of the micro-objective

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can be obtained through this measurement system. While the grating moves backwards with respect to the micro-objective, the diffraction distribution at other further distance after grating can be imaged. In our experiment, the grating is placed on the mobile platform with high precise, and the experimental measurement of the diffraction of grating in deep Fresnel region is realized with the help of the movement backwards of the grating. To verify the reliability of the experimental results, we also provide the corresponding theoretic results. The comparison shows the experimental results are consistent with the theoretic ones. We think that the microscope-magnification method can be used in the observation and measurement of the diffraction of complex sub-wavelength structure in near field and deep Fresnel region.

2. The principle of microscope-magnification method

To measure diffraction of grating in the deep Fresnel field, we present the microscope-magnification method. Schematic diagram of the microscope-magnification method is shown in Fig. 1. The laser beam passes through the expanding and collimation system and changes into the parallel light. Then through the reflector, it impinges upon the grating placed on the mobile platform. The grating located on the objective plane of the microscope is magnified by the micro-objective, and then imaged by two lenses. The magnified image of grating is finally received by a two-dimensional CCD. The received pattern is saved by the computer. To find the exact image of grating, the white light is used firstly, and the grating moves constantly until the clear image of grating appears on the computer screen. Here, the grating is just on the objective plane of the micro-objective. Then the laser beam is replaced. For adjusting conveniently, an attenuator and a shutter are used in the optical path. When the grating moves away from the micro-objective, the image system still magnifies the diffraction distribution just on the objective plane of micro-objective. It is just equivalent to the case that the detector moves away the grating and detects the intensity distribution at different distance behind the grating. This equivalence can be seen clearly from the inserted diagram on the right upper corner of Fig. 1. Thus, the magnified image of diffraction intensity distribution at the different distance away from the grating is obtained.

In practical experiment, the micro-objective with the numerical aperture 0.9 and the magnification 100 is used. The lens combination includes two camera lenses with focal length 240 mm. In order to shift grating accurately, we place the grating on the nanometer platform with precision 10 nm which is set on the other movable platform with precision 1 μm. Two-dimensional CCD with No. Cascade1 K is used to receive the intensity distribution. Owing to its high sensitivity and low noise, the ideal pattern can be obtained. The diffraction pattern is finally memorized by the computer as the data file. Two one-dimensional gratings with line density 300 L/mm and 600 L/mm are chosen as the experimental samples. The opening rates of two gratings are 0.5. According to the formula of Talbot distance of grating $z_N=2Nd^2/\lambda$, we can easily calculate the first Talbot distances z_1 (with $N=1$) of these two gratings illuminated by the parallel light with the wavelength $\lambda=632.8$ nm are 35.12 μm and 8.78 μm, respectively. Since the practical sizes of two gratings are about 5 cm, the propagation distance under Fresnel approximate condition needs to satisfy $z \gg 0.43$ m. Obviously, many theoretical Talbot distances of these two gratings do not satisfy this condition, and these distances dissatisfying the condition locate in deep Fresnel diffraction region.

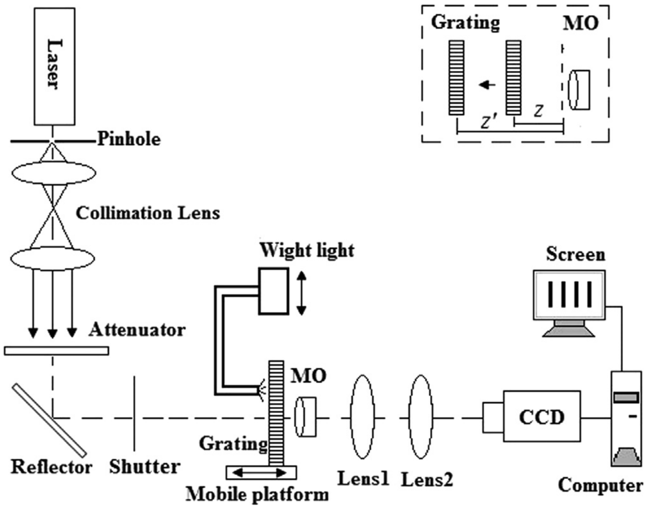

Fig. 1. Schematic diagram of the microscope-magnification system. MO is the microobjective.

3. The experiment result and the analysis

According to microscope-magnification method, we measure the diffraction of grating with line density 300 L/mm and 600 L/mm in deep Fresnel region. Starting from the position that the grating is on the objective plane of the microobjective, we shift the grating backward with the help of the mobile platform, and record the corresponding diffraction intensity distribution always on the objective plane of micro-objective. Fig. 2 shows several recorded pictures of the grating with line density 300 L/mm, where Fig. 2(a) is the image of grating, and Fig. 2(b)–(f) are the diffraction distributions when the grating moves backward 20 μm, 25 μm, 30 μm, 35 μm and 45 μm, respectively. These results correspond to the diffraction patterns of grating at the corresponding distance in deep Fresnel region.

From the experimental results in Fig. 2, we can see that the diffraction pattern changes with the movement of grating. When the moving distance of grating is equal to 20 μm, the bright fringe is narrower than that in the image of grating. When the grating moves backwards 25 μm, each bright fringe in the diffraction pattern of Fig. 2(c) is modulated by one dark fringe into two narrow bright fringes. As the grating moves backward 30 μm, the modulation by dark fringes gets more obvious and the split bright fringes get narrower. Obviously, these distributions are different from the grating structure. From the diffraction pattern shown in Fig. 2(e), we can see that the spatial occupancy rates of bright and dark fringes are almost equal and the modulation of dark fringes is weak. It is similar to the grating structure. Thus, we also call it as the quasi-Talbot image of the grating as before since this distribution is similar but not completely equal to the grating structure. This distribution locates 35 μm away from the grating, which has a small difference 0.12 μm from the first Talbot distance of grating. When the grating moves 45 μm, the number of fringes seems to rise twice since the split of the bright fringes.

Fig. 3 gives the diffraction patterns of grating with line density 600 L/mm when the grating moves backward different distance, and these patterns are also equivalent to the diffractions of grating at different propagation distance in deep Fresnel region. Fig. 3(a) shows the image of grating, and Fig. 3(b)–(f) are diffraction distributions with the grating moving backward 5 μm, 10 μm, 20 μm, 25 μm and 35 μm, respectively. From Fig. 3(b), we can see that each bright fringe is evenly split by straight dark fringe into two. When the grating moves 10 μm, the slight secondary bright fringe appears among two adjacent main bright fringes. The spatial occupancy rates of bright and dark fringes among the pattern in