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The influence of the polarization effect in Talbot self-imaging of high-density gratings

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ABSTRACT

The Talbot self-imaging of high-density gratings with different period at half Talbot distance for different polarization is analyzed with the finite-difference time-domain (FDTD) method. The numerical results indicate that the Talbot self-imaging of high-density gratings is obviously different for different polarization when the period d of the grating between 2λ and 3λ, which is verified through experimental results with the scanning near-field optical microscopy (SNOM) technique. Furthermore, the Fourier spectrum (far field) generated by the gratings is also given with the rigorous coupled-wave method, which is in agreement with the near field.

1. Introduction

When a periodic object is illuminated by a monochromatic light wave, an image of the object will appear at some distant planes behind the object, which is called the Talbot effect [1]. The Talbot effect has a variety of applications, such as Talbot array illumination [2], the Talbot effect of atomic-matter waves [3] and orthogonal encoding holographic volume storage [4]. The Talbot effect is well explained with the scalar Fresnel integral method [5], when the period of the grating is much larger than the wavelength of the incident beam. For high-density gratings, its period is comparable with the wavelength, the scalar theory is not effective and the vector methods have to be resorted, such as the boundary-element method, the rigorous coupled-wave analysis, and the finite-difference time-domain (FDTD) method. Some interesting optical phenomenon will appear.

The FDTD method is a powerful tool for simulating the propagation of electromagnetic waves without any assumption in the Maxwell's equations [6,7]. The popularity of the FDTD method continues to grow as computing cost continues to decline. Nowadays, the FDTD method is one of the most popular numerical methods for the solution of electromagnetic problem. It is also applied to analyze the diffractive optical elements (DOEs) [8,9] and the polarization optical response of rough surfaces [10]. Wei et al. analyzed subwavelength mesoscale air-dielectric structures and found a novel subwavelength focusing effect [8]. Judkins and Ziolkowski analyzed the nonperfectly conducting metallic thin-film gratings [9]. Here it is used to investigate the influence of the polarization effect in Talbot self-imaging of high-density gratings. We try to recognize the relation between the polarization effect and the period of the grating by analyzing the polarization effect in the Talbot self-imaging of high-density gratings in the near field. We may think that the polarization effect must be more obvious for a grating with a small period. But the results of the simulations with the FDTD method illustrate that polarization effect is more obvious for gratings with period d between 2λ and 3λ. It is verified through experiments with the scanning near-field optical microscopy (SNOM) technique [8]. Furthermore, the Fourier spectrum (far field) generated by the gratings with three typical periods is also offered with the rigorous coupled-wave method, which is in good agreement with the near field.

2. Numerical simulation

The FDTD algorithm used here is the most standard one based on the YEE lattice. For liner, isotropic material, the Maxwell's equations can be written as:

$$\nabla \times E = -\mu \frac{\partial H}{\partial t} - \sigma^* H, \tag{1}$$

$$\nabla \times H = \varepsilon \frac{\partial E}{\partial t} + \sigma E, \tag{2}$$

where ε, μ, σ and σ^* are permittivity, permeability, the medium's electric conductivity and magnetic conductivity, respectively. The example of the diffraction grating used here is assumed to be made of perfect conductor. So the relationship is satisfied as follows: $\mu_0 = \mu$, $\sigma^* = 0$. In three-dimensional Cartesian coordinate system, Maxwell's equations can be decoupled into two sets of three. The

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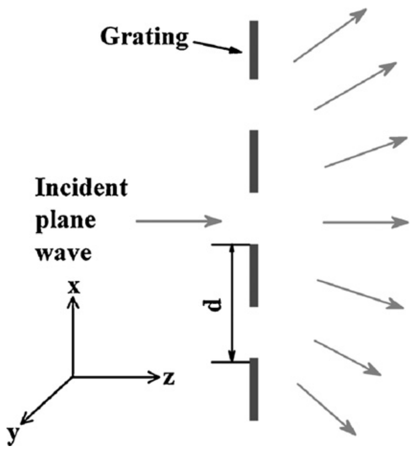

Fig. 1. Grating structure employed here.

first set (E_y, H_z, and H_x) is called TE polarization. The second set (H_y, E_z, and E_x) is called TM polarization. For TE polarization, by using Yee's grids and applying the central different expressions, the solutions of Maxwell's equations reduce to the following:

$$E_y^{n+1}(i,k) = \frac{2\varepsilon(i,k)-\sigma(i,k)\Delta t}{2\varepsilon(i,k)+\sigma(i,k)\Delta t}E_y^n(i,k) + \frac{2\Delta t}{2\varepsilon(i,k)+\sigma(i,k)\Delta t} \times \left[\frac{H_x^{n+1}(i,k)-H_x^{n+1}(i,k-1)}{\Delta z} - \frac{H_z^{n+1}(i,k)-H_z^{n+1}(i-1,k)}{\Delta x}\right], \quad (3)$$

$$H_x^{n+1}(i,k) = H_x^n(i,k) + \frac{\Delta t}{\mu(i,k)}\frac{E_y^n(i+1,k)-E_y^n(i,k)}{\Delta z}, \quad (4)$$

$$H_z^{n+1}(i,k) = H_z^n(i,k) + \frac{\Delta t}{\mu(i,k)}\frac{E_y^n(i,k+1)-E_y^n(i,k)}{\Delta x}. \quad (5)$$

Here, Δz, Δx and Δt are lengths of the unit cell in the z and x directions and a single time step, respectively. In the simulation, we let $\Delta x = \Delta z = \lambda/20$, $\Delta t = \Delta x/2c$. Integer values i and k denote the position of sample points in the z and x direction. Similarly, for TM polarization, the solutions of Maxwell's equations can be reduced to another three difference equations. The propagation of the electromagnetic field is simulated with the difference equations step by step in the time domain.

The diffraction gratings used here are assumed to be made of perfect conductor as illustrated in Fig. 1. The opening ratio and the thickness of the coated metal film on the gratings are 0.5 and 120 nm, respectively. The grating period d is a variable. The outside medium is air. The incident waves are plane waves, and the amplitude is set to unity for simplicity. The wavelength of the incident plane wave is 0.6328 μm. Because the grating is periodic in x direction, the field values on the bottom and top boundaries are set identical to each other [11]. This can reduce the number of sample points. In z direction, a second-order Mur's absorbing boundary condition [12] is applied to reduce unwanted reflections. The convergence of the solution has been verified in reference [13]. In addition, we have compared our numerical results with those in references [8] and [11], and they are the same.

The gratings with different periods form λ to 4λ have been investigated. Numerical results indicate that near-field distribution and the Talbot self-imaging of the high-density grating are different for the different polarization states. For each example, we compare the intensity distribution of the time-averaged Poynting vector at 1/2 Talbot distance for TE and TM polarization. We find that the intensity of the bright stripes of the Talbot images for TE polarization is very higher than for TM polarization for some cases. Fig. 2 shows the ratio of intensity of the time-averaged Poynting vector at the middle of bright stripe of the Talbot images with the various grating period, which is defined as:

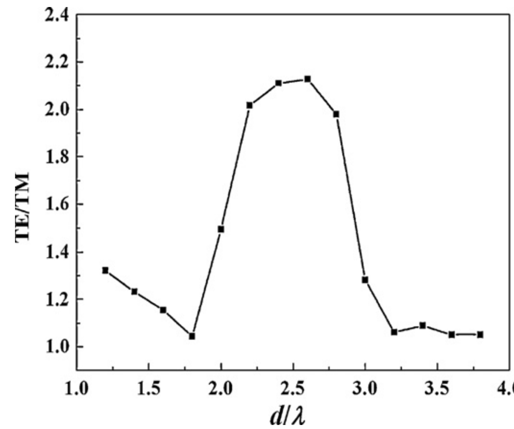

Fig. 2. The ratio of intensity of the time-averaged Poynting vector at the middle of bright stripe of the Talbot images at 1/2 Talbot distance with the various grating periods from λ to 4λ. Notice that at $d/\lambda = 2.5$, the difference of the polarization Talbot effect for TE and TM modes is significant.

$$\frac{\mathrm{TE}}{\mathrm{TM}} = \frac{\left\langle\left|\vec{E}(x,z,t)\times\vec{H}(x,z,t)\right|\right\rangle_{t\,\mathrm{TE}}}{\left\langle\left|\vec{E}(x,z,t)\times\vec{H}(x,z,t)\right|\right\rangle_{t\,\mathrm{TM}}}\begin{pmatrix} z = 0.5Z_t \\ x = 0.75d \end{pmatrix}, \quad (6)$$

where $Z_t = 2d^2/\lambda$, d is the period of the grating, λ is the wavelength of the laser; $y = 0.75d$ locates the middle of the bright stripe near the zero, i.e. at the middle of the peak near the zero as shown in Fig. 3. As illustrated in Fig. 2 the difference of the Talbot image for TE and TM polarization is obvious, when the grating period is between 2λ and 3λ. When the grating period is larger than 3λ, the difference is gradually diminishing.

Here we choose three gratings with typical periods of 1.5λ, 2.5λ, and 3.5λ to show the influence of the polarization effect in Talbot self-imaging of high-density gratings with different period. To see the detail of the difference of the Talbot images for TE and TM polarization, the intensity distribution of the time-averaged Poynting vector at 1/2 Talbot distance of these three gratings for both polarization are shown in Fig. 3(a), (b), and (c), respectively. The solid line is for TE polarization and the dash line is for TM polarization. We can see that the intensity of the images for TE polarization is higher than for TM polarization for all of these three cases. But for the grating with period of 2.5λ, the intensity of the images for TE polarization is much higher (about a factor of two) than for TM polarization, and the profile of the bright stripes is obvious different. For TM polarization, there is a groove at the middle of the bright stripes instead of a peak. For other two cases, the profile of the bright stripes is same except of the difference of the intensity.

3. Experiment

To verify the results of the simulation, a Talbot SNOM method is employed to detect the near-field distribution of a grating with density of 630 lines/mm (∼2.5λ). This method combines the Talbot self-imaging effect of the grating and the conventional SNOM technique. It has been applied to evaluation of high-density grating [13,14]. Schematic illustration of experimental system of the Talbot SNOM method for observation of the polarization Talbot effect of a high-density grating is shown in Fig. 4. A Helium–Neon (He–Ne) laser with a wavelength of 0.6328 μm is used as the light source. First, the linearly polarized light from He–Ne laser is converted into circularly polarized light by a quarter wave plate. Then the polarization state of the incident beam to the grating can be controlled accurately by rotating the polarizer. A near-field optical