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Limits of scalar diffraction theory for multilayer diffractive optical elements

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ABSTRACT

We presented the optimal surface relief heights of multilayer diffractive optical elements (MLDOEs) with the extended scalar diffraction theory. Comparisons of diffraction efficiency and polychromatic integral diffraction efficiency (PIDE) with different periods are described and simulated with extended scalar diffraction theory and scalar diffraction theory. The results show that the limits of scalar diffraction theory for MLDOEs and the minimum zone width of MLDOEs is different from that of traditional single-layer diffractive optical elements.

1. Introduction

Diffractive optical elements' (DOEs) negative dispersion characteristic is usually used to achromatism or apochromatism in imaging optical systems, and the scalar diffraction theory is used to design DOEs and analyze the energy distribution in the diffraction field. The results are valid for diffractive structures that have very large ratio of period to wavelength [1]. When the period is smaller than the wavelength of incident light, the DOEs could only be analyzed with the rigorous electromagnetic theories. The intermediate theory which is called extended scalar diffraction theory is presented in Ref. [1], which is used to analyze the range of periods from one wavelength to ten wavelengths for traditional single-layer diffractive optical elements. In recent years, the multilayer diffractive optical elements (MLDOEs) which are used to increase the diffraction efficiency in a wide waveband are reported [2–4], and the imaging characteristics and the distribution of the periods are the same as traditional single-layer phase DOEs [5]. The diffraction efficiency is calculated with the scalar diffraction theory, and the limits of scalar diffraction theory have been analyzed in Refs. [6,7]. To our knowledge, there is no paper to discuss the design process of MLDOEs with consideration of period width of MLDOEs. In this paper, we presented the optimal surface relief heights of multilayer diffractive optical elements (MLDOEs) with the extended scalar diffraction theory, and the minimum zone width of MLDOEs calculated with the extended scalar diffraction theory is compared with that of scalar diffraction theory. The diffraction efficiency and polychromatic integral diffraction efficiency (PIDE) with different periods of MLDOEs are both calculated. The results show the limits of scalar diffraction theory for MLDOEs.

In this paper, firstly, the principle of the MLDOEs with scalar diffraction theory, and the surface relief heights and the design orders of the two deep harmonic diffractive elements are given. Secondly, we get the optimal relief heights of MLDOEs with the extended diffraction theory. Thirdly, as an example, a MLDOE was designed to show that the minimum zone width is reasonable to be analyzed with scalar diffraction theory, and the diffraction efficiencies and PIDEs of the optimal design

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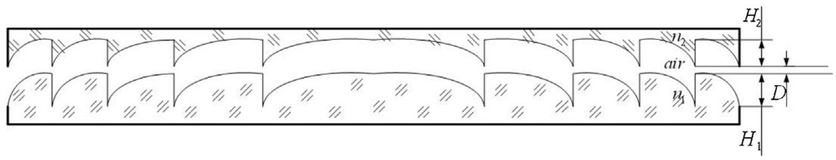

Fig. 1. Structure of MLDOEs, H_1 and H_2 are the surface relief heights of the HDEs, i is thick of the air gap between them.

of MLDOEs with different periods are compared with those with scalar diffraction theory. At last, we gave the limitations of scalar diffraction theory for MLDOEs.

2. Design principle of the MLDOEs

The MLDOEs usually consist of two deep harmonic diffractive elements (DHDEs) whose zone widths are the same as the traditional phase DOEs and the surface relief heights are also the same as the harmonic diffraction elements [5]. A typical MLDOE is shown in Fig. 1a, and the small gap between them is air. According to Ref. [3], the phase retardation $\phi(\lambda)$ as a function of wavelength λ at a given period is:

$$\phi(\lambda) = k[n_1(\lambda) - 1]H_1 + k[n_2(\lambda) - 1]H_2 = 2\pi m \tag{1}$$

where k is wave number $2\pi/\lambda$, m is the diffraction order, $n_1(\lambda)$ and $n_2(\lambda)$ are the refractive index, and H_1 and H_2 are the surface relief heights of the first and the second DHDE. After selecting two different materials and λ_1 and λ_2, the two design wavelengths in the design waveband, we can obtain the following relation,

$$\begin{aligned} &k_1((n_1(\lambda_1) - 1)H_1 + (n_2(\lambda_1) - 1)H_2) = m2\pi, \\ &k_2((n_1(\lambda_2) - 1)H_1 + (n_2(\lambda_2) - 1)H_2) = m2\pi \end{aligned} \tag{2}$$

By solving Eqs. (2), the surface relief heights of the two DHDEs can be found.

$$\begin{aligned} H_1 &= \frac{m\lambda_1(n_2(\lambda_2) - 1) - m\lambda_2(n_2(\lambda_1) - 1)}{(n_1(\lambda_1) - 1)(n_2(\lambda_2) - 1) - (n_1(\lambda_2) - 1)(n_2(\lambda_1) - 1)}, \\ H_2 &= \frac{m\lambda_1(n_1(\lambda_2) - 1) - m\lambda_2(n_1(\lambda_1) - 1)}{(n_1(\lambda_1) - 1)(n_2(\lambda_2) - 1) - (n_1(\lambda_2) - 1)(n_2(\lambda_1) - 1)} \end{aligned} \tag{3}$$

According to the relationship between diffractive order and microstructure height, $H_1(n_1(\lambda_1) - 1) = m_1\lambda$ and $H_2(n_2(\lambda) - 1) = m_2\lambda$, the design orders of the DHDEs for different wavelength can be written as:

$$\begin{aligned} m_1 &= \frac{m\lambda_1(n_2(\lambda_2) - 1) - m\lambda_2(n_2(\lambda_1) - 1)}{(n_1(\lambda_1) - 1)(n_2(\lambda_2) - 1) - (n_1(\lambda_2) - 1)(n_2(\lambda_1) - 1)} \frac{(n_1(\lambda) - 1)}{\lambda}, \\ m_2 &= \frac{m\lambda_1(n_1(\lambda_2) - 1) - m\lambda_2(n_1(\lambda_1) - 1)}{(n_1(\lambda_1) - 1)(n_2(\lambda_2) - 1) - (n_1(\lambda_2) - 1)(n_2(\lambda_1) - 1)} \frac{(n_2(\lambda) - 1)}{\lambda} \end{aligned} \tag{4}$$

According to Eqs. (4), the diffraction order of the MLDOE is $m = m_1 + m_2 = 1$ for the design wavelength.

The diffraction efficiency and PIDE of MLDOEs can be written as [8]:

$$\eta_m = \sin c^2(m - \frac{\varphi(\lambda)}{2\pi}) \tag{5}$$

$$\bar{\eta}_{m\ \mathrm{int}}(\lambda_1, \lambda_2) = \frac{1}{\lambda_{\max} - \lambda_{\min}} \int_{\lambda_{\min}}^{\lambda_{\max}} \sin c^2(m - \frac{\varphi(\lambda)}{2\pi}) d\lambda \tag{6}$$

where sinc(x) = sin$\pi x/\pi x$, $\lambda_{\min}$ and $\lambda_{\max}$ are the minimum and the maximum wavelengths of the design waveband.

3. Optimal heights of MLDOEs

Here, the extended scalar diffraction theory is used to the optimal design of the MLDOE. The principle of the optimal design of the MLDOE for oblique incidence on the substrate of the first DHDE and travel through the first DHDE to the second DHDE is shown in Fig. 2. The miniature diffractive structure is considered as refractive prism for convenient analysis with diffraction equation and Snell's law. The angles, θ_i and θ_d are incidence angle and diffraction angle of MLDOEs. The diffraction angle,$\theta_{\mathrm{d}j}$ is determined by the grating equation for the jth DHDE, and the refraction angle, $\theta_{\mathrm{r}j}$ is determined by the Snell's law for the jth DHDE, and the α_j is an inclination factor for the jth DHDE, $\alpha_j = H_j/T$.