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Analysis of materials selected for multilayer diffractive optical elements

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ABSTRACT

An analysis model to optimize the materials selected for multilayer diffractive elements (MLDOEs) is presented with approximate Cauchy dispersion formula of refractive index and the maximum polychromatic integral diffraction efficiency (PIDE). The analysis model presents that the maximum PIDE of MLDOEs consisting of two materials with large Abbe number difference and small partial dispersion difference can be generated. The scope of application and the relationship between diffraction efficiencies of MLDOEs with different material pairs and different design wavelength pairs are presented and simulated with the analysis model of MLDOEs.

1. Introduction

Diffractive optical elements (DOEs) have been widely used in hybrid diffractive-refractive optical system for the visible spectrum and IR wavebands to correct the achromatic aberration and various monochromatic aberrations, reduce the secondary and produce an arbitrary phase distribution since DOEs have a unique negative chromatic dispersion characteristic and the optical characteristic of an aspheric surface. However, the diffraction efficiency of conventional single-layer surface relief DOEs decreases quickly when the wavelength deviates from the design wavelength, which hinders the application in broadband optical systems. There are many papers to discuss the design principle of multilayer diffractive optical elements (MLDOEs) for improving the diffraction efficiency in a wideband [1–8]. In Ref. [3], the materials selection principle of MLDOEs is presented that the absolute surface relief structure heights of two harmonic diffractive elements (HDEs) are small when the Abbe number difference of the two materials of MLDOEs is large. Eq. (19) in Ref. [6], the simplified design model for diffraction efficiency of MLDOEs is presented with no consideration of material dispersion. In Ref. [7,8], the analyses of materials selected for MLDOEs are discussed with most design examples. But there has been no an analysis model to optimize materials selected for MLDOEs and no discussion of the relationship between the diffraction efficiencies and the selected material pairs of MLDOEs. In this paper, the principle of optimize materials selected for MLDOEs is presented with consideration of polychromatic integral diffraction efficiency (PIDE) [9]. The maximum PIDEs of MLDOEs composed with different material pairs are compared with consideration of the Abbe number and partial dispersion of the materials selected using the simplify design model with approximate Cauchy dispersion formula of refractive index. At last, the field of application of simplify design model is presented with comparisons of diffraction efficiencies of MLDOEs for different material pairs and different design wavelength pairs which are determined with consideration of maximum PIDE. The result can be used to optimize the materials selected of MLDOEs.

2. Design principle of MLDOEs

The MLDOE which consists of two harmonic diffractive elements (HDEs) with different dispersive optical materials is aligned as shown in Fig. 1.The two HDEs have concentric diffraction gratings. According to Ref. [3], the phase retardation $\phi(\lambda)$ as a function of wavelength λ at a given zone period as shown in Fig. 1 is

$$\phi(\lambda) = \frac{2\pi}{\lambda}((n_1(\lambda) - 1)H_1 + (n_2(\lambda) - 1)H_2) = m2\pi, \tag{1}$$

where m is diffraction order at the two design wavelengths, H_1 and H_2 are the surface relief heights of the HDEs, and $n_1(\lambda)$ and $n_2(\lambda)$ are the refractive index of the first-layer material and the second-layer

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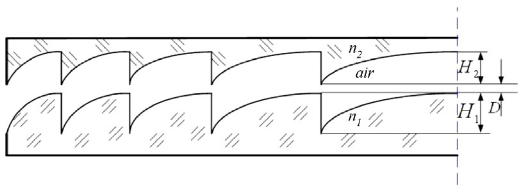

Fig. 1. Structure of MLDOEs, H_1 and H_2 are the surface relief heights of the HDEs, D is thick of the air gap between them.

material. After selecting two different materials and λ_1 and λ_2, the two design wavelengths in the design waveband, the surface relief heights of the two HDEs, according to Refs. [3,5], are

$$H_1 = \frac{m\lambda_1(n_2(\lambda_2)-1) - m\lambda_2(n_2(\lambda_1)-1)}{(n_1(\lambda_1)-1)(n_2(\lambda_2)-1) - (n_1(\lambda_2)-1)(n_2(\lambda_1)-1)},$$
$$H_2 = \frac{m\lambda_2(n_1(\lambda_1)-1) - m\lambda_1(n_1(\lambda_2)-1)}{(n_1(\lambda_1)-1)(n_2(\lambda_2)-1) - (n_1(\lambda_2)-1)(n_2(\lambda_1)-1)}. \quad (2)$$

So, when the Abbe number difference of the two materials of MLDOEs is large, the absolute denominators of Eq. (2) are relatively big. The absolute surface relief structure heights of two HDEs, thus, are small [3].

Using Eqs. (1) and (2), the mth order diffraction efficiency of the MLDOEs can be written as

$$\eta_m = \sin c^2\left(m - \frac{\phi(\lambda)}{2\pi}\right), \quad (3)$$

where $\mathrm{sinc}(x) = \sin\pi x/\pi x$, and the corresponding PIDE of the MLDOEs for a given wideband is [9]

$$\bar{\eta}_{m\ \mathrm{int}}(\lambda_1, \lambda_2) = \frac{1}{\lambda_{\max} - \lambda_{\min}} \int_{\lambda_{\min}}^{\lambda_{\max}} \sin c^2\left(m - \frac{\phi(\lambda)}{2\pi}\right) \, d\lambda, \quad (4)$$

where $\lambda_{\min}$ and $\lambda_{\max}$ are the minimum and the maximum wavelengths of the design waveband.

The simplify design model of MLDOEs is presented with the approximate Cauchy dispersion formula in Ref. [10], and the formula and the phase retardation expression Eq. (1) of MLDOEs with these two materials are

$$n_i(\lambda) = a_i + \frac{b_i}{\lambda^2}, \quad (5)$$

$$\phi(\lambda) = \frac{2\pi}{\lambda} m \frac{\lambda^2\lambda_1(\lambda_1+\lambda_2) + {\lambda_2}^2(\lambda^2 - {\lambda_1}^2)}{\lambda^2(\lambda_1+\lambda_2)}. \quad (6)$$

where, $n_i(\lambda)$ is the refractive index of the material, a_i and b_i are dispersion coefficients. The refractive index of the two different materials are expressed with Eq. (5), so the Abbe number v_d of the two materials are different and the partial dispersion of the two materials are both $P_{gf} = 0.54096$, and the absolute value of the ratio of partial dispersion difference to Abbe number difference is zero.

Eq. (6) shows that the phase retardation of the MLDOE is independent of all materials' dispersion coefficients.

3. Analysis of materials selected for multilayer diffractive optical elements

Three MLDOEs, as examples for visible waveband, are designed with $m = 1$.The three MLDOEs are composed of three pairs of different materials, respectively, which are polycarbonate (PC) and polystyrene (PS), N-SSK8 and poly-methyl methacrylate (PMMA), N-FK51A and P-SF67 [11,12], and the refractive index of the materials are shown in Fig. 2.

With Eqs. (1), (3) and (6), the difference of diffraction efficiencies of MLDOEs with two different design wavelength pairs, 400 and 700 nm, F- and C-lines, are shown in Fig. 3. From Fig. 3, the

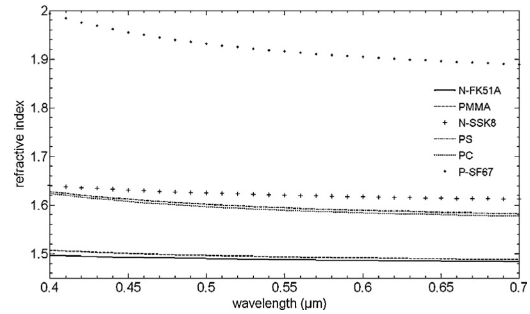

Fig. 2. Refractive index versus wavelength.

difference of diffraction efficiency at wavelength 465 nm is 29.42%, the biggest among three MLDOEs when the design wavelength pair is 400 and 700 nm. The difference of diffraction efficiency, with F- and C-lines as design wavelength pair, is smaller than 1.82% when the wavelength is longer than 471 nm, but the difference is large in short wavelength region. Based on this analysis, the difference of diffraction efficiency is too big to give out the principle of materials selected for MLDOEs.

Based on the method for designing MLDOEs with accurate formula of refractive index in Ref. [5], we, however, used approximate Cauchy dispersion formula of refractive index. The PIDEs for different design wavelength pairs are shown in Fig. 4a, and the maximum PIDEs for the first design wavelength, changed from 400 to 700 nm, are shown in Fig. 4b. From Fig. 4, the maximum PIDE is 99.620%, and the corresponding design wavelength pair is 440.3 and 606.1 nm.

Furthermore, the relationship between maximum PIDEs and material pairs selected is found. Firstly, the Abbe number and partial dispersion of the six materials and the absolute values of the ratio of partial dispersion difference to Abbe number difference for any two materials used to design MLDOEs are calculated. Secondly, the maximum PIDEs and corresponding design wavelength pairs are determined according to Ref. [5]. The relationship between maximum PIDEs and selected material pairs is shown in Fig. 5.The maximum PIDE of the MLDOEs composed of N-SSK8 and PMMA is 99.59%, the largest among these MLDOEs examples, design wavelengths being 438.3 and 602.5 nm. At the same time, the absolute value of the ratio of partial dispersion difference to Abbe number difference is the smallest among these material pairs, which is 0.062×10^{-3}. The maximum PIDE and this absolute ratio are near those that composed of two materials expressed with approximate Cauchy dispersion formula. We also found that the maximum PIDE of the MLDOE composed of PC and PS is the lowest, 97.37%, and the absolute ratio of partial dispersion difference to Abbe number difference is the largest among these material pairs, and the corresponding design wavelengths are 424.8 and 573.8 nm. According to this analysis and Fig. 5, the conclusion is drawn that maximum PIDE

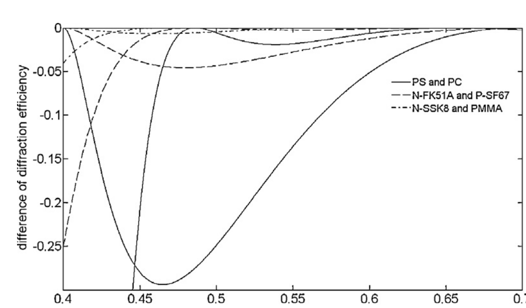

Fig. 3. Diffraction efficiency difference of MLDOEs with three different material pairs at two different design wavelength pairs, 400 and 700 nm, 486.1 and 656.3 nm.