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Original research article

Effect of ambient temperature and substrate material selection on diffraction efficiency for diffractive optical elements

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ABSTRACT

A mathematical model of the diffraction efficiency change with the ambient temperature for the single-layer diffractive optical elements (SLDOEs) is presented, and its effects are analyzed in this paper. According to the deduced relation, the SLDOEs made of different substrate materials are discussed in the visible and infrared wavebands in a wide temperature range. The results show that the diffraction efficiency for the plastic SLDOE declines faster at the lower ambient temperature, but for the GE SLDOE declines faster at the higher ambient temperature. The diffraction efficiency change is obviously different with the selection of the substrate material. Therefore, the method of substrate material selection is put forward for the SLDOEs to reduce the impact of ambient temperature. The analysis result can be considered during optical engineering design with the DOEs.

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1. Introduction

Diffractive optical elements (DOEs) can achieve the achromatization and athermalization of optical system, especially in the infrared and plastic optical systems [1–6]. These optical systems are mostly applied to military and aerospace systems. For military and aerospace optical systems, temperature is one of the most important environment influences. The ambient temperature change can cause the diffraction efficiency reduction, and further, the decline of the modulation transfer function (MTF) of optical systems [7,8].

In Ref [9], the authors have designed plastic diffractive-refractive compact zoom lenses for visible-near-IR spectrum. According to the optimal combination of the dispersive properties of the optical plastic and the DOEs allowed the acceptable correction of the chromatic aberration and spherochrmatism in all configurations to be obtained. However, the ambient temperature influence on the DOE is not considered. In Ref [10], a long-wave infrared (LWIR) hybrid infrared optical system which is passively athermalized over the ambient temperature range -40 to 60 °C has been designed. In order to minimize the number of components, the DOE is employed, and the designed system can work correctly at a wide temperature range. However, the diffraction efficiency decrease accounting for the ambient temperature change is not considered, so the given results are not accord with the actual. In Ref [11], the effect of the environment temperature change on the diffraction efficiency only at the design wavelength has been discussed. So the diffraction efficiency change at other wavelengths of

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a broad waveband cannot accord with the given conclusions. In addition, the substrate material selection method for the single-layer DOEs (SLDOEs) in a wide ambient temperature range is not mentioned.

In this paper, the diffraction efficiency change accounting for the ambient temperature variation is analyzed, and the theoretical relation is deduced in Section 2. By using deduced relation, the actual diffraction efficiency can be calculated as ambient temperature changes. In Section 3, the effects of ambient temperature on diffraction efficiency for the polymethyl methacrylate (PMMA) SLDOE in the visible light and the germanium (GE) SLDOE in the infrared are discussed in detail, respectively. The results show that the diffraction efficiency for the PMMA SLDOE declines faster at the lower ambient temperature, but for the GE SLDOE declines faster at the higher ambient temperature. In Section 4, the method of the substrate material selection for the SLDOEs is put forward. The diffraction efficiency change factor $M(\lambda_0)$ is introduced to determine the reasonable substrate material. For different substrate materials, the diffraction efficiency change factors $M(\lambda_0)$ are different, and the lower absolute value of $M(\lambda_0)$ indicates the smaller impact of ambient temperature.

2. Relation of diffraction efficiency and ambient temperature

When the ambient temperature change, the correlated relief height [12] and substrate material index of the DOEs are change at the same time. The thermal expansion coefficient and thermo-optic coefficient of the substrate material can be used to describe the above change, respectively. The change of the profile for the SLDOEs accounting for the environment temperature change is illustrated in Fig. 1.

For illustration, the change of the profile is depicted more exaggeratedly than actual. The red on the upper part of Fig. 1 represents expansion of the correlated relief height from H_0 to H_{a1} as ambient temperature increases. The blue on the lower part represents contraction of the correlated relief height from H_0 to H_{a2} as ambient temperature decreases. The middle part represents the initial profile at the design temperature.

To calculate the reduction of diffraction efficiency due to ambient temperature change for the SLDOE, we applied the scalar approximation theory. The mth order diffraction efficiency for the SLDOEs can be expressed as [13,14]

$$\eta_{\mathrm{d}}^{\mathrm{m}} = \sin c^2\left(m - \frac{\phi_{\mathrm{d}}}{2\pi}\right), \tag{1}$$

where ϕ_{d} is the designed phase retardation of the SLDOEs. It can be written as

$$\phi_{\mathrm{d}} = \frac{2\pi}{\lambda} H_0(n - n_0), \tag{2}$$

where n and n_0 are the refractive index of the substrate material and surrounding medium, normally the surrounding medium is air. H_0 is the design correlated relief height of the SLDOEs. Differentiating Eq. (2) with respect to temperature T, it can be expressed as

$$\frac{\mathrm{d}\phi_{\mathrm{d}}}{\mathrm{d}T} = \frac{2\pi}{\lambda}\left[\frac{\mathrm{d}H_0}{\mathrm{d}T}(n - n_0) + H_0(\frac{\mathrm{d}n}{\mathrm{d}T} - \frac{\mathrm{d}n_0}{\mathrm{d}T})\right], \tag{3}$$

where $\mathrm{d}n/\mathrm{d}T$ is the thermo-optic coefficient of substrate material, $\mathrm{d}n_0/\mathrm{d}T$ is the thermo-optic coefficient of surrounding medium. The coefficient of thermal expansion (CTE) α is the fractional change in the correlated relief height with a change in the ambient temperature T, which can be written as

$$\alpha = (1/H_0)(\mathrm{d}H_0/\mathrm{d}T). \tag{4}$$

Substituting Eq. (4) into Eq. (3), the expression can be written as

$$\frac{\mathrm{d}\phi_{\mathrm{d}}}{\mathrm{d}T} = \frac{2\pi}{\lambda}\left[\alpha H_0(n - n_0) + H_0(\frac{\mathrm{d}n}{\mathrm{d}T} - \frac{\mathrm{d}n_0}{\mathrm{d}T})\right]. \tag{5}$$

When ambient temperature uniformly changes from T_0 to $T_0 + \Delta T$, the variation of phase retardation, $\Delta\phi$, can be expressed as

$$\Delta\phi = \frac{2\pi}{\lambda}\left[\alpha H_0(n - n_0) + H_0(\frac{\mathrm{d}n}{\mathrm{d}T} - \frac{\mathrm{d}n_0}{\mathrm{d}T})\right]\Delta T. \tag{6}$$

From Eq. (6), we know that the change of phase retardation depends on the CTE and index variation of substrate material. The actual phase retardation of the SLDOEs can be expressed as

$$\phi_{\mathrm{a}} = \phi_{\mathrm{d}} + \Delta\phi. \tag{7}$$

Substituting Eq. (2) and Eq. (6) into Eq. (7), the expression can be simplified as

$$\phi_{\mathrm{a}} = \frac{2\pi}{\lambda}\left[H_{\mathrm{a}}(n - n_0) + H_0(\frac{\mathrm{d}n}{\mathrm{d}T} - \frac{\mathrm{d}n_0}{\mathrm{d}T})\Delta T\right], \tag{8}$$

where H_{a} is the actual correlated relief height after ambient temperature change, which can be expressed as

$$H_{\mathrm{a}} = H_0(1 + \alpha\Delta T). \tag{9}$$

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