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Effect of birefringence of lens material on polarization status and optical imaging characteristics

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ABSTRACT

In most cases of molding with glass or optical polymers, it is expected that there will be birefringence caused by the internal mechanical stresses remaining in the molding material. The distribution of the residual stress can be annealed by slow cooling, but this approach is disadvantageous with respect to the shape accuracy and manufacturing time. In this study, we propose an analytical model to calculate the diffracted field near the focal plane by considering two primary parameters, the orientation angle of the fast axis and the path difference. In order to verify the reliability of the analytical model, we compared the measured beam spot of the F-theta lens of the laser scanning unit (LSU) with the analytical result. In addition, we analyzed the calculated result from the perspective of the polarization status in the exit pupil. The proposed analysis method can be applied to enhance the image quality for cases in which birefringence occurs in a lens material by suitably modeling the amplitude and phase of the incident light flux.

1. Introduction

For plastic aspheric lenses, which are mainly applied to low-cost optoelectronic systems such as phone cameras, digital printing optics, and optical data storage, injection-molding methods are used to achieve mass production at a low cost. In order to produce a plastic aspherical lens, a uniform injection-molding system must be maintained to obtain a lens having the desired optical characteristics. There have been many studies on the injection molding of aspherical plastic lenses, and the quality has been improved considerably by improving the level of aspheric mold production and stabilizing the injection conditions. However, in order to further improve the productivity of the lens to lower the manufacturing cost, the problem of quality deterioration owing to birefringence caused by high-speed injection has become a technical issue.

During the molding process for optical components, the mechanical residual stresses inside the material results in unintentional birefringence, and subsequently induces degradation in the optical characteristics of the imaged beam spot. The problem has worsened as optical materials employed in countless applications have shifted from glass to optical polymers, which require low-cost materials. While birefringence occurs in both materials, it is much more severe in injection molding with optical polymers [1,2].

As mentioned earlier, the greatest difference between injection-molded lenses and glass lenses is that the optical performance is significantly degraded owing to the presence of more severe birefringence (internal distortion). The birefringence observed in the injection-molded lens is largely divided into two types: the first type is cooling distortion, which is caused by the rapid cooling of the molten resin on the surface of the mold, and the second type is shear distortion, which occurs when the pressure is applied to the resin during solidification, in order to improve the transferability of the shape after completion of filling [3–7].

The degree of birefringence varies depending on the photo-elasticity factor (the degree of change in the refractive index when pressure is applied) and the magnitude of the distortion generated during injection molding. Therefore, when the same resin is considered, the amount of the induced birefringence varies depending on the molding conditions and the mold structure. The birefringence, which is significantly induced in the injection-molded lens, causes a resultant phase delay between the light rays inside the optical element, leading to a difference in the imaging point between the light flux propagating through the fast axis and the light flux propagating through the slow axis. This results in a distortion of the beam spot diffracted by the phase delay. In the case of F-theta lenses that are applied to digital printer devices with a lens length of 300 mm and a lens thickness less than 15 mm, when the

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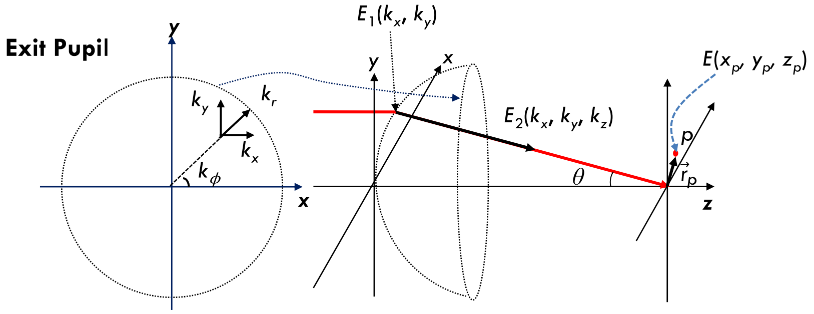

Fig. 1. Conceptual simulation model to determine vectorial electric field calculation for diffraction considering Abbe's sine condition.

optical polymer is rapidly injected, there are significant fluctuations in the cooling-rate, and the shearing stress becomes severe. Therefore, the degradation of the printed image, which is due to birefringence, can be more significant when compared with the application examples of other injection-molding lenses [8].

Until now, studies on birefringence in injection lenses have focused on calculating the allowable amount of birefringence by comparing the measured birefringence amount with the experimentally obtained images and improving the mold structure and injection process to minimize birefringence in the injection process [9,10]. In this study, we first propose an optical simulation method that can directly calculate the diffracted profile considering the difference between the refractive index and the distorted phase. Secondly, we verified the analysis method by making comparisons with beam-spot profile measurement data using an F-theta lens with birefringence. Finally, we discuss the influence of birefringence according to various incident polarization conditions by using the validated analysis method.

2. Theoretical background

The diffracted beam-spot profile of the imaging system near the focal plane, which satisfies Abbe's sine condition, as shown in Fig. 1, can be described by Eq. (1) in Cartesian coordinates [11].

$$E_{img}(r_p) = \frac{-i}{2\pi}\iint_{\Omega}\frac{E_0(k_x,k_y)}{k_z}e^{i(\vec{k}\cdot\vec{r}_p)}dk_x dk_y \qquad -k\sin\theta_{max} \le k_x, k_y \le k\sin\theta_{max}. \tag{1}$$

where $E_0(k_x, k_y)$ is the Fourier transform of the electric-field distribution in the exit pupil, including the state of polarization. The focused electric field at specific image positions, $E_{img}(r_p)$, can be calculated by integrating diffracted plane waves over the two-dimensional (2D) domain of wave vectors, k_x and k_y, considering its capable numerical aperture, NA = $\sin\theta_{max}$. In the case where birefringence occurs in the injected lens, the diffraction integral can be calculated considering the change in the amplitude and phase delay caused by the birefringence on the exit pupil. In the case of phase and amplitude modulation by intrinsic factors of the optical system, such as the phase delay or amplitude variation, Eq. (1) can be rewritten as follows:

$$E_{img}(r_p) = \frac{-i}{2\pi}\iint_{\Omega}\frac{E_1(k_x,k_y)}{k_z}e^{i(\vec{k}\cdot\vec{r}_p)}A_m\left(k_x,k_y\right)e^{iW_m(k_x,k_y)}dk_x dk_y. \tag{2}$$

where $A_m(k_x, k_y)$ and $W_m(k_x, k_y)$ are amplitude and phase-modulation parameters of each plane wave in the exit pupil by birefringence, respectively. When the light flux passes through a material with birefringence, which provokes a phase delay, α, with the fast axis at angle, β, with respect to the horizontal axis, the status of the electric field in the exit pupil in free space can be described using only Eqs. (3) and (4) [12].

$$E_1 = T^{-1}BTE_0$$

$$T = \begin{bmatrix}\cos\beta & \sin\beta\\ -\sin\beta & \cos\beta\end{bmatrix}, \qquad B = \begin{bmatrix}e^{-ik_0\alpha} & 0\\ 0 & e^{ik_0\alpha}\end{bmatrix} \tag{3}$$

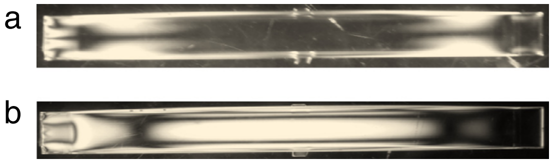

Fig. 2. Imaging lens of an LSU obtained with a projector composed of two crossed polarizers. (a) image showing flow-induced residual stress: a nonuniform phase delay between the fast axis and the slow axis is induced at both sides of the lens. (b) image showing thermally induced residual stress: owing to differences in the cooling rate, a tensile stress is induced in the central area in the vertical direction, and a compressive stress is induced on both edges in the vertical direction.

$$E_1 = \begin{bmatrix}\left(e^{-ik_0\alpha}\cos^2\frac{\beta}{2} + e^{ik_0\alpha}\sin^2\frac{\beta}{2}\right)E_{0x} + \frac{1}{2}\sin\beta\left(e^{-ik_0\alpha} - e^{ik_0\alpha}\right)E_{0y}\\ \frac{1}{2}\sin\beta\left(e^{-ik_0\alpha} - e^{ik_0\alpha}\right)E_{0x} + \left(e^{-ik_0\alpha}\sin^2\frac{\beta}{2} + e^{ik_0\alpha}\cos^2\frac{\beta}{2}\right)E_{0y}\end{bmatrix} \tag{4}$$

For the vectorial electric fields that are diffracted in the exit pupil, considering the vector-field rotation and projection described in Ref. [13], the focused plane waves, $E_2(k_x, k_y)$, can be obtained for the condition where E_1 is illuminated in the exit pupil of the optics. To calculate the electric field at the focal plane, the amplitude and phase variation of E_1 over the exit pupil should be counted to form $A_m(k_x, k_y)$ and $W_m(k_x, k_y)$, respectively.

3. Verification of proposed analysis model

In this section, we verified the calculation results obtained by the simulation model proposed in the previous section. To do this, we compared it with the measurement results of the beam-spot profile for an image-forming lens in a laser scanning unit. The core function of the F-theta lens in a laser scanning unit in an electro-photographic system is to satisfy the linearity between the rotating angle of the polygon mirror and the image-forming height on the photoconductive drum. Therefore, it has a slender shape with a thickness that varies continuously. In addition, as the gate is located at one of the ends, the birefringence occurs as shown in Fig. 2. Differences in the local cooling rates result in thermally induced residual stresses, and a holding pressure to minimize shrinkage leads to residual stresses due to resin flow. Figs. 3 and 4 show the measurement results of birefringence with the direction of the fast axis and the amount of phase delay.

As previously observed in Fig. 2, the optical path difference between the fast axis and its orthogonal slow axis becomes critical on two sides of the lens. Further, it is more severe near the gate of the injection mold. Even though birefringence also occurs in the central region of the lens, it has a negligible effect on the optical performance, as the degree of phase delay is quite small in the effective aperture of the lens. As shown in Figs. 3 and 4, in comparison with the sample having weak