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Direct laser-writing of diffractive optical elements in photopolymer layers

Markus Fratz, Dietmar Eberhard, Wolfgang J. Riedel, Dominik M. Giel
Fraunhofer Institute for Physical Measurement Techniques IPM, Heidenhofstraße 8, 79110 Freiburg, Germany
Markus.Fratz@ipm.fraunhofer.de

Abstract: We present on direct writing of diffractive optical elements in thin polymer layers. The direct-writing process introduces optical birefringence in the polymer. The resulting elements can be described as polarization holograms. Experimental results are demonstrated.

OCIS codes: (090.1970) Diffractive Optics; (090.2890) Holographic Optical Elements

1. Introduction

Polarization holography has attracted high interest during the last decade. This fact is mainly based on theoretical studies that proof the ability of such holograms to reach extremely high diffraction efficiencies [1] or to generate optical systems with unique properties [2]. But experimental realizations of polarization holograms have so far been limited to the far infrared region of the electromagnetic spectrum [3] and/or had to be fabricated with high effort due to the fact that these holograms were based on form-birefringence based on sub-wavelength structures. Contrary to this Azo-benzene polymers can produce birefringence based on anisotropy in the molecular range.

The Azo-benzene polymer we use for generating diffractive optical elements reacts on linear polarized green or blue illumination with the formation of birefringence [4]. By variation of the orientation of the linear polarization the orientation of the primary axis of the birefringence can be controlled. The result of the illumination process is a space-variant retarder plate. For simplicity we concentrate the mathematical considerations on the practically most relevant case of a space-variant half-wave plate. The mathematical description of such an optical element is usually done by means of Jones-Mathematics. In every point (x_m, y_m) the Jones-Matrix T can be written as:

$$\mathbf{T}(x_m, y_m) = i\begin{bmatrix} -\cos^2(\alpha(x_m, y_m)) + \sin^2(\alpha(x_m, y_m)) & -2\cos(\alpha(x_m, y_m))\sin(\alpha(x_m, y_m)) \\ -2\cos(\alpha(x_m, y_m))\sin(\alpha(x_m, y_m)) & \cos^2(\alpha(x_m, y_m)) - \sin^2(\alpha(x_m, y_m)) \end{bmatrix} \quad (1)$$

Here $\alpha(x_m, y_m)$ denotes the angle between the x-axis of a x-y-coordinate system lying in the plane of the diffractive optical element and the fast propagation axis in a point (x_m, y_m) of the space-variant half-wave plate. Illuminated with a right-hand circular polarized wave propagating in the positive z-direction $E(x_m, y_m, 0-) = [1, i]^T$ the wave vector after passing through the half-wave plate can be calculated as:

$$E(x_m, y_m, 0+) = T(x_m, y_m)E(x_m, y_m, 0-) = [i, 1]^T \exp(i(-2\alpha(x_m, y_m))) \quad (2)$$

The emerging wave can clearly be seen to be of circular polarization, while the rotation direction of the electromagnetic wave has changed compared with the incoming wave. At the same time the rotation angle $\alpha(x_m, y_m)$ introduces a phase shift of $2\alpha(x_m, y_m)$ to the wave. Thus space-variant half-wave plates can be considered as a special kind of kinoform elements in case of circular polarized illumination. As a result the anisotropic structures written with a short wavelength laser can be used as a diffractive optical element for light sources with higher wavelength. The absorption and thus the write/read edge of the material used in our experiments lies in the region of 550 nm.

2. Apparatus for direct writing of diffractive optical elements

The Apparatus used for the direct writing of diffractive optical elements is depicted in fig. 1. The light of a frequency-doubled Nd:YAG Laser is coupled into a polarization maintaining mono-mode fiber. After leaving the fiber the light passes through a fiber collimator and a crystal-optical polarization rotator. By application of variable high voltages this device allows for maintenance of the polarization state of the writing laser beam. After two lenses for beam expanding purposes the light travels through an aspheric lens (focal length 6.3 mm) which focuses all light onto the sample covered with an azo-benzene polymer layer of about 2 µm thickness. The sample that can either be transmissive or reflective is placed on a two dimensional scanning stage. While the slow axis (y-axis) of the scanning stage is moved stepwise the fast axis is moved continuously. To avoid disturbing effects of this continuous movement and the transient oscillations of the polarization rotator the laser is run in pulsed mode. The amount of laser power in the plane of the polymer was measured to be 1.1 mW. The time which the saturation effect described in [4] is reached after was experimentally evaluated to be approx. 1 ms. Therefore every point of the polymer is illuminated for 1ms while the movement between two neighbouring points usually is set to 4 ms.

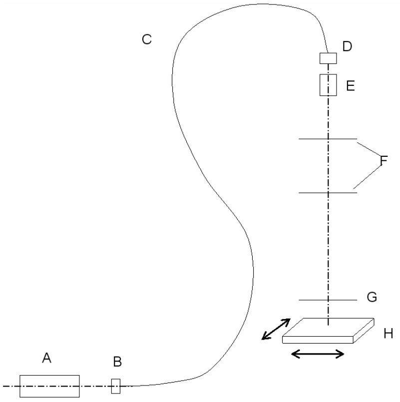

Figure 1: principle of the apparatus for direct writing

A: Nd:YAG laser; B: Fiber coupler; C: polarization maintaining fiber; D: fibre collimator; E: crystal-optical polarization rotator; F: beam expanding optics; G: focussing lens; H: 2D scanning stage

3. Experimental results

To evaluate the achievable lateral resolution as well as the number distinguishable polarization steps in the direct writing process various test charts have been written into the polymer and were observed under a polarization microscope. Results are shown in figure 2. Figure 2A shows a test chart for determination of lateral resolution. The finest structures on the right correspond to 1.25 µm and are clearly resolved. Figure 2B shows a test chart consisting of 256 different angles of the primary axis of the birefringence imprinted in the polymer. The linear variation of these angles from the top to the bottom of the image manifests in a sinusoidal variation of observable intensity. The areas of different orientation angles can clearly be distinguished.

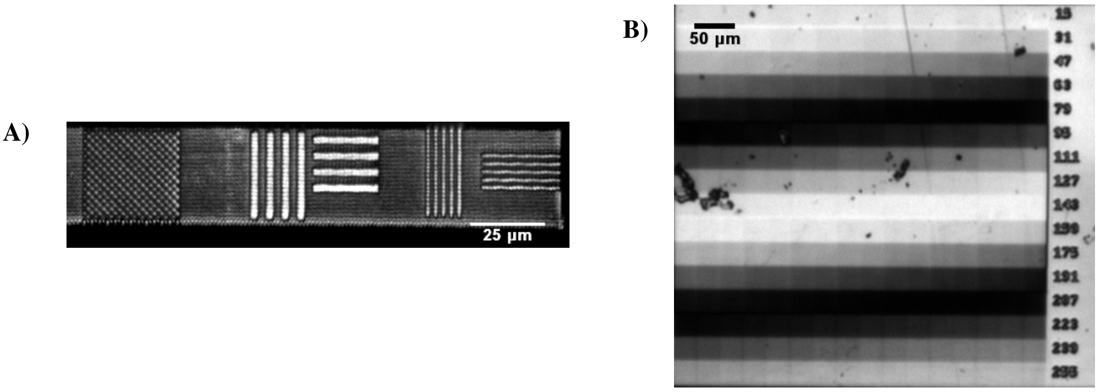

Figure 2: Direct-written structures observed under a polarization microscope

A: Lateral; finest structures correspond to 1,25 µm

B: Resolution chart in terms of polarization; 256 different polarization angles were written into the polymer

To proof the ability to write diffractive optical elements into the polymer a microlens array was fabricated (fig. 3). The array consists of 14x14 microlenses. The focal length of the lenses was chosen as $f = 5mm$ for an illumination wavelength of $\lambda = 670nm$. The orientation of birefringence $\alpha(x_m, y_m)$ was calculated analytically as:

$$\alpha(x_m, y_m) = \frac{\pi}{\lambda}\left[f - \left(x_m^2 + y_m^2 + f^2 \right)^{0.5} \right] \tag{3}$$

Each lens consists of 200 x 200 Pixels with 1.2 µm x 1.2 µm lateral extension. Thus each lens is 240 µm x 240 µm in size and the total dimension of the whole array is 3360 µm x 3360 µm. The substrate for the 4 µm polymer layer was sapphire. An image of a single lens of the array under a polarization microscope at 20x magnification is depicted in figure 3A.

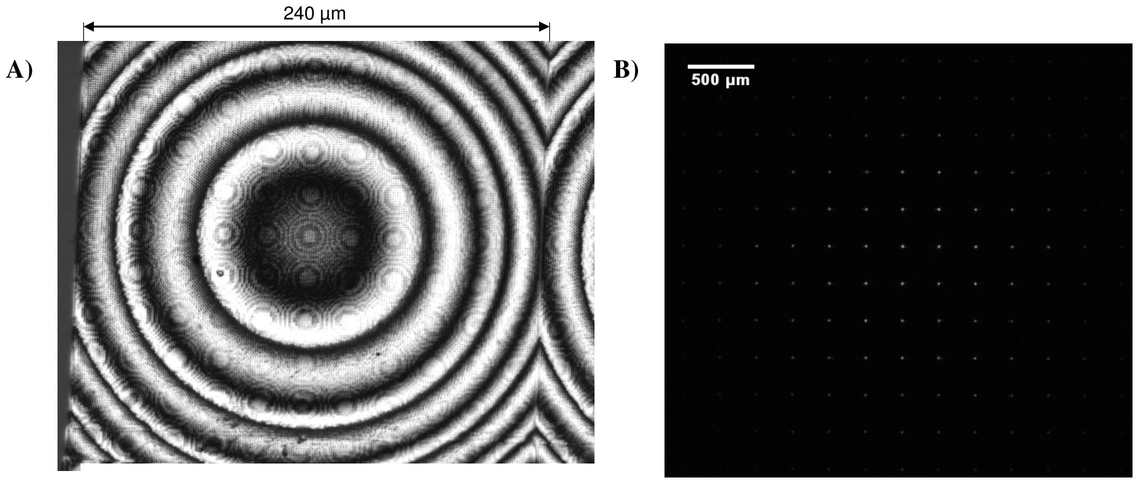

Figure 3: Direct-written microlens array

A: Image of one lens of the array imaged with a polarization microscope

B: Diffracted field of the microlens array on a CMOS-Camera; the array was illuminated with a circular polarized laser beam and the camera was positioned in the focal plane of the microlens array

To test the performance of the microlens array it was illuminated with a collimated diode laser emitting at 670 nm. The linear polarized laser beam had to pass through a quarter-wave plate to generate circular polarization. The diffracted field behind the diffractive microlens array was recorded by a CMOS-Camera. The camera was placed in the focal plane of the microlenses. The recorded image is depicted in fig. 3B. The array of focal spots is clearly observable. Furthermore it is pointed out that no zero order and no twin images which would manifest in a light background and a regular light grid (similar to the diffraction pattern generated by a pinhole array) can be realized. The Gaussian intensity profile of the illuminating laser beam results in darker spots towards the margins of the observed plane.

As a conclusion it can be stated that diffractive optical elements based on azo-benzene polymers have been demonstrated experimentally. While the demonstrated optical element only consists of simple lenses more complex optical functions can be generated with little effort. The small feature dimensions and the number of distinguished polarization steps will provide a large space in terms of design freedom.

4. References

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