Frontiers in Optics, OSA Technical Digest (2009), paper PDPC2

Fabrication of polarization holograms controlling amplitude and phase

Markus Fratz[1,2,*], Dominik M. Giel[2], Peer Fischer[1,2]
[1] *Fraunhofer Institute for Physical Measurement Techniques IPM, Heidenhofstraße 8, 79110 Freiburg, Germany*
[2] *Rowland Institute at Harvard, Harvard University, 100 Edwin H. Land Boulevard, Cambridge, Massachusetts 02142*
Author e.mail adress: markus.fratz@ipm.fraunhofer.de

Abstract: We demonstrate complex holograms that impart arbitrary amplitude and phase profiles onto a transmitted beam and thereby open new possibilities in the control of optical beams. An efficient means of generating vortex beams is shown.
OCIS codes: (090.1970) Diffractive Optics; (090.2890) Holographic Optical Elements

1. Introduction

Polarization holograms are based on structures that exhibit spatially varying birefringence. They have been used for optical data storage [1], polarization measurements [2], or to realize diffractive optical elements [3,4]. Computer generated polarization holograms have so far been restricted to a spatially varying birefringence, where the magnitude of the birefringence is constant [2,3,4]. For circularly polarized light these elements are equivalent to pure phase holograms. Recently, we have demonstrated the realization of the first polarization hologram where both the orientation of the birefringence as well as its retardance is encoded in an azobenzene polymer [5]. Here, we present an efficient and fast way of recording phase and amplitude polarization holograms and demonstrate their application in the field of active beam-shaping.

Polarization holograms can be treated as spatially varying retarders. If they are considered to be thin, then the Jones matrix formulism is the most common way to characterize their function. The Jones matrix of a general retarder is given by:

$$T = \begin{bmatrix} A\cos^2\rho + B\sin^2\rho & (A-B)\sin\rho\cos\rho \\ (A-B)\sin\rho\cos\rho & B\cos^2\rho + A\sin^2\rho \end{bmatrix} \quad (1)$$

A=exp(-iδ/2) and B= exp(iδ/2) are the complex transmission coefficients of the primary axis of the retarder. Note that the absorption of the hologram is assumed to be constant and can be neglected. ρ is the angle between the hologram coordinate system and the fast axis of the retarder. Every point of the hologram plane acts as such a retarder, but δ and ρ vary from point-to-point across the hologram plane [5].

In the following we will only consider illumination of the hologram with a left circularly polarized plane wave $E_{in} = [1,i]^T$. The local retarder described by eq. (1) transforms this wave into:

$$E_{Out} = \cos\left(\frac{\delta}{2}\right)\cdot\begin{bmatrix}1\\ i\end{bmatrix} + \sin\left(\frac{\delta}{2}\right)\cdot\exp\left(i\left(2\rho+\frac{\pi}{2}\right)\right)\cdot\begin{bmatrix}1\\ -i\end{bmatrix} \quad (2)$$

The transmitted wave E_{out} can be interpreted as the superposition of two circularly polarized beams: A left-circularly polarized wave whose amplitude is proportional to cos(δ/2); and a right-circularly polarized wave whose amplitude is sin(δ/2) and whose phase is proportional to 2ρ. If only the second of the two terms on the right-hand side of equation (2) is filtered by standard polarization optics, the described retarder can be used to control the amplitude and the phase of the transmitted wave.

2. Experimental

The polarization holograms are experimentally realized in azobenzene-polymer films [6]. The polymer is spin-coated on an aluminum mirror. The thickness of the polymer layer is approx. 2 µm. When illuminated with linearly polarized light of wavelength 550 nm or shorter, isomerization-cycles are induced in the polymer and result in exceptionally large birefringences. The orientation of the birefringence is perpendicular to the polarization plane of the light and can thus be controlled. The birefringence remains stable after the illumination with green light and can be used for the diffraction of beams with wavelength above 600 nm (in our case 670 nm).

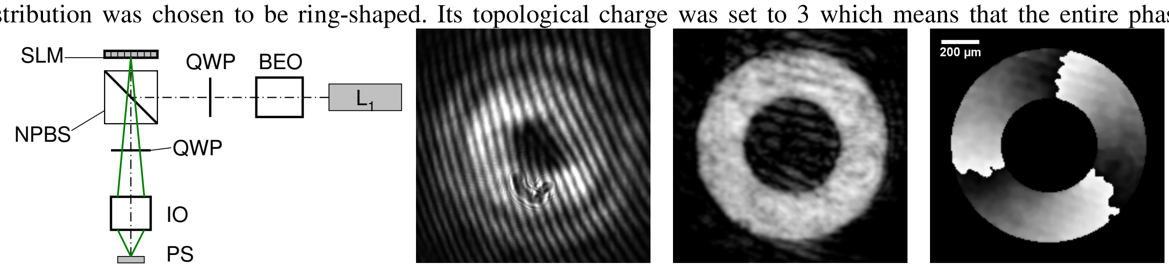
As a result polarization holograms in azobenzene polymers can be fabricated by illuminating the polymer with a spatially varying polarization pattern. Phase-only spatial light modulators (SLM) can generate those polarization patterns [7]. Our SLM-based experimental setup for the fabrication of polarization holograms in azobenzene polymer films is shown in figure 1 (a). The beam expanding optics (BEO) expands the laser (L_1, 532 nm, 30 mW) to the size of the spatial light modulator (HoloEye HEO1080P phase-only liquid crystal SLM). The imaging objective (IO) images the SLM onto the plane of the photo active polymer sample (PS). In this configuration the polarization

Frontiers in Optics, OSA Technical Digest (2009), paper PDPC2

of the light in each of the 1920 x 1080 pixels of the SLM is linear, but the rotation angle of the linear polarization can be computer-controlled by the voltage applied to each SLM-pixel. The orientation of the linear polarization in an SLM-pixel defines the orientation ρ of the corresponding area of the polymer sample. If the polarization pattern displayed by the SLM is not static during the exposure time, the maximum birefringence is not reached and, as the polymer is rewritable, previously induced birefringences can be erased. By choosing the ratio of time appropriately during which the polarization pattern is static or dynamically changed the induced birefringence after exposure can be controlled. This effect can be used to control the magnitude of the birefringence δ pixel-by-pixel in the polymer layer.

3. Experimental results

As an example we have fabricated a polarization hologram for the generation of a vortex beam. Its amplitude distribution was chosen to be ring-shaped. Its topological charge was set to 3 which means that the entire phase



(a) **(b)** **(c)** **(d)**

Figure 1**:** (a) Schematic of the setup for writing polarization holograms. L_1: write laser (532 nm); BEO: beam expanding optics; NPBS: non-polarizing beam splitter; SLM: spatial light modulator; QWP: quarter-wave plate; IO: imaging objective; PS: polymer sample. (b) Interferogram of a vortex beam from a polarization hologram. (c) Amplitude image of the polarization hologram for vortex beam generation.(d) Phase Image of the polarization hologram for vortex beam generation.

space of [0; 2π[is covered three times during one rotation. The diffracted beam was recorded using a digital holographic setup as described in ref. [8]. The resulting interferogram is shown in fig. 1 (b). From this interferogram the amplitude and phase distribution in the plane of the polarization hologram can be reconstructed numerically. The results are shown in fig. 1 (c) and (d), respectively. The measured ring-shaped amplitude is shown in fig. 1 (c). The measured spiral phase is depicted in fig. 1 (d).

Recording polarization holograms with SLMs as demonstrated, can readily be extended to other beam shapes. Furthermore, it can be used in conjunction with a digital-read out to optimize the complex holograms during the write-step.

4. References

[1] Várhegyi, Kerekes, Sajti, Ujhelyi, Koppa, Szarvas, Lőrincz, “Saturation effect in azobenzene polymers used for polarization holography”, Appl. Phys. B **76**, 397-402 (2003).
[2] P. Pagliusi, C. Provenzano, A. Mazzulla, L. Giorgini, and G. Cipparrone, "Spectrograph Based on a Single Diffractive Element for Real-Time Measurement of Circular Dichroism," Appl. Spectrosc. **62**, 465-468 (2008).
[3] G. Martinez-Ponce, T. Petrova, N. Tomova, V. Dragostinova, T. Todorov, and L. Nikolova, "Bifocal-polarization holographic lens," Opt. Lett. **29**, 1001-1003 (2004).
[4] M. Fratz, S. Sinzinger, and D. Giel, "Design and fabrication of polarization-holographic elements for laser beam shaping," Appl. Opt. **48**, 2669-2677 (2009).
[5] M. Fratz, D. Giel, and P. Fischer, "Digital polarization holograms with defined magnitude and orientation of each pixel's birefringence," Opt. Lett. **34**, 1270-1272 (2009).
[6] Eickmans, Bieringer, Kostromine, Berneth, Thoma, “Photoaddressable Polymers: A New Class of Materials for Optical Data Storage and Holographic Memories”, Jpn. J. Appl. Ph. **38,** 1835-1836 (1999).
[7] J. Davis, D. McNamara, D. Cottrell, and T. Sonehara, “Two-Dimensional Polarization Encoding with a Phase-Only Liquid-Crystal Spatial Light Modulator”, Appl. Opt. **39**, 1549-1554 (2000).
[8] D. Carl, M. Fratz, M. Pfeifer, D. Giel, and H. Höfler, "Multiwavelength digital holography with autocalibration of phase shifts and artificial wavelengths," Appl. Opt. **48**, H1-H8 (2009).