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Fabrication of ideal geometric-phase holograms with arbitrary wavefronts: supplementary material

JIHWAN KIM[1], YANMING LI[1,2], MATTHEW N. MISKIEWICZ[1], CHULWOO OH[1,3], MICHAEL W. KUDENOV[1], AND MICHAEL J. ESCUTI[1,*]

[1]Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina 27606, USA
[2]Currently at Apple Inc., Flat Panel Display, Cupertino, California 95014, USA
[3]Currently at Intel Corporation, Technology and Manufacturing Group, Hillsboro, Oregon 97124, USA
[*]Corresponding author: mjescuti@ncsu.edu

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1. MATERIALS

All substrates were borosilicate glass with 0.7 mm thickness, 1 inch square area, and broadband anti-reflection coating on one side. For the LPP, we employed LIA-C001 (DIC CORP). For the reactive LC, we used RMS10-025 ($\Delta n \approx 0.16$ @ 589 nm, MERCK KGaA), diluted with additional solvent propylene glycol methyl ether acetate (PGMEA) in the ratio of 3:7 (RMS:PGMEA) by weight, which we label "Mixture1". For the broadband GP lens sample only, two further mixtures were processed [1,2], in the ratios of 0.004:1 and 0.003:1 (Mixture1:chiral) by weight, with chiral dopants CB15 and MLC-6247 (both from MERCK). We label them "Mixture2a" and "Mixture2b", respectively. The optical adhesive NOA-65 (NORLAND) was used to laminate a second substrate as an endcap to minimize interface reflection.

2. COATING & ASSEMBLY

First, the LPP was spincoated (2000 rpm, 45 s) onto the substrates, and then baked on a hotplate (110 °C, 1 min). Second, these samples were exposed to the complex polarization map created by either the interferometer or the direct-write scanner, as detailed below. Third, the reactive LC layer was spincoated onto the LPP layer, and then polymerized with blanket UV light ($\sim$ 5 mW/cm^2, 5 min, within dry N2). Finally, we laminated a second substrate using the optical adhesive, followed by constant press and curing with the UV light for 20 min.

For nearly all samples, we spincoated (600 rpm, 45 s) and polymerized two layers of LCP Mixture1 to reach the desired thickness of $\sim 2\ \mu$m. For the broadband GP lens only, we spincoated (700 rpm, 45 s) and polymerized Mixture2a, and then spincoated (800 rpm, 45 s) and polymerized Mixture2b.

3. LITHOGRAPHY

The interferometer was constructed on an optical table (NEWPORT) with standard vibration isolation using a 325 nm HeCd laser (KIMMON ELECTRIC), PBSs, mirrors, and a QW plate (all from CVI LASER OPTICS). These were arranged such that each arm of the interferometer had $\sim$ 4 mW/cm^2 within 3 cm diameter beams. For the GP lens (Fig. 1.a), the object was a UV-graded plano-convex lens (100 mm focal length, 50 mm diameter, THORLABS). For the GP axicon, the object was a UV-graded plano-convex axicon ($\sim 179°$ apex angle, ALTECHNA). For the GP prism (*i.e.*, large period PG), no object was used, as we achieved the same effect by rotating the final PBS slightly ($\sim 0.01°$). All interferometer samples were exposed with a total fluence of $\sim$ 2 J/cm^2, for typically 4 min.

The direct-write instrument was also arranged on an optical table and the same laser above, a KD*P series pockels cell (CONOPTICS) plus QW plate (CVI LASER OPTICS) for the polarization control stage, an 40X objective lens (NEWPORT), and the ILS200LM 2D XY translation stage (NEWPORT). Scan times depend on element size and scan profile, but are usually 1-5 min/cm^2. This configuration gives $\sim$ 10 nm resolution, over a 200x200 mm^2 area, and $\Phi(x, y)$ accuracy $\sim 0.1°$.

4. CHARACTERIZATION

All images in Fig. 2.iii and 4.iii were taken by a BX51-P polarizing optical microscope (OLYMPUS). The measured phase in Fig. 2.i was calculated from several images, as follows. With the source light polarized at 0°, images were captured at three analyzer axes (0°, 45°, and 90°), and the partial Stokes vector was calculated for each pixel ($S_0 = I_{0^\circ} + I_{90^\circ}$, $S_1 = I_{0^\circ} - I_{90^\circ}$, and $S_2 = 2I_{45^\circ} - S_1$). An estimate of the effective optical axis angle was found via $2\Phi = \tan^{-1}((S_0 - S_1)/S_2)$, wherein output of the inverse tangent function was unwrapped. This is equal to the geometric phase (with $\pm$ sign) of the primary (+) and conjugate (−) waves.

In Fig. 2a.iv, nearly collimated white light (~ 5 mm diameter) was circularly polarized and directed into the GP lens. A white card was arranged to bisect the output beam, which was photographed. In Figs. 2b.iv, 2c.iv, and 4.iv, the GPH was illuminated with a circularly polarized 633 nm HeNe laser (~ 2 mm diameter) and the far-field output intensity was measured by a CCD camera, in some cases with one or more relay lenses.

In Fig. 3a, a HeNe laser beam expanded to ~ 16 mm diameter was circularly polarized and directed into the GPH, while the beam profile was measured at the focal plane using a slit-scanning beam profiler (THORLABS). In Fig. 3b, nearly collimated (±2°) and unpolarized white light was directed into the GPH, and the total transmittance of all three output waves was measured using an integrating sphere connected to a mini-spectrometer (OCEAN OPTICS). The leakage wave alone was measured subsequently with two orthogonal polarizers (COLORLINK JAPAN) placed before and after the GP lens. The primary and conjugate efficiencies were calculated as the difference between these two measurements.

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