Binary volume phase masks in photo-thermo-refractive glass

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Permanent binary phase masks with planar surfaces and high tolerance to laser radiation are recorded in the volume of photo-thermo-refractive glass using the contact copying technique and binary amplitude master masks. Conversion of a Gaussian beam to higher order modes is shown.
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The use of phase masks that provide a predetermined profile of phase retardation across the aperture of optical beams is an efficient method for beam control and shaping (see e.g., [1–3]), beam splitting, and coronagraphy [4–6]. It is known that phase can be controlled either by varying the physical thickness or the local refractive index of a plane parallel window. Conventional methods of such optical element fabrication are based on spatially selective etching or deposition [1–6]. However, one of the main drawbacks of such techniques is that these elements are very sensitive to their working condition (such as dust and humidity), as the phase profile is controlled by very shallow grooves. With the development of new phase photosensitive media, it becomes possible to spatially control the local refractive index and therefore to record similar phase plates without changing the local physical thickness of the plate. One of the most advanced photosensitive materials is photo-thermo-refractive (PTR) glass. PTR glass exhibits refractive index change after successive exposure to ionizing radiation and thermal treatment at temperatures above the glass transition temperature and is commercially used for the recording of diffractive holographic elements (volume Bragg gratings) [7] and refractive elements (Fresnel lenses) [8]. The main features of these optical elements are their low absorption and scattering in the visible and near IR spectral range and their high laser induced damage threshold, which make them very suitable in high power laser applications [9,10]. In this Letter, we demonstrate that the linear photo-sensitivity of PTR glass paves a way to the recording of high efficiency two-dimensional binary phase masks for the conversion of a Gaussian beam into higher order Hermite–Gaussian and Laguerre–Gaussian modes.

Let us consider the method for converting a Gaussian beam into a higher order TEM_{mn} mode and LG_{mn} mode. Transforming a Gaussian beam into higher order modes can be achieved with 100% conversion efficiency using an interferometric arrangement [11], but this can be time-consuming to align and is sensitive to vibrations. Transformation into the TEM_{11} mode or LG_{04} mode can also be achieved using binary phase masks containing either four or eight sectors in an azimuthal pattern, respectively, with each sector having a phase incursion shifted by π relative to the phase incursion of the adjacent sectors (see Fig. 1) [4–6]. However, this is achieved at the expense of reduced conversion efficiency and is inherently chromatic, as wavelengths far from the design wavelength will not achieve a π phase shift. While all previous demonstrations of such binary masks have been carried out by local modification of the sample's thickness, we will consider in this Letter mode convertors on the basis of volume phase masks (VPMs), where phase incursion is produced by local variations of refractive index.

Before fabricating any prototypes of a VPM, it is important to understand first the function that these masks will perform, and most importantly to determine the efficiency of mode conversion. Calculation of the efficiency first relies on the fact that the Hermite–Gaussian modes (and Laguerre–Gaussian modes) are orthogonal:

$$\left| \iint E^*_{n_1 m_1} E_{n_2 m_2} \mathrm{d}A \right|^2 = \delta_{n_1 n_2} \delta_{m_1 m_2}. \tag{1}$$

Here A is area, δ is the Kronecker delta, (*) denotes complex conjugation, and E_{nm} is the electric field of the mode of order n, m. For Hermite–Gaussian modes, the field for a given mode at the beam waist is defined as [12]

$$E^{\mathrm{HG}}_{nm}(x, y) = E_0 H_n\left(\frac{\sqrt{2}x}{w_0}\right) H_m\left(\frac{\sqrt{2}y}{w_0}\right) e^{\frac{-(x^2+y^2)}{w_0^2}}, \tag{2a}$$

and for Laguerre–Gaussian modes, it is defined as

$$E^{\mathrm{LG}}_{nm}(r, \phi) = E_0 \left(\frac{\sqrt{2}r}{w_0}\right)^{|m|} L_n^{|m|}\left(\frac{2r^2}{w_0^2}\right) e^{\frac{-r^2}{w_0^2}} e^{im\phi}. \tag{2b}$$

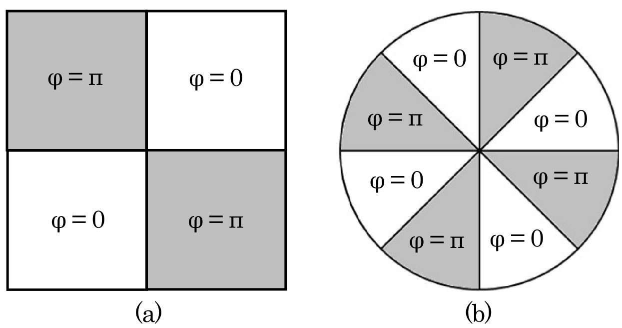
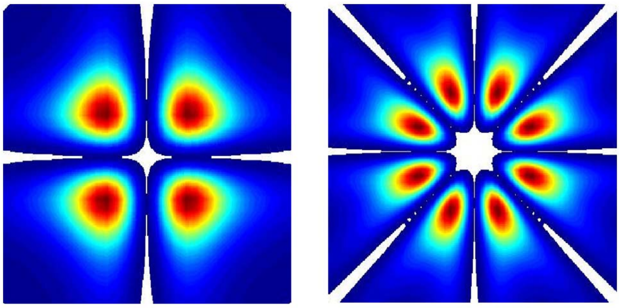


Fig. 1. Phase profile for a four-sector (a) and eight-sector (b) phase mask.



(a) (b)

Fig. 2. (Color online) Theoretical far field intensity profile produced by the (a) four-sector and (b) eight-sector VPM.

Here H_n is the Hermite polynomial of order n and $L_n^{|m|}$ is the associated Laguerre polynomial of order n. It should be noted that a more general formulation for these modes exists when not at the beam waist. Also note that the lowest order mode is always a standard Gaussian beam. A Gaussian beam transmitted through a VPM with a given phase distribution will thus no longer be exactly the same as the lowest order mode, and conservation of energy will thus require that some energy be present in higher order modes. The conversion efficiency can therefore be defined as

$$\eta = \frac{\left| \iint E_{nm}^{*} E_{00} T \mathrm{d}A \right|^2}{\int |E_{nm}|^2 \mathrm{d}A \cdot \int |E_{00} T|^2 \mathrm{d}A}, \qquad (3)$$

where T is the transmittance function of the phase mask and the denominator servers as a normalization factor.

Let us now analyze how to design such VPMs. Since the VPMs are binary, the phase profiles may be represented as signum functions, with the four-sector mask and eight-sector mask having a transmittance function of

$$T_4(x, y) = \exp(i\varphi_{\mathrm{avg}})\mathrm{sign}(x)\mathrm{sign}(y), \qquad (4a)$$

$$T_8(x, y) = \exp(i\varphi_{\mathrm{avg}})\mathrm{sign}(x)\mathrm{sign}(y) \cdot \mathrm{sign}(x + y)\mathrm{sign}(x - y), \qquad (4b)$$

respectively. Here φ_{avg} is the phase incursion due to the passage of the beam through the glass, which, without loss of generality, we will assume to be zero. A Gaussian beam passing through the centers of such VPMs will have a far field intensity distribution shown in Fig. 2. The distribution of energy, however, may not be similar to the higher order mode of the same width as the Gaussian beam, since the bucket for a higher order mode is much larger than the bucket for a Gaussian beam. Therefore, it is evident that the width w of the mode in question may not be equal to the width u_0 of the incident beam for optimal conversion and thus the efficiency should be defined in terms of the relative widths:

$$\eta(w, u_0) = \frac{\left| \iint E_{nm}^{*}(w) E_{00}(u_0) T \mathrm{d}A \right|^2}{\int |E_{nm}(w)|^2 \mathrm{d}A \cdot \int |E_{00}(u_0) T|^2 \mathrm{d}A}. \qquad (5)$$

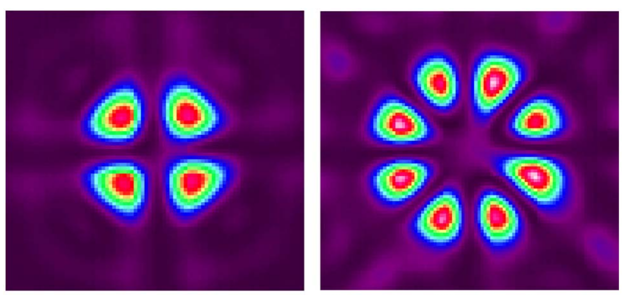
For a given incident beam width u_0, calculations indicate that the maximum conversion efficiency of the four-sector VPM into the TEM_{11} mode is 68.4% (when $w/u_0 = 0.577$) and the maximum efficiency of the eight-sector VPM into the LG_{04} mode is 29% (when $w/u_0 = 0.445$).

In order to validate this model, we fabricated two phase masks in 25 mm × 25 mm PTR glass plates using the contact copying technique and binary amplitude master masks. A master binary amplitude mask was first recorded lithographically in a fused silica plate for each pattern. This mask permitted selective exposure of the PTR glass with the designed profiles in order to achieve a lower refractive index only in the UV-exposed regions. The PTR window was then placed in contact with the master with matching fluid in between them and homogeneously exposed to UV radiation from a He–Cd laser at 325 nm with a dosage of 1 $\mathrm{J/cm^2}$. The samples were then developed at a temperature of ~520 °C and the refractive index change was then characterized using a liquid-cell shearing interferometer [13]. A refractive index change of 208 ppm and 175 ppm was achieved for the four-sector VPM and eight-sector VPM, respectively. As the total phase incursion is given by

$$\varphi = \frac{2\pi \Delta n L}{\lambda}, \qquad (6)$$

the plates were subsequently polished down to $L = 1.52$ and 1.81 mm, respectively, with a flatness better than $\lambda/4$ at 633 nm in order to secure a π phase shift between the unexposed and the exposed regions at $\lambda = 633$ nm. It should be noted that during recording there is diffraction of the UV beam at the edges of the amplitude mask. This results in a transition region of approximately 6 μm width between the sectors, which has a negligible effect on the conversion efficiency. Finally, the samples were bleached [14], resulting in total losses, mostly by scattering, of 1% in the VPM (ignoring Fresnel reflection).

The phase masks were placed in a collimated single mode beam from a He–Ne laser emitting at 633 nm with a Gaussian intensity distribution, a beam diameter at $1/e^2$ of 6.64 mm. The intensity distribution of the transmitted beam was characterized in the focal plane of a lens (Fig. 3). Excellent agreement with the theoretical intensity distribution can be observed. In order to relate quantitatively the experimental profile to the theoretical field profile, we first convert the theoretical field profile into



(a) (b)

Fig. 3. (Color online) Experimental far field intensity profile produced by the (a) four-sector and (b) eight-sector VPM.

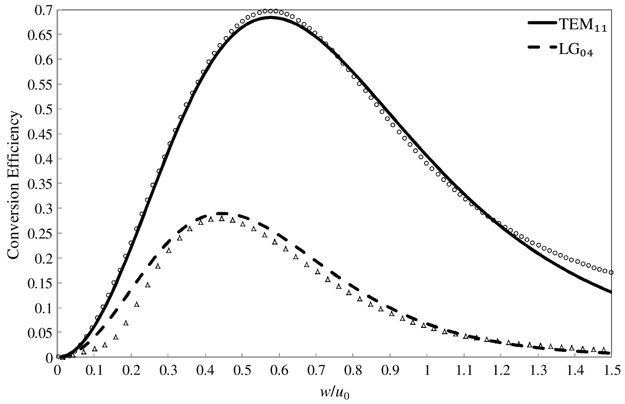


Fig. 4. Theoretical (curves) and experimental (dots) conversion efficiency of a beam of width u_0 into the TEM_{11} and LG_{04} modes of width w.

an intensity distribution. Rewriting Eq. (5) to account for this gives

$$\eta(w,u_0) = \frac{\left| \iint \left| E^*_{nm}(w) \right| \sqrt{I(u_0)} \mathrm{d}A \right|^2}{\int I(u_0)\mathrm{d}A \cdot \int |E_{nm}(w)|^2 \mathrm{d}A}. \quad (7)$$

Here $I(u_0) = |E_{00}T|^2$. Figure 4 shows the dependence of conversion efficiencies on the ratio of sizes of the original and converted modes for four-sector and eight-sector VPMs. One can see good agreement between the theoretical and the experimental conversion efficiencies.

It is shown that volume phase masks with plane parallel polished surfaces recorded in PTR glass are new elements for the control of the intensity profile of laser beams. Two prototypes are demonstrated that convert a Gaussian beam to the TEM_{11} mode or the LG_{04} mode with near-theoretical profiles. These phase masks are very robust such that the element is written within the volume of the plate and cannot be deleted or altered. The masks are also highly suitable to high power and high energy (CW or pulsed) applications. Further, the refractive index change can be adjusted as necessary for use at any wavelength.

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