Spatial beam shaping by quartz crystal plano-convex lens

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Based on the optical activity of quartz crystal, we proposed a scheme for shaping the spatial intensity distribution of a linearly polarized laser beam by utilizing a quartz crystal plano-convex lens in combination with a polarizer. The intensity profile of the shaped laser beam can be easily switched from one profile to another by controlling the polarization direction of the incident laser beam.

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The shaping of the light intensity distribution is important for many sectors of science and engineering[1]. In a high-energy laser system, in order to reduce self-focusing effect, improve the safe operating flux and counteract the spatially inhomogeneous amplification in the main amplifiers, it is necessary to convert the Gaussian intensity distribution of a collimated laser beam into a desired one[2]. Driven by the ever-increasing demands of applications, several techniques are proposed[3], such as birefringent lenses[4], beam segmentation[5], the binary-amplitude mask and spatial light modulator associating with liquid crystal light valve[6]. In this letter, we proposed and demonstrated a scheme to modulate the intensity distribution of a linearly polarized laser beam based on the optical activity of quartz crystal. The theoretical basis and the schematic diagram of the regulable intensity distribution modulator was described, then the experimental results were presented.

When a linearly polarized monochromatic laser beam passes through a quartz crystal plate along the principal axis, the vibration plane will be rotated by a certain angle φ which is proportional to the thickness d of the traversed medium

$$\varphi = \alpha(\lambda) \cdot d, \quad (1)$$

where $\alpha(\lambda)$ is the specific rotation along the principal axis of the quartz crystal whose unit is °/mm, at room temperature[7]

$$\alpha(\lambda) = \frac{9.5639}{\lambda^2 - 0.0127493} - \frac{2.3113}{\lambda^2 - 0.000974} - 0.1905, \quad (2)$$

where λ is the wavelength in micrometers.

Based on the fact that the rotated angle is proportional to the thickness, we fabricated a quartz crystal plano-convex lens with its optical axis exactly parallel to the principal axis of the quartz crystal. Let a plane polarized, collimated, monochromatic laser beam normally incident on the flat surface of the lens, so the laser beam will traverse along the principal axis of the quartz crystal and the vibration plane will be rotated. Because the thickness of the lens varies with radial position, the rotated angle will vary with radial position. Then the polarization-rotated beam is collimated by a lens, after passing through a linear polarizing filter, we can obtain an intensity modulated laser beam. In comparison with previous techniques, the quartz crystal plano-convex lens is easier to be fabricated and can be used in high-power laser systems because of its high-damage-threshold. In addition, the technique offers convenient high-dynamic-range tools for the spatial shaping of laser beam.

Figure 1 schematically illustrates the optical arrangement of the spatial light modulator. The modulator comprises a half-wave plate, a quartz crystal plano-convex lens, a spatial-filter pinhole, a collimating lens and a polarizer. The half-wave plate is used to rotate the polarization state of the plane polarized light. The plane polarized wave is normally incident on the wave plate, and the plane of polarization is at an angle θ with respect to the fast axis. After passing through the plate, the original plane wave is rotated through an angle 2θ, so we can change the intensity profile of the output laser beam. The passing axis of the polarizer is parallel to the vibration plane of the initial beam. Note that the modulator is a very similar structure to a spatial filter, which indicates that the scheme has three functions: spatial filter, beam expander and intensity distribution modulator. In this letter, we deal only with the last function.

Here, we present the theoretical analysis of the scheme as a spatial light modulator. Let the distance between the radial position and the optical axis be r, the curvature radius of the quartz crystal plano-convex lens be R

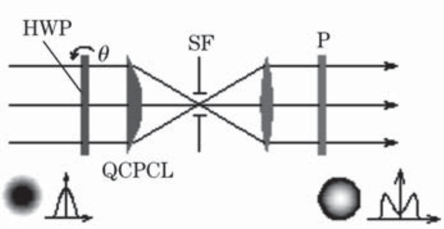

Fig. 1. Schematic diagram of the spatial light modulator. HWP: half-wave plate; QCPCL: quartz crystal plano-convex lens; SF: spatial-filter pinhole; P: polarizer.

and the lens aperture be D, then the lens thickness $d(r)$ along the radial direction can be represented as

$$d(r) = \sqrt{R^2 - r^2} - \sqrt{R^2 - (\frac{D}{2})^2}. \quad (3)$$

For simplicity, we assume that the focal length of the collimating lens is equal to the focal length of the quartz crystal plano-convex lens. According to Malus' cosine-squared intensity law, substituting Eq. (2) into Eq. (1), the transmittance function of the spatial light modulator is

$$T(r) = \cos^2[\alpha(\lambda) \cdot d(r) + 2\theta]$$

$$= \cos^2\{\alpha(\lambda) \cdot [\sqrt{R^2 - r^2} - \sqrt{R^2 - (\frac{D}{2})^2}] + 2\theta\}. \quad (4)$$

We fabricated a quartz crystal plano-convex lens (R = 31 mm, D = 40 mm), and successfully modulated the intensity distribution of a collimated linearly polarized laser beam (λ = 532 nm, α = 27 °/mm, and the beam diameter is approximately 26 mm) in our experiment. The calculated transmittance curves of the modulator are shown in Fig. 2. The calculated results indicate that the transmittance curves are axisymmetric and the transmittance curve can be conveniently switched by rotating the half-wave plate.

The experimental results and their comparison with the calculated results are shown in Fig. 3. The initial beam with approximately Gaussian irradiance profile (a) can be transformed into another desired profile (b) or (c) after passing through the modulator. The plot (d) indicates that the experimental results are well consistent with the calculated curves.

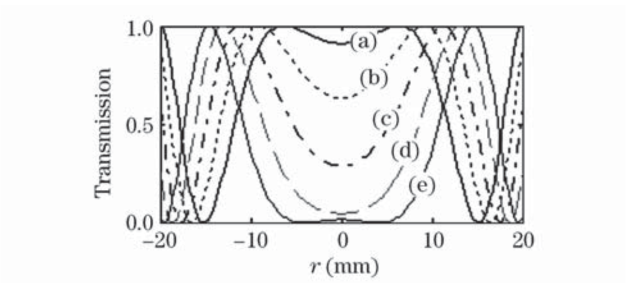

Fig. 2. Transmittance curves of the spatial light modulator. (a) $\theta = 0°$, (b) $\theta = 10°$, (c) $\theta = 20°$, (d) $\theta = 30°$, and (e) $\theta = 40°$.

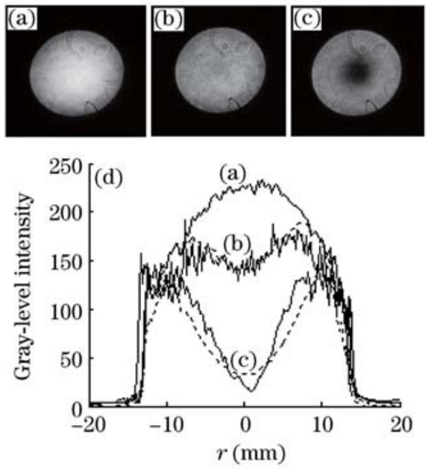

Fig. 3. Experimental and calculated results. (a) The initial beam, the shaped beams (b) $\theta = 10°$ and (c) $\theta = 25°$, (d) the comparison of experimental (solid curve) and calculated (dashed curve) curves in plot.

In conclusion, we proposed a new scheme that modulates the intensity distribution of a collimated linearly polarized laser beam by use of a quartz crystal plano-convex lens in combination with a polarizer. The modulator is verified to be in good agreement with the theoretical analysis in the experiments.

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