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# Orbital angular momentum beams engineering with liquid-crystal converter and a kW fs digital laser

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**Abstract:** We report on a versatile orbital angular momentum beam generation from a 61 channels coherent beam combining femtosecond digital laser by using liquid-crystal polarization converter. © 2023 The Author(s)

## 1. Introduction

Orbital Angular Momentum (OAM) laser beams are characterized by a helical wavefront carrying a phase singularity at the center. In the far field, it results in a null central intensity surrounded by a donut-shaped distribution of light. These OAM beams find widespread applications in high-field physics [1]. The NanoXCAN project aims to develop an X-ray source by highly (relativistic regime) concentrating the laser electric field on Cu nanoparticles producing energetic hard X-rays. Optical needles are suitable beams to achieve this objective [2]. To generate a needle beam with an ultra-long depth of field and micrometer-scale transverse confinement, a radially polarized OAM beam is required. In our previous work [3,4], we successfully demonstrated the generation of OAM beams by applying helical phase profiles to the 61 channels of XCAN in a digital mode. In this study, we present for the first time, far field donut beam engineering through the combined use of a Coherent Beam Combination (CBC) femtosecond digital laser and a liquid-crystal q-plate designed to sustain high average power. The q-plate, featuring a fractional topological charge of  $q = 1/2$  at its center, acts as a Radial Polarization Converter (RPC) [5]. It allows to generate a coherently combined orbital angular momentum beam with polarization control.

## 2. Experimental setup and results

The experimental setup for direct generation of polarized OAM beams from a coherently combined femtosecond digital laser is illustrated in Fig.1. The q-plate, that has been designed by *Arcoptix* to withstand 1 kW average power, is inserted in the kW-pixilated laser path between the focusing lens  $L_1$  and the focal plane (FP) where all 61 tiled beams are accurately phased and coherently added. A half waveplate ( $\lambda/4$  or  $\lambda/2$ ) is inserted to properly control the orientation of the linearly polarized 61 beams on the q-plate axis. A half waveplate (HWP) is inserted to properly control the orientation of the linearly polarized 61 beams on the q-plate axis.

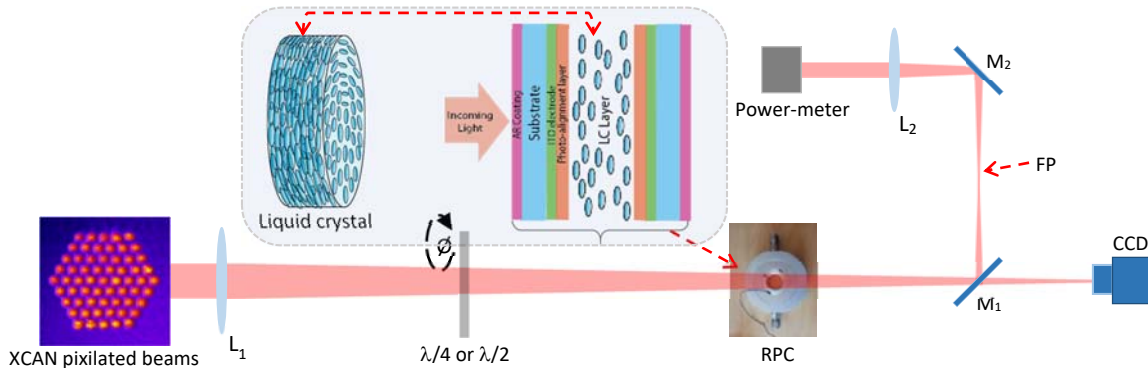


Fig. 1. Experimental setup of the coherently-combined orbital angular momentum generation.

At high average power, temperature gradient across the q-plate can cause significant phase shift variations. This is due to the relatively important temperature dependency of the Liquid Crystal (LC) birefringence, which is approximately 0.5 % per °C. These phase distortions affect the output beam. To reduce temperature gradients, a q-plate that minimizes light absorption has been developed. As shown in the inset of Fig.1, when the light propagates through the q-plate, it first passes through an anti-reflection coating, followed by a 3 mm thick transparent substrate, a thin transparent (Indium-Tin-Oxide, ITO) electrode, a thin (~200 nm) photo-alignment layer, and finally the liquid crystal layer (20 μm thick). In a symmetric way, the light traverses again the photoalignment, ITO and Substrate layers before exiting the q-plate.

The light absorption is mainly caused by the two substrates and two electrode layers. The absorption caused by the LC layer is not significant. To transfer efficiently the heat towards the water-cooled LC cell housing, the substrate material must also carry a high thermal conductivity. Furthermore, to avoid additional phase distortion,

the substrate material should also have a low birefringence. To fulfil all the aforementioned constraints, we choose to rely on 3 mm thick sapphire substrates coated with an AR coating and a 100 nm thick ITO transparent electrode. Indeed, Sapphire exhibits a low absorption (100 ppm/cm at 1 $\mu$ m), a very good thermal conductivity (25 W/m $^2$ C) and a low birefringence (0.01 at 1 $\mu$ m). Finally, the largest absorption contribution is due to ITO layer. The electrode has an approximate thickness of 100 nm (a typical thickness in LC technology) and an absorption coefficient of 500 cm $^{-1}$  at 1 $\mu$ m corresponding to 2-3 % absorption. The 93 % transmitted light hits the mirror M $_1$  where a portion (~0.1 % transmission) of the combined OAM is sent to a CCD camera for spatial diagnostics, while the reflected part is collimated (L $_2$ ) and directed to a power-meter.

First, a flat phase is applied to XCAN digital laser. A donut far field can then be obtained by adjusting the HWP angle and by applying a voltage (3.2 V) across the RPC electrodes. Fig. 2(a) shows a typical far field for an HWP reference angle  $\emptyset_1$ . Similar donuts are only obtained for a multiple of 45 $^\circ$  from this reference angle. Identical far fields are obtained for each rotation of 90 $^\circ$ . These results correspond to a polarization rotation of 90 $^\circ$  and 180 $^\circ$  respectively for each of the 61 input beams of the q-plate and thus, radial or azimuthal polarization is obtained at the RPC output. The HWP is then replaced by a quarter waveplate (QWP). The linear polarizations of the 61 input beams are then transformed into circular polarizations. Consequently, a beam carrying circular polarization emerged at the output (Fig. 2(b)). The q-plate is finally operated at high laser average power up to 950 W. The donut intensity distribution is rather well conserved, with some degradation starting from 800 W (fig.2(c,d)).

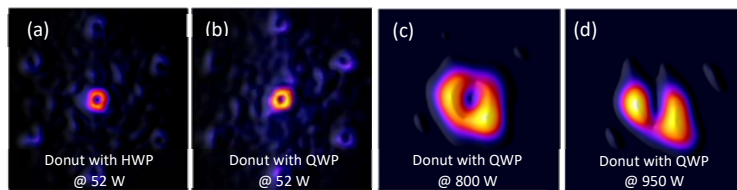


Fig. 2. Donuts generation as a function of the incident polarization (a,b) and at high average power (c,d).

An interesting result of this study is obtained when combining the digital mode of the XCAN laser with the q-plate. Indeed, when applying helical phase to XCAN’s 61 channels, higher order radially (azimuthally) polarized OAM beams could be obtained. As seen in the previous paragraph, when using the q-plate together with a flat phase programmed on the 61-channels, a radially (azimuthally) polarized beam (with a topological charge  $m = -1$ , (yellow numbering) is obtained (Fig.3(c)). When the q-plate is combined with the helical phase applied to XCAN at different orders (white numbers is Fig.3), higher order radially (azimuthally) polarized OAM beams are then obtained. OAM beams with global topological charges of  $l = -3$  to  $+3$  (red numbering) are depicted in Fig.3(a-g) while applying helical phase orders between  $m = -2$  and  $m = 4$  respectively. Thus, higher order OAM beams with circular polarization are also obtained when the input beam is circularly polarized.

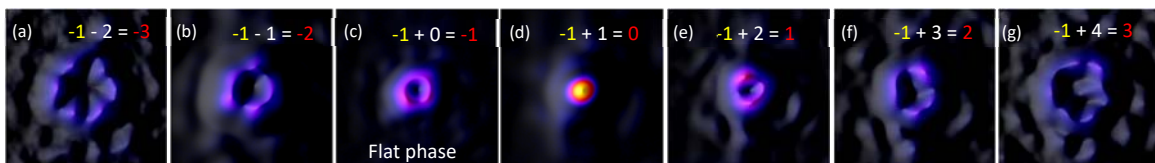


Fig. 3. Far field donuts generated when associating q-plate with helical phase applied on XCAN.

### 3. Conclusion

A q-plate based polarization converter is developed and tested at high average power to radially/azimuthally (circularly) polarize OAM beams from a CBC kW-femtosecond digital laser. Experimental far field polarization distribution measurement and cross evaluation with (currently under development) modelling will be presented. Foreseen implementation of polarization adjustment at each of the 61 channels level should offer more versatility for a fully control of beam shaping and energy distribution.

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