Vortices in femtosecond laser fields

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ABSTRACT

We experimentally generate optical vortices in the output beam of Ti:Sapphire laser emitting 20-fs pulses. Screw phase dislocations are imposed in each spectral component of the short pulses by aligning computer-generated hologram within a 4f-setup.

Keywords: phase dislocation, optical vortex, femtosecond pulse

1. INTRODUCTION

An optical vortex (OV) is an isolated point singularity in a wavefront screw-type phase distribution. At the singularity point both the real and imaginary parts of the field amplitude are zero (i.e., also the field intensity). From mathematical point of view the phase profile is described by an $exp(im\theta)$ multiplier, where θ is the azimuthal coordinate and the integer number m is called topological charge. The interest in generating OVs in femtosecond laser fields is motivated by the possibility to create short bursts of photons which total angular momentum can be varied independent from the field polarization by changing the topological charge[1] m. The challenge here is to impose the phase dislocation in each spectral component of the short pulse without spatial chirp of the background and to keep the pulse width and shape as undistorted as possible[2].

The known methods applicable in the cw and quasi-cw regime are not suitable for femtosecond (e.g. Ti:sapphire) lasers. Mode converters can not be used since mode-locking is achieved only if the resonator is aligned to emit the fundamental transverse mode TEM_{00}. Transparent spiral wave plates may work in the visible and near infrared spectral range in the liquid-crystal version only[3]. Such a device preserves the beam path of an optical system and has a conversion efficiency near 100%. The magnitude of the phase jump of the OV, however, will deviate from π for the different spectral components of the short pulse and the modulator does not seem applicable after regenerative/multipass amplifiers. It is well known[4] and widely used to generate OVs in a controlled way computer-generated holograms (CGHs) produced photolithographically[5]. Such a grating build in in a dispersionless 4f-system[6] is, in our view, an adequate solution of the formulated problem. First successful experimental results obtained with 20-fs laser pulses from Ti:Sapphire oscillator are presented and discussed in the following.

2. THEORETICAL DESCRIPTION

The analyzed 4f-setup is sketched in Fig. 1. The diffraction of a wave with an initial electrical field amplitude $E(x_0,y_0)$ and wavelength λ along the propagation axis s is described by the Fresnel integral

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$$E(x,y,s)=\frac{e^{i\frac{2\pi}{\lambda}s}}{i\lambda s}\iint E(x_o,y_o,0)e^{i\frac{\pi}{\lambda s}[(x-x_o)^2+(y-y_o)^2]}dx_o dy_o \ . \tag{1}$$

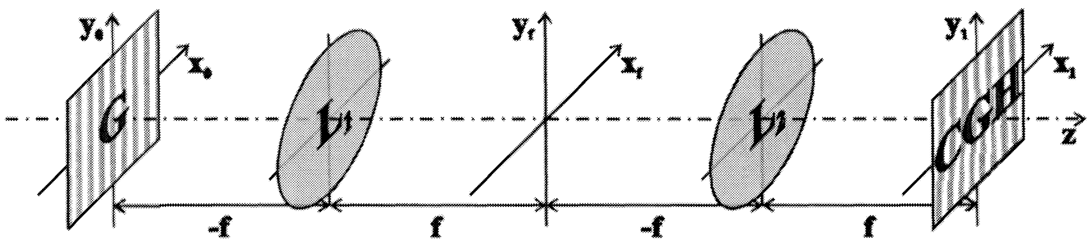

Figure 1 Scheme of the 4f setup analyzed theoretically.

Since the phase introduced by a single thin lens of a focal length f is given by

$$t(x,y)=e^{-i\frac{\pi}{\lambda f}(x^2+y^2)}, \tag{2}$$

the field distribution in the Fourier plane of such lens of an infinite aperture is

$$E(x_f,y_f,f)=\iint E(x_o,y_o,-f)e^{-i\frac{2\pi}{\lambda f}(x_o x_f+y_o y_f)}dx_o dy_o \ . \tag{3}$$

In the particular case of an incoming Gaussian beam

$$E(x_o,y_o)=E_o e^{-\frac{x_o^2+y_o^2}{\sigma_o^2}} \tag{4}$$

the first-order diffracted wave just after the first diffraction grating (see Fig. 1) is described by

$$E'(x_o,y_o)=\frac{1}{\pi}E_o e^{-\frac{x_o^2+y_o^2}{\sigma_o^2}}e^{i\frac{2\pi}{d}x} \tag{5}$$

and the electric field distribution in the (x_f, y_f) plane is obtained in the form

$$E(x_f,y_f)=\frac{\sigma_o^2}{\lambda f}e^{-\frac{(x_f-\frac{\lambda f}{d})^2+y_f^2}{(\frac{\lambda f}{\pi\sigma_o})^2}} \ . \tag{6}$$

In Eqs. 5, 6 d is the period of the diffraction grating (CGH). Applying the Fourier-transformation (1) again one gets the field distribution in front of the second diffraction grating (CGH)

$$E(x_1,y_1)=\frac{1}{\pi\lambda^2 f^2}e^{-\frac{x_1^2+y_1^2}{(\beta\sigma_o)^2}}e^{i\frac{2\pi}{\beta d}x_1} \ . \tag{7}$$

In this way we derived the following analytical expression for the electric field amplitude at the exit of the 4f system

$$E'(x_1,y_1)=\frac{1}{\pi^2\lambda^2 f^2}e^{-\frac{x_1^2+y_1^2}{(\beta\sigma_o)^2}}e^{i\varphi(x_1,y_1)}e^{i\frac{2\pi}{d}(1+\frac{1}{\beta})x_1} \ , \tag{8}$$

where β is the angular magnification of the system ($(1+\beta)\to 0$). The last multiplier in (8) accounts for the spatial dispersion at the exit of the 4f-setup. Since $\beta = -1$ for perfect 4f-alignment, vortices generated in each individual spectral component will be recombined spatially and temporally to overlap at the exit without spatial chirp. With lenses introducing negligible material dispersion the system can be called 'zero dispersion pulse compressor with spatial beam shaping'.

The transmission function of a grating can be written in the form

$$T(x,y)=\sum_{n=-\infty}^{\infty}C_n e^{in\frac{2\pi}{d}x}e^{in\varphi(x,y)}, \quad (9)$$

where the coefficients $C_n=\dfrac{\sin n(\pi/2)}{n\pi}$. Obviously, even diffraction-order beams are absent and the first-order beam is described by

$$T(x,y)=\frac{1}{\pi}e^{i\frac{2\pi}{d}x}e^{i\varphi(x,y)}. \quad (10)$$

In the truly one-dimensional and two-dimensional (OV) cases studied in this work

$$\varphi(x,y)=\begin{cases}0 & y\le 0\\ \pi & y\ge 0\end{cases} \quad \text{, and } \varphi(x,y)=\theta, \quad (11)$$

respectively, θ is the azimuthal coordinate and m=1.

3. EXPERIMENTAL RESULTS

In this work Ti:sapphire Kerr-lens mode-locked oscillator pumped by intracavity-doubled Nd:YVO4 (Millenia Vi) is used. The oscillator emits nearly transform-limited sub-24-fs pulses at a repetition rate of 78 MHz with a mean power of 200 mW at a central wavelength of 797 nm. The 4f-setup is folded in the (x_f,y_f)-plane by two silver-coated mirrors. Single large-aperture (2.5 cm) quartz lens with a focal length f=20 cm is aligned carefully to minimize aberrations. In the experiment we used binary CGHs produced photolithographically with periods d=30 µm aligned in a way first to reconstruct the phase dislocation and dark beam encoded. Side part of the same grating with parallel stripes is used as an effective second grating to recombine the spectral components after the folding mirrors.

As seen from Eq.10, the only phase dislocation produced in the spectral components of an ultrashort pulse without 4f-setup is the one-dimensional one, provided the dislocation is encoded in the CGH perpendicular to the grating stripes. This is seen in Fig. 2, in the frames recorded with a CCD-camera with a 12 µm resolution, and in the respective transverse slices. In this case the presence of spatial chirp and pulse-front tilt of the femtosecond pulse is inevitable.

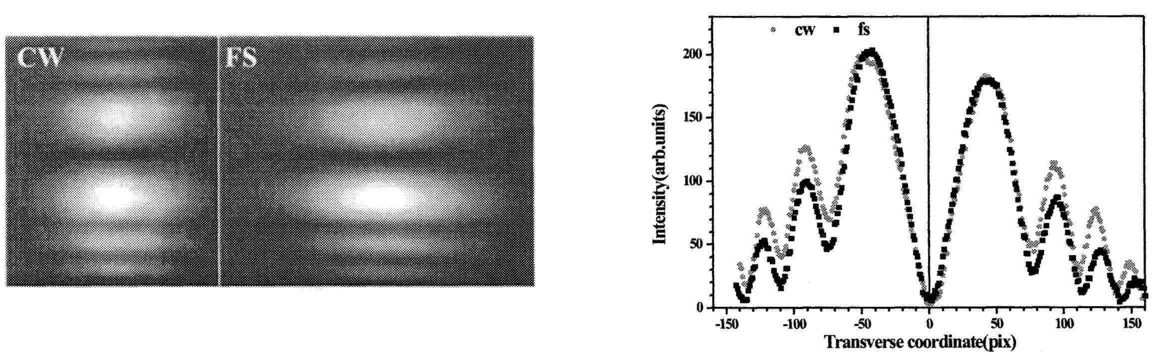

Figure 2 Left panel: Grayscale images one-dimensional dark beams (containing 1D phase dislocations) 35 cm behind the CGH, in cw and fs regime. No 4f-setup is used. Right: Corresponding vertical cross-sections.

When an OV is generated by a single CGH (no 4f-setup) the vortices generated in each spectral component are not recombined. The presence of spatial chirp and pulse-front tilt of the pulse is accompanied by a reduced dark beam contrast (see Fig. 3). The beam smearing increases with increasing the propagation path length.

In Fig. 4 we show grayscale images of optical vortices in cw (left) and fs regime (right) and comparative transverse slices. Interference lines in the frame recorded in cw are clearly seen. They appear due to slight overlapping of the OV beam exiting the 4f-system with a beam reflected directly from the CHG substrate. In the fs regime both interference and speckles disappear. Unlike Fig. 3, the contrast of the femtosecond OV is gradually improved but still not maximal. One potential source of this problem could be a non-perfect alignment (i.e. presence of real magnification within the 4f-setup causing β to deviate from -1; see Eq.8). Second, weak background signal due to reflection from the CGH, integrated in time, is probably recorded by the CCD-camera. No interference is seen in the recorded frame due to the huge temporal offset between the OV beam/pulse and the weak background which makes this contribution difficult to recognize. Further attempts to optimize the experimental conditions are under way.

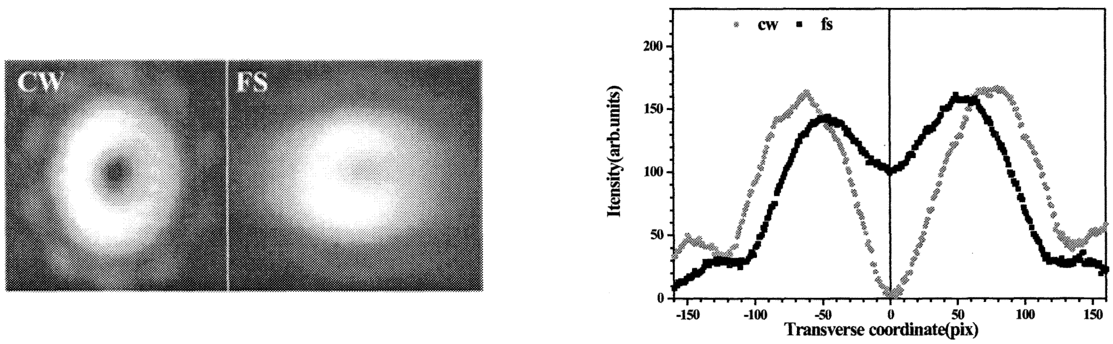

Figure 3 Left panel: Grayscale images two-dimensional OV beams (containing 2D screw-phase dislocations) 35 cm behind the CGH, in cw and fs regime. No 4f-setup is used. Right: Corresponding vertical cross-sections.

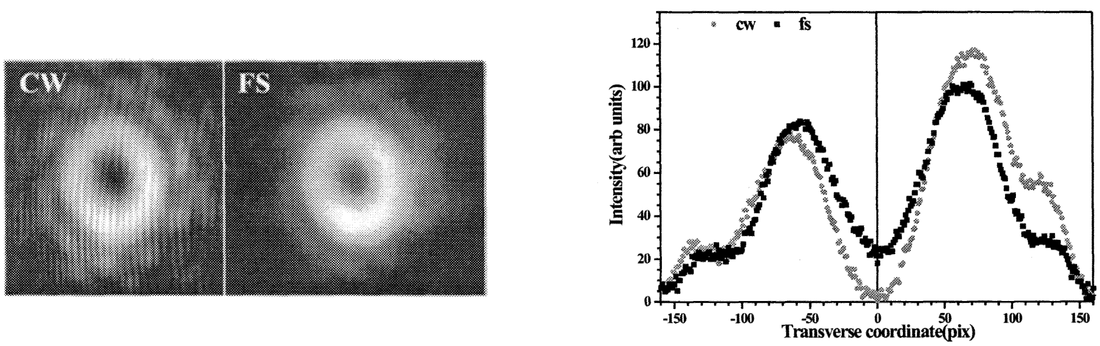

Figure 4 Left panel: Optical vortices recorded 35 cm after the 4f-setup in cw and fs regime. Right: Corresponding vertical cross-sections.

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