Phase dislocations in femtosecond laser fields

K. Bezuhanov*[1], A. Dreischuh[1], G.G. Paulus[2,3], and H. Walther[2,4]
[1]Department of Quantum Electronics, Sofia University, 5, J. Bourchier Blvd, BG-1164 Sofia, Bulgaria
[2]MPI für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany
[3]Texas A&M University, Deprtment of Physics, College Station TX 77843-4242, USA
[4]Sektion Physik, Ludwig-Maximillians-Universität, Am Coulombwall 1, D-85747 Garching, Germany

ABSTRACT

We experimentally generate optical vortices in the output beam of a 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. The analysis shows that phase dislocations can be generated also at the stage of femtosecond pulse compression.

Keywords: phase dislocation, optical vortex, femtosecond pulse, 4f-setup, grating compressor

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 m[1]. 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 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 or doudle-pass compressor[6] is, in our view, an adequate solution of the formulated problem. First successful experimental results obtained with 20-fs laser pulses from a Ti:sapphire oscillator are presented and discussed in the following. If the output grating of a pulse compressor is replaced by a suitable CGH, phase dislocation can be created in femtosecond laser fields at the pulse-compressing stage too.

2. THEORETICAL DESCRIPTION

2.1. Computer generated holograms

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

* kalojan@uni-sofia.bg

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$$T(x,y)=\sum_{n=-\infty}^{\infty} C_n e^{in\frac{2\pi}{d}x} e^{in\varphi(x,y)}, \qquad (1)$$

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

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

In the truly two-dimensional (OV) cases studied in this work $\varphi(x,y)=\theta$, θ is the azimuthal coordinate and $m=1$.

2.2. 4f- setup

The analyzed 4f-setup is sketched in Fig. 1.

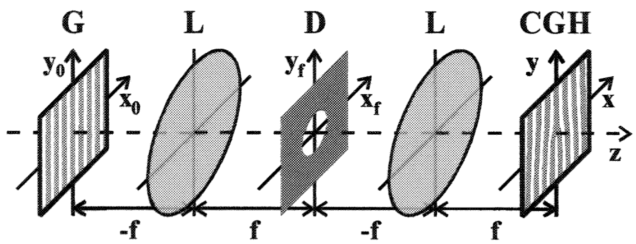

Fig. 1 Scheme of the 4f setup analyzed theoretically. f, focal length; L, lens; G, grating; CGH, computer generated hologram; D, diaphragm.

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

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

In the particular case of an incoming Gaussian beam

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

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

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

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

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

In Eqs. 5, 6 d is the period of the diffraction grating. Applying the Fourier-transformation (3) 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. The last multiplier in Eq. (8) accounts for the spatial dispersion at the exit of the 4f-setup. Since $\beta = -1$ for perfect 4f-alignment, $(1+\beta) \rightarrow 0$ and vortices generated in each individual spectral component will be recombined spatially and temporally to overlap at the exit without spatial chirp.

2.3. Double-pass grating compressor

The analized compressor is sketched in Fig. 2. The last grating is replaced by the CGH of a period *d*, equal to that of the other gratings

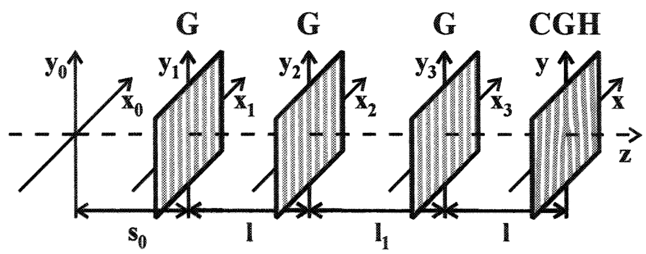

Fig. 2 Scheme of the double-pass compressor analyzed theoretically.

In order to evaluate the field distribution the input plane is shifted at the distance s_0 in front of the first grating. This shift is unspecified and, as it will be shown later, can be set equal to zero. The transmission function of the gratings and the CGH are described as follows:

$$T(x_1, y_1) = \frac{1}{\pi} e^{i\frac{2\pi}{d}x_1} \qquad T(x_2, y_2) = \frac{1}{\pi} e^{-i\frac{2\pi}{d}x_2}$$
$$T(x_3, y_3) = \frac{1}{\pi} e^{-i\frac{2\pi}{d}x_3} \qquad T(x, y) = \frac{1}{\pi} e^{i\frac{2\pi}{d}x} e^{i\varphi(x,y)} \tag{9}$$

Plus or minus sign in the phase term refer to beam propagation in first or in minus first diffraction order of the respective grating. The analysis consists in evaluating the diffraction integral

$$E(x, y, s) = \frac{e^{i\frac{2\pi}{\lambda}s}}{i\lambda s} \iint E(x_o, y_o, 0) e^{i\frac{\pi}{\lambda s}[(x-x_o)^2+(y-y_o)^2]} dx_o dy_o \tag{10}$$

between the planes in which the gratings are located. In this way we described the field in front of the CGH

$$E(x,y)=\frac{1}{\pi^3}e^{-i\frac{2\pi}{\lambda}l\left(\frac{\lambda}{d}\right)^2}e^{-i\frac{2\pi}{d}x}\frac{e^{i\frac{2\pi}{\lambda}s}}{i\lambda s}\iint E(x_o,y_o)e^{i\frac{\pi}{\lambda s}[(x-x_o)^2+(y-y_o)^2]}dx_o dy_o . \quad (11)$$

We obtained the output electric field amplitude in form

$$E'(x,y)=\frac{1}{\pi^4}E_{diff.}(x,y)e^{i\frac{2\pi}{\lambda}\left[s-l\left(\frac{\lambda}{d}\right)^2\right]}e^{i\varphi(x,y)}, \quad (12)$$

where $E_{diff.}$ is the input electric field amplitude diffracted in the course of the optical beam propagation in the compressor. The phase term in Eq. (12) is in agreement with the clasical results of Martinez, Gordon and Fork[7].

3. EXPERIMENTAL RESULTS

In this work a Ti:sapphire Kerr-lens mode-locked oscillator pumped by intracavity-doubled Nd:YVO4 laser (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. A 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. The frames are recorded with a CCD-camera with a 12 μm resolution.

When a phase dislocation of any kind is generated by a single CGH (no 4f-setup) in the spectral components of a fs-pulse, the angular dispersion causes the spectral component to separate. Spatial chirp and pulse-front tilt of the pulse are presented and the dark beam contrast reduces rapidly with increasing the propagation path length (see Fig. 3 and Fig. 4.). Only 1D phase dislocation encoded in the CGH perpendicular to the grating stripes propagates with a maximal modulation dept.

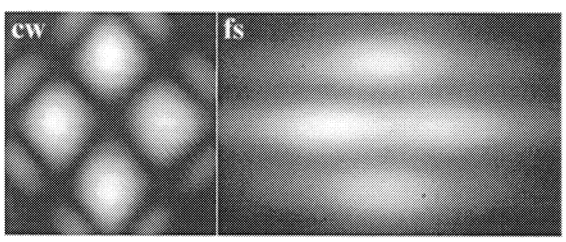

Fig. 3. Grayscale images of quasi-2D dislocation 35 cm behind the CGH in cw and fs regime. No 4f-setup is used.

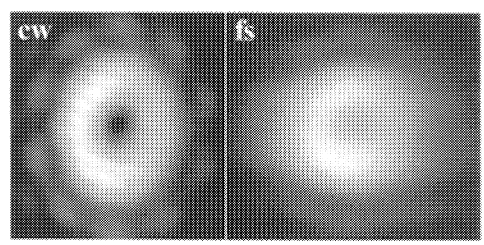

Fig. 4. The same as in Fig. 3., but 2D optical vortices are generated.

In Fig. 5. 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. 4, 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 wich makes this contribution difficult to recognize. Further attempts to optimize the experimental conditions are under way.

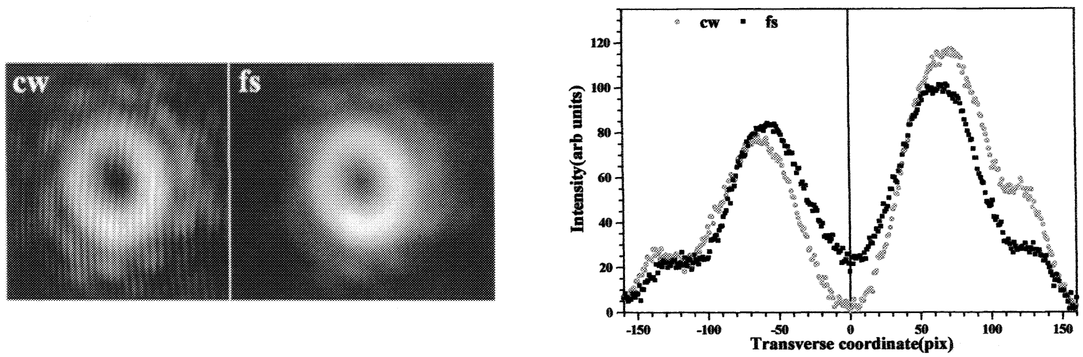

Fig. 5. Optical vortices recorded 35 cm after the 4f-setup in cw and fs regime (left) and the transversal cross-sections (right).

CONCLUSION

In these work we show theoreticaly, that dark beams with phase dislocations in femtosecond laser fields can be generated by using a dispersionless 4f-setup or a grating compressor in which the last grating is replaced by a computer generated hologram. Exerimental results obtined with 20-fs laser pulses passing through a 4f-setup are presented.

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