Vortices in femtosecond laser fields

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We experimentally generate optical vortices in the output beam of a 20-fs Ti:sapphire laser. Screw phase dislocations are imposed on the spectral components of the short pulses by aligning a computer-generated hologram in a dispersionless 4*f* setup.

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An optical vortex (OV) is an isolated point singularity in a wave front with a screw-type phase distribution. Since the phase is indeterminate at the singularity point, both the real and the imaginary parts of the field amplitude (i.e., also the field intensity) are zero.[1] Such a phase profile is described by an $\exp(il\theta)$ multiplier, where θ is the azimuthal coordinate and integer number l is called the topological charge. The interest in generating OVs in femtosecond laser fields is motivated by the possibility of creating short bursts of photons, the total angular momentum of which can be varied independently of the field polarization by the topological charge.[2] The helical phase distribution also provides a new degree of freedom in the phase control of high-harmonic generation. The challenge, however, is to impose the phase dislocation on all the spectral components of the short pulse while keeping the pulse width and shape as undistorted as possible[3] and the pulse front untilted.

The known methods that are applicable in the cw and the quasi-cw regimes are not suitable for femtosecond lasers. Astigmatic transverse-mode converters[4] cannot be used directly, since mode locking is achieved only if the resonator is aligned to emit the fundamental TEM_{00} mode. The approach[5] to preparing a Hermite–Gaussian-like (HG_{01}) mode at the entrance of the converter[4] by splitting and spatially offsetting a HG_{00} mode that is out of phase seems feasible but requires an additional interferometrically controlled delay line. Immersed transparent spiral wave plates[6] are less flexible in dynamically controlling the phase distribution than are liquid-crystal modulators structured in pie slices.[7] Both devices preserve the beam path, but the latter exhibits an energy-conversion efficiency near 100%. In both cases, however, the magnitude of the phase jump of the OV will deviate from π for the different spectral components of the short pulse, and such modulators do not seem to be applicable after regenerative or multipass amplifiers. Another known[8] and widely used method of generating OVs in a controlled way is the use of computer-generated holograms (CGHs). Such a grating aligned as part of a dispersionless 4*f* system[9] is, in our view, an adequate solution of the formulated problem. What we believe to be the first successful experimental results obtained with 20-fs laser pulses are presented and discussed below.

We first analyze the 4*f* setup illustrated in Fig. 1. The diffraction of a monochromatic wave with an initial electrical field amplitude $E_{\mathrm{in}} = E(x_0, y_0, 0)$ and wavelength λ along propagation axis s is described by the Fresnel integral

$$E(x,y,s) = \frac{\exp\left(i\,\frac{2\pi}{\lambda}\,s\right)}{i\lambda s} \iint E_{\mathrm{in}} \times \exp\left\{i\,\frac{\pi}{\lambda s}\,[(x-x_0)^2 + (y-y_0)^2]\right\} \mathrm{d}x_0 \mathrm{d}y_0 . \tag{1}$$

Taking into account the phase introduced by a single thin lens with an infinite aperture and focal length f, one can calculate the field distribution,

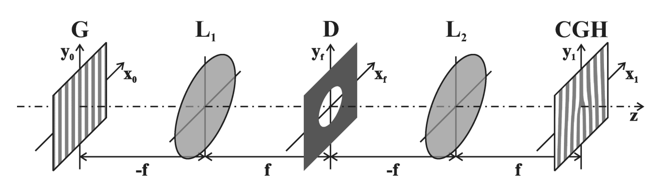

Fig. 1. Illustration of the 4*f* setup that is analyzed theoretically. G, diffraction grating; CGH, computer-generated hologram with an encoded phase singularity; L_1, L_2, lenses of equal focal length f; D, iris diaphragm. The input, Fourier, and output planes are denoted by indices 0, f, and 1, respectively.

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$E_f = E(x_f, y_f, f)$, in the Fourier plane. The iris diaphragm does not affect the propagation of the first-order diffracted beam passing through the $4f$ system and removes all other beams. In the particular case of an incoming Gaussian beam, $E_{\text{in}} = E_0 \exp[-(x_0{}^2 + y_0{}^2)/\sigma_0{}^2]$, the first-order diffracted wave just after the first grating, G (see Fig. 1), is described by

$$E'(x_0, y_0) = (1/\pi)E_0 \exp\left(-\frac{x_0{}^2 + y_0{}^2}{\sigma_0{}^2}\right)\exp\left(i\,\frac{2\pi}{d}\,x\right), \tag{2}$$

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

$$E(x_f, y_f) = \frac{\sigma_0{}^2}{\lambda f}\,E_0 \exp\left[-\frac{\left(x_f - \dfrac{\lambda f}{d}\right)^2 + y_f{}^2}{\left(\dfrac{\lambda f}{\pi\sigma_0}\right)^2}\right]. \tag{3}$$

In Eqs. (2) and (3), d is the period of both gratings (G and the CGH). Applying the Fourier transform again, one obtains the field distribution in front of the CGH:

$$E(x_1, y_1) = \frac{1}{\pi\lambda^2 f^2}\,E_0 \exp\left[-\frac{x_1{}^2 + y_1{}^2}{(\beta\sigma_0)^2}\right]\exp\left(i\,\frac{2\pi}{\beta d}\,x_1\right). \tag{4}$$

In the transmission function of a binary diffraction grating consisting of perfectly reflecting and transmitting stripes of equal widths, even diffraction-order beams are absent,[10] and the first-order beam is given by $T(x, y) = (1/\pi)\exp(i2\pi x/d)\exp[i\varphi(x, y)]$. In this way we derived the following analytical expression for the electric field amplitude $E'(x_1, y_1)$ at the exit of the $4f$ system:

$$E' = \frac{1}{(\pi\lambda f)^2}\,E_0 \exp\left[-\frac{x_1{}^2 + y_1{}^2}{(\beta\sigma_0)^2}\right]\exp[i\varphi(x_1, y_1)] \times \exp\left[i\,\frac{2\pi}{d}\left(1 + \frac{1}{\beta}\right)x_1\right], \tag{5}$$

where β is the angular magnification of the system and $\varphi(x_1, y_1)$ is the phase encoded in the CGH. In the truly two-dimensional (OV) case studied in this Letter, $\varphi(x, y) = \theta$ for a topological charge $l = 1$. The last multiplier in Eq. (5) accounts for the spatial dispersion at the exit of the $4f$ setup. For perfect alignment ($\beta = -1$) the $4f$ system cancels for the spatial dispersion introduced by grating G and the CGH. Vortices generated in each individual spectral component are recombined spatially and temporally to overlap at the exit without spatial chirp. Inasmuch as no spatial filtering is performed in the Fourier plane, the low resolution, $d\lambda/dx_f = 150$ nm/mm, is acceptable. Spatial beam shaping and temporal pulse shaping within a single $4f$ system would require much more dense gratings and lenses–focusing mirrors of shorter focal lengths.

In this Letter a Ti:sapphire Kerr-lens mode-locked oscillator pumped by intracavity-doubled Nd:YVO_4 (Millenia Vi) is used. It emits nearly transform-limited 20-fs pulses[11] at a repetition rate of 78 MHz with a mean power of 200 mW at a central wavelength of 797 nm. In the experiment a binary CGH produced photolithographically with a stripe period of $d = 30$ μm is used. Function $T(x, y)$ indicates that the only phase dislocation that is produced in the spectral components of an ultrashort pulse with a single grating (i.e., no $4f$ setup) and ensures maximal modulation depth is one-dimensional, provided that the dislocation is encoded in the CGH perpendicular to the grating stripes. In this case the presence of spatial chirp and pulse-front tilt of the femtosecond pulse are inevitable. This is seen in experimental frames recorded with a CCD camera with 12-μm resolution and will be discussed in the future. When an OV is generated by a single CGH, the vortices generated in different spectral components are not recombined. The presence of spatial chirp and pulse-front tilt of the pulse is accompanied by reduced dark beam contrast (see Fig. 2). As expected, the beam smearing was found to increase with increasing propagation path length. The $4f$ setup (Fig. 3) is folded in the (x_f, y_f) plane by a silver-coated mirror. A large-aperture (2.5-cm) quartz lens with focal length

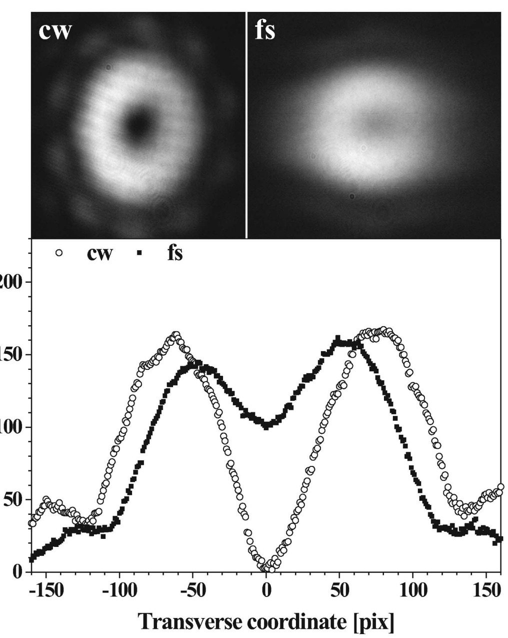

Fig. 2. Top, gray-scale images of OV beams 35 cm behind the CGH, for cw and femtosecond (fs) laser beams. No $4f$ setup is used. Bottom, vertical cross sections.

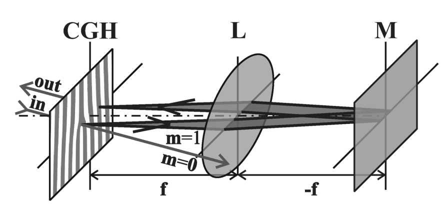

Fig. 3. Scheme of the $4f$ setup used in the experiment. L, quartz lens of focal length $f = 20$ cm; M, folding mirror; m, diffraction orders.

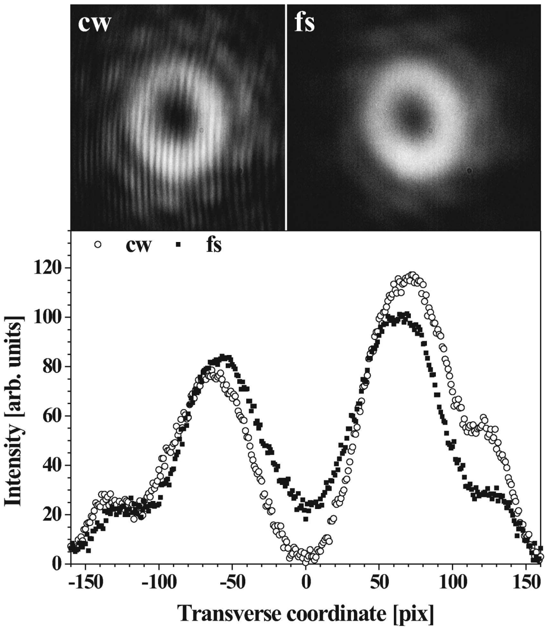

Fig. 4. Top, optical vortices recorded 35 cm after the 4f setup in the cw and the fs regimes. Bottom, vertical cross sections of the optical vortices in both regimes.

$f = 20$ cm is aligned carefully to minimize aberrations. The CGH is positioned to reconstruct the encoded phase dislocation on the background beam. In the peripheral part of this grating the stripes are parallel. Therefore, such a region can serve as a second grating to recombine the spectral components at the exit. In Fig. 4 we show experimental results obtained with this 4f setup. Images of optical vortices in the femtosecond and the cw regimes are recorded successively by turning the mode locking on or off and keeping the alignment unchanged. Interference lines in the frame recorded in the cw regime can be clearly seen. They appear as a result of slight overlap of the OV beam exiting the 4f system with a beam reflected directly from the CHG substrate. Because of the lack of temporal overlap and the reduction of the coherence length, both interference and speckles disappear in the femtosecond regime. Unlike in Fig. 2, the contrast of the femtosecond OV is gradually improved and can be maximized by filtering out all parasitic reflections. An estimate based on the visibility of the interference structure in the cw regime (Fig. 4) shows a $10 \pm 3\%$ contribution of such reflections to the background signal in the vortex core. Recent work[12] confirming predicted chromatic effects in the vortex region at a slightly uncompensated spectral dispersion[13] is indicative of the importance of precise alignment. A deeper understanding of the spatiotemporal behavior of focused femtosecond beams with phase singularities should be of both theoretical and experimental interest. Our results demonstrate the principal possibility of creating vortices in femtosecond optical fields by use of binary photolithographically produced CGHs. The first-order diffraction efficiency of such CGHs is limited[10] (10%). For real ultrashort pulse applications higher efficiencies are desired. Binary CGHs and structured liquid-crystal modulators[7] can be used to reconstruct OV beams for a subsequent truly holographic recording of the pattern on a substrate coated with photoresist.

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