Over 1-mJ intense ultrashort optical-vortex pulse generation with programmable topological-charge control by chirped-pulse amplification

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Abstract: We demonstrated the generation of over 1-mJ intense optical-vortex pulses of which topological charges were programmably controlled by computer-generated holograms. The pulse duration was characterized to be 27 fs by two-dimensional spectral shearing interferometry.

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1. Introduction

Optical vortices attract growing attention during last decade because of their various applications – quantum information processing, laser ablation, optical tweezers, etc. The essential property of optical vortex is its spatially-varying phase distribution. Combination of recent phase control techniques in time or frequency domain with spatial phase control to generate optical vortices is a reasonable approach. It enables us to carry out ultrafast nonlinear spectroscopy and high-field interaction with matter.

We have already demonstrated the generation of 56-μJ, 5.9-fs ultrashort optical-vortex pulses by using optical parametric amplification (OPA) [1]. The key device in our previous work was an optical-vortex converter with a spatial-variant waveplate. This device has advantages of ultrabroadband applicability and of high throughput. On the other hand, the topological charge of optical vortices generated by it is uniquely determined by the structure or design of the spatial-variant waveplate. Therefore, in order to change topological-charge value, replacement of the waveplate and realignment of the amplifier are required, which implies the low flexibility of the experimental setup.

The computer-generated hologram (CGH) [2] is widely used for the generation of optical vortices, enabling us to generate light with arbitrary topological charges, even as a charge-mixed state. However, it is not suitable for ultrashort (or ultrabroadband) input pulses because its essential effect of diffraction causes angular dispersion. In earlier study [3], although 4-f setup was proposed to compensate for the angular dispersion, the total throughput is quite low (less than several percents) owing to the low diffraction efficiency ($\sim$10%–$\sim$20%) of the CGH.

In the present paper, we report the generation of mJ-class intense ultrashort optical-vortex pulses by Ti:sapphire-based chirped-pulse amplification of the seeding optical vortices generated by the 4-f vortex converter with a CGH. Low throughput of the 4-f setup can be easily recovered in the amplification process, thus our configuration enables us to obtain intense ultrashort optical-vortex pulses with programmable topological-charge control.

2. Experiments and Results

Our system consists of two Ti:sapphire-based amplifiers and a 4-f optical-vortex converter located between them. The output from a Ti:sapphire laser oscillator (repetition rate: 80 MHz, 730 – 880 nm, averaged power: $\sim$500 mW) was temporally-stretched by a grating-based pulse stretcher and amplified by a home-built 1st-stage Ti:sapphire regenerative laser amplifier (repetition rate: 1 kHz). A 2-μm-thick etalon filter [4] was utilized to compensate for the so-called gain narrowing effect due to bandwidth limitations of a Pockels cell, polarizers and other components. The output from the regenerative amplifier was attenuated to $\sim$70 μJ/pulse, which is below the damage threshold of a spatial light modulator (SLM, Hamamatsu photonics X10468, 792 $\times$ 600 pixels, design wavelength range: 700 – 900 nm) in our 4-f optical-vortex converter.

The primary reason why optical-vortex conversion was done after regenerative amplification is that the amplification process is greatly affected by the dominant transverse eigenmodes of the amplifier cavity itself, thus it is difficult to well amplify the seeding vortices. Moreover, if we amplify very weak nJ-level optical-vortex pulses directly in the amplifier, non-negligible amplified spontaneous emission (ASE) might arise in the beam center by the spatially-Gaussian-shaped pump beam, which is quite different from the doughnut-like beam shape of the seeding optical vortex. This undesirable ASE can be greatly decreased by optical-vortex conversion after pre-amplification. After passing through the optical-vortex converter, the generated optical vortices were amplified again by a 2nd-stage 4-pass amplifier, and the frequency-chirp was compensated for by a grating-based pulse compressor. This 2-stage amplification enables us to generate intense broadband optical-vortex pulses with pulse energy more than damage threshold of the optical-vortex converter with the SLM.

The beam profiles of the amplified optical vortices and the corresponding interferograms by astigmatic transformation [5] are shown in Fig. 1. Seen clearly, the topological charges of the output were well-controlled with topological-charge flexibility by changing the CGH patterns, and the amplified vortices have the common center point in all cases. The pulse energies after frequency-chirp compensation were 1.1, 1.3, 1.2 and 1.0 mJ for topological charges of $m = 0$, 1, 2, and 3, respectively. The typical temporal profile of the amplified optical-vortex pulses ($m = 0-3$) were characterized by a two-dimensional shearing interferometry apparatus (Fig. 2(a)). As shown in Fig. 2(b), the pulse duration was evaluated to be 27 fs (the corresponding Fourier-transform limited pulses: 24 fs), which is close to that of one of the typical shortest pulses directly from Ti:sapphire amplifiers.

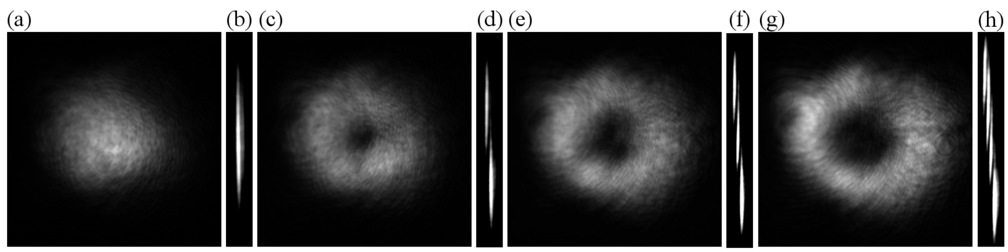

Fig. 1. Measured beam profiles of the amplified optical-vortex pulses with topological charges of (a) $m = 0$, (c) $m = 1$, (e) $m = 2$ and (g) $m = 3$, together with the corresponding interferograms by astigmatic transformation in the cases of (b) $m = 0$, (d) $m = 1$, (f) $m = 2$ and (h) $m = 3$, respectively.

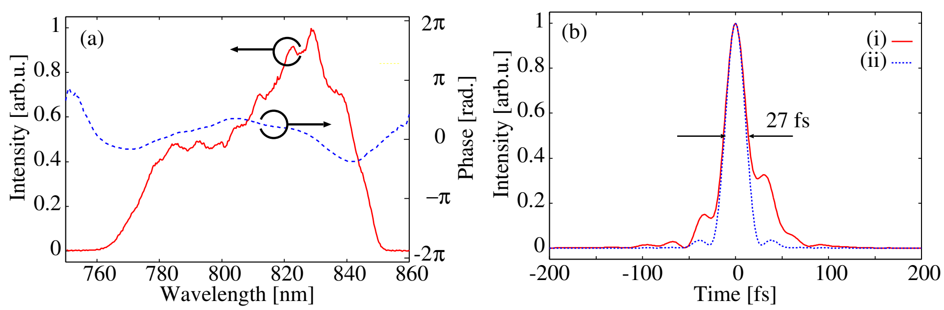

Fig. 2. (a) Measured spectrum and reconstructed spectral phase of the amplified optical-vortex pulses ($m = 0$). (b) Temporal profiles of (i) the reconstructed (27 fs, $m = 0$) and (ii) the corresponding Fourier-transform-limited optical pulses (24 fs).

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