Spatiotemporal dynamics of femtosecond pulses shaped by diffractive optical elements (DOEs)

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Abstract: We present a complete experimental characterization and simulation of the spatiotemporal and spatio-spectral effects taking place when a femtosecond pulse is shaped by a diffractive optical element.
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1. Introduction

Ultrafast femtosecond lasers have found many applications in fields like spectroscopy, high-field physics, medicine or laser processing. Some of these applications have been demonstrated to benefit from diffractive shaped beams [1]. For example, flat-top beams (FTBs) are preferred to Gaussian profiles in micromachining since they yield minimal edge roughness. A common approach to obtain a shaped profile is by means of a phase-only diffractive optical element (DOE) and a Fourier lens. However, due to the broadband nature of femtosecond pulses, space-time coupling effects can happen since the shaped profile is formed for a given wavelength λ at a plane [2]

$$z = f\,\frac{\lambda_{DOE}}{\lambda} \qquad (1)$$

being f the focal length of the Fourier transforming lens and λ_{DOE} the wavelength the DOE was designed for.

Therefore, a complete characterization is mandatory to assess the usefulness of diffractive shaped pulses for further applications. In this contribution, we report the complete spatiotemporal dynamics and propagation of femtosecond shaped pulses, both with simulations and experiments. In particular, we have analyzed a Gaussian-to-flat-top DOE and a diffractive lens (DL).

2. Results and discussion

For the experimental characterization we employed the STARFISH technique, which consists on measuring the spatially-resolved spectral interferences by using a fiber couples as interferometer [3]. The experimental setup is shown in Fig. 1. The laser delivers 100 fs pulses at 1 kHz repetition rate and a central wavelength of 795 nm. A spatial filter was used to obtain a clean Gaussian beam; the profile and wavefront were checked with a CCD camera and a wavefront sensor. The beam was then split in two replicas: the first one acted as a reference and was characterized by means of a standard technique, such as FROG. The DOE was placed in the second arm (test), which is motorized along the transverse axis. A CCD was put at the Fourier plane in order to monitor the spatial profile of the shaped beams.

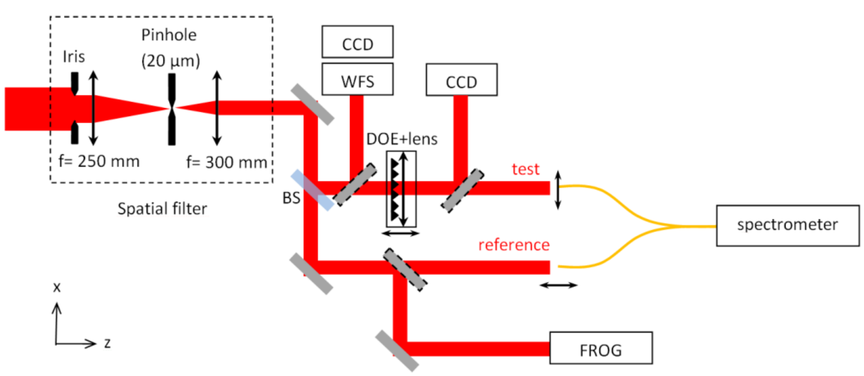

Fig. 1. Experimental setup for the spatiotemporal characterization of diffractive shaped beams (see details in the text).

As DOEs we employed a DL and a Gaussian-to-flat-top shaper. The focal length of the DL depended on the wavelength according to (1) and was designed for a wavelength of 532 nm (f=200 mm). The FTB shaper was designed to work at 800 nm with a 200 mm focal length lens, and provided a 4 mm-FTB from a 6 mm Gaussian beam. In both cases, experimental results were corroborated by simulations. For this purpose, the Fresnel integral was numerically solved:

$$U(r,z,\lambda) = \frac{2\pi}{iz\lambda}\exp\left(\frac{i\pi r^2}{z\lambda}\right)\exp\left(i\frac{2\pi z}{\lambda}\right)\int_0^\infty U_0(\rho,\lambda)\exp\left(-i\frac{\pi\rho^2}{f\lambda_{DOE}}+i\frac{\pi\rho^2}{z\lambda}\right)J_0\left(\frac{2\pi r\rho}{\lambda z}\right)\rho d\rho \qquad (2)$$

being U_0 the electric field at the plane of the DOE.

For the DL, an example of the results at a propagation distance of 106 mm, which corresponds to the focus of the central wavelength of our laser, is shown in Fig. 2. Under these conditions, redder wavelengths are diverging, while shorter ones are still converging. In the spatio-spectral domain, the beam waist is minimized at the central wavelength, increasing for shorter and longer frequencies. The spatiotemporal intensity (Fig. 2a) corresponds to the far-field structure with a main broadened central peak, and a train of pulses in the wings coming from the ring structure [4].

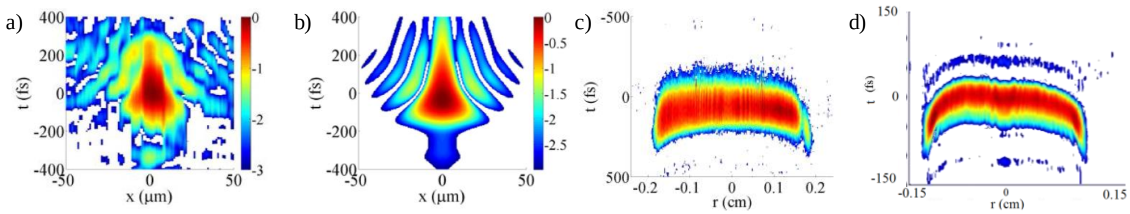

Fig. 2. Comparison between the a) experimental and b) simulated spatiotemporal maps at the focus of a diffractive lens. Spatiotemporal maps of c) 100 fs and d) 30 fs FTBs at a distance of 200 mm from the DOE (same color scale as in panel a) applies to c) and d)).

For the FTBs, two sets of experiments were conducted, with a 100-fs and a 30-fs laser. In the first case, the beam size changed monotonically with the wavelength. As a direct consequence, the spatial profile of the FTB is slightly blurred. This wavelength dependence also reflects on the form of side tails in the temporal domain (Fig. 2c), being the pulse lengthened at the edges of the flat-top. This effect is more pronounced for shorter pulses. For the 30-fs laser source (Fig. 2d), the pulse front presented a curvature in such a way that the pulse is delayed at the borders of the FTB by approximately 50 fs with respect to the central part.

3. Conclusions

In conclusion, we have demonstrated the potential of the STARFISH technique for the spatiotemporal characterization of DOEs. Space-time coupling effects have been observed for both, DLs and top-hat shapers. In the case of the DLs the ring structure gives rise to a train of pulses in the temporal domain. In contrast, femtosecond FTBs presents a monotonically increasing beam size with the wavelength and a curvature in the pulse front. The results of this study will be helpful, for example, to understand the filamentation dynamics with DLs [5] and to assess the validity of top-hat shapers for femtosecond laser processing.

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