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Spatio-temporal propagation of ultrashort pulses controlled by structured optical elements

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We present a method for analyzing and synthesizing SOE's that control the spatial and temporal characteristics of femtosecond light pulses. These elements utilize the diffraction, refraction, and dispersive effects that appear in the femtosecond regime. Although there are fundamental limitations in the degree of control that is achievable, we show the potential of this technique with two examples: a SOE to improve simultaneously the spatial and temporal resolution of a lens and a SOE to generate ultrafast pulse sequences.

The generation of temporally shaped optical waveforms is important for applications such as optical communication and the study of ultrafast processes in matter. As a consequence, various techniques for temporal pulse shaping have been developed [1-4]. However, in some applications like microscopy or materials processing, the spatial characteristics are critical as well. Several works have studied the influence of lenses and mirrors on the spatial and temporal properties of pulsed beams [5]. In this work we investigate the possibility of simultaneously controlling spatial and temporal features of ultrashort pulses by the use of a single structured optical element (SOE).

We consider an ultrashort light pulse incident on a thin element, which can modulate amplitude and phase, and observe its propagation in the half free space behind it, as shown in Fig. 1. In general, the SOE may possess refractive and diffractive surfaces, as well as multiple layers of different materials. As opposed to the situation found in classical diffractive optical problems, the broadband and coherent character of the illumination produce unique effects. The difference between phase and group velocity within the material produces time delays among different portions of the wave propagating along different paths. The group velocity dispersion leads to pulse stretching. Refraction and diffraction at the boundaries modulate the wave-fronts and introduce dispersion. As a result the spatial intensity distribution at a given observation plane differs dramatically for different frequency bands, while the temporal characteristics at each location may be completely different from those of the incoming pulse.

In order to have a detailed evaluation of the spatial and temporal effects we need to consider a full solution of Maxwell equations. Nevertheless, under certain circumstances, that depend on the structure of the SOE, we can consider different simplifications as using a scalar representation of the electric field and a thin element approximation. Accordingly, at each temporal frequency the field across a plane immediately behind the element is calculated as the product of the incident field and a (frequency dependent) transmittance function. The diffracted field for each frequency component is calculated using a decomposition in plane waves. The frequency dependent spatial distribution that results from this solution can be transformed into the spatio-temporal field distribution by means of a (temporal) Fourier transformation.

The transmittance function can be evaluated from the geometry and the material properties of the SOE. The phase modulation includes the spatially and wavelength dependent phase delay that is responsible for dispersion in the material composing the optical element. To calculate the diffracted field we need to know

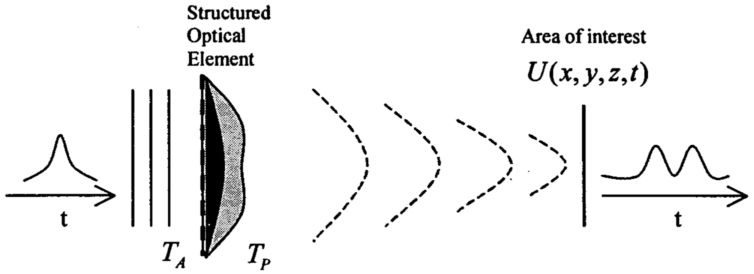

Figure 1: Graphical representation of the spatio-temporal shaping problem

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the dispersion characteristics of the material and the spatial and temporal shape of the incident pulse. For the purpose of this paper we expanded the index up to second order about the central frequency and considered an incident pulse of spatial plane waves and a Gaussian temporal dependance.

In the first example we consider the problem of focusing ultrashort light pulses. It is well known that singlet lenses produce pulse spreading in time relative to the input field, and beam spreading in space relative to the diffraction limit achievable with monochromatic light [5]. Pulse spreading is caused by the propagation time difference (PTD) and by the group velocity dispersion (GVD) in the material. The pulse width is also wider at later times because of the apodization effect caused by the PTD. These spatio-temporal effects are shown in Fig. 2(a) for a cylindrical lens (BK7 glass, f/15, 30cm focal length) and a 15 fs pulse centered at 620nm.

We designed a SOE consisting of a refractive-diffractive cylindrical pair to improve the focusing function in two ways, namely compensating for the chromatic first order dispersion and reducing the material thickness, which leads to a significantly reduced GVD. The diffractive structure was optimized numerically to attain a maximal spatio-temporal focusing. as shown in Fig. 2(b). In this case, compared to the situation of Fig. 2(a), the peak intensity is 63% larger, the pulse duration (17 fs at FWHM) is 21% shorter, and the spot-size (FWHM) is at least 16% smaller.

In a second example we explored the possibilty of shaping the pulse intensity in time at the focal point of a spherical lens. For this purpose we propose to attach a binary-amplitude computer-generated hologram. Fig.3. depicts the response of such a system when optimized to produce a train of femtosecond pulses.

In conclusion, in the femtosecond regime the diffraction and refraction effects are entangled with dispersive phenomena. SOE are intended to compensate and utilize these effects to attain useful optical functions. The analysis and synthesis of such elements is more intricate than in the case of classical diffractive optical elements; i.e. the requirements for ultrafast optics go beyond the achromatization considerations usually applied to incoherent broadband illumination. The analysis and examples that we show here are a first attempt to generate a new class of ultrafast optical elements.

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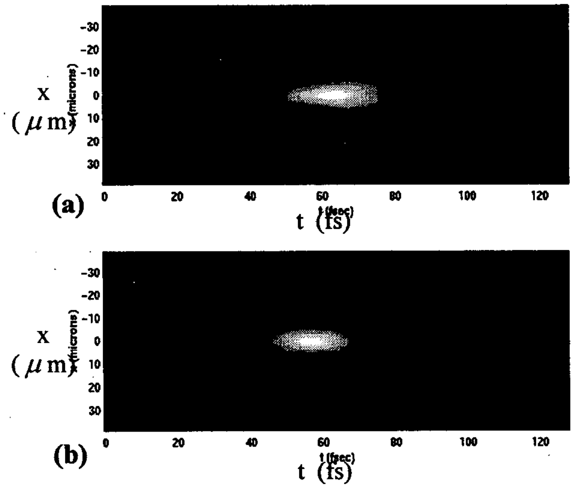

Figure 2: Spatio-temporal response to a 15 fs pulse (focal length 30cm, f/15): (a) Singlet lens, (b) optimized SOE lens.

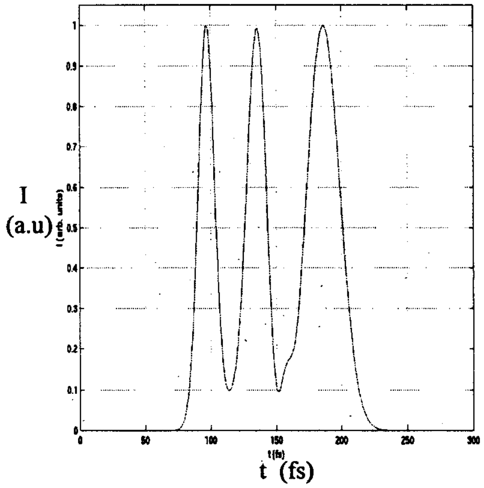

Figure 3: Normalized axial time response to a 15 fs pulse of the optimized SOE, showing a three pulse train.