Application Note 8010

Pulse Shaping
Application Note

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Shaping ultrafast optical pulses with liquid crystal spatial light modulators

Why shape femtosecond laser pulses?

Ultrashort pulses are routinely used to excite dynamic processes in quantum-mechanical systems. The shape of the temporal intensity envelope plays a large role in the excitation dynamics, and hence the outcome of the process. The ability to "coherently control" or drive an experiment with a shaped optical field is one of the most intriguing applications in the field of ultrafast phenomena today.

However, even if coherent control isn't the goal, there are pragmatic reasons to consider programmable pulse shape control when using femtosecond lasers. A pulse shaper provides the ultimate control in terms of dispersion and amplitude compensation. The pulse shaper can be used to ensure that the pulse delivered on target is precisely the desired pulse, e.g., it can effectively pre-compensate for dispersive optics. This is especially useful if the optical dispersion changes during the experiment as it can for example, in multiphoton microscopy.

Multiphoton optical microscopy

Multiphoton microscopy is, without doubt, one of the most desirable tools to have in a modern biological laboratory. It enables high-resolution, dynamic studies of biological systems. In these microscopes, image contrast is generated through any of a number of nonlinear optical processes: two photon absorption fluorescence (TPAF), second harmonic generation (SHG), third harmonic generation (THG), etc. In each case, the imaging efficiency depends on the width of the excitation pulse. Second order processes depend linearly on the pulsewidth (e.g., TPAF, SHG), while third order and higher processes depend nonlinearly on pulsewidth. The shorter the pulsewidth, the more efficient each of these processes becomes. A typical multiphoton microscope will need dispersion compensation on the order of 5000 fs^2, which is readily achieved with a pulse shaper. Objectives can account for 10 to 20% of this dispersion. Thus as soon as the objective is changed, the dispersion compensation will need to be re-optimized. A pulse shaping system accommodates this change in dispersion without the need for realignment.

Ultrafast pulse shaping - how it works

How ultrafast laser pulses are shaped is fairly easy to understand from a qualitative point of view. If one realizes that an ultrashort pulse is composed of many frequencies of light, all of which sum coherently to create the temporal intensity envelope, then it is fairly easy to see that by removing frequencies or manipulating when frequencies arrive at a given point in space relative to one another, it is possible change the way these different frequencies interfere, and hence the temporal shape of the pulse.

Pulse shaping is typically done in the frequency domain, as there are no electronics fast enough to allow for programmable control of the pulse in the temporal domain. In order to experimentally realize shaping in the frequency domain of a pulse, the apparatus shown Fig. 1 is often used [1]. Known variably as a "4-*f* line", "zero-dispersion line", or "Martinez stretcher", this apparatus makes use of the angular dispersion and a lens to access the frequency domain of the pulse. In the first part of the apparatus, the frequencies of the pulse are angularly dispersed by a diffraction grating (though any element that induces angular dispersion as a function of frequency will work). The angularly dispersed light is then collimated with a lens of focal length *f*, placed at one focal length from the grating. The lens serves two purposes: First, it spatially maps the frequency content of the pulse onto a plane (the Fourier plane, Figure 1), and second, it focuses each frequency. By now modulating the amplitude and/or phase of each frequency in this focal plane, the pulse shape in time will, ultimately, be modified. After modulation, the spectrum is then collected by a second lens,and imaged to a second diffraction grating, whereupon the frequencies once again interfere to create the pulse in time.

So how is the modulation accomplished? It is quite easy to simply block certain frequencies of light in the Fourier plane to prevent them from combing with the rest of the spectrum. Often times, a more useful approach is to leave all of the spectrum in the pulse, but to change the *phase* of each frequency. In this manner, shaping pulses becomes a problem of creating programmable optical delay for each frequency of light in the pulse. For this, liquid crystal spatial light modulators are a superb choice.

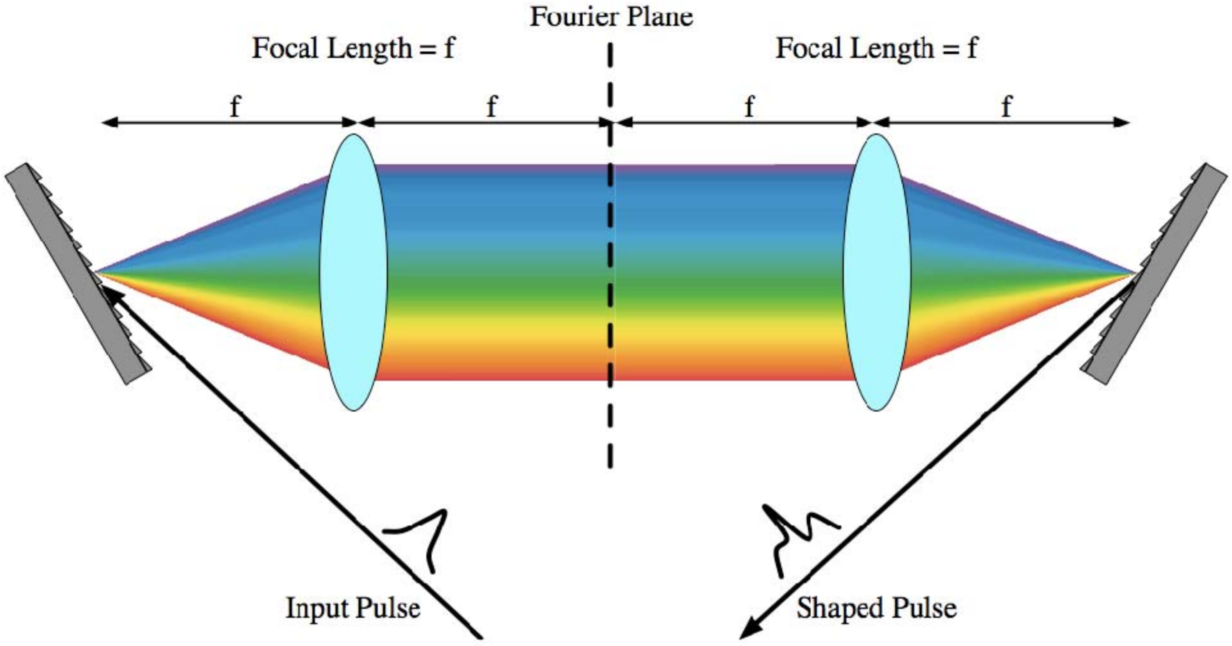

Figure 1: Typical ultrashort laser pulse shaper layout. The spectrum is angularly dispersed and focused to a central focal plane. A modulator placed at this plane can now operate on the amplitude and phase of individual frequencies of the light pulse.

By placing a liquid crystal spatial light modulator in the Fourier plane of the apparatus shown in Fig. 1, one has the ability to alter the optical path length of each frequency of light, changing the spectral phase of the pulse. Because the temporal and spectral domains of an ultrashort pulse are related by a Fourier transform, changing the spectral phase allows the user to synthesize pulse shapes in the temporal domain.

Advantages of LC SLMs from BNS

Liquid crystal spatial light modulators from Boulder Nonlinear Systems are an ideal device to use as the dynamic element in an ultrashort pulse shaping apparatus. The unique construction of these LC SLMs makes them very useful for several reasons. The reflective design of these SLMs makes it possible to use highly reflective coatings to achieve very good throughput. In typical cases, the devices will reflect up to 95% of the incident intensity, a very desirable situation when optical power is of concern to the experiment. Also, because the pixels sizes are very small (1.6 - 1.8 µm pitch), it is possible to write very accurate phase masks to the pulse. This is also advantageous because each frequency of light is over-sampled on the modulator, meaning there are multiple pixels on each of the focused frequencies. This allows one to use the LC SLM as a programmable diffractive optic to steer individual frequencies out of the aperture of the system, thereby allowing for amplitude modulation. By applying properly designed phase masks, it is possible to simultaneously modulate the amplitude and phase of the pulse with a single BNS LC SLM [2, 3, 4].

Compact, high-resolution pulse shaping geometries with BNS modulators

When designing a pulse shaping apparatus, many parameters must be considered. Issues such as spectral resolution, spot size, degrees of freedom, efficiency, etc., must all be taken into account to design an appropriate pulse shaper for a given application. In addition, with lab space at a premium, one of the most desirable characteristics of a pulse shaper design is a small footprint on the optical table.

LC SLMs from BNS are an optimal choice for meeting all these design criteria - high-resolution, high efficiency, compact pulse shaper designs are easily implemented[2-5]. Fig.2 illustrates a compact, grism-based pulse shaper developed at the Center for Microintegrated Optics for Advanced Bioimaging and Control (MOABC), located at the Colorado School of Mines [4]. Note that because the LC SLM is reflective, this pulse shaper is built in a folded geometry, thus reducing its size by a factor of 2 when compared to the traditional geometry shown in Fig. 1. The result is a pulse shaper with high spectral resolution, that has essentially the footprint of a dollar-bill!

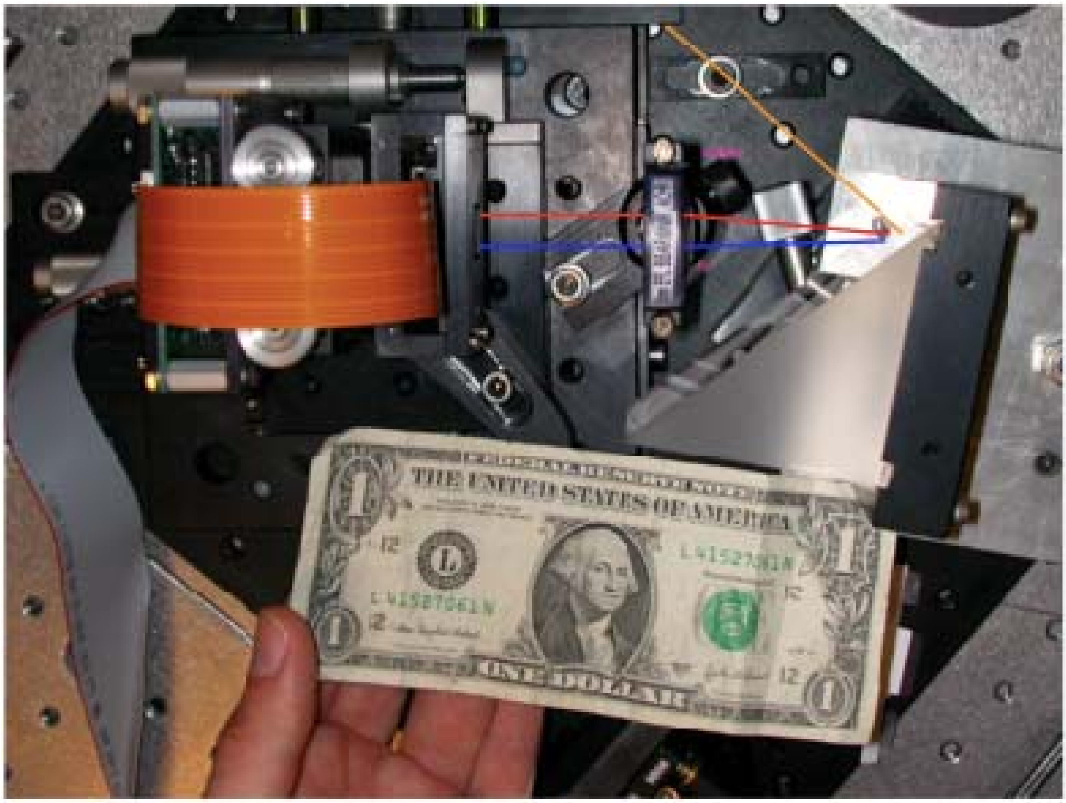

Figure 2: A very compact, grism-based ultrashort pulse shaper [4]. The unshaped pulse (orange line) is angularly dispersed by the grism (1480 lines/mm reflective gold grating, BK7 prism). The angularly dispersed spectrum is then spatially mapped to the BNS LC SLM with a 50-mm-efl achromatic lens. Because the LC SLM is reflective, the achromat is used off-axis to achieve a height change between the input (unshaped) pulse and the output (shaped) pulse. Thus the shaped pulse comes out of the apparatus on the same line it entered (orange line), but it is roughly 2 cm lower.

References

[1] A.M. Weiner, *et al.*, J. Opt. Soc. Am. B, **5**(8), 1988.
[2] J.J. Field, *et al.*, Opt. Commun., **278**(2), 2007.
[3] J.W. Wilson, *et al.*, Opt. Express, **15**(14), 2007.
[4] J.J. Field, *et al.*, Opt. Lett., **32**(21), 2007.
[5] S. Postma, *et al.*, Rev. Sci. Instrum., **76**(123105), 2005.

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