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Characterization of a liquid-crystal ultrafast pulse shaper for ultra-broadband applications

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ABSTRACT

By combining broadband common-path spectral interferometry with an iterative fitting algorithm the phase response of a liquid-crystal spatial light modulator has been characterized from 400 to 770 nm, equivalent to a frequency bandwidth of 0.36 PHz. The resulting calibration not only maps the response of the device as a function of wavelength and voltage, but also provides sufficient information to recover the thickness of the liquid-crystal cell and the wavelength dependent refractive index of the liquid-crystal. The technique has applications in amplitude and phase shaping of pulses from broadband super-continuum and optical parametric oscillator/amplifier sources.

1. Introduction

Ultrafast pulse shapers provide control over the spectral phase—and in some cases the spectral intensity—of femtosecond pulses, enabling the generation of spectral and temporal profiles tailored to the needs of specific experiments [1]. Examples include liquid-crystal spatial light modulators (LC-SLMs) [2], acousto-optic programmable dispersive filters (AOPDFs) [3], and deformable mirrors [4], which have been used to shape pulses for coherent control [5], ultraviolet to mid-infrared spectroscopy [6,7] and Raman frequency-comb compression [8].

An important emerging application of LC-SLMs is their use in pulse shaping over broad bandwidths. A suitably characterized broadband, high-resolution LC-SLM can be used to compress multiple spectral regions simultaneously, enabling few-cycle pulse generation from coherent supercontinua [9], phase and amplitude shaping of tunable optical parametric oscillators (OPOs) [10], and the coherent synthesis of near-single-cycle optical pulses, which exploits broadband carrier-envelope offset (CEO) control [11–13] to synthesize a single frequency comb from a number of individual pulse sequences spanning a wide frequency bandwidth. Recently, we reported a synchronously-pumped OPO in which we achieved zero-offset CEO locking across a bandwidth of 0.66 PHz by using a novel CEO stabilization approach [14]. By enabling the relative carrier phases of the pulses to be held constant, such CEO stabilization is a critical prerequisite for coherent pulse synthesis; however optimizing the synthesis outcome also requires the group delay to be carefully managed across the full synthesis bandwidth. A suitable LC-SLM can be used to adjust the group delay dispersion of the participating pulses in a way that maximizes their mutual temporal overlap, while simultaneously compressing each pulse to its transform-limited duration.

Implementing programmable phase control over a bandwidth approaching a PHz requires a technique that can acquire the characteristically nonlinear dependence of the modulator phase with both wavelength and applied voltage. An established method for obtaining the voltage-dependent phase calibration of an LC-SLM is to operate the device between crossed polarizers oriented at $\pm 45^{\circ}$ to the alignment direction of the liquid crystals, and use the measured transmission $T(V)$ to infer the phase change by using $\phi(V) = \arccos(1-2T(V))$. While this approach could be applied to broad-bandwidth calibration, to date it has only been demonstrated for narrow frequency bandwidths (see Table 1). This arccos inversion also shows high sensitivity around $\phi \sim m\pi$ (m is an integer), so is more vulnerable to intensity noise than techniques such as spectral interferometry which yield linear fringe shits as a function of modulator phase. An alternative method by Tanigawa et al. utilized spectroscopic polarimetry to characterize a proprietary ultrabroadband LC-SLM for phase and amplitude modulation [15,16]. A summary of current characterization methods is shown in Table 1.In this paper we introduce a powerful new calibration protocol, which not only maps the phase response of the device as a function of wavelength and voltage across nearly one octave (400–700700400–700 nm), but also provides sufficient information to

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Table 1
Summary of common LC-SLM characterization methods.

Publication	Shaper geometry	Frequency bandwidth (PHz)	Characterization method
[2,17,18]	Grating	0.006	Amplitude modulation after polarization rotation
[19]	Grating/prism	0.019	Spectral interferometry and Fourier-sideband filtering
[15][a]	Prism	0.881	Spectroscopic polarimetry [16]
This work	Prism	0.360	Spectral interferometry and phase modeling

[a] Non-commercial LC-SLM.

Table 2
Output wavelengths from the pump laser and OPO.

Wavelength (nm)	400	470	530 and 570	640	770
Origin	$2\omega_p$	$\omega_p+\omega_s$	$2\omega_s$	$\omega_p+\omega_i$	ω_p

recover the thickness of the liquid-crystal cell and the wavelength-dependent refractive index of the liquid-crystal.

2. Experiment

The source used in the calibration of the LC-SLM was a Ti:sapphire-pumped femtosecond OPO, which has been described in detail elsewhere [14]. Broadband tunable visible pulses were generated by multiple non-phasematched frequency-mixing processes (Table 2), typically with tens-of-mW-level average powers, and were output coupled through a folding mirror, along with the depleted pump. In this work we used an OPO ring geometry which achieved efficient single-pass frequency mixing in the PPKTP gain crystal, while having the additional benefits of reducing the intracavity material dispersion and providing the visible outputs in a single beam.

The pulse shaper was a folded 4*f* system (Fig. 1), in which the incident and returning beams were coupled in and out by a prism, and had a small relative vertical offset to allow the shaped pulses to be isolated and analyzed. The collinear pump and visible beams were angularly dispersed with a fused silica prism placed at the front focal plane of a 500 mm achromatic doublet [20]. The achromatic doublet ensures that the all test wavelengths are focused to the same plane, with the added advantage that no additional group delay is added to the propagating pulses. Our experiment used a 12,288-pixel reflective liquid-crystal-on-silicon (LCOS) LC-SLM (12,288 Linear Series, Boulder Nonlinear Systems) situated at the back focal plane of the lens. The LC-SLM had an array size of 19.66 mm with a 1.6 μm pixel pitch, comprising a 1.0 μm electrode and a 0.6 μm gap. A custom dielectric high-reflectivity coating was applied to the backplane of the LC-SLM, with the reflectivity optimized at the five shortest wavelengths presented in Table 2. The dielectric coating prevented diffraction from the inter-pixel regions of the backplane, and increased the optical efficiency of the device. Notably, the LC-SLM used in our work had a much higher pixel density than many of the devices used for ultrafast pulse shaping, which typically possess 640 pixels or less. Normally LC-SLMs require the spectral focus to match the pixel period, in order to maximize the spectral resolution. By contrast, the high-pixel density of the LC-SLM we used meant that each spectral focus included a large number of pixels, providing a capability (not exploited in this work) for simultaneous high-resolution phase and amplitude control. The spectral foci at the wavelength extremes of 400 nm and 800 nm were 170 μm and 340 μm respectively; each focus included >100 pixels, and the corresponding resolutions were 0.33 nm at 400 nm and 0.67 nm at 800 nm.A prism-based shaper was preferred over a design using a diffraction grating because it offers greater double-pass efficiency, considerably lower wavelength-dependent loss, and avoids problems associated with overlapping diffraction orders when the bandwidth approaches an octave. The material dispersion introduced by the prism can be compensated either before or after the shaper, or by choosing a prism with low intrinsic material dispersion, such as the fused silica prism used in this work.

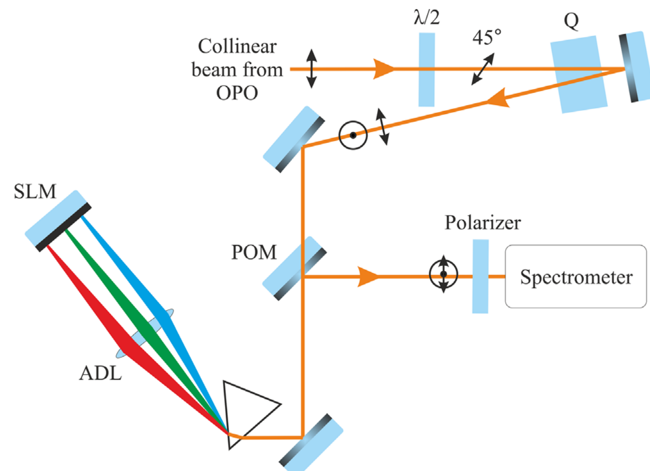

Fig. 1. Layout of the LC-SLM characterization apparatus. ADL: achromatic doublet lens, POM: vertical pick-off mirror, Q: quartz plate, and SLM: spatial light modulator.

3. Calibration

The purpose of the shaper calibration is to produce a function providing the optical phase written by the shaper as a function of both wavelength and applied voltage. The procedure necessitated two distinct calibration steps which yielded separate functional maps of frequency-to-pixel number and voltage-to-phase. The frequency-to-pixel calibration followed a standard method [20] and is provided here only for completeness. The wavelength-dependent voltage-to-phase calibration adopted a novel approach which is significant because of its intrinsic ability to handle broadband data in a single measurement.

3.1. Frequency-to-pixel number calibration

The spatial distribution of the frequencies across the surface of the LC-SLM was not linear, but was determined by the material dispersion of the fused silica prism. The prism was oriented for minimum deviation in the focal plane of the LC-SLM. The broad bandwidth of the dispersed spectrum provided a slightly different minimum deviation angle for every wavelength; however each angle produced a similar focal pattern on the LC-SLM surface, so the exact setting was not critical. The wavelength map across the device was revealed by writing a phase step about a given pixel. As each wavelength is focused on to more than one pixel