## Optical retarder system with programmable spectral retardance

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An optical system that works as a retarder waveplate with programmable spectral retardance is proposed. The system is based on a pixelated liquid crystal on silicon (LCoS) spatial light modulator (SLM). The input light beam is spectrally dispersed and different spectral components are projected onto different pixels of the LCoS-SLM. A different retardance is then addressed for each pixel, adapted to the incoming wavelength. Light reflected from the SLM is then recombined by the same setup. In this way a programmable polarization spectrum can be encoded. We illustrate the broadband characterization that is required for proper use of the system. Then several examples are shown, including spectral compensation to yield retarders with constant retardance, retarders with abrupt changes in the spectral retardance function, or bandpass variable retarder filters. The system is also demonstrated to provide programmable light spectrum generation. © 2014 Optical Society of America

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Waveplates or retarders are key elements in most optical systems requiring control of the state of polarization (SOP) [1]. Multiple-order waveplates are composed of a single layer of anisotropic material. They introduce a multiple number of cycles in the retardance between ordinary and extraordinary waves, plus the desired phase difference (modulo  $2\pi$ ). Therefore, they exhibit strong dispersion since the retardance rapidly grows as the wavelength is reduced [2-4]. On the contrary, zero-order waveplates present reduced dispersion and therefore are less sensitive to temperature or wavelength variations. True zero-order retarders have the specified retardance with no additional waves, and are produced with a very thin anisotropic layer. Compound zero-order waveplates are obtained by combining two anisotropic layers with different width and orthogonal orientation of their neutral axes [5]. Most quality multiple-order or zero-order waveplates are fabricated with quartz [6]. Alternatively, polymer retarders usually act as low-order waveplates [7.8]. Nevertheless, all these waveplates show some spectral retardance variation, and this is the reason both multiple and zero-order waveplates are designed for specific wavelengths.

However, sometimes it is convenient to use waveplates with a broadband retardance. Achromatic waveplates are designed to give the same retardance for two different wavelengths and therefore present reduced variations for wavelengths in between [9]. This is usually achieved by combining two materials with opposite spectral dispersion. Fresnel rhombs are alternative waveplates whose retardance undergoes very small spectral variation [10]. The reason is that the retardance is caused by the phase shift between the internal reflection of the transverse electric (TE) and transverse magnetic (TM) modes, instead of by differences in the ordinary and extraordinary refractive indices.

Liquid-crystal (LC) waveplates are tunable since the phase shift of the extraordinary wave can be adjusted via the applied voltage. The electric field causes the LC director to tilt, and this reorientation of the birefringent material relative to the incident light changes the effective extraordinary refractive index. Thus, LC waveplates can be adjusted to provide desired retardance for a specific wavelength. The LC layer acts as a low-order waveplate, thus displaying the typical spectral dispersion of such waveplates [11,12].

In this work, we present an optical system based on a liquid crystal on silicon (LCoS) spatial light modulator (SLM) that acts as a waveplate with a programmable spectral retardance function. Therefore, it allows engineering the spectral properties of the waveplate and reproducing all the previously described waveplates. The system is inspired in other similar systems employed in pulse-shaping applications [13]. Here, the goal is to demonstrate control of the SOP along the spectrum, i.e., generating at will any specific SOP( $\lambda$ ) function. One of its possible direct uses is the generation of specific synthetic light spectra [14], with direct applications in hyperspectral imaging and colorimetry. Adaptive SOP( $\lambda$ ) functions can also find applications in spectral polarimetry and spectroscopic ellipsometry [15].

The optical setup scheme is shown in Fig. 1. The input light is a supercontinuum beam from Fianium (model SC400). This light source is particularly useful here since it provides a laser beam with broadband spectrum. The beam is directed onto a nonpolarizing beam splitter (BS). The transmitted beam then traverses a blazed grating (Edmund Optics, with 600 grooves per mm), which



Fig. 1. Scheme of the optical system.

disperses the input light. We use light diffracted onto the first diffraction order. An achromatic converging lens is located at the focal length from the blazed grating, in order to produce a collection of dispersed parallel rays that are then directed onto the LCoS-SLM, placed at the lens back focal plane. We employ a Hamamatsu LCoS-SLM (model X10468-01) designed to operate in the visible range. This SLM is a parallel-aligned display that acts as a pixelated linear waveplate, with  $792 \times 600$  pixels of 20 µm pixel size and 98% fill factor. The modulated reflected light follows the reversed path, and the lens and blazed grating recombine all the spectral components again on the first diffraction order. This recombined beam propagates toward the BS. The reflected output beam is registered with a Stellar-Net spectrometer (model EPP-2000) in order to analyze the spectrally modulated beam.

The system in Fig. 1 introduces some losses, mainly at the BS, the LCoS-SLM, and the grating. Nevertheless, as we shown next, it acts as a linear waveplate with programmable spectral retardance. The neutral axes are fixed by the LCoS-SLM director axis, and the retardance is controlled via the voltage signal, which depends on the addressed gray level (*g*). Since the spectral components are spatially separated, a different voltage can be applied to each spatial component, and a given spectral retardance function  $\Phi(\lambda)$  can be encoded at will.

In order to properly operate the programmable waveplate system, different previous calibrations are required. First, the LCoS spectral retardance must be determined, both as a function of the wavelength and as a function of the addressed gray-level signal. Two linear polarizers are placed at the input and output beams. The input polarizer is oriented at 45° with respect to the LC director axis. The output polarizer is placed either parallel or crossed with respect to the first polarizer. In this situation, the output normalized intensity is given by  $i_p = \cos^2(\Phi/2)$  for parallel polarizers, or  $i_c = \sin^2(\Phi/2)$  for crossed polarizers, where  $\Phi$  is the retardance introduced by the LC retarder, and also any other retardance that could be introduced by the BS.

For a constant addressed gray level, the retardance  $\Phi$  depends on the wavelength, and decreases monotonically versus  $\lambda$  [16]. This results in an oscillatory intensity spectral function that can be used to derive the  $\Phi(\lambda)$  function, as it was shown in [8] for a polymer waveplate, or in [11] for a LC modulator. This is shown in Fig. 2. Figure 2(a) shows the spectrometer measurements when the LCoS-SLM is addressed by uniform screens with



Fig. 2. (a) Normalized spectral intensity measured with parallel polarizers for gray levels g = 255, g = 128, and g = 0. (b) Corresponding spectral retardance obtained by fitting the experimental data.

gray levels g = 0, g = 128, and g = 255, respectively. Two spectrometer captures were taken in each case: one with parallel polarizers  $(I_p)$  and another with crossed polarizers  $(I_c)$ . They were then normalized for each wavelength as  $i_p = I_p/(I_p + I_c)$ , in order to be comparable with the relation  $i_p = \cos^2(\Phi/2)$ . The results in Fig. 2(a) show more than one complete oscillation in the range from 475 to 800 nm, thus indicating more than  $2\pi$  retardance variation. The number of oscillations in the spectrum diminishes as the gray level increases, indicating a reduction in the retardance. A secondary rapid oscillation is observed in the spectrum, caused by multiple internal reflections inside the LCoS device [12]. However, if we ignore this effect, a good approximation of the spectral retardance function can be retrieved by fitting these normalized data to  $\cos^2(\Phi/2)$ , assuming a Cauchy relation, as in [11]. Each figure includes a continuous curve with the best fit. The corresponding spectral retardance function is shown in Fig. 2(b). This procedure was repeated for various gray levels, in order to obtain a good approximation of the  $\Phi(\lambda, g)$  function.

Once this information was processed, we obtained a table of correspondence between retardance, wavelength, and addressed gray level, which makes it possible to define the function  $g(\lambda, \Phi)$  that generates the desired  $\Phi(\lambda)$  retardance function. In order to design a full programmable retarder, the LCoS SLM should provide at least a  $2\pi$  retardance modulation for all wavelengths in the selected range. This is shown to be the case here (see [Fig. 2(b)]).

Another calibration requirement is an accurate determination of the spatial location on the SLM screen where each wavelength is impinging. This is obtained by displaying a narrow vertical line on the SLM. Such a narrow line affects only a narrow spectral band, which can be easily identified in the spectrometer. As a result, a mapping function  $x = x(\lambda)$  is obtained, where x denotes the pixel location where the wavelength  $\lambda$  impinges. Thus, finally, a gray-level image  $g(x(\lambda), \Phi(\lambda))$  can be encoded



Fig. 3. Experimentally measured spectra for constant spectral retarders: (a) HWR, (b) FWR, and (c) QWR.

on the LCoS-SLM, where a gray-level g is selected at the pixel location x to produce the desired retardance  $\Phi(\lambda)$  for the wavelength  $\lambda$  impinging in this pixel. Note that the required spatial function to be displayed on the SLM is one-dimensional and therefore only a linear array of LC pixels would be useful for this purpose.

A first set of experimental results is presented in Fig. 3. Here the goal is to reproduce retarders with constant retardance, independent of the wavelength. Thus, the inherent LC retardance dispersion shown in Fig. 2 must be compensated. The input polarizer is kept oriented at 45° to the neutral axis of the LCoS-SLM. The output analyzer is also maintained in the system, in order visualize the changes in the emerging SOP( $\lambda$ ) function. Two curves are presented for each case, corresponding to the analyzer orientation parallel (blue curve) or crossed (red curve) to the input polarizer.

First, a broadband half-wave retarder (HWR) is designed. The results are shown in Fig. <u>3(a)</u>. This is obtained by selecting gray levels that provide  $\Phi = 3\pi$  in the complete wavelength range. We select this retardance value,  $\Phi = 3\pi$ , since it is available for all wavelengths (see [Fig. <u>2(b)]</u>). The red curve in Fig. <u>3(a)</u>, obtained with the crossed polarizer configuration, reproduces the complete spectrum of the supercontinuum source (the figure reproduces directly the spectrometer measurement, in arbitrary units, for simplicity). On the contrary, the blue curve corresponding to the parallel polarizer configuration is almost zero for all wavelengths. This shows that the typical HWR action that rotates the input linear SOP occurs for all wavelengths and therefore light of all wavelengths is completely absorbed by the analyzer.

In Fig. 3(b), a similar result is obtained, but the curves for parallel and crossed polarizers are exchanged. In this

case a full-wave retarder (FWR) has been designed. This is achieved by selecting the gray levels to get  $\Phi = 4\pi$  in the range from 475 to 675 nm and  $\Phi = 2\pi$  in the range from 675 to 800 nm. Now, no variation in the input SOP occurs for any wavelength. Therefore, full transmission is obtained for the parallel polarizer configuration, while no transmission is obtained for the crossed polarizer configuration. Finally, in Fig. 3(c), a quarter-wave retarder (QWR) is generated for all wavelengths. Now the experiment shows two similar spectra for both polarization components, both with half the intensity distributions of Figs. 3(a) and 3(b). This indicates that circular polarization is approximately generated for all wavelengths, as expected for a QWP. The result is not entirely perfect, probably due to the multiple reflection effects mentioned above, but it closely illustrates the procedure. Therefore, these results report retarder designs with a programmable selection of a constant wavelengthcompensated retardance.

A second interesting case is shown in Fig. <u>4</u>. In Fig. <u>4(a)</u>, we produce a spectral retarder that acts as a FWR up to 600 nm, but it drastically changes to become a HWR for wavelengths larger than 600 nm. It is therefore a two-band retarder, with an abrupt change at 600 nm. Therefore, abrupt rotation on the SOP occurs at this wavelength. Note that such spectral variation in the SOP is impossible to get with standard waveplates, which always present smooth retardance variations. Another similar example is shown in Fig. <u>4(b)</u>, with a three-band retarder acting as a FWR up to 575 nm, as a HWR in between 575 and 640 nm, and as a QWR for wavelengths greater than 640 nm. This kind of flexibility cannot be achieved with any actual retarder, to our knowledge.

Finally, different experiments related to the generation of synthetic spectrum profiles are presented. Figure <u>5</u> displays designs where a broadband HWP as in Fig. <u>3(a)</u> is selected, but different FWP bands are introduced in different ranges. The analyzer is selected here parallel to the input polarizer. In Fig. <u>5(a)</u> narrow FWR bands of 10 nm bandwidth are selected centered at 500, 550, 600, 650, and 700 nm, respectively. This means that the input-linear SOP oriented at  $45^{\circ}$  is now rotated to



Fig. 4. Experimentally measured spectrum for: (a) two-band HWR/FWR and (b) three-band HWR/FWR/QWR.



Fig. 5. Experimentally measured spectrum for: (a) a broadband HWR with narrowband FWR centered at 500, 550, 600, 650, and 700 nm wavelengths; (b) a broadband HWR with a FWR band centered at 600 nm, of 10, 25, 50, 80, and 120 nm bandwidth.

become linearly polarized at 135° in the whole spectrum, where the HWR is acting, except in the FWR narrowband, where it remains in the original SOP. Since the polarizers are now parallel, a dark spectrum is observed except for a narrow intense peak located at the corresponding selected wavelengths.

Figure 5(b) further illustrates the flexibility of the proposed optical system, now by changing the bandwidth of the FWR band. In all cases it is centered at 600 nm, but the bandwidth is changed from 10 nm, to 25, 50, 80, and 120 nm, respectively. Therefore, the intense band in the middle-of-the-dark spectrum becomes wider. The possibility to control the retardance of the LCoS-SLM pixel by pixel provides enormous flexibility to generate any variable broadband waveplate.

In conclusion, we have designed a system that acts as an optical retarder where the retardance spectral characteristics can be defined at will, and it can be reprogrammed in real time, so it is completely adaptive. This great flexibility might be very useful to generate light beams that require specific spectral polarization content, i.e., a controlled  $SOP(\lambda)$  function. In addition, by simply adding an output analyzer, the system allows to tailor the spectral intensity of light.

The proposed optical system was probed experimentally through different examples, which include broadband constant phase-shift retarders, and retardance bands of variable bandwidth and variable central wavelength. These examples demonstrate the great flexibility and versatility of the proposed setup. A great number of applications, such as hyperspectral imaging, spectral polarimetry, ellipsometry, interferometry or colorimetry, among others, can benefit from this fully controlled spectral retardance system.

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