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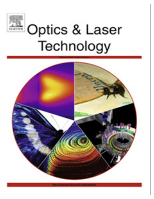

Full length article

Quantitative performance of a polarization diffraction grating polarimeter encoded onto two liquid-crystal-on-silicon displays

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ABSTRACT

We present a quantitative analysis of the performance of a complete snapshot polarimeter based on a polarization diffraction grating (PDGr). The PDGr is generated in a common path polarization interferometer with a Z optical architecture that uses two liquid-crystal on silicon (LCoS) displays to imprint two different phase-only diffraction gratings onto two orthogonal linear states of polarization. As a result, we obtain a programmable PDGr capable to act as a simultaneous polarization state generator (PSG), yielding diffraction orders with different states of polarization. The same system is also shown to operate as a polarization state analyzer (PSA), therefore useful for the realization of a snapshot polarimeter. We analyze its performance using quantitative metrics such as the conditional number, and verify its reliability for the detection of states of polarization.

1. Introduction

Polarimetry is a light-measuring technique [1] used in many different applications such as materials inspection [2], remote sensing [3], astronomy [4], biomedical applications [5], ophthalmology [6], among others. Due to this large amount of applications, there exist many different polarimeter systems proposed in the literature, each one presenting its particular characteristics. In general, we can distinguish between Stokes and Mueller polarimeters, if they are light-measuring or sample-measuring devices. Polarimeters can also be grouped as punctual beam or image polarimeters, depending on their capability to differentiate polarization spatial variations. Finally, we can distinguish between time-sequential or snapshot polarimeters.

When dealing with real-time applications, the use of snapshot polarimeters is mandatory. There are a number of snapshot polarimeters described in the literature, which are mainly based on amplitude-division (AD) or wavefront-division (WD) architectures. AD polarimeters [7–10] are usually based on optical arrangements where the input beam is split in different sub-beams by using a collection of beam-splitters or prisms. Those sub-beams are then simultaneously analyzed by means of different polarization analyzers (PA) (i.e., different states of polarization where the input beam is projected). Those PAs are commonly achieved by placing different combinations of linear retarders and polarizers on the different sub-beams. A minimum number of 4 independent PAs are required. In general, the systems are bulky and require of synchronization between different radiometers to simultaneously record the different flux measurements. On the contrary, WD polarimeters [3,11] are usually based on a set of PAs that measure different parts of the input wavefront.

In this manuscript we design, optimize and implement a new type of AD polarimeter based on polarization diffraction gratings (PDGr), capable to perform punctual beam, snapshot and complete polarization metrology. PDGrs have been studied since many years, and they have been proposed for polarimetric measurements [12]. They are diffraction gratings based on a one-dimensional local periodic variation of the polarization transmission [13] and they are usually designed to be either polarizer or waveplate periodic structures, where the orientation of the transmission axis of the polarizer [14], or the principal axis of the wave-plate is periodically rotated [15].

Initial experimental realizations of PDGr based polarimeters were based on using micro-structured PDGr designed for IR light with large wavelengths [16]. The realization of PDGr for visible wavelengths required advances in microfabrication processes

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[17–19]. Recently, PDGr have been proposed for different types of polarimeters [20,21]. An alternative to produce PDGr has been the well stablished liquid-crystal technology. For instance, PDGr were demonstrated with ferroelectric displays [22,23], or with parallel-aligned nematic displays [24–26], and a punctual beam time-sequential polarimeter based on a simple PDGr was demonstrated in [27]. However, liquid crystal displays present limitations in the polarization states that can be generated, and this limits the types of PDGr that can be implemented. Therefore, these above mentioned PDGr cannot be applied to produce a complete single-shot polarimeter.

Recently a new concept for generating PDGr was introduced in [28]. In this work, the PDGr was generated by encoding two independent phase-only diffraction gratings on two orthogonal states of polarization. The phase-only gratings were designed according to the optimal method for designing laser beam splitters [29]. This is a powerful grating design method, which can be used to select a number of target diffraction orders with a given constraint in their relative intensities [30] and/or phases [31]. The proper combination of two of such gratings, each one affecting different and orthogonal states of polarization, can be used to design arbitrary PDGrs, as demonstrated in Ref. [28]. In that work, an optical reflective architecture was used, employing a special transmissive parallel-aligned liquid crystal display. However, reflective liquid-crystal on silicon (LCoS) displays are much more common and commercially available nowadays.

In this work, we show an alternative optical architecture based on two LCoS displays to encode PDGr following the technique initiated in [28]. In addition, we analyze the implementation of a snapshot punctual polarimeter based on this system. The proposed polarimeter system is capable of simultaneously generate all the required PAs. Moreover, alignment of the set-up is not extremely demanding as occurring in other polarimeter proposals. In addition, as the LCoS performance can be optimized to different wavelengths, simply by addressing the proper electrical sequences [32], the proposed set-up could be used to perform multi-channel polarimetry.

The outline of this manuscript is as follows. In Section 2, we first introduce the optical architecture and describe the details of the experimental system. Then, in Section 3, we present the design of the two optimal phase-only gratings that constitute the PDGr. Section 4 presents the experimental results. The accuracy and quality of the PDGr based polarimeter are quantified according to well stablished quality metrics. Finally, Section 5 presents the conclusions of the work.

2. Optical architecture

Fig. 1 shows the scheme of the optical setup. The polarimeter comprises two LCoS spatial light modulators in a Z configuration. An input He-Ne laser ($\lambda = 633$ nm) is first spatially filtered and collimated by means of lens L1. A polarization state generator (PSG) composed of a linear polarizer (P1) and a quarter wave-plate (QWP) is used to control the state of polarization of this beam before it reaches the first modulator. This PSG is used in the calibration step and in the performance analysis to introduce in the polarimeter beams with known polarization states.

The two modulators are arranged in a Z configuration as indicated in Fig. 1. The angle between the incident ray and the reflected ray on each modulator is of $\beta = 11°$. Modulators LCoS1 and LCoS2 are conjugated planes by means a 4f system obtained with two lenses L2 and L3, with the same focal length, $f = 200$ mm, thus obtaining a unit magnification. Both modulators are parallel-aligned LCOS displays, with the liquid crystal director aligned horizontally with respect to the laboratory framework. They are modulators from Holoeye, Pluto model, with 1920×1080 pixels and 8 μm pixel pitch. LCoS1 is designed to operate in the visible range, while LCoS2 is originally designed to operate in the near infrared range (NIR II). This kind of devices have been extensively used for displaying phase-only diffraction gratings [33]. The retardance versus addressed gray level was previously calibrated for both modulators for the wavelength of 633 nm, following the method described in Ref. [34]. The results are shown in Fig. 2. LCoS1 display provides a phase modulation depth up to more than 2π in the complete gray level range, while LCoS2 display reaches the 2π phase modulation for a gray level less than 100.

Parallel-aligned LCoS displays only modulate the linear polarization component parallel to the LC director. In our devices, this corresponds to the horizontal direction. Therefore, a phase pattern addressed to LCoS1 modulates the horizontal component of the input beam. A half-wave plate (HWP) is added after lens L3, oriented at 45°, to transform the horizontal linear polarization component into the vertical polarization component and vice versa. Then, the beam illuminates the LCoS2 display. A phase pattern addressed to this second display is therefore now encoded on the original vertical polarization component in the input beam (which was unaffected by LCoS1). In this way, the two orthogonal horizontal and vertical polarization components of the input beam can be independently modulated with these two modulators.

Finally, the Fourier transform plane is retrieved at the back focal plane of another convergent lens L4, with focal length $f = 150$ mm, and a microscope objective (10×) produces a magnified image onto a CCD Basler piA1000 60gm camera. When necessary, an analyzer (P3) is placed in between the objective and the camera to select the appropriate polarization component.

3. Polarization grating design

The PDGr design used in this experiment has been previously described in Ref. [28]. It is designed to work as a PSG that yields six target diffraction orders $k = \pm 1, \pm 2, \pm 3$, when it is illuminated with linearly polarized light oriented at 45°, where the states of polarization in each order correspond to linear states oriented at 0°, 45°, 90° and 135°, and the two circular right (RCP) and left (LCP) states.

The above-stated polarizations are generated by addressing a different phase-only diffraction grating to the LCoS1 and LCoS2 displays, one modulating the initial horizontal polarization component (Grating H) and the other modulating the initial vertical polarization component (Grating V). Following [28], these phase-only gratings are calculated as:

$$\exp(i\phi(x)) = \frac{g(x)}{|g(x)|} = \sum_{k=-\infty}^{+\infty} G_k \exp(i2\pi kx/D), \tag{1}$$

where

$$g(x) = \sum_{k\in T} \mu_k e^{i\alpha_k} \exp(i2\pi kx/D). \tag{2}$$

Here in Eq. (2) the summation is performed only on the selected set (T) of target diffraction orders. D denotes the period of the grating. μ_k and α_k are numerical parameters that must be determined numerically to fulfill the required restrictions on the Fourier coefficients G_k of the phase only gratings in Eq. (1). These Fourier coefficients are complex numbers

$$G_k = |G_k| \exp(i\beta_k). \tag{3}$$

Therefore, restrictions can be imposed on the intensity $i_k = |G_k|^2$ of the target diffraction orders, on their phases β_k, or in both magnitudes. The efficiency of the grating design (η) is defined as the summation of the relative intensities in the target orders, i.e. [28]: