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Second order diffractive optical elements in a spatial light modulator with large phase dynamic range

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ABSTRACT

A study of the diffraction efficiency of a spatial light modulator with a large dynamic phase range is reported. We use a phase-only device that reaches 4π phase modulation depth for the wavelength of 454 nm. This allows operating phase-only diffractive optical elements in the second harmonic diffraction order, instead of in the usual first diffraction order. This type of implementation shows advantages in terms of resolution and diffraction efficiency. Experimental results are reported for blazed diffractive gratings and diffractive lenses.

1. Introduction

Diffractive optical elements (DOEs) play an important role in many optical technologies [1]. Liquid crystal (LC) spatial light modulators (SLMs) are useful devices for implementing a variety of programmable DOE, mainly when they produce pure-phase modulation characteristics [2]. Usually, a pure phase-only modulation with a phase modulation range reaching 2π radians is desired. Initial works in this field involved twisted nematic and parallel-aligned LC-SLMs [3,4]. The goal of reaching faster optical responses led to a reduction of the liquid crystal layer in modern devices. This motivated the use of elliptical polarization configurations to achieve a phase-only regime [5], but it reduced the overall phase modulation range. In some devices, the available phase dynamic range is actually shorter than 2π radians in standard configurations. Strategies have been demonstrated either to optimally encode a phase-DOE onto a limited phase modulation device [6], or to enlarge the phase modulation range by unconventional polarization configuration, this phase improvement requiring a reduction of the average intensity transmission [7].

Modern LC on Silicon (LCoS) modulators work in reflection, thus providing larger values of the phase modulation range. In addition, some LCoS devices like parallel-aligned nematic (PAL), or vertically aligned nematic (VAN) act as electrically controlled birefringence (ECB) displays, i.e., programmable linear wave-plates. Phase-only modulation is therefore obtained in these devices simply by orienting the input linear polarization parallel to the LC director axis. Therefore, phase-only LC devices with phase modulation range larger than 2π are nowadays commercially available.

In this paper, we examine the diffraction properties of two-dimensional DOEs displayed in a parallel-aligned LCoS display with a dynamic phase range reaching 4π radians. This doubled phase depth, compared to standard 2π phase modulation, allows operating DOEs in the second harmonic diffraction order. It is shown that this operation presents advantages in terms of spatial resolution. For example, it permits reducing the diffraction efficiency loss induced when the displayed DOE presents high spatial frequency components, near the resolution limit of the device [8,9].

The paper is organized as follows. First, in the next section we examine the theory for the blazed grating with different phase modulation depth, in particular when the phase range exceeds the usual 2π range. Then, in Section 3 we present experimental results obtained with a phase-only LCoS display, capable of reaching 4π phase modulation for an operating wavelength of 454 nm. We show how the blazed grating can be operated in the second harmonic component. Then, the approach is extended to other diffractive elements, in particular to a diffractive lens. We show that operating in this second harmonic component improves the diffraction efficiency of the displayed lens. Finally, the last section presents the conclusion of the work.

2. Blazed grating with variable phase depth

Let us first analyze a one dimensional blazed phase diffraction grating. It can be expressed as a linear phase dependence

$$g(x) = \exp\left(i\varphi(x)\right) = g_0(x) \otimes \frac{1}{p}\mathrm{comb}\left(\frac{x}{p}\right), \quad (1)$$

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where $\otimes$ denotes the convolution operation; the comb($\cdot$) function is defined as

$$\text{comb}\left(\frac{x}{p}\right)=p\sum_{n=-\infty}^{n=+\infty}\delta(x-np), \quad (2)$$

being p the period of the grating, and

$$g_0(x)=\exp\left(i\frac{2\pi x}{p}M\right)\text{rect}\left(\frac{x}{p}\right), \quad (3)$$

denotes the function defining a single period of the grating (sometimes it is referred to as the slit function [10,11]). The rect(x) function is defined as 1 if $|x|<1$, and zero elsewhere. The blazed grating phase profile is sketched in Fig. 1(a). The parameter M in Eq. (3) controls the phase dynamic range of the blaze grating. The phase ramp has a maximum variation $\Phi_{max}=2\pi M$; the standard blazed grating ($\Phi_{max}=2\pi$) is obtained for $M=1$.

The intensity of the Fourier transform of Eq. (1) is given by

$$I(u)=|G_0(u)|^2\frac{1}{p^2}\text{comb}\,(up), \quad (4)$$

where $G_0(u)$ is the Fourier transform of $g_0(x)$, u denoting the spatial frequency coordinate. Considering the slit function in Eq. (3), its Fourier transform squared modulus can be expressed as:

$$|G_0(u)|^2=p^2\text{sinc}^2(p(u-Mu_1)), \quad (5)$$

where $u_1=1/p$ is the fundamental frequency of the grating (first harmonic order). The sinc function is defined as $\text{sinc}(x)=\sin(\pi x)/(\pi x)$. The relative intensity I_n of each diffraction order is given by the function $I(u)$ evaluated at the harmonic frequencies $u_n=nu_1$, $n=0,\pm1,\pm2\ldots$. In this case, for an arbitrary value of M, they are given by:

$$I_n=\text{sinc}^2(n-M) \quad (6)$$

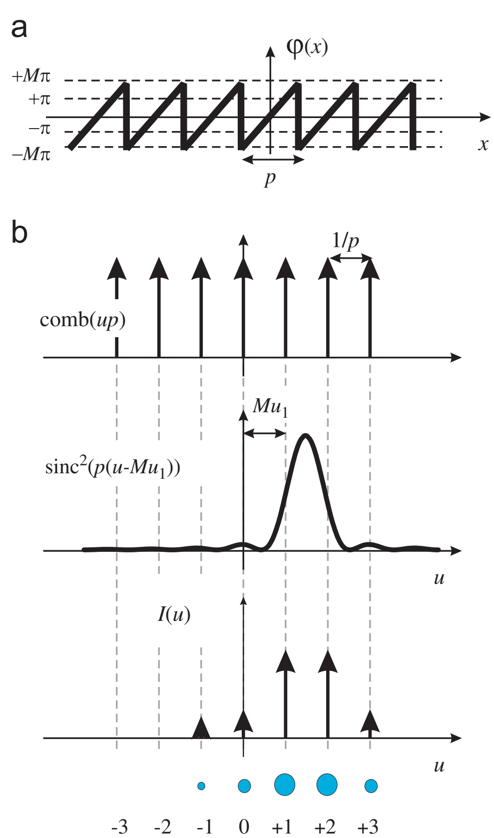

Fig. 1. (a) Phase profile $\varphi(x)$ of the blazed grating. Parameter M controls the phase dynamic range and (b) different functions involved in the generated Fourier pattern.

In order to intuitively understand the phenomena, Fig. 1(b) shows a profile of the functions comb(up), $\text{sinc}^2(p(u-Mu_1)$ and $I(u)$, for a value $M=1.5$. Note that the comb function gives the position of the diffracted orders at locations $u_n=nu_1$. The squared sinc function is an envelope function that modulates the relative intensity of the diffraction orders. The position of this envelope function is controlled by the M parameter, being the maximum located at the spatial frequency $u=Mu_1$. For instance, for $M=1$ ($\Phi_{max}=2\pi$) and for $M=2$ ($\Phi_{max}=4\pi$), the maximum of this envelope function is centered at the first (u_1) and at the second ($u_2=2u_1$) harmonic orders, respectively. And the zeros of the sinc function exactly coincide with the rest of harmonic frequencies u_n. Thus, the light is fully diffracted either onto the first ($n=1$) or onto the second ($n=2$) diffraction order in each case.

Values of M lower than one lead to a diffraction pattern where the most intense orders are $n=0$ and $n=1$. For instance, for $M=0.5$, $I_0=I_1=40.5\%$. This situation ($M<1$) has been analyzed in SLM devices showing a limited phase modulation range, less than 2π radians [6]. The spatial variation of this M parameter has been a very useful technique to encode amplitude information onto a phase only function [12], however, always limited to the range (0,1). Here, on the contrary, we consider extending the typical (0,1) range to values $1<M<2$, where the envelope function is centered between the first and the second harmonic orders, thus being both of them the most intense ones. For instance, for $M=1.5$, $I_1=I_2=40.5\%$. Next, we present experimental verification of this Fourier theory.

3. Experimental results with a large phase modulation LCoS display

We have experimentally generated such blazed gratings with a parallel-aligned Hammamatsu LCoS-SLM (X10468 series), with 792×600 pixels of size $20\times20\ \mu m^2$. The rise and fall response times at a wavelength of 633 nm are 10 ms and 35 ms, respectively, which can be assumed similar for the device recommended range of operation (from 400 nm to 700 nm). The polarization of the input beam was selected as linearly polarized along the liquid crystal director axis, in order to obtain a phase-only modulation output. In that configuration, this LCoS-SLM provides a modulation depth range from around 2.3π at 700 nm to 6.4π. We measured the phase modulation range versus the addressed grey level at typical wavelengths using a calibration method based on displaying a two-level grating on the LCoS and measuring the intensity of the zero and first diffraction orders [13]. For the operating wavelengths $\lambda=633$ nm (He–Ne laser), $\lambda=514$ nm and $\lambda=454$ nm of a tunable Ar ion laser, we obtained 2.4π rad, 3.2π rad and 4π rad phase modulation range, respectively. The latter has been used in this work to illuminate the SLM display. From the measured values, fitting models can be used to predict phase changes at other wavelengths in the range [14]. Once the device was calibrated, blazed gratings with different M parameter were displayed on the SLM, by addressing adjusted gray level images via PC. The corresponding diffraction patterns were captured with a CCD camera, (Basler, scA1390-17fc, with 1392×1040 pixels).

Fig. 2 shows the experimental result with a grating with period $p=64$ pixels, where we progressively increase the phase depth to have values $\Phi_{max}=0$, π, 2π, 3π and 4π, respectively (steps of 0.5 in the M parameter). The experiments are performed in equal conditions and show agreement with Eq. (6). We calculated, in each case, the diffraction efficiency η_k as the intensity of the kth diffracted order respect to the incident light on the SLM.