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Calibration of the complete Jones matrix of SLMs

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ABSTRACT

Spatial light modulators are very common in many applications. They are used to implement amplitude, phase and polarization masks. In order to optimize its performance, it is important to characterize it, which means determining its Jones matrix. Here we present a method which consists on performing several intensity measurements for each gray level. It is simple enough that can be quickly performed, but offers much better results than previous methods.

Keywords: Spatial light modulator, Jones matrix, polarimetry, optical metrology.

1. INTRODUCTION

Spatial light modulators (SLMs) are a common tool in many optics laboratories. They are used for many applications like beam shaping[?,1,2], holography[3,4], atomic physics[5], quantum optics[6], among many others. SLMs based in liquid crystal displays (LCDs) and liquid crystal on silicon (LCoS) are the most common for such applications, as they allow both amplitude, phase and even polarization modulation. This is accomplished placing some polarizers and retarders in the path of the light beam before and after the SLM. Then, these elements must be rotated to switch between different configurations. The rotation angles of those elements can be calculated if the Jones matrix of the SLM for each gray level is known.

Several methods have been proposed for determining the Jones matrix of an SLM. They are divided in two types. The first one models the liquid crystal molecules and how they affect light[7,8]. The second one ignores the physical mechanism of how light is affected and considers only the light variations[9–16]. This second method has the advantage that can be used for any SLM, as it does not require prior knowledge about the SLM fabrication materials. Among them, only[10] determines the complete Jones matrix of the SLM. This method allows calibrating each pixel individually. However, as it is based on microscopic interferometric measurements of few pixels each time, the setup is very complex and difficult to utilize, the precision is not very high and must be repeated many times in order to characterize the complete SLM. The rest of the methods characterize the SLM as a whole, ignoring any possible difference between pixels. Refs. [13–16] directly characterize the behavior of the SLM in amplitude or phase modulation, and try to optimize it. Refs. [9,11,12] determine the Jones matrix of the SLM using a simple setup, but considering that the SLM behaves as a pure retarder.

Here, we present a new calibration method. This method is similar to the methods described in[9,11,12], as it uses a simple setup. However, we drop the assumption that the SLM behaves as a pure retarder. Even as this approximation may be valid for many SLMs, it is not for all of them. Here we compare the results obtained using our method and the one developed by Moreno and coworkers[9], the one which produces the best results among them for our SLM.

2. CALIBRATION METHOD

The complete Jones matrix of each pixel of the SLM can be described as

$$J_{SLM} = \exp(i\Phi) \begin{bmatrix} J_0 & J_1 \exp(i\delta_1) \\ J_2 \exp(i\delta_2) & J_3 \exp(i\delta_3) \end{bmatrix}, \tag{1}$$

being J_i the matrix element amplitude and δ_i the matrix element complex phase and Φ the global phase. All coefficients will depend on the gray level of the pixel. In order to calibrate the SLM, the Jones matrix for each gray level, and thus the matrix elements J_i, δ_i and Φ must be calculated.

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The calibration method we propose requires 10 intensity measurements with a uniform gray level in the SLM. This allows calculating all J_i and δ_i, while Φ must be measured using a different method. It requires placing the SLM between a polarization state generator (PSG) and a polarization state analyser (PSA). A PSG is a system that allows generating any polarization state, while a PSA is a system that presents maximum transmission for a given polarization state (the analyzed state) and none for its orthogonal state. We will denote the PSG and PSA state using the bra-ket notation[17]. In the case of the PSG:

$$|\phi,\chi\rangle = \begin{bmatrix} \cos\chi\cos\phi - i\sin\chi\sin\phi \\ \cos\chi\sin\phi + i\sin\chi\cos\phi \end{bmatrix}, \tag{2}$$

being φ the state azimuth and χ the state ellipticity angle. In the case of the PSA:

$$\langle\phi,\chi| = |\phi,\chi\rangle^{\dagger}, \tag{3}$$

where † denotes the hermitian conjugate.

The 10 intensity measurements which must be performed are the following:

$$I_1 = |\langle 0^{\text{o}}, 0^{\text{o}}| \, J_{SLM} \, |0^{\text{o}}, 0^{\text{o}}\rangle|^2 = J_0^2, \tag{4a}$$

$$I_2 = |\langle 0^{\text{o}}, 0^{\text{o}}| \, J_{SLM} \, |90^{\text{o}}, 0^{\text{o}}\rangle|^2 = J_1^2, \tag{4b}$$

$$I_3 = |\langle 90^{\text{o}}, 0^{\text{o}}| \, J_{SLM} \, |0^{\text{o}}, 0^{\text{o}}\rangle|^2 = J_2^2, \tag{4c}$$

$$I_4 = |\langle 90^{\text{o}}, 0^{\text{o}}| \, J_{SLM} \, |90^{\text{o}}, 0^{\text{o}}\rangle|^2 = J_3^2, \tag{4d}$$

$$I_5 = |\langle 0^{\text{o}}, 0^{\text{o}}| \, J_{SLM} \, |0^{\text{o}}, -45^{\text{o}}\rangle|^2 = \left(J_0^2 + J_1^2 + 2J_0J_1\sin\delta_1\right)/2, \tag{4e}$$

$$I_6 = |\langle 0^{\text{o}}, 0^{\text{o}}| \, J_{SLM} \, |45^{\text{o}}, 0^{\text{o}}\rangle|^2 = \left(J_0^2 + J_1^2 + 2J_0J_1\cos\delta_1\right)/2, \tag{4f}$$

$$I_7 = |\langle 0^{\text{o}}, 45^{\text{o}}| \, J_{SLM} \, |0^{\text{o}}, 0^{\text{o}}\rangle|^2 = \left(J_0^2 + J_2^2 + 2J_0J_2\sin\delta_2\right)/2, \tag{4g}$$

$$I_8 = |\langle 45^{\text{o}}, 0^{\text{o}}| \, J_{SLM} \, |0^{\text{o}}, 0^{\text{o}}\rangle|^2 = \left(J_0^2 + J_2^2 + 2J_0J_2\cos\delta_2\right)/2, \tag{4h}$$

$$I_9 = |\langle 90^{\text{o}}, 0^{\text{o}}| \, J_{SLM} \, |0^{\text{o}}, -45^{\text{o}}\rangle|^2 = \left[J_2^2 + J_3^2 + 2J_2J_3\sin(\delta_3 - \delta_2)\right]/2, \tag{4i}$$

$$I_{10} = |\langle 90^{\text{o}}, 0^{\text{o}}| \, J_{SLM} \, |45^{\text{o}}, 0^{\text{o}}\rangle|^2 = \left[J_2^2 + J_3^2 + 2J_2J_3\cos(\delta_3 - \delta_2)\right]/2. \tag{4j}$$

This system of equations can be inverted to calculate the Jones matrix parameters:

$$J_0 = \sqrt{I_1}, \tag{5a}$$

$$J_1 = \sqrt{I_2}, \tag{5b}$$

$$J_2 = \sqrt{I_3}, \tag{5c}$$

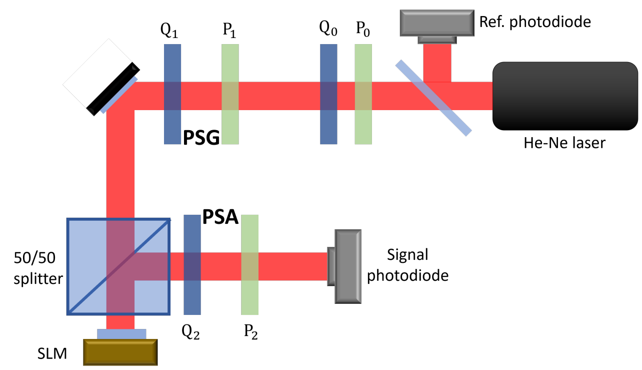

Figure 1. Schematic representation of the experimental setup.

$$J_3 = \sqrt{I_4}, \tag{5d}$$

$$\delta_1 = \arctan\left(\frac{2I_5 - I_1 - I_2}{2I_6 - I_1 - I_2}\right), \tag{5e}$$

$$\delta_2 = \arctan\left(\frac{2I_7 - I_1 - I_2}{2I_8 - I_1 - I_2}\right), \tag{5f}$$

$$\delta_3 = \arctan\left(\frac{2I_9 - I_3 - I_4}{2I_{10} - I_3 - I_4}\right) + \delta_2, \tag{5g}$$

where arctan considers the sign of both the numerator and the denominator in order to obtain a result between 0º and 360º. This method allows calculating the Jones matrix parameters for a given gray level value. A set of 10 intensity measurements must be performed for each gray level of the SLM in order to completely characterize it.

The global phase Φ must be determined using additional measurements like the ones described in Refs.[9,16,18].

3. EXPERIMENTAL SETUP

Figure 1 shows the scheme of the experimental setup. It consists on a He-Ne laser, a beam sampler and a reference photodiode, a polarizer and a quarter waveplate to generate circularly-polarized illumination. It is followed by a PSG and a PSA composed by a rotating polarizer and quarter waveplate, a non-depolarizing 50/50 beam splitter and an HoloEye LC-R-2500 SLM (resolution 1024x768, 256 levels, 19 μm square pixels). Finally, the light reaches a second photodiode. The intensity measurements of the signal photodiode are normalized respect to the ones of the reference photodiode in order to eliminate laser power fluctuations.

Many polarization calculations had to be preformed. We used *py_pol* open source library[19,20] in order to do them.

4. RESULTS

Figure 2 shows the result of HoloEye LC-R-2500 calibration using Moreno and coworkers method[9] and our method. This result has several features worth noting. First, the absolute value of the components, J_i, greatly deviates from each other except maybe for J_2. Complex phases δ_1 and δ_2 also differ in both models while δ_3 is somehow similar. Moreover, δ_1 and δ_2 show one of the problems that may arise with Moreno method, a jump in the phase around 180º when the sign of one of its matrix elements varies. Our method does not present such a problem.

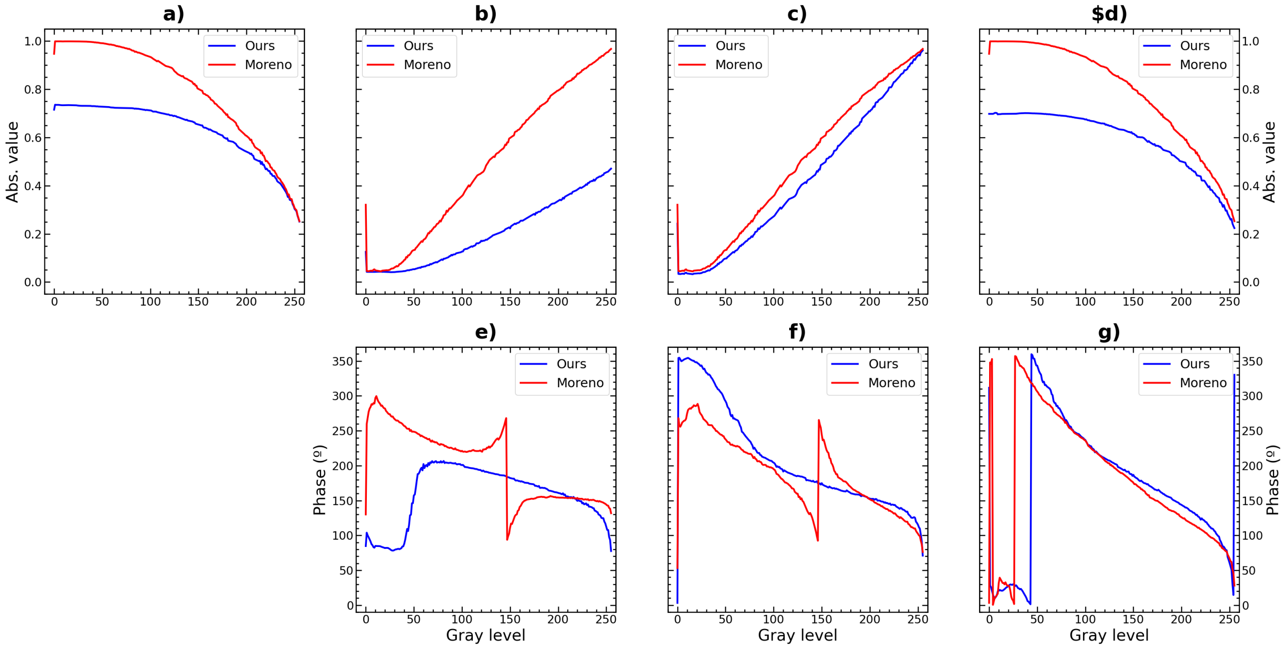

Figure 2. a-d) Calculated Jones matrix elements absolute value J_1 to J_3. e-g) Calculated Jones matrix elements complex phase δ_1 to δ_3.

Figure 3 shows the absolute value of the determinant of the calculated Jones matrices for ours and Moreno method. The difference is enormous. Moreno method assumes that the SLM can be modeled as a pure retarder, which forces the condition $|\det(J_{SLM})| = 1$. We do not use that assumption, and we obtain a value of $\approx$0.51, which proves the utility of using a more general method that drops the assumption that the SLM must behave as a pure retarder. Finaly, the calculated absolute value of the determinant presents a surprisingly low variation between gray levels.

5. CONCLUSION

We have implemented a new simple method for calculating the complete Jones matrix of SLMs. The method requires performing 10 intensity measurements for each gray level of the SLM pixels. This method does not make the assumption that the SLM behaves as a pure retarder, as it is the case of our SLM. Finally, this method can be used to characterize the Jones matrix of any optical element, not only SLMs.

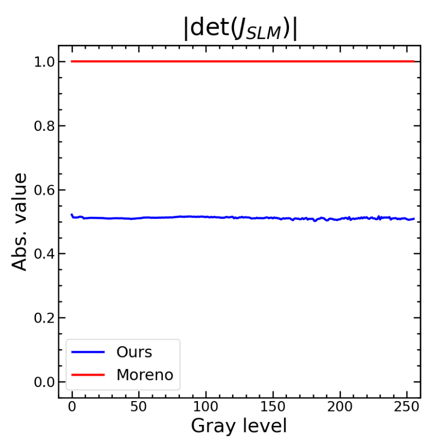

Figure 3. Calculated absolute value of the determinant of the Jones matrices calculated using ours and Moreno method.

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