

Calibration of Linearly Aligned Nematic Liquid Crystal based Spatial Light Modulators

Paul Balondrade and Sébastien M. Popoff

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1. Introduction

We published previously a tutorial presenting a technique to calibrate spatial light modulators (SLM) [1]. The approach was based on measuring the interference between two paths that have been reflected off two different regions of the SLM. This technique is always valid but requires aligning a mask, using a lens and capturing and treating images of interference patterns. Nowadays, most phase only SLMs based on liquid crystals use linearly aligned nematic crystals. Unlike twisted nematic liquid crystals, they allow phase only modulation on one polarization while not affecting the orthogonal polarization. This feature can be used to simplify the calibration setup to characterize the SLM with a common path interferometer, not requiring a precise alignment [2]. Furthermore, it only needs a photo-detector, compared to a digital camera in the previously presented approach. This is convenient to measure the inevitable phase fluctuations of an SLM, usually around a 100 to 400 Hz frequency. In this document, we briefly describe the principle of the characterization scheme as presented in [2] and show typical results of the calibration and the phase fluctuations.

2. Calibration of linearly aligned liquid crystal SLMs

The goal is to determine the correspondence between the pixel values of an image sent to the SLM (encoded in 8 bits, i.e 256 values for the devices tested) and the resulting phase modulation of the light reflected off of the SLM. Typical phase only SLMs are composed of vertically aligned liquid crystals (Figure 1). At rest, light propagating on the z -axis is sensitive to the anisotropy of the liquid crystals. As a result, the material is birefringent, the light sees two optical indices: an ordinary index n_o along the x -polarization and an extraordinary index n_e along the y -polarization. The index n_y seen by a y -polarized light can be set to n_o by applying a voltage on the liquid crystal plate, whereas the index n_x for the x -polarization stays unchanged (see figure 1). In the general case, the index for the y -polarization $n_y(V)$ depends on the input voltage and

can be tuned between n_o and n_e .

$$n_x = n_o \quad (2.1a)$$

$$n_y(V) \in [n_o, n_e] \quad (2.1b)$$

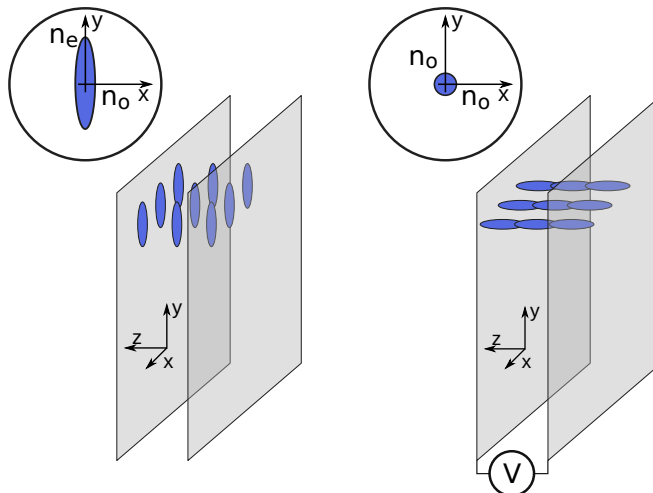


Figure 1: Vertically aligned nematic liquid crystals at rest (left) show birefringence. It disappears upon application of a strong voltage (right).

We use this feature to characterize the phase modulation by observing the interferences between the two paths propagating with x and y -polarizations. The principle of the setup is presented in Figure 2. A laser beam polarized is rotated at 45 degrees with respect to the orientation of the liquid crystals and sent onto the SLM through a Beam Splitter (BS). The optical field arriving at the SLM is identical for the two polarizations.

$$E_x = E_0/\sqrt{2} \quad (2.2a)$$

$$E_y = E_0/\sqrt{2} \quad (2.2b)$$

with E_x and E_y the optical fields on the x and y -polarization and E_0 the initial optical field amplitude. All field values are given to within a global phase.

Due to the birefringence, after the reflection off the SLM the two polarization components have accumulated two different phases.

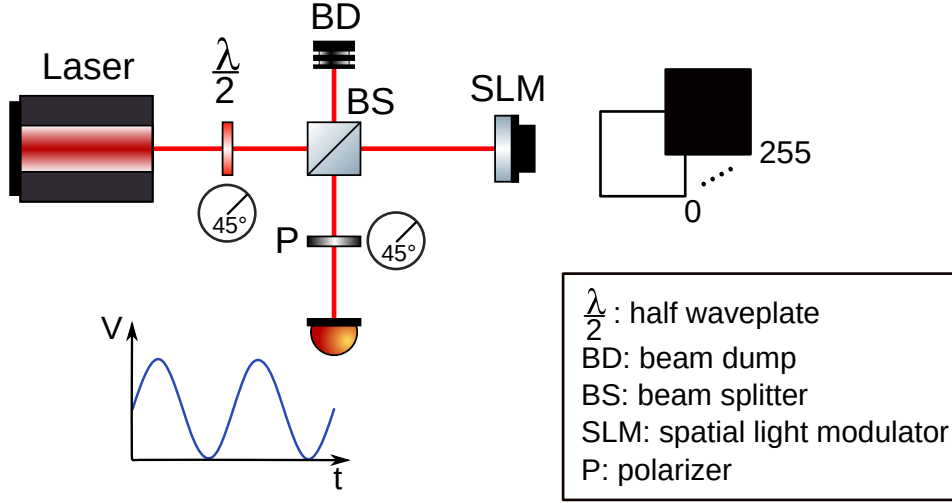


Figure 2: Schematic representation of the optical setup.

$$E_x^{\text{SLM}} = E_0 e^{ik2en_x} = E_0 e^{i\phi_0} \quad (2.3a)$$

$$E_y^{\text{SLM}} = E_0 e^{ik2en_y(V)} = E_0 e^{i(\Delta\phi(V)+\phi_0)} \quad (2.3b)$$

with e the thickness of the SLM. The phase terms are given by:

$$\phi_0 = k2en_o \quad (2.4a)$$

$$\Delta\phi(V) = k2e [n_y(V) - n_o] \quad (2.4b)$$

After reflection on the beam splitter, the 45 degree polarization is selected by the analyzer. Thus, the two components of the light interfere and the resulting intensity on the photodetector is modulated according to:

$$I \propto \cos^2 \left(\frac{\Delta\phi(V)}{2} \right) \propto \frac{1}{2} [1 + \cos(\Delta\phi(V))] \quad (2.5)$$

We experimentally measure the intensity as a function of the pixel values on the SLM. We show in figure 3 experimental data for SLMs from the three majors brands: a *Meadowlark Optics* High Resolution 1920 x 1152, a *Hamamatsu* X13138-07 and a *Holoeye* PLUTO. One can directly extract the pixel value corresponding to the 2π phase modulation by measuring the period of the oscillating signal. Typicallay, when using a device designed for a wide range of wavelengths or when using an input wavelength different from the one the SLM is calibrated for, the factory calibration may not provide a linear response and one needs to learn the lookup table of the pixel value. To do so, one can fit the experimental curve with the cosine function, which is somewhat

less direct that the technique relying on the measurement of the spatial fringes [1]. To illustrate linear phase calibration, we use the Meadowlark SLM which allow to change the onboard calibration by modifying the correspondence between the 8bit pixel values and the voltage values sent to the pixels encoded on 10 bits. To calibrate the device and have a linear relation between the pixel value and the phase modulation between 0 and 2π , we find for each desired phase value the closest point in the calibration data. We show in figure 3c and 3d the experimental characterization of the phase modulation before and after calibration.

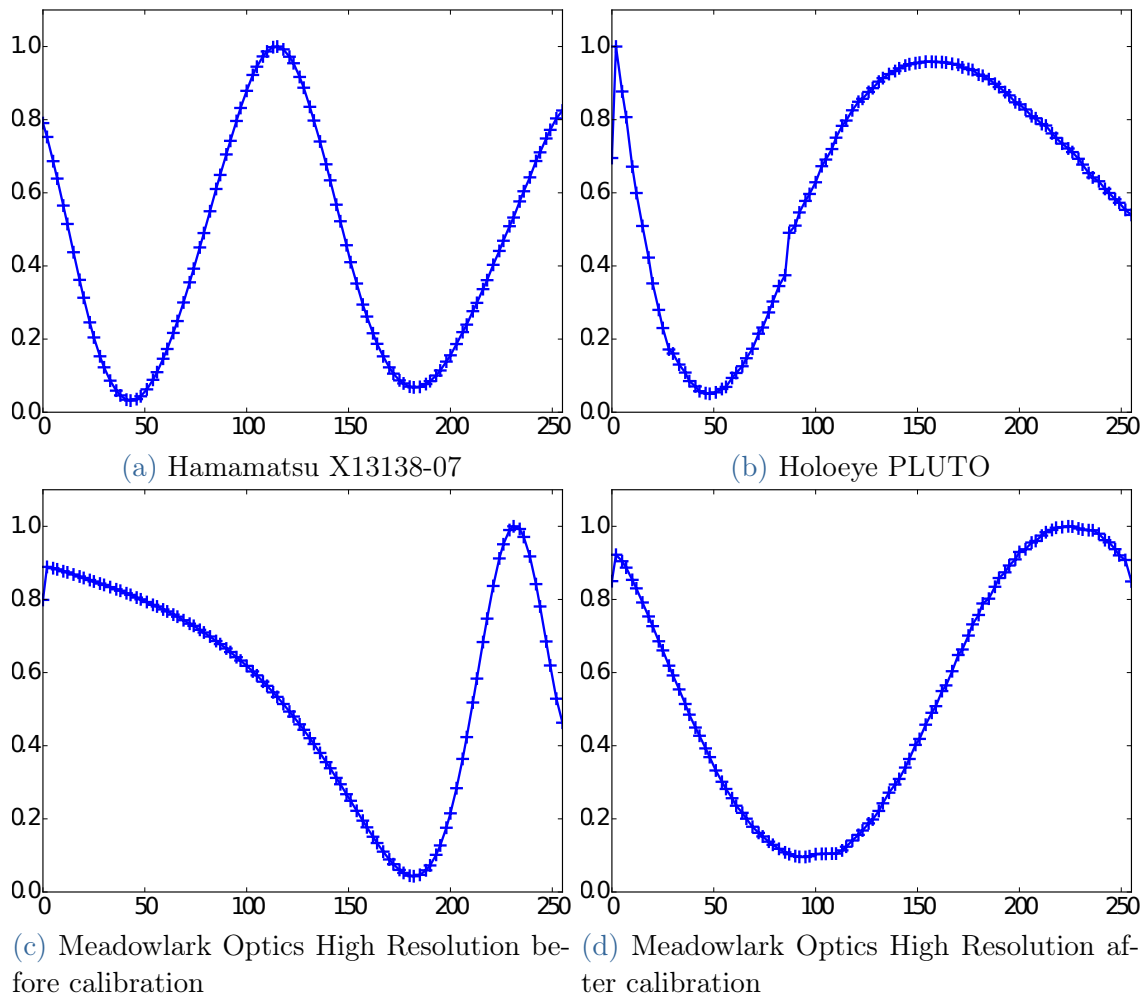


Figure 3: Intensity (arbitrary units) of the interference signal as a function of the pixel value (0 to 256).

3. Characterization of phase fluctuations

Due to the electrical addressing control scheme (that can be digital for Holoeye devices or analog for the Hamamatsu or BNS/Meadowlark ones) and the needed for regular

depolarization of the liquid crystals to avoid permanent damage, rapid phase fluctuations occurs [3]¹. Depending on the brand and the model, these fluctuations usually occur between 100 Hz and 400 Hz. Unlike the approach with Young slits/holes [1], the technique presented here to characterize the phase modulation has the advantage of only needing a photodetector, which allow a fast detection without requiring expensive instruments. Let's write the phase modulation as a static term depending only on the voltage applied and a zero mean fluctuation term:

$$\Delta\phi(V, t) = \Delta\phi_0(V) + \delta\phi(V, t) \quad (3.6)$$

For $\Delta\phi_0(V) = \pm\pi/2 \pmod{2\pi}$, the measured intensity reads:

$$I(V, t) = I_0(V) + \delta I(V, t) \quad (3.7a)$$

$$\delta I(V, t)/I_0(V) \approx \mp\delta\phi(V, t)/\Delta\phi_0(V) \quad (3.7b)$$

Using the calibration of the previous step, we identify the voltage values corresponding to $\Delta\phi_0(V) = \pm\pi/2 \pmod{2\pi}$, set the whole SLM to this value and measure the temporal fluctuations of the intensity. We show in figure 4 fluctuations measured for the three tested devices. Please note that one should not compare quantitatively those results as they were obtained with different conditions and with devices not in the most optimized conditions. In particular, the Holoeye device, which shows large fluctuations due to its digital addressing scheme, was a demo unit, not updated with the latest firmware and we did not use the addressing configuration designed to reduce phase fluctuations (by decreasing the bit depth).

¹Note that it has been proposed to lower the temperature of the SLM to reduce the phase fluctuations, increasing the viscosity of the liquid crystals. One should take into account that it will likely decrease the achievable refresh rate too.

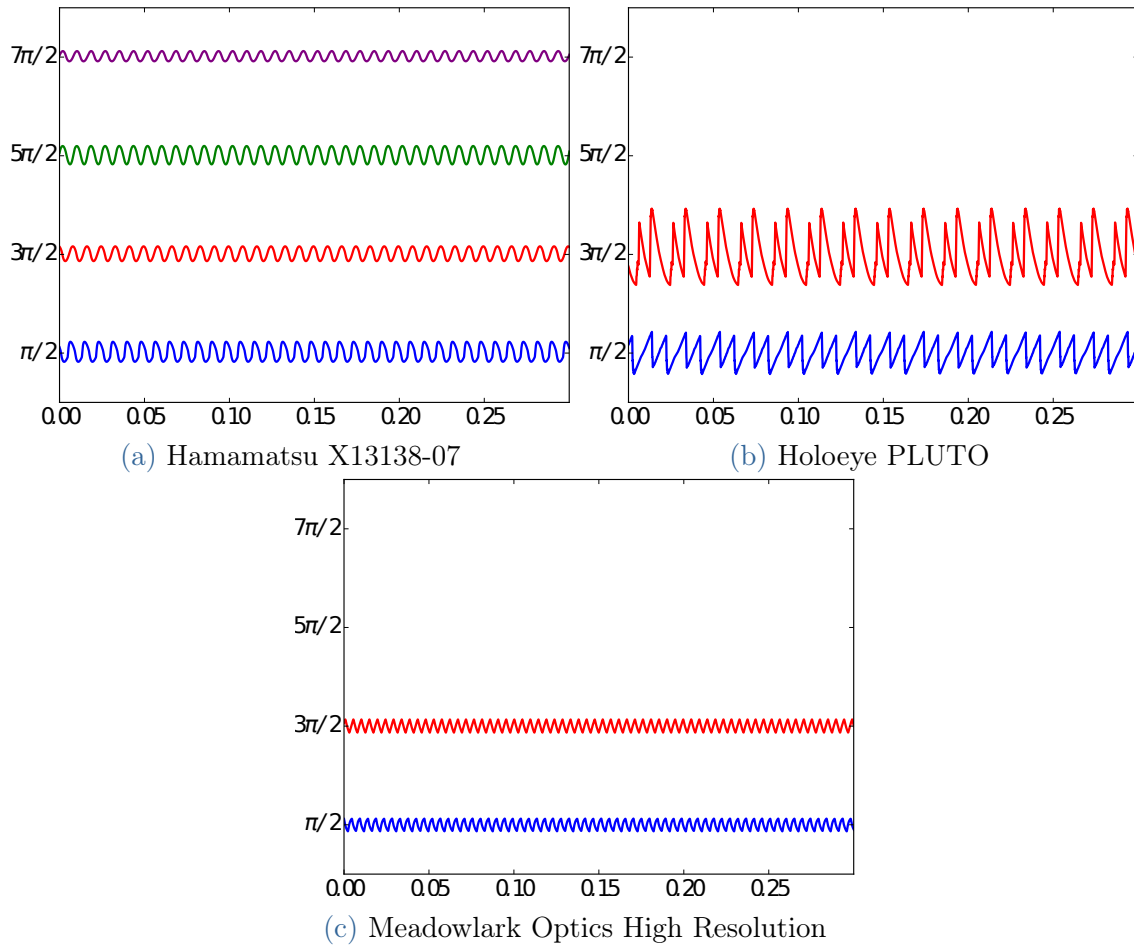


Figure 4: Intensity fluctuations (in arbitrary units) of the interference signal as a function of the time (in seconds).

References

- [1] How to characterize and calibrate a phase only slm, <http://wavefrontshaping.net/index.php/component/content/article/57-community/tutorials/spatial-lights-modulators-slms/60-how-to-characterize-and-calibrate-a-phase-only-slm>, accessed: 2018-09-15.
- [2] A. Farré, M. Shayegan, C. López-Quesada, G. A. Blab, M. Montes-Usategui, N. R. Forde, and E. Martín-Badosa, *Optics Express* Positional stability of holographic optical traps **19**, 21370 (2011).
- [3] A. Lizana, I. Moreno, A. Márquez, C. Iemmi, E. Fernández, J. Campos, and M. J. Yzuel, *Optics Express* Time fluctuations of the phase modulation in a liquid crystal on silicon display: characterization and effects in diffractive optics **16**, 16711 (2008).