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Abstract :

We describe a simple technique for the determination of the complex transmittance of a spatial light modulator. The technique uses the variation of the diffraction efficiency of Ronchi gratings imprinted on the SLM, as a function of the grating contrast. The measurement is made on the central peak of the diffraction structure with a monopixel detector only. The technique can also be used in quasi real time in order to adjust the SLM in the expected working regime (phase only modulation for example).

Liquid crystal based Spatial Light Modulators (SLM) are components that are used in a great number of image processing systems, such as correlators, optical neural networks or holographic memories. In all these systems the images can be inserted as both phase and/or amplitude modulation. If it is easy to measure the amplitude response of the SLM, its phase response is more difficult to evaluate. Different methods were proposed [1-7], they were mainly interferometric measurements using for example Mach-Zehnder interferometers. More recently methods using Ronchi gratings (or more generally diffracting structures) were proposed [8,9], these methods avoid the use of interferometric methods, but they require a precise analysis of the amplitude of the different diffraction peaks.

We here propose a simple and robust technique derived from the Ronchi grating measurement that only requires the use of a monopixel detector, and that can give the complex transmittance of a SLM. It is based on the study of the time evolution of the zeroth order of the Fourier transform of a Ronchi grating imprinted on the SLM, as the contrast of the grating is varied. This time evolution is directly linked to the contrast of the grating and thus to the complex transmittance of the SLM, allowing the determination of this transmittance as a function of the grey level of the image.

The SLM we used is issued from an Epson video projector. It is a TFT active matrix twisted nematic liquid crystal SLM. The experimental set-up is presented in Fig. 1. The SLM is placed between a polarizer and an analyzer correctly oriented to have pure phase modulation, its electronic is used with brightness and color potentiometers both at zero [7]. The amplitude of the phase modulation that is controlled by the contrast potentiometer (at zero level the phase modulation amplitude is at its minimum and at level 10 it is at its maximum, both these values being used in this experiment). The image is sent on the SLM through a personal computer. After the SLM a Si detector is placed at the Fourier plane of a lens, with a hole to select only one diffraction peak. The whole system is illuminated by a spatially filtered Argon laser emitting at 514nm.

A Ronchi grating is made of a succession of lines having different transmissions and a squared profile (Fig. 2). It is very easy to imprint such an image on a SLM, we simply send on the SLM an image constituted of a succession of lines with a grey level n_W for a “white” line and n_B for a “black” line. Light will then diffract on the grating, and an observation of the diffraction structure in the Fourier plane gives a structure of diffraction peaks that depends on the contrast of the grating.

The amplitude transmission $t(\xi,\eta)$ of the SLM with the grating is :

$$t(\xi,\eta) = \sum_{n=-\infty}^{+\infty} a_n \, \Pi\left(\frac{\xi - np}{a}\right) \qquad (1)$$

$\Pi(\xi)$ being a “gate” function of width a and height 1. The width a is taken smaller or equal to the grating step p, in order to take into account the interpixel spacing (we will suppose it completely opaque) (Fig.2). a_n is the amplitude of the window number n, its value is $a_n = a_W = T(n_W)\, e^{i\varphi(n_W)}$ for n

complex transmission and $\varphi(n)$ its phase. In order to simplify the calculation we will suppose that both dimensions of the SLM are infinite, i.e. we have an infinite number of lines of infinite length. The amplitude of the diffracted beam in the Fourier plane is given by the Fourier transform of t(ξ,η), which value is :

$$A(u,v) = \sum_{n=-\infty}^{+\infty} \delta\left(u - \frac{n}{2p}\right) \frac{\sin\left(\frac{\pi a n}{2p}\right)}{\frac{\pi n}{2p}} \left(T(n_W)e^{i\varphi(n_W)} + (-1)^n T(n_B)e^{i\varphi(n_B)}\right) \quad (2)$$

As we have a≠p, even without a written grating we observe peaks that correspond to the diffraction on the pixelated structure of the SLM. When, as in our case, we write every two lines, the diffraction peaks due to the grating appear at half distance of the diffraction peaks due to the pixel structure. If we want to take into account the finite dimensions of the SLM, we just have to replace the Dirac function in equation (2) by a function characteristics of the aperture of the SLM. If the aperture is sufficiently large, this broadening is nevertheless negligible compared to the distance between the different peaks, and the infinite approximation is justified. In the same kind of argument, the pixelated structure of each lines would be responsible of diffraction peaks in the other direction (along v) adding new terms in equation (2) with similar structure. Taking into account this exact structure would complicate the calculation, but without changing the expression of the central peak.

The respective height of the peaks is given by the last term of equation (2) that depends on the contrast of the grating (then on “black” and “white” levels n_B and n_W). Thus a measurement of the height of adjacent peaks allows the determination of the transmittance of each line and thus of grey levels. The problem is that the measurement depends on other parameters of the system, as indicated by the first terms of equation (2), what may complicate the determination. Nevertheless this technique was already successfully used [8].

We prefer another measurement much simpler and robust. We place a detector on the central peak of the diffraction structure. The measured intensity is deduce from (2) and is equal to :

$$I(0,0) = I_0\left(T^2(n_W) + T^2(n_B) + 2T(n_W)T(n_B)\cos\left(\varphi(n_W) - \varphi(n_B)\right)\right) \quad (3)$$

We fix the “black” level, and vary the “white” level. The intensity of the central peak changes due to diffraction following a law that depends on the phase change $\varphi(n_W) - \varphi(n_B)$. Thus a simple measurement of I(0,0) as a function of the grey level n, gives the phase φ(n). This simple measurement is only valid if T(n) does not vary, what is rarely the case. In order to remedy to this we add a measurement with a uniform “white” image. Then the detected intensity is :

$$I(0,0) = 4I_0 T^2(n_W) \quad (4)$$

This intensity can be easily compared to the “black” value, and normalized to it. With both measurements we can separately determine φ(n) et T(n) (normalized to “black” level n_B).

The interest of this measurement is that it does not require any calibration, only relative measurements are necessary. For example I_0 can be easily eliminated, the fact of not knowing its exact value does not prevent the measurement. Any effect due for example to the real number of lines, can be neglected, as soon as the central peak is narrow enough to have no overlap with the first peak, and that all its energy is collected by the detector.

An example of a measurement curve is given in Fig. 3. To obtain this signal we send a series of images successively uniform and with a Ronchi grating. The “black” level corresponds to n_B=0 and the “white” level is varied between n_W = 0 and 255 with a step of 5 between the images. So the first image is uniform with a level 0, the second image is a grating with levels 0 and 0, the third image is uniform with level 5, the fourth image is a grating with levels 0 and 5, and so on until the last image which is a grating with levels 0 and 255. Each image is presented for about 1.5s, in order to be sure to reach the steady state. The presented curve is numerically filtered (Fourier transform - low pass filter - inverse Fourier transform) from the 25Hz noise due to the flicker noise of the SLM [4]. The upper envelope (neglecting the transitory spike at image change) gives the uniform image signal, whereas the lower envelope gives the grating response (still not considering the spikes). We see that very high diffraction efficiencies can be obtained as we have a quasi perfect extinction of the central peak (Fig. 3, around t=50s, that corresponds to $n_W \approx 70$). This indicates that phase shifts greater than π can easily be obtained.

At high contrast of the grating ($\Delta\varphi>\pi$) a spike can be observed each time the image is changed. This spike is attributed to the finite response time of the SLM. Indeed when the grating image is applied to the SLM, the SLM takes a certain time to reach its steady state value. As the steady state value corresponds to a phase shift greater than π, during the build-up there is an instant at which the phase shift reaches the value of π, corresponding to a complete depletion of the central peak. After passing this maximum, diffraction efficiency decreases to reach its steady state value.

So for each value of the grey level, we can measure the intensity I_{uni} of the uniform image normalized to the signal obtained with an uniform “black” image :

$$I_{uni} = \frac{4I_0 T^2(n_W)}{4I_0 T^2(n_B)} = \left(\frac{T(n_W)}{T(n_B)}\right)^2 \quad (5)$$

which gives the normalized amplitude transmission $T_{norm}(n) = T(n)/T(n=0)$.

Then the intensity I_{grat} of the central peak in presence of the grating is determined and normalized to the signal obtained with an uniform “black” image :

$$I_{grat} = \frac{1}{4}\left(\frac{T^2(n_W)}{T^2(n_B)} + 1 + 2\frac{T(n_W)}{T(n_B)}\cos(\varphi(n_W) - \varphi(n_B))\right) \quad (6)$$

From it we deduce the normalized phase shift $\Delta\varphi(n) = \varphi(n) - \varphi(n=0)$, knowing the normalized amplitude transmission.

At this point several problems occur in this measurement. The first problem is a classical one. Indeed we can reach values of the phase shift greater than π. We thus cannot determine directly $\Delta\varphi$ from I_{grat}, we will have to unwrap the phase to determine the full variation of $\Delta\varphi$. The second problem is the fact that close to a maximum or a minimum of diffraction efficiency ($\Delta\varphi \approx k\pi$), the extraction of $\Delta\varphi$ from I_{grat} becomes very uncertain (values of $\cos(\varphi(n_W) - \varphi(n_B))$ greater than 1). To solve this problem we make a second measurement for which we change the “black” level using the 255 value instead of 0 and performed exactly the same measurements. We thus determine normalized amplitude transmission and normalized phase shift values as previously, but now normalized to the 255 value. Then we renormalized to the zero value using $T(255)/T(0)$ and $\varphi(255)-\varphi(0)$, that are given in both measurements. The advantage of this technique is that maximum and minimum values occurs for different values of n (if it ever occurs we can use another “black” level that allows the measurement) and zones of uncertainty do not overlap. Moreover, in order to unwrap the phase of one measurement we can use the other curves for which unwrapping positions are distinct.

The treatment described here gives the results shown in Fig. 4, where the values of $T_{norm}(n) = T(n)/T(0)$ and $\Delta\varphi(n) = \varphi(n) - \varphi(0)$ are extracted from the data of Fig. 3. Here two measurements were performed with a “black” image corresponding to n=0 (circles) and to n=255 (cross). We see that the parts where there is a problem do not overlap and that these two simple measurements allow a good determination of the complex transmittance of the SLM. For the normalized amplitude transmission, the accordance is rather good both measurements giving the same result. On these curves we can see that almost linear phase shift greater than 2π can be obtained, with moderate variation of transmission.

We can obtain even better results with another setting of the SLM (Fig. 5). In this condition we have quasi linear phase shift between 0 and π, with almost no amplitude modulation, leading to a SLM working as a nearly pure phase modulator.

As a conclusion we demonstrate a simple technique for the measurement of the complex transmittance of a SLM as a function of the grey level. This technique is certainly not perfect, mainly concerning the accuracy of the measurement, due to the presence of some missing points. But it has the great advantage of being very simple and of requiring neither interferometric set-up, very often delicate to align and to stabilize, nor CCD camera, that have generally poor linearity and dynamics. The extraction of the data can require some treatment, especially to unwrap the phase, in the case of phase shifts greater than π, but in general it is rather simple and can be easily automated.

More over this simple method can easily be used to adjust the SLM. The raw data of Fig. 3 can easily be used for this purpose. Adjustment of the polarizer, analyzer and electronics of the SLM can be made in quasi-real time (some tens of seconds or even less) to obtain the expected working regime of a SLM. For example just looking at the upper envelope of the raw signal which is proportional to the amplitude transmission of the SLM (Fig. 3) we see the residual amplitude modulation. We can minimize it in order to obtain a phase only modulator, this optimization being performed on the whole curve and not on a single value of the grey level.

In these measurements we also confirm that it is possible to obtain quasi phase only modulation with our SLM, with linear response between 0 and π, and quasi linear response between 0 and 2.5π.

The accuracy of the measurement is rather good and certainly sufficient for most of application of this SLM.

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Figure Caption

Figure 1 : Experimental set-up. SF : Spatial filter, P,A : Polarizers, FP : Fourier Plane.

Figure 2 : Ronchi grating sent to the SLM

Figure 3 : Raw data (after filtering of the 25Hz noise) of the measurement of complex transmittance of the SLM. The contrast potentiometer of the SLM is at level 10. The "black" level is at n_B=0.

Figure 4 : Normalized phase shift (black symbols) and normalized amplitude transmission (grey symbols) of the SLM. The contrast potentiometer of the SLM is at level 10. The "black" level is at n_B=0 for circles and n_B=255 for crosses .

Figure 5 : Normalized phase shift (black symbols) and normalized amplitude transmission (grey symbols) of the SLM. The contrast potentiometer of the SLM is at level 0. The "black" level is at n_B=0 for circles and n_B=255 for crosses .

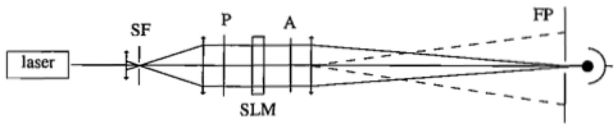

Figure 1

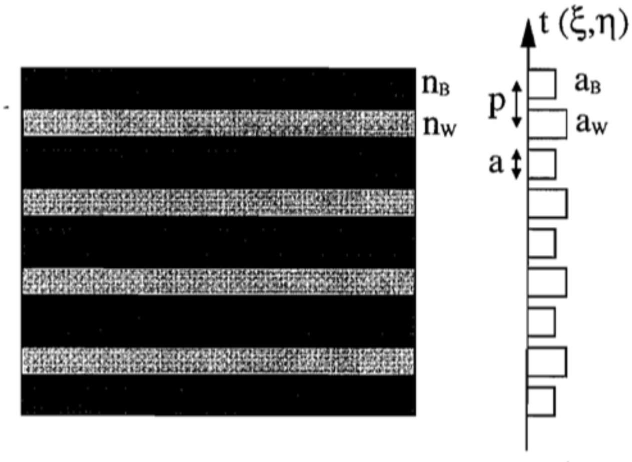

Figure 2

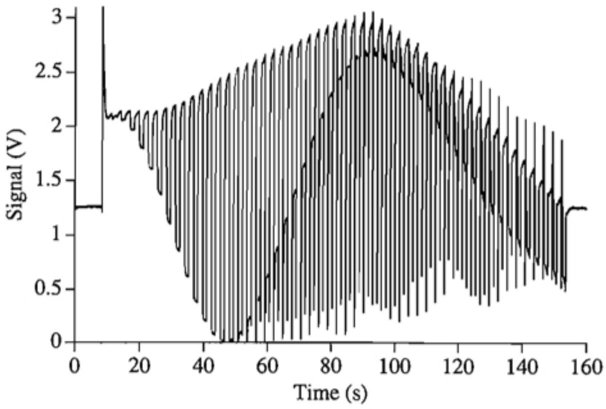

Figure 3

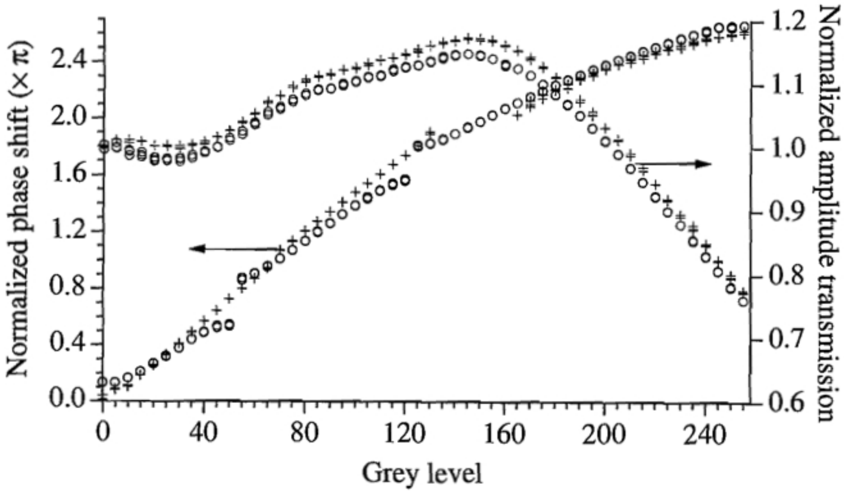

Figure 4

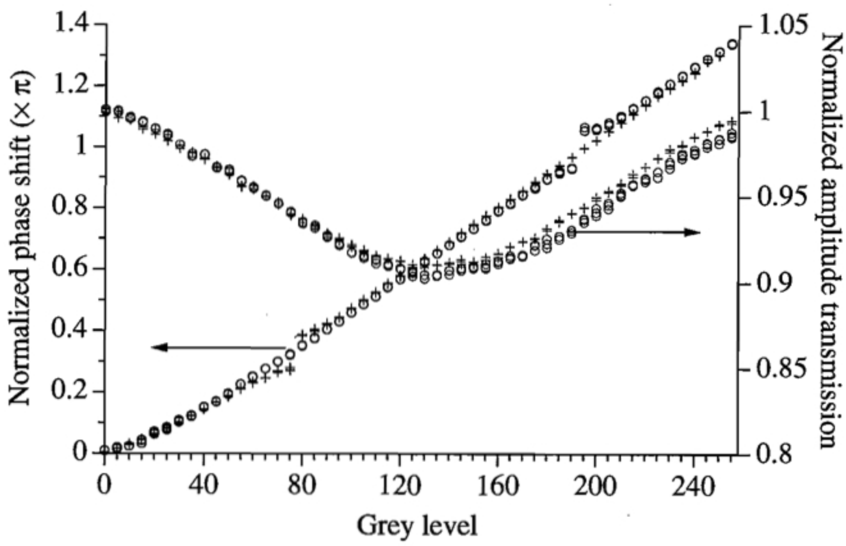

Figure 5