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Amplitude and phase coding measurements of a liquid crystal television

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Presented are amplitude and phase coding, and flicker measurements of liquid crystal panels from the commercially available Epson video projector, for configurations maximizing the contrast. For laser illumination it is found that a contrast as high as 1000 can be achieved, while for white light illumination it is reduced to a still acceptable value of about 60. However it appears that the flicker should be a more limiting factor in practical situations. It is also observed that amplitude and phase modulation are always coupled.

1. Introduction

For a number of time-consuming operations such as convolution or correlation of images, analog optical systems can exhibit interesting speed owing to their inherent parallelism, whenever their accuracy is sufficient for the particular application considered. The key to the realization of such optical systems is the availability of reasonable cost spatial light modulators (SLM) with sufficient resolution and contrast, as it appears that these devices are usually the limiting components in practical situations. In this paper we study the Epson liquid crystal television (LCTV) panels, which are part of a commercially available video projector, and offer an attractive quality/price ratio. They offer small dimensions, good resolution and practical interfaces, and have received much attention recently [1,2].

The amplitude coding properties in terms of the grey level of an input image are characterized experimentally, in configurations where the contrast (ratio of the maximum transmitted intensity to minimum transmitted intensity) is optimized. More specifically, the transmitted intensity coding, and the related phase coding and temporal fluctuations of the transmitted intensity are examined. Similar measurements were reported for the Thomson–Toshiba LCTV by Mazé et al. [3], and for the Epson LCTV by Kirsch et al. [1]. The latter are found to be slightly different from ours.

In sect. 2 the Epson LCTVs and their main characteristics are described briefly. In sect. 3 polarization and amplitude coding measurements with both monochromatic and white light illumination are presented, which for the former were not reported before for the Epson LCTV. In particular, it is shown that a contrast as high as 1000 is achievable, this appears to be different from the previously reported value of 80 [1]. In sect. 4 phase coding measurements are presented and its coupling with amplitude coding is discussed. Finally in sect. 5 the time behaviour of the SLMs is measured and the possibility of using grey level images is discussed in relation with the integration time of the system containing the SLM. Section 6 gives our final conclusions.

2. Description of the Epson SLM

The three liquid crystal panels included in the Epson video projector can be removed from it, their polarizer sheet taken away and their connecting ribbons prolongated. Then it is possible to use these panels as SLMs, using the projector's video interface to input an image from a camera or a frame grabber, and the projector's electronics to write this image onto the SLMs. As only black and white images are considered, the three channels carry the same signal.

On the projector front panel there are three potentiometers labelled "brightness", "contrast" and "color". Only the luminance signal is chosen for addressing the SLM so that the latter has no effect. But the "brightness' and "contrast" potentiometers control directly the transformation of grey level to applied voltage as explicitly shown in sect. 3.

The liquid crystals used are of the twisted nematic (TN) type. See ref. [4] for a detailed explanation of that structure. Their most important features are only summarized briefly here. When no voltage is applied, the molecular directors are parallel to the substrate orientation and thus form a helicoidal structure. When voltage is applied the molecules tend to align in the direction of the induced electric field. Thus the liquid crystal acts as a birefringent medium whose characteristics depend on the applied voltage, and hence on the grey level. Use of polarizer and possibly of an analyzer permits to control the amplitude and phase of the emergent light, which have in general a mutual dependence.

3. Amplitude coding and contrast measurement

In this section the measurement of the transmitted intensity between polarizer and analyzer is presented, and the contrast optimization is discussed. The experimental set-up is shown is fig. 1, and is similar to those in refs. [1,3].

The LCTV is placed between polarizer and analyzer, and the illuminating plane wave is either white light or monochromatic light from a laser. A circular aperture in the back focal plane of a Fourier lens selects the zeroth order of the diffraction pattern corresponding to the pixel structure of the LCTV. However, the detector was also positioned just after the analyzer, and no significant differences were found. The filtered wave is then collected by a detector, which averages out the temporal fluctuations of the measured intensity. An uniform image with a given grey level is written onto the LCTV, so that the intensity is averaged over many pixels.

In order to find the polarizer/analyzer configurations that optimize the contrast, a uniform image with grey level 0 is written onto the SLM. Then angular positions of the polarizer and analyzer yielding the best extinction are looked for, while the "brightness" setting is simultaneously optimized for reasons that will be explained later. Two such positions are found, and labelled configurations 1 and 2.

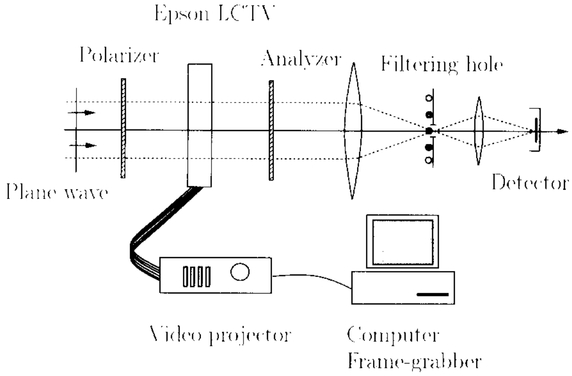

Fig. 1. Experimental set-up for polarization and contrast measurement. The illuminating plane wave is either white light or monochromatic light.

As the polarization of the light incident on the LCTV is rectilinear, at a given time the emerging light is elliptically polarized. But because of the flicker this polarization fluctuates. The polarization ratation, ellipticity and phase measurements presented in this paper are averaged over a video period, and must be understood as mean values.

Then if for a given grey level the analyzer is rotated and the transmitted intensity monitored, two maxima and two minima are observed. Moreover, if the analyzer is removed, it is observed that the total transmitted intensity does not depend on the grey level, which allows us to consider only normalized values. From this the polarization rotation and the ellipticity can be determined very simply. The results are plotted versus grey level for both an argon laser source ($\lambda = 514.5$ nm) and a white light source, for the rotation angle in fig. 2, and for the intensity ellipticity in fig. 3. One can observe that the rotation angle is a monotonic function of the grey level for the white light source but not for the argon laser source. The maximum ellipticity is larger for the argon laser source than for the white light source.

Now, if the analyzer is set to its position yielding the best extinction for a 0 grey level image, and if the transmitted intensity is recorded versus the grey level,

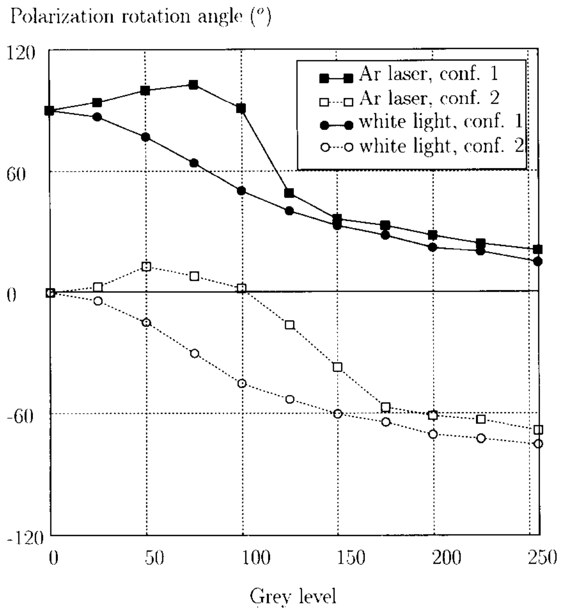

Fig. 2. Polarization rotation angle versus grey level for configurations 1 and 2, defined by the positions of the polarizer maximizing the contrast, for both monochromatic illumination (argon laser, $\lambda=514.5$ nm) and white light illumination. Lines are only visual guides.

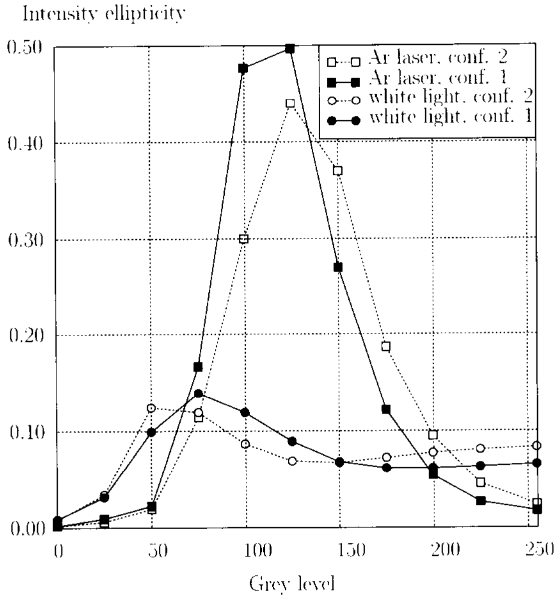

Fig. 3. Intensity ellipticity versus grey level for configurations 1 and 2, defined as in fig. 2, for both monochromatic illumination (argon laser, $\lambda=514.5$ nm) and white light illumination. Lines are only visual guides.

a squared amplitude coding or intensity coding of the SLM is obtained. Figure 4 shows the results for both an argon laser source ($\lambda=514.5$ nm) and a white light source. For both the intensity coding is an increasing function of the grey level. The contrast $C=I_{\max}/I_{\min}$ was found in all cases to be very nearly the same both configurations 1 and 2. For the white light source $C=60$ was obtained, which is considered satisfactory for projection applications. But remarkably with the argon laser source $C=1000$ was obtained, which is far more than the values reported elsewhere in the literature [1], which are under 100. The contrast for a HeNe laser source ($\lambda=632.8$ nm) was also measured and $C=1300$ was found (table 1).

To try and explain these differences, the importance of the setting of the potentiometers "brightness" and "contrast" must be stressed. We crudely interpret the "brightness" potentiometer as an offset voltage applied to the pixels whatever their grey level, and the "contrast" potentiometer as a gain relating the voltage above the offset to the grey level. This simple description seems to comply well with the data, as it can be observed that the curves in fig. 4 are images in affinities along the grey level axis. Then when looking for the best extinction for a 0 grey level image the setting of "brightness" is crucial for the final contrast obtained. This procedure is not equivalent to looking for the extinction with no voltage applied (i.e. with the SLM disconnected from the projector).

The optimal setting is not the same for all wavelengths, whence the difference between monochromatic and white light illumination.

The contrast for an isolated pixel was also measured. The SLM was illuminated directly with the HeNe laser ($\lambda=632.8$ nm), and a single pixel was imaged onto the detector with a high magnification optical system. A contrast value $C=400$, lower than with the previous set-up, was obtained. This can be accounted for by remarking that the illumination is no more a plane wave at the pixel dimensions scale, but contains many slightly different incidences. As the optimal setting depends on the incidence, the contrast must be smaller.

One can remark that a linear amplitude coding or a linear intensity coding with grey level can be

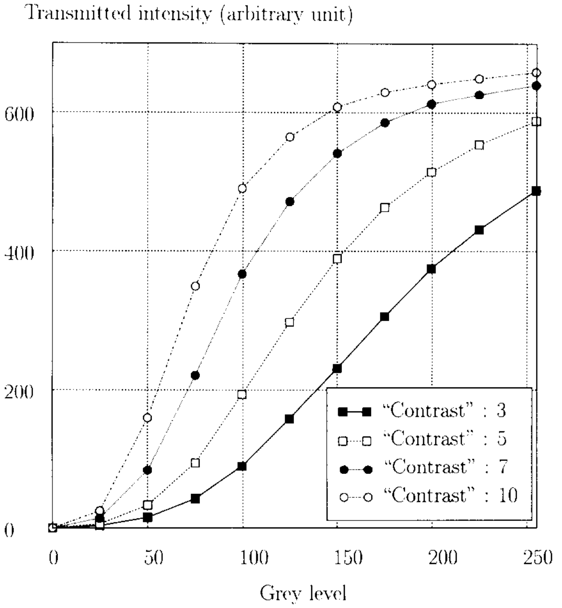

Fig. 4. Transmitted intensity versus grey level for different settings of the "Contrast" potentiometer for both configurations 1 and 2, defined by the positions of the polarizer and the analyzer maximizing the contrast, and for monochromatic illumination (argon laser, $\lambda=514.5$ nm) and white light illumination. The shapes of the curves are identical for all four cases and are not all plotted for clarity, but the intensity contrasts are different depending on the illumination. Lines are only visual guides.

Table 1
Maximum contrasts achieved for white light and monochromatic plane wave illumination.

	Illumination		
	White light	Argon laser $\lambda=514.5$ nm	HeNe laser $\lambda=632.8$ nm
Contrast	~60	~1000	~1300

achieved by applying an inverse look-up table (LUT) on the original grey level image.

4. Phase coding measurement

In this section, the phase coding associated with the intensity coding in configurations 1 and 2 is determined using a Mach–Zehnder type interferometer (fig. 5).

A monochromatic plane wave illuminates the interferometer set to produce fringes. The object beam passes through a LCTV preceded by a polarizer set in configuration 1 or 2. An image consisting of several regions of different grey levels is written onto the LCTV. The reference beam passes through a polarizer and a half-wave plate. The analyzer is set in configuration 1 or 2 corresponding to maximum contrast. A camera records the different fringes patterns corresponding to the different grey level regions in the image.

For the maximum contrast configurations of the polarizer and analyzer that are considered in this paper, the intensities associated with different grey levels in the object beam vary from 1 to 1000. As a consequence, the intensity and visibility of the different fringe patterns also vary on a large scale, and may exceed the dynamic range of the camera. To overcome this problem, the reference intensity is first adjusted in order to roughly obtain the same visibility for all grey level regions. This adjustment is done by rotating the half-wave plate in the reference beam. Then neutral densities are placed in front of the cam-

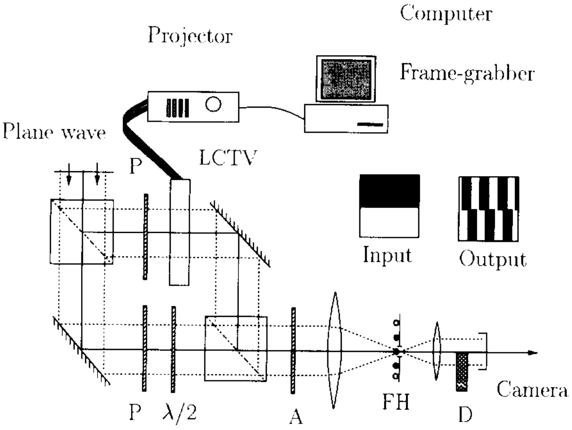

Fig. 5. Experimental set-up for phase-shift measurement. P stands for polarizer, A for analyzer, FH for filtering hole and D for density. The input image on the LCTV is either composed of two uniform regions with grey level 0 and n (for the phase-shift measurement), or of a continuously varying grey level image (for a qualitative observation of the phase-shift versus grey level curve). The Mach–Zehnder interferometer produces shifted fringes.

era to attenuate the brightest fringe patterns. This does not modify the fringes visibility.

Another solution would be to rotate the analyzer slightly to lower the contrast. However, as both the measured modulus and phase depend on the chosen polarizer/analyzer configuration, the phase would be altered. Indeed, the measured phase would be correct for grey levels not too close to 0, but incorrect for grey levels close to 0.

Firstly an image consisting of a "continuously" varying grey level in the vertical direction was used as input (more precisely line number 0 had grey level 0, ... line number n grey level n, ... line number 255 grey level 255). Thus the phase shift was observed versus grey level, and the modulo 2π indetermination was avoided. In order to obtain a quantitative measurement of the phase shift, images consisting of two regions of grey level 0 and n were used as input. Figure 6 is a plot of the results for argon laser ($\lambda = 514.5$ nm) illumination. The accuracy of this measurement was roughly estimated not to be better than 10%. The maximum phase shift is about 290° for configuration 1 and 415° for configuration 2. These values are quite large.

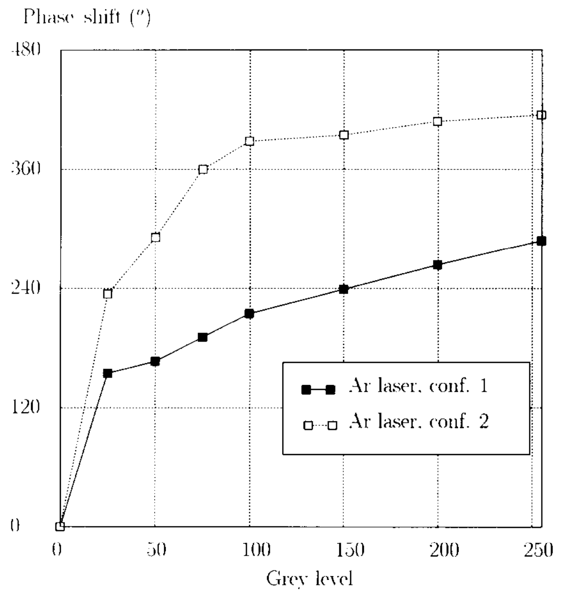

Fig. 6. Phase-shift versus grey level, for an argon laser illumination ($\lambda = 514.5$ nm), and for configurations 1 and 2, defined as in fig. 4. Grey level 0 is the phase reference. Lines are only visual guides.

One can note that the phase shift is not 0 for any configuration, in contrast to ref. [1]. Our results imply that the amplitude and phase modulation are coupled, thus forbidding pure amplitude modulation with only one Epson SLM. However, for grey levels larger than 100, the phase modulation is almost constant, at least for configuration 2. Then if one is ready to sacrifice some of the available contrast and operate at grey levels above 100, the phase modulation does not affect much the amplitude response. This effect was reported for another kind of SLM as well, the Hughes LCLV [5].

Similarly, without use of a polarizer, a phase modulation is obtained with no intensity modulation, but coupled with a polarization modulation. Again, for grey levels above 100, this modulation is minimized, but the phase modulation range is also reduced.

5. Flicker

In this section the temporal behaviour of the transmitted intensity is measured. The experimental set-up is the same as that of fig. 1, but the detector output is monitored with an oscilloscope. When a uniform image is written onto the SLM, periodic intensity fluctuations at 25 Hz are observed (flicker), around the mean value of the intensity, the quantity measured in sect. 3. The 25 Hz frequency obviously corresponds to the video rate (PAL-SECAM standard). The relative total intensity fluctuation is defined by the ratio $(I_{max} - I_{min})/2I_{mean}$. Table 2 shows this quantity for argon laser ($\lambda = 514.5$ nm) illumination.

These fluctuations are not negligible for any grey level. Hence if the integration time is smaller than 40 ms, to a given grey level will no more correspond one value for the transmitted intensity, so that the number of available effective grey levels will be strongly reduced. However, binary images might still be used with an acceptable effective contrast. But if the detector rate is simply chosen to be 25 Hz, then to a given grey level corresponds a given value of the transmitted intensity (i.e. the mean value of sect. 3), and grey level coding is possible.

Table 2
Total relative intensity fluctuation versus grey level for argon laser illumination ($\lambda = 514.5$ nm) and configuration 2, defined as in fig. 4. The values for configuration 1 are similar.

	Grey level										
	0	25	50	75	100	125	150	175	200	225	255
Mean transmission (%)	0.1	1	3.7	22.6	51.3	73.8	87.2	94.9	97.4	98.5	100
Relative fluctuation (%)	16	40	48.5	18	7.2	4.5	2.6	2.1	2.3	2.9	3

6. Conclusion

The modulation characteristics of the Epson liquid crystal television was studied with both monochromatic and white light sources in view of the coding of grey level images. For the amplitude coding, it was shown that very high contrast values can be obtained with monochromatic light (around 1000), and that even under white light illumination they remain sufficiently large (more than 60) for practical purposes. The phase coding was then measured and was found to be never negligible, thus forbidding pure amplitude coding. However, at the expense of some reduction in contrast, a small phase modulation may be obtained, as reported previously for LCLV SLM's [5]. Finally the flicker was studied, and the possibility of using grey levels was discussed with respect to the integration rate of the detector.

Let us consider an important practical example, the optical correlator, and see what practical consequences these measurements have upon this particular system. In this case one must encode an input and/or a filter, which can be complex valued, and are generally determined by algorithms designed to optimize the correlation function measurement under a certain number of constraints [6]. When the Epson liquid crystal valve, or a similar device, is to be used as an SLM in a coherent correlator to encode an image or a filter, the algorithm determining that image or filter should take into account the actual amplitude and phase coding achievable, *before* the optimization occurs [7,8], which is quite a strong constraint, furthermore not easy to handle numerically.

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