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Pixel size and pitch measurements of liquid crystal spatial light modulator by optical diffraction

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Abstract. We present a simple technique for the determination of pixel size and pitch of liquid crystal (LC) based spatial light modulator (SLM). The proposed method is based on optical diffraction from pixelated LC panel that has been modeled as a two-dimensional array of rectangular apertures. A novel yet simple, two-plane measurement technique is implemented to circumvent the difficulty in absolute distance measurement. Experimental results are presented for electrically addressed twisted nematic LC-SLM removed from the display projector.

Keywords. Liquid crystal displays; spatial light modulator; optical diffraction.

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1. Introduction

Liquid crystal-based materials have several uses ranging from commercial applications in various projection displays, computer screens, liquid crystal television to research in scientific areas like optical correlation, beam steering, matched filtering, polarization control, optical data processing, wavefront correction using adaptive optics, holographic data storage etc [1–6]. These devices are capable of modulating light depending on the applied voltage and polarization state of the input light. One of the important figures of merit is its spatial resolution that is determined by the size and total number of cells in the panel. Present developments of LC technology have focused on increasing their pixel resolution through reduction in panel's thickness and their pixel pitch. In majority of the applications, ideally one would like to have an array of square pixels having equal pitch in the horizontal and the vertical directions. However, some departure from square pixel shape and pitch may result due to the manufacturing constraints and environmental changes like temperature or mechanical stresses. To our knowledge, we did not come across any detailed studies to accurately measure these variations (if any) in the available literature. We find that a simple diffraction-based measurement can be used effectively to discern any meaningful variations from the square pixel shape and also the horizontal and the vertical pitch.

In §2 we explain the theoretical background for the proposed method. Experimental procedure and results are discussed in §3, followed by conclusion in §4.

2. Background

The two-dimensional pixelated array of LC panel can be formed by repeating an elementary rectangular aperture of size $(a \times b)$ spaced p and q apart in (ξ, η) plane, respectively, as shown in figure 1. Mathematically, it is obtained by the convolution operation between rectangle and comb functions as [7]

$$t_A(\xi,\eta) = \frac{1}{pq}\left[\operatorname{rect}\left(\frac{\xi}{a}\right) * \operatorname{comb}\left(\frac{\xi}{p}\right)\right]\operatorname{rect}\left(\frac{\xi}{L}\right) \times \left[\operatorname{rect}\left(\frac{\eta}{b}\right) * \operatorname{comb}\left(\frac{\eta}{q}\right)\right]\operatorname{rect}\left(\frac{\eta}{H}\right), \tag{1}$$

where $*$ designates the convolution operation, $\operatorname{rect}(\cdot)$ and $\operatorname{comb}(\cdot)$ functions have their usual definitions given in ref. [7]. The terms within square brackets in eq. (1) represent step and repeat function which is truncated by finite sized window $\operatorname{rect}(\xi/L)$ and $\operatorname{rect}(\eta/H)$. The complex amplitude transmittance of the aperture in eq. (1), when illuminated by a plane monochromatic light of wavelength λ and unit-amplitude, is given by

$$E_A(\xi,\eta) = t_A(\xi,\eta). \tag{2}$$

The field distribution at any point $P(x, y)$ on the screen placed at a distance z away from the aperture plane is given by the Fresnel–Kirchhoff diffraction formula [8]

$$E_o(x,y) = \frac{1}{\mathrm{i}\lambda}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\frac{\mathrm{e}^{\mathrm{i}kr}}{r}E_A(\xi,\eta)\mathrm{d}\xi\mathrm{d}\eta. \tag{3}$$

In the far-field (Fraunhofer) approximation, eq. (3) becomes

$$E_o(x,y) = \frac{\mathrm{e}^{\mathrm{i}kz}\mathrm{e}^{\mathrm{i}\frac{k}{2z}(x^2+y^2)}}{\mathrm{i}\lambda z}\mathcal{F}\left\{E_A(\xi,\eta)\right\}, \tag{4}$$

where

$$\mathcal{F}\left\{E_A(\xi,\eta)\right\} = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}E_A(\xi,\eta)\,\mathrm{e}^{-2\pi\mathrm{i}(f_x\xi+f_y\eta)}\mathrm{d}\xi\mathrm{d}\eta \tag{5}$$

is the Fourier transform of the transmitted field immediately behind the aperture and $f_x = x/\lambda z$, $f_y = y/\lambda z$ are the spatial frequencies in the x and y directions, respectively. Substituting eq. (2) into eq. (5) and using convolution theorem and similarity property of the Fourier transforms we get

$$\mathcal{F}\left\{E_A(\xi,\eta)\right\} = abLH\left[\operatorname{sinc}(af_x)\operatorname{comb}(pf_x)\right] * \operatorname{sinc}(Lf_x) \times \left[\operatorname{sinc}(bf_y)\operatorname{comb}(qf_y)\right] * \operatorname{sinc}(Hf_y). \tag{6}$$

Finally, the intensity distribution of the diffraction pattern at the screen is given by

$$I(x,y) \simeq |E_o(x,y)|^2 = |\mathcal{F}\{E_A(\xi,\eta)\}|^2. \tag{7}$$

A typical simulation of the intensity diffraction pattern of the LC panel is shown in figure 2, where, the pixel size and the pitch are related to modulating sinc and comb functions, respectively. The influence of different components of the LC panel is clearly seen in the diffraction pattern. Now the pixel size can be determined from the condition for minima, i.e., $af_x = 1$ and $bf_y = 1$. Similarly, the expressions for the pitch can be written as

$$p = \frac{1}{f_x} = \frac{\lambda z}{x} \tag{8}$$

and

$$q = \frac{1}{f_y} = \frac{\lambda z}{y}. \tag{9}$$

As expected, the scale inversion from diffracting elements in the aperture plane ($L > p > a$ in figure 1) and the width of the corresponding intensity peaks in the diffraction plane ($1/a > 1/p > 1/L$ in figure 2) is the direct consequence of the Fourier theory.

3. Experiment and results

The basic experimental schematic to perform the optical diffraction-based measurements is shown in figure 3. The SLM consists of twisted nematic LC panel (Sony

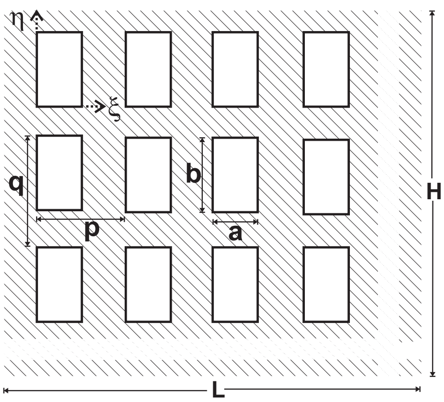

Figure 1. A typical geometry of two-dimensional LC panel.

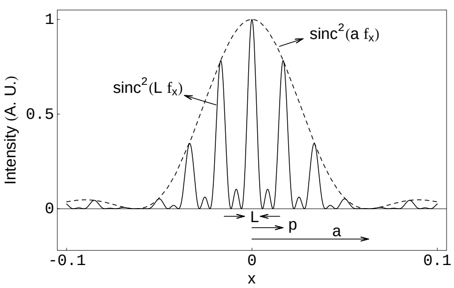

Figure 2. Diffraction pattern simulation of LC panel in the x-direction.

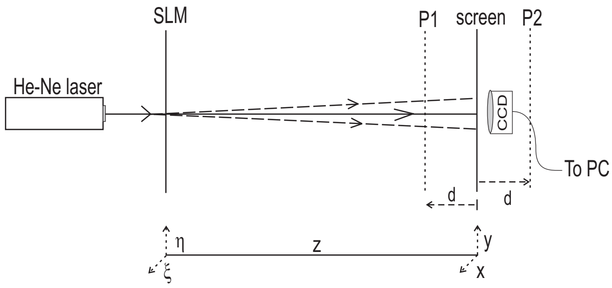

Figure 3. Basic lay-out of experimental set-up.

LCX016AL–6; number of pixels: 832 × 624) removed from a projector meant for desktop presentation. It is placed at aperture plane $(\xi, \eta, 0)$ and illuminated by normally incident He–Ne laser beam at 543.5 nm. The diffraction pattern is captured by a computer-controlled CCD camera (Pulnix TM-1320-15CL; number of pixels: 1300 × 1030; pixel size: $6.7 \times 6.7\,\mu$m) placed at a distance z in the (x, y) plane. A precise alignment and positioning of all the elements were ensured before making the measurements. The data were digitally processed and analyzed using National Instruments IMAQ Vision and LabVIEW softwares. In each measurement, 20 frames were captured and averaged to minimize the random noise in detection process. The fringing effect due to coherent illumination of CCD is removed by low pass Fourier filtering of the image data. Figure 4 shows one of the CCD images of the diffraction pattern obtained after averaging and filtering operation. Discrete artifacts present in figure 4 are due to downsizing of the image for display purpose. The desired accuracy in distance measurement from aperture plane to the screen may not be possible because of non-availability of an instrument to measure the distance accurately over a longer distance. Further, the hinderance caused by SLM and CCD housing assembly results in an additional uncertainty in determining the exact object and image planes. This limitation is overcome by recording the diffraction pattern at two different planes denoted by P1 and P2 in figure 3. The CCD camera (without imaging lens) is mounted on a micron accuracy translation stage which has a maximum range of 10 mm. If the plane P1 and P2 are at a distance of $z-d$ and $z+d$, respectively, from the aperture, then the modified expression for pitch (eq. (8)) at plane P2 and P1 can be written as

$$p = \frac{\lambda(z+d)}{x_2} \tag{10}$$

and

$$p = \frac{\lambda(z-d)}{x_1}, \tag{11}$$

respectively. By eliminating the z dependence from eqs (10) and (11), we get the expression for pitch as

$$p = \frac{2\lambda d}{x_2 - x_1}. \tag{12}$$

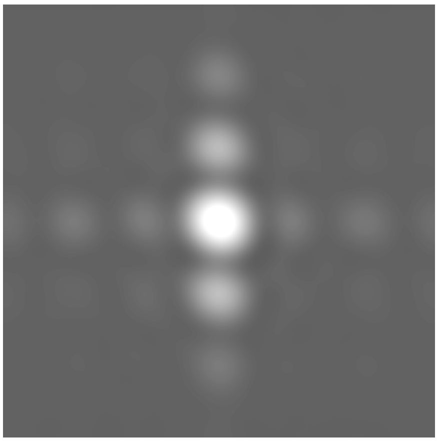

Figure 4. CCD image of the LC diffraction pattern after averaging and low-pass filtering.

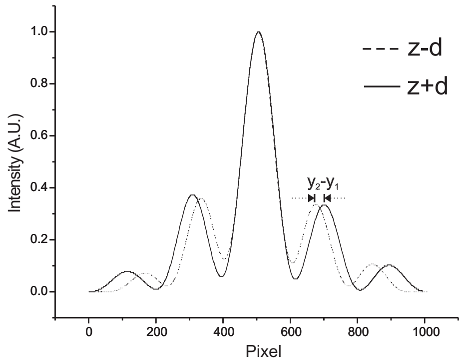

Figure 5. Intensity line profile of a diffraction pattern along the y-direction, recorded at two different planes that are 10 mm apart.

A similar expression obtained for the pitch in y-direction is $q = 2\lambda d/(y_2 - y_1)$. Figure 5 shows the intensity line profile along the y-direction for a diffraction pattern that is recorded at two different planes at a distance $z+d$ and $z-d$. A centroid detection algorithm was used to locate the intensity peaks and pixel distances in secondary maxima. The pitch values p and q measured in two directions are 31.8 ± 1.3 μm and 36.8 ± 1.7 μm, respectively. The direct measurement of pixel dimensions a and b from the CCD image was not possible. That is because, the threshold for intensity minima of the modulating $\mathrm{sinc}^2(\cdot)$ function cannot be determined uniquely due to unavoidable background noise. Therefore, a nonlinear best parameter fit together with the measured values of p and q is used to obtain $a \approx 28.6$ μm and $b \approx 31.6$ μm.

In our opinion, the apparent discrepancy between the square pixel pitch ($\approx 32\,\mu$m) specified by the manufacturer and the experimentally measured values is partly due to anisotropic stress caused by the ambient temperature variations and the protective housing assembly around the LC panel. It is also to be noted that we have not taken into account the refractive index of the LC material and the fact that LC cell has a finite thickness. This, however, will not alter the diffraction pattern in any significant way.

4. Conclusion

A simple optical diffraction-based technique was implemented to measure the pixel size and pitch of a LC-based SLM. Further, the difficulty to measure the distance z in conventional diffraction-based experiment is circumvented by two-plane measurements of diffraction pattern which is more accurate and easier to implement.

Finally, we emphasize that the variations in pixel size and/or pitch can seriously degrade the performance of certain applications like page-oriented holographic data storage where one-to-one imaging of SLM and CCD pixel is most desired [9]. Any significant departure from a square-shaped pixel can be helpful in evaluating the suitability of the LC-based SLM for holographic data storage system and adaptive optics-based wavefront corrections.

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