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Modulation transfer function of a liquid crystal spatial light modulator

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Abstract

The modulation transfer function (MTF) of a pixelated liquid crystal spatial light modulator (LC-SLM) has been derived as a function of the fill factor. Based on the formula, we have investigated the dependence of the MTF on the orientations and spatial frequency of the input patterns. Furthermore, we have proposed and demonstrated a method for improving the MTF of a LC-SLM. © 1999 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

In the information age, display technology is becoming increasingly essential in many aspects. For optical information processing and data storage applications, the display devices are called the spatial light modulators (SLMs). The requirements for a good SLM include flat-panel, light-weight, high contrast, low driving voltages and low power consumption, etc. The SLMs that have been used for optical information processing are liquid crystal television (LCTV), liquid crystal light value (LCLV), digital movable mirror arrays (DMD), magneto-optical spatial light modulator (MO-SLM), micro-channel plate spatial light modulator (MSLM), and multiple quantum well devices (MQW), and so on. Among these devices, the electrically addressed liquid crystal spatial light modulator (LC-SLM) has been the most popular because they are in good optical quality, easy operation, and commercially available [1,2]. For an optical system, the transmission characteristics of a SLM plays an important role in determining the performance of the system [3]. The transmission characteristic of a SLM can be described by the modulation transfer function (MTF) [4], which is defined as a relationship between the input and output signals, is a function of the spatial frequency of the input signal.

In this paper, we first introduce the modulation transfer function of a liquid crystal spatial light modulator by deriving an expression for the MTF for a pixelated LC-SLM. Then an optical system was set up to measure the MTF of a LC-SLM, and the dependence of the MTF with respect to the orientation and spatial frequency of the input patterns is

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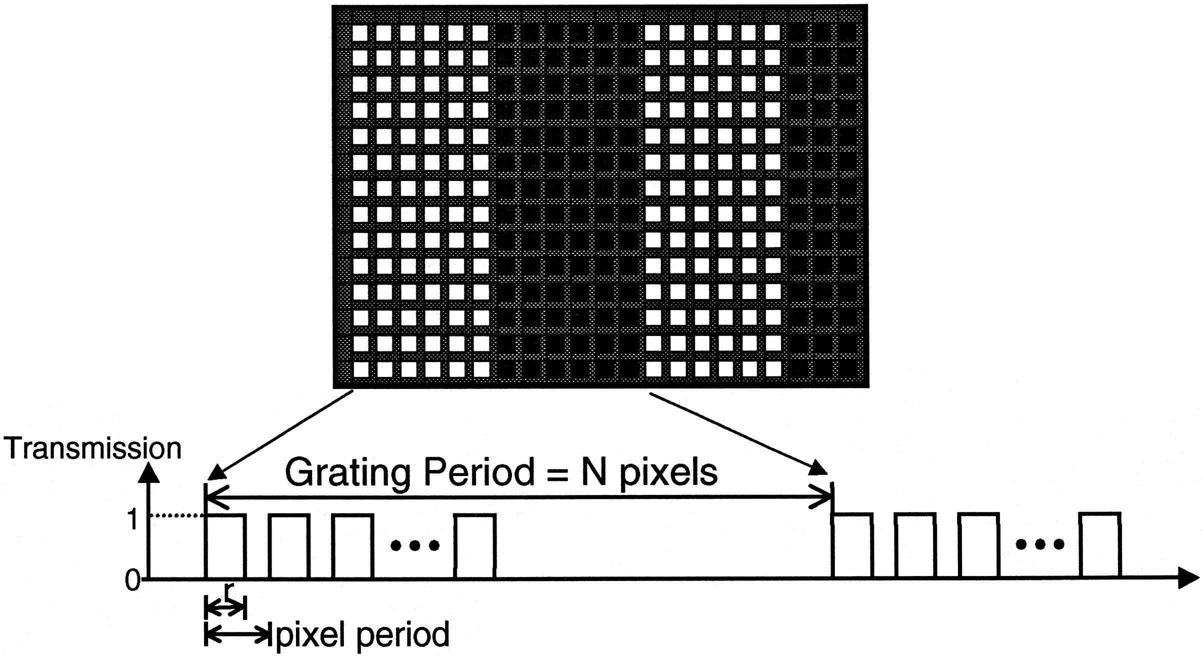

Fig. 1. Vertical grating input to LC-SLM.

described. Finally, we present a driving technique for improving the MTF of a LC-SLM.

2. Modulation transform function of LC-SLM

In general, the MTF of a system represents its capability of transferring the modulation depth from the input to output signals. Experimentally, the MTF of a system can be characterized by measuring the modulation depth of the output signal when a simple grating is the input signal. For a LC-SLM, the MTF can be defined as the diffraction efficiency of the displaying grating pattern, which is measured at the Fourier plane of the SLM. The diffraction efficiency is calculated as the ratio of the first-order diffraction intensity with respect to the zero-order intensity. By this definition, the MTF describes the LC-SLM's capability of displaying patterns at different spatial frequencies.

Analytically, the MTF of a LC-SLM can be calculated by the Fourier series expansion technique. Shown in Fig. 1 is a grating of vertical lines, which is displayed on a LC-SLM. It is interesting to note the pixelated structure of each vertical line produced by the liquid crystal pixels. In the figure the liquid crystal pixels are assumed to be in a squared structure with a fill factor of r, and the pixel pitch is normalized to be 1. Also, the bright pixels represent ON LCD-pixels with optical transmission of 1 and the dark pixels are the OFF LCD-pixels that block

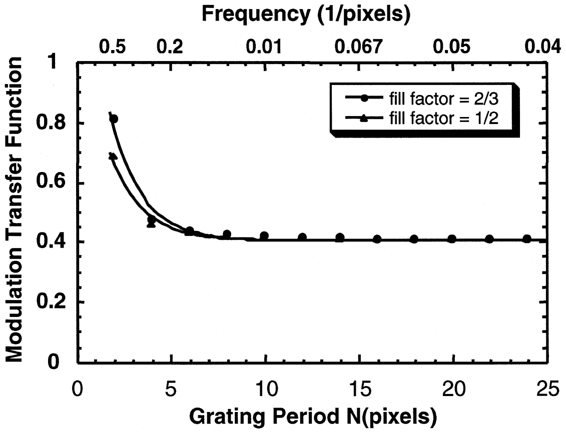

Fig. 2. Modulation transfer function of an ideal LC-SLM for the fill factor $r = 1/2$ (triangle) and $r = 2/3$ (circle) between the grating period $N = 2, 4 \ldots 24$.

off the light. The MTF of the pixelated structure of the grating can be derived by using the Fourier series expansion and is written as following:

$$MTF = \frac{4(a^2 + b^2)}{\pi^2 r^2} \tag{1}$$

where

$$a = \sum_{n=0}^{N-1} \cos\left[\frac{2\pi}{N}\left(n + \frac{r}{2}\right)\right]\sin\left(\frac{\pi r}{N}\right)$$

$$b = \sum_{n=0}^{N-1} \sin\left[\frac{2\pi}{N}\left(n + \frac{r}{2}\right)\right]\sin\left(\frac{\pi r}{N}\right)$$

where N is the number of pixels in one grating period on the LC-SLM. For a LC-SLM, the minimum period is $N = 2$, which corresponds to the pattern of ON and OFF for every alternative pixels. The pattern shown in Fig. 1 represents the case $N = 12$. By using Eq. (1), we calculated the MTF value of a LC-SLM and plot the theoretical curve as a function of N of the input grating ($N = 2, 4, \ldots, 24$), and with the fill factor r as a parameter, as shown in Fig. 2. According to our definition of the grating period, the spatial frequency is equal to $1/N$. It can be seen in Fig. 2 that the MTF for the LC-SLM is high at high grating frequencies and it becomes uniform at low frequencies. It can also be seen that the fill factor does not affect the MTF, except for the grating with maximum spatial frequency ($N = 2$).

3. Measurement of MTF

Fig. 3 shows the optical setup for measuring the MTF of a LC-SLM. Gratings with various grating periods and different orientations (along the vertical and horizontal directions) are generated by a computer, displayed on the SLM, and then Fourier transformed by lens L_1 ($f = 84.1$ cm). A photo-detector located at the focal plane is used to measure the intensities of the first-order diffraction and the direct transmission beams, respectively. Then the MTF is obtained by calculating the ratio of these intensities.

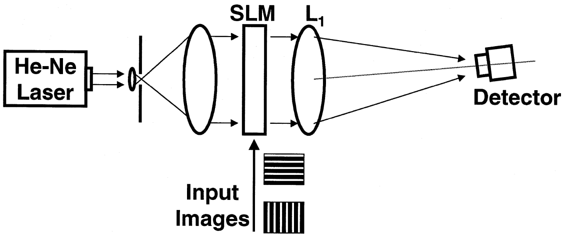

Fig. 3. Schematic diagram of an experimental setup for measuring MTF.

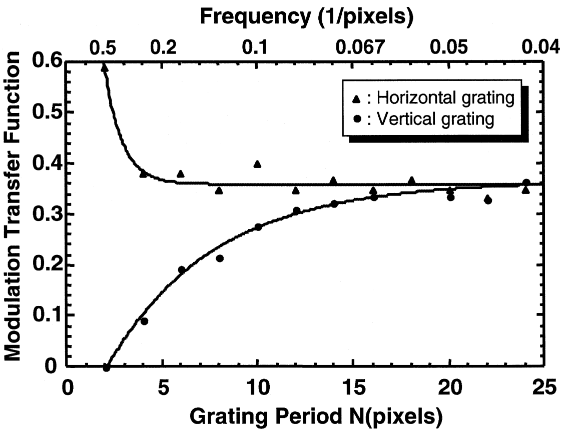

Fig. 4. Measurements of MTF of a LC-SLM for horizontal (triangle) and vertical (circle) gratings.

Fig. 4 shows the experimental results for the vertical and horizontal gratings. It can be seen that the horizontal gratings produce a similar MTF as the theoretical curves shown in Fig. 2. On the other hand, the vertical gratings have poor MTF at small grating periods. It means that the high frequency vertical gratings cannot be displayed with good fidelity. If we define the cutoff frequency of a SLM as the spatial frequency that produces MTF below 0.1, then this LC-SLM has a cut-off frequency for vertical gratings at $N = 4$.

4. Discussions

Now we examine the characteristics of LC-SLM displays and explore the possibility of improving the MTF. Let us first examine the display of gratings by different LC-SLMs. Fig. 5 shows some microscopic images of the vertical and horizontal gratings, which are displayed on different LC-SLMs. These LC-SLMs are driven by the input images which are stored in a frame grabber. It can be seen that in the middle column the LC-SLM1 displays grating pat-

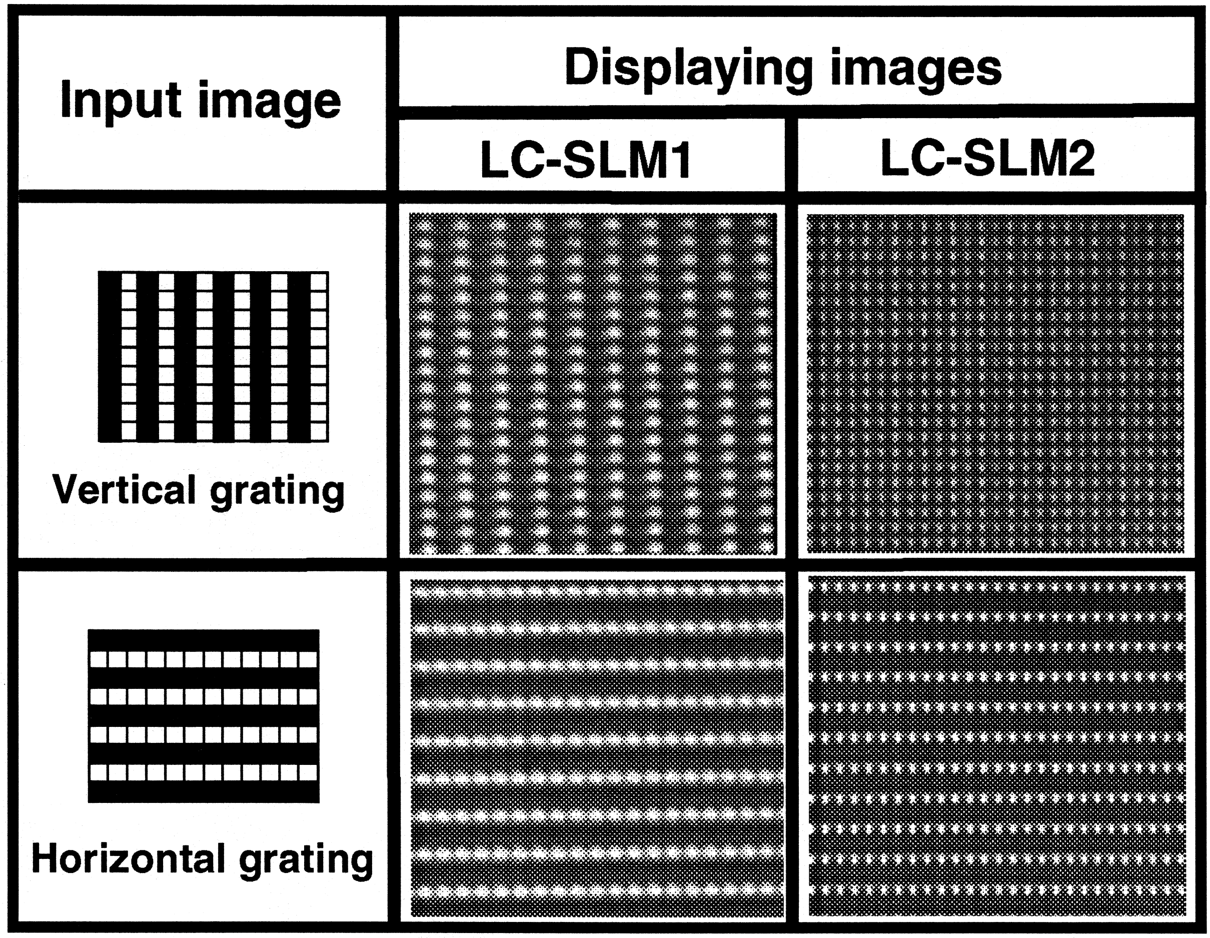

Fig. 5. Microscopic images of gratings displayed on two LC-SLMs.

terns with high contrast for both the vertical and horizontal orientations. They are in good fidelity with the input gratings. On the other hand, the right column shows that the vertical gratings are not displayed well by LC-SLM2. The vertical lines are displayed with smeared gray levels such that the vertical grating structure of the input image is completely lost. In order to improve this phenomenon, let us examine the addressing technique of the LC-SLM.

The display of a LC-SLM is controlled by two synchronization signals. One is for the vertical scanning and the other is for the horizontal scanning. The input pattern to be displayed is sent into the LC-SLM in a scanning format such that each horizontal line is sampled by the horizontal synchronization signal and transferred through a shift register along the horizontal direction. Each time when one horizontal line is in place, the whole line signal is latched. Then the next horizontal line is sampled and latched in a similar way. In this way, an image pattern is loaded line-by-line from top to bottom of the image frame.

Fig. 6 shows the synchronization signals for a LC-SLM with 320×240 resolutions. In the figure the top row shows that the video signal is displayed at the frame rate of one frame per $1/30$ s. Each video frame is divided into 240 rows. The middle row shows that each row of video signal is displayed between two consecutive horizontal synchronization clocks, which is at the rate of one line per $1/30 \times 1/240$ s. During the scanning of each horizontal

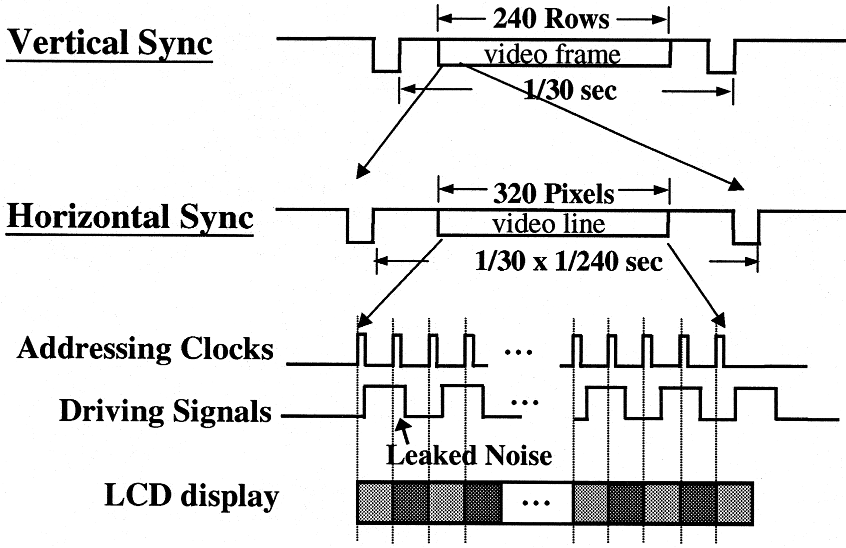

Fig. 6. The timing clocks for the LC-SLM.

line, horizontal addressing clocks are used to address the 320 liquid crystal pixels so that the VGA signals from the data bank (the frame grabber of a personal computer) can drive the LC pixels. The TFT (thin-film transistor) capacitor of the LC pixel which is addressed by the clock pulse will be charged up by the corresponding driving signal. And the charged voltage determines the gray level of the addressed LC pixel. In our case the driving signals of the grating patterns are binary. If the addressing clocks are not aligned perfectly with the driving signals, then the gray levels of the neighboring pixels will be affected. For the example shown in the figure the driving signal is a vertical grating with $N = 2$. The figure shows that some of the first bit is leaked to the second pixel, hence the TFT capacitor of the first pixel is charged up but not completely and that of the second pixel is charged a little bit. As a result, the first pixel, which should be fully bright, displays with a reduced brightness. On the other hand, the second pixel, which should be totally dark, is lighted up by the leaked voltage.

Fig. 7 shows the displays of grating patterns with grating period of $N = 2$, but for different orientations. The left-hand column shows that, the input pattern is a vertical grating and the addressing clocks do not align perfectly with the input driving signal. Thus, the dark pixels are lighted up and the intensity of the bright pixels are decreased. As a result, the contrast of the output image is reduced. The situation is different for a horizontal grating, as shown in the right-hand column. In this case, each horizontal line is either totally bright or dark. During the horizontal line scanning period all the pixels in one horizontal line are either charged up or maintained un-activated. Thus, there is no such problem of misalignment between the addressing clocks and the driving signals. The upper-right part of Fig. 7 shows the clocks and driving signals of one totally bright horizontal line, and the lower part shows the LC-SLM display of the complete frame. It is seen that the horizontal gratings can be displayed with high fidelity.

Note that the misalignment phenomenon occurs only at the boundaries between bright and dark lines of vertical grating. The middle part of a grating line, which remains at either bright or dark state, can always be displayed well. Since low spatial frequency gratings (with large N) have less boundaries, they could be displayed with high fidelity. That is the reason why they produce better MTF than that of high frequency vertical gratings, as was shown in Fig. 4. Therefore, we need only to find a method for improving the MTF for high frequency vertical gratings.

Based on the above discussion, it is realized that the timing alignment between the addressing clocks

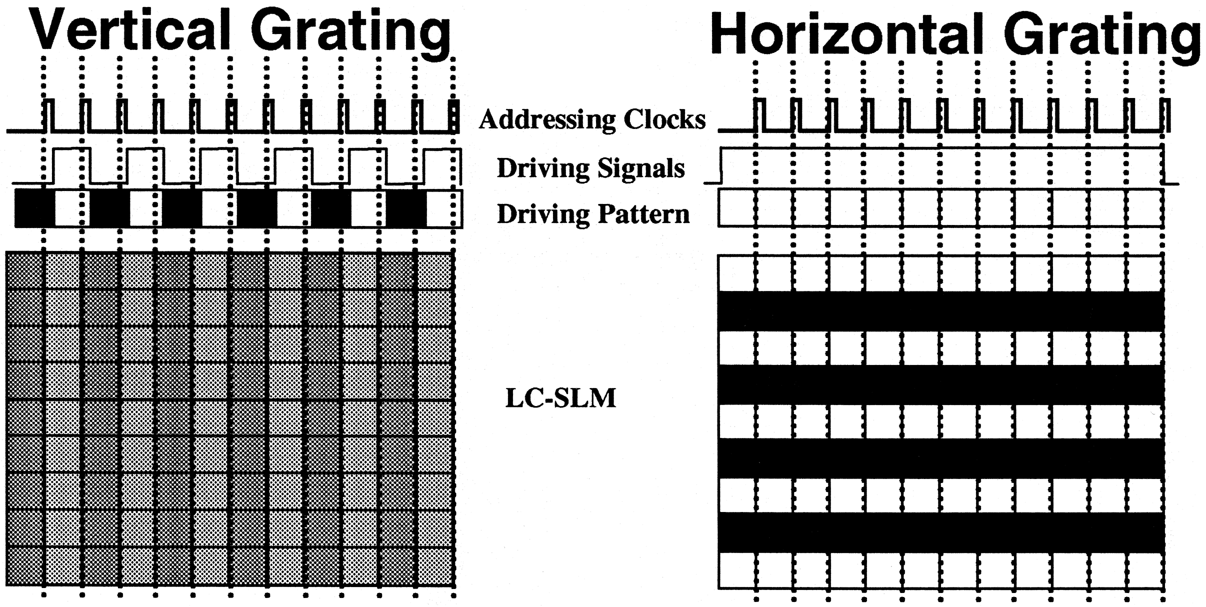

Fig. 7. Output images of an electrically addressed LC-SLM with vertical and horizontal gratings ($N = 2$).

and the driving signals is a crucial factor that determines the displaying capability of a LC-SLM for vertical grating patterns. If misalignment occurs, then the contrast of the displaying pattern is reduced and the modulation transfer function is decreased. Therefore, it is important to be able to align the timing between the addressing clocks for the LC pixels and the driving signal from the frame grabber. Usually this could be achieved by adjusting the timing clocks of the driving circuit of the LC-SLM with using the 'tracking' control button. But even with this, if the pulse width of the driving signal of the ON-state is wider than that of the addressing clock, misalignment also arises. To alleviate this effect, it is also necessary to be able to adjust the pulse width of the driving signal for each pixel. This could be achieved only with some special LC-SLMs.

In our case, our LC-SLM has a resolution of 320×240 pixels. The device was driven by a VGA signal from a frame grabber with 640×480 pixels. The VGA signal was automatically transformed to 320×240 resolutions by the driving circuit of the LC-SLM. For example, to display a vertical grating with $N = 2$, the corresponding pattern on the frame grabber would be $N = 4$. Normally this would be a pattern with two bright and two dark pixels in one period on the frame grabber. Experimental results show that this vertical grating might not be displayed with high fidelity, as was shown in LC-SLM2 of Fig. 5. And this produces a MTF that is below the cutoff value. In order to alleviate the problem, the pulse width of the driving signal for ON-state LC pixels should be adjustable. But our LC-SLM has no access for achieving that. We have found another technique for displaying a vertical grating with $N = 2$. We reduced the number of bright pixels of the frame

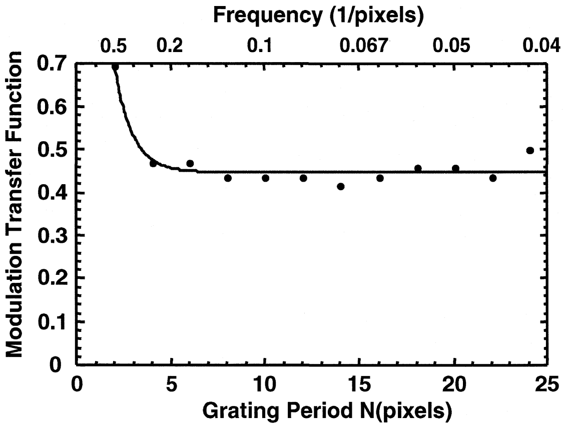

Fig. 8. Improved MTF of a LC-SLM for vertical gratings.

grabber from two to one. In other words, one bright plus one dark pixels of the VGA were used to drive one LC ON-pixel, and two consecutive dark VGA pixels were used to drive one LC OFF-pixel. Thus, the pulse width of the driving signal for the ON-pixels was reduced to half so that it would not leak into the OFF-pixel. The brightness of the ON-pixel was reduced slightly. But then the vertical grating can be displayed with high fidelity. This technique has been applied to vertical gratings with all other frequencies, viz., for a vertical grating with a period of N-pixels the number of bright pixels on the frame grabber was $N-1$. The resulted MTF for vertical gratings is shown in Fig. 8. It is seen that the MTF curve has been improved.

5. Conclusion

In summary, we have introduced the modulation transfer function of an electrically addressed LC-SLM, which is used to characterize the frequency response of the device. We have derived an expression for the MTF of an ideal LC-SLM, and we have set up an optical system to measure the MTF. Experimental results show that the MTF of a pixelated LC-SLM is reduced for high frequency vertical grating patterns if the addressing clocks are not perfectly aligned with the driving signal. Finally, we have demonstrated that by a proper adjustment of the timing and the pulse width of the driving signal the MTF of vertical gratings can be improved.

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