Effects of phase flicker in digitally driven phase-only LCOS devices on holographic reconstructed images

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Phase flicker can degrade the performance of holographic applications at both device level and application level. On the device side, the meaningful phase modulation resolution is proved to be limited by the overlapping between adjacent phase levels caused by flicker. Here the tolerance of the overlapping for different modulation levels is provided. The frame rate of the device is also constrained by the phase flicker. The balance between low flicker and fast LC response for fast frame rate is quantitatively analysed. On the application side, the effects of real phase flicker on the performance of blazed gratings and image holograms are investigated using the temporal phase flicker profiles measured from a phase-only LCOS device, and they are shown to be comparable to that introduced by quantization level and amplitude noise respectively.

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1. INTRODUCTION

Phase-only liquid crystal on silicon (LCOS) devices have become one of the most promising optical engines for digital holographic applications. As the users, we would like to accurately show the designed digital hologram on the device and then obtain high quality replay of the hologram. To achieve such performance, there are at least three key requirements for the device in terms of the phase depth: 1) Phase uniformity across the panel. 2) Linear definition between the phase and the gray level, i.e., phase linearity. 3) Well-defined digitized phase levels, i.e., phase flicker.

Phase flicker is of the most interest here as the instability of the phase modulation depth introduced by the temporal fluctuation can lead to unexpected degradation of the system performance. For example, one of the current challenges for holographic 3D displays is a very small image size, which is limited by the information bandwidth of the light engine and the transmission rate of data bus. The spatial information bandwidth of LCOS devices is reduced by its low phase resolution, which is constrained by phase flicker. When it comes to telecommunication applications like wavelength selective switch (WSS), phase flicker is one of the fundamental causes for device level crosstalk [1], resulting in the leakage of light intensity to unwanted diffraction orders. In holographic optical tweezer systems, the trapping stability of single atoms is hindered by the intensity flickering, which can be a direct result of the phase flicker at the hologram plane [2].

Some previous studies have analysed the effects of phase flicker in different holographic systems, trying to demonstrate the resulting influence. Martínez *et al.* [3] simulated the static and dynamic performance of a blazed grating that has an N-pixel period quantitatively. The phase flicker was approximated by a triangular time-dependent profile proposed in [4]. The performance of the blazed gratings was found possibly not to be influenced with less than 30° amplitude for the flicker retardance. Wang *et al.* [1] obtained the phase flicker by using the same technique as Martínez *et al.* did and briefly discussed how it could affect the device level crosstalk of WSS systems. The deviation introduced by the phase fluctuation would generate higher orders, i.e., static crosstalk. Yang *et al.* [5] simulated the effect of phase flicker on the image quality of replay fields. Two phase-only holograms with randomly deviated phase levels from the ideal one generated by the Fienup algorithm [6] were reconstructed. The quality of the perceived image was shown to be severely degraded.

In this work, not limited to a specific application or operational scenario, we would like to explore quantitatively the effects of the phase flicker from a wider scope, i.e., at both device level and application level, to provide an overview and help the end users have better understanding of this phenomenon. On the device side, the investigation looks into the limitations introduced by phase flicker on the resolution of phase modulation and the switching speed which affects the frame rate. On the application side, the evaluation includes the impact of phase flicker on fundamental multilevel phase elements, in terms of blazed gratings and holograms of binary images. A comparison of the effects introduced by phase flicker and the one caused by other commonly known noises is also provided to precisely demonstrate the influence of the flicker.

2. CHARACTERIZATION OF PHASE FLICKER

The LCOS devices can be driven by either an analog addressing scheme or a digital addressing scheme, and phase flicker can be profound in digitally driven devices. The liquid crystal (LC) director responds to the root-mean-square (RMS) value of the applied voltage to produce incremental changes in birefringence, and hence the required number of gray levels. The position of the LC director can fluctuate with the time-pulse-constructed digital driving waveforms, and hence introduces undesired ripples in phase, i.e., phase flicker. *Fig. 1* illustrates the origin of phase flicker in a phase-only LCOS device.

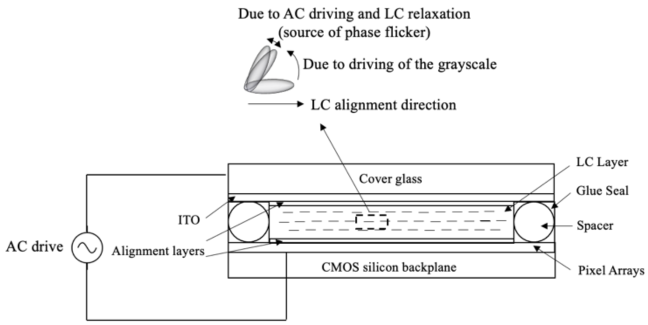

Fig. 1 The origin of phase flicker in a phase-only LCOS device. ITO: indium tin oxide; AC: alternating current; CMOS: complementary metal oxide semiconductor.

As the change of phase depth during modulation normally cannot be measured directly, the light intensity is collected instead for the further derivation of corresponding phase information. The optical layout of the characterization system is shown in *Fig. 2*.

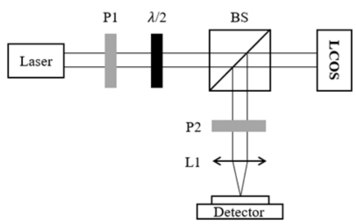

Fig. 2 Optical layout of the characterization system.

The incident beam is firstly linearly polarized by polarizer P1. A phase delay is then introduced by the half-wave plate λ/2 to ensure the polarization direction of the beam is crossed with that of the second polarizer P2 and is also 45° to the LC alignment direction of the LCOS device.

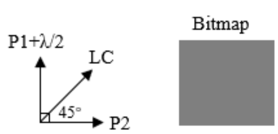

Fig. 3 (a) Polarization directions of the elements. Note that P1+λ/2 means the polarization direction of the incident beam after passing P1 and λ/2. (b) An example of a bitmap displayed on the LCOS device.

The polarization directions of the elements are illustrated in Fig. 3(a). The output intensity is measured by the photodetector when a bitmap (i.e., with one gray level uniformly applied to all the areas in the bitmap as shown in Fig. 3(b)) is displayed on the LCOS device. Since high accuracy is required for the measurements, a 1550 nm infrared laser with a ~1 mm light spot is adopted as it will not be affected by the ambient light. The LCOS device was assembled in house [7] based on a JDC SP55 digital backplane [8].

The relationship between the phase depth and the output intensity of the system can be described as [9]

$$\delta = 2\,sin^{-1}\sqrt{I_{nor}} \tag{1}$$

where, I_{nor} is the normalized intensity. *Fig. 4* shows two examples of the temporal phase fluctuations calculated from the intensity data experimentally measured at gray levels 150 and 192. In this work, phase flicker is defined as the standard deviation of the temporal phase fluctuation which is less dependent on the extreme values (i.e., unexpectedly high, or low outliers) of the oscillation. Hence, phase flicker can be calculated as 0.002π at gray level 150 and 0.0021π at gray level 192. The phase flicker information for other gray levels can be obtained similarly.

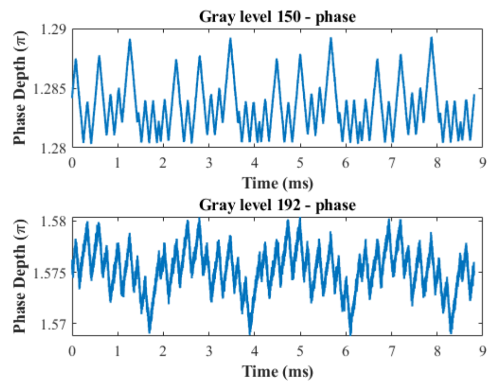

Fig. 4 Temporal phase fluctuations at gray levels 150 and 192 at λ= 1550 nm.

3. EFFECTS OF PHASE FLICKER AT DEVICE LEVEL

Table 1 compares the specifications of some latest phase-only LCOS SLM products from main commercial suppliers. Among all these key features of the device, how phase flicker can result in limitations for phase modulation resolution and input frame rate is of the most interest in this section.

Manufacturer	Product	Resolution (pixels)	Pixel Pitch (μm)	Filling Factor (%)	Input Frame Rate (Hz)	Phase Modulation Resolution (bit)
BNS [10]	-	1536×1536	20	96	-	8
CamOptics [11]	CONIR-4K70	4096×2400	3.74	>90	60	8
Forth DD [12]	M180	2048×2048	8.2	>94	3.6K[a]	1
Jasper [13]	JDN714V03P2	4096×2400	3.74	>90	60	8
Hamamatsu [14]	X15223-16R	1280×1024	12.5	96	60	8
HOLOEYE [15]	GAEA-2	4160×2464	3.74	90	60	8
Meadowlark [16]	HSP1920	1920×1152	9.2	95.7	-	8/12[b]
Santec [17]	SLM-200	1920×1200	8.0	>90	60 or 120	10[b]
Thorlabs [18]	EXULUS-4K1	3840×2160	3.74	>90	30	8

[a]indicates frame rate of binary switching.

[b]indicates analogue driving scheme. All the other products listed are digitally driven.

Table 1 Latest phase-only LCOS SLMs provided by commercial suppliers.

Phase modulation resolution reflects the ability of the device to approximate the quantized phase levels as close as possible to continuous phase in the ideal case. Input frame rate is vital when the panel is used for holographic applications that require dynamic display of the holograms.

A. Phase modulation resolution

Normal LCOS users would just assume that the phase levels of the device are constant and stable. However, it is not the case in reality. *Fig. 5* illustrates the phase levels measured from a real device [9], and they are not as what people assumed. At each level, the phase oscillates around its desired value and the fluctuation-caused overlapping between levels can be observed. This kind of overlapping, i.e., phase flicker, makes it difficult to separate the adjacent levels so that limits the actual phase modulation resolution of the device.

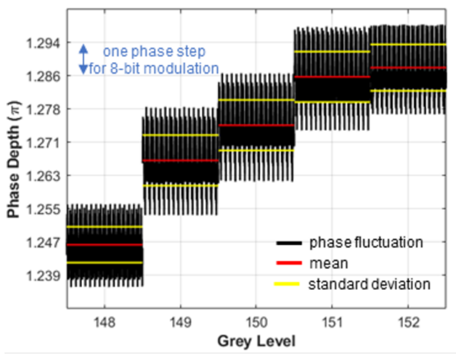

Fig. 5 Experimentally measured phase levels of a real LCOS device from [9].

Analogue LCOS devices are traditionally associated with better performances in terms of the phase flicker compared to the digital ones, as the analogue driving waveforms change the applied voltage at a constant frequency with the transient phase changes only occur in few milliseconds after the voltage changes [19]. By taking this advantage, Santec has already released its 10-bit analogue LCOS SLM for phase modulation [17]. Inoue *et al.* [20] even developed an analogue LCOS device that could be controlled by 12-bit signals for optical phase-only modulation. However, a phase resolution higher than 8-bit remains a challenge for digitally driven LCOS devices with the constraint of phase flicker. Even if the digital driver is able to provide driving signals with higher bit resolution, the temporal phase oscillation limits the actual phase resolution to be at the same level as the driving signal.

Phase Modulation Resolution	Requirements of Phase Flicker
6 bits	≤0.0151π
7 bits	≤0.0075π
8 bits	≤0.0038π
9 bits	≤0.0019π
10 bits	≤0.0009π
11 bits	≤0.0005π
12 bits	≤0.0002π

Table 2 The requirements of phase flicker for different phase modulation resolutions

By utilizing the method of computing the separation probability [9], which indicates the probability of staying within one phase level without overlapping with any adjacent levels, the requirements of phase flicker for different phase modulation resolutions can be derived and listed in *Table 2*. Note that a separation probability of 70% (rounded number for the probability of being within one standard deviation of the mean) is assumed for the calculation and the phase flicker is averaged over all addressed levels. Only when the phase flicker stratifies the requirements, can the meaningful phase modulation resolution be achieved practically.

B. Input frame rate

Except for the phase modulation resolution, input frame rate is another important property of the device. The ability of the LCOS device to refresh at a certain rate does not mean that the liquid crystal inside will have a good response at this rate, i.e., achieve the desired phase depth. This kind of driving circuitry introduced refresh ability cannot represent the input frame rate of the panel, which is directly associated with the LC response. Hence it is beneficial to investigate the optimal performance of both phase flicker and LC response (i.e., relatively minimized phase flicker and fast LC response time) for the phase modulation depth of 2π, i.e., typically used in digital holographic applications.

Methodology

When loading a series of holograms (i.e., a video) dynamically, rather than a static hologram, onto the LCOS at a certain frequency, there are two rates during this operation:

- Input video frame rate: i.e., input frame rate mentioned previously, determined by the users.
- LCOS output frame rate: determined by the settings of the LCOS driver.

LC response time is not directly measured. Instead, the video frame rate is varied to test if the LC could follow the rate and achieve the desired phase depth of 2π. There is an easy way to vary the video frame rate, which is to enable both red channel (R) and green channel (G) of the driving board. The colour sequence within one output frame time follows the pattern of RG. Continuously displaying a red bitmap of a certain gray level creates the scenario of bitmap switching, as the gray level (i.e., a certain voltage level) will only be implemented when it comes to the red channel part in the driving waveform, and black (i.e., zero intensity) occurs for the rest part of the green channel. Therefore, the video frame rate is twice the LCOS output frame rate. *Fig. 6* illustrates an example of how to identify if a 2π phase depth has been reached in a simple way. When a red bitmap of gray level 255 is displayed, the bitmap switching is equivalent to changing from gray level 255 to gray level 0. The corresponding transient intensity change is measured by the photodetector and as shown in the figure. The phase levels are ϕ_1 and ϕ_2 before and after switching, respectively. The phase change $\Delta\phi$ here is greater than 2π but less than 3π. By using this approach, the video frame rates at which the phase modulation depth of 2π is achievable can be obtained by adjusting the boundary voltages of the driving signal.

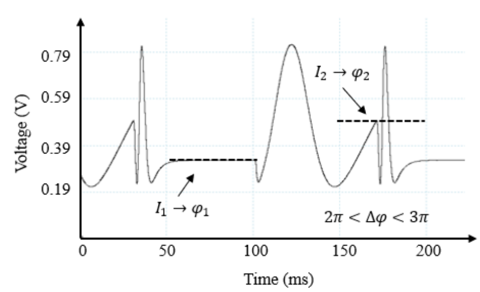

Fig. 6 An example of how to identify the phase modulation depth at λ=1550 nm.

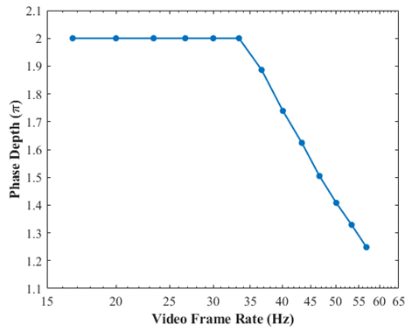

Fig. 7 How video frame rate affects the ability of LC to reach a 2π phase modulation at λ=1550 nm.

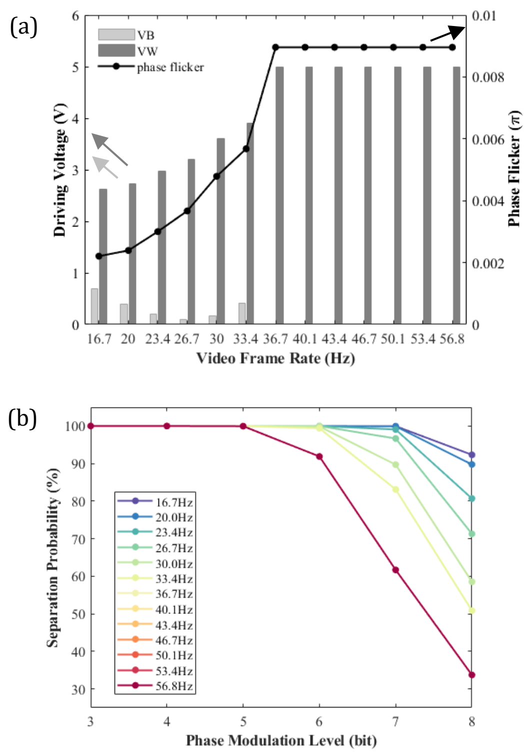

Fig. 8 (a) Phase flickers and driving voltages corresponded to the video frame rates in *Fig. 7* at λ=1550 nm. (b) Separation probability for different phase modulation levels at different video frame rates at λ=1550 nm.

Results

The ability of LC to reach a 2π modulation is assessed for different video frame rates at λ=1550 nm and T=30 °C by adjusting the driving voltages as shown in *Fig. 7*. We can see that the 2π phase depth cannot be achieved when the video frame rate is higher than 33.4 Hz, which means any dynamic holograms displaying at a frequency higher than 33.4 Hz at λ=1550 nm will cause an inadequate LC response.

According to author's previous study [21] , the best phase flicker performance occurs at the shortest unit time of the driver, i.e., the fastest LCOS output frame rate. Hence, the phase flicker values corresponded to the different set of driving voltages used in *Fig. 7* are measured with the LCOS output frame rate of 454 Hz, which is the highest rate currently available.

As can be seen from *Fig. 8*(a), when the video frame rate exceeds 33.4 Hz, 2π cannot be reached even with the largest set of driving voltages of the driver, i.e., VB=0V, VB=5V where VB and VW are the boundary voltages of the driving signal. The averaged phase flicker over 256 gray levels increases as the frame rate increases as the driving voltage gets higher. When the frame rate passes 33.4 Hz, the phase flicker value saturates at a level because of the same voltage difference of 5V. *Fig. 8*(b) shows that the 8-bit modulation cannot be maintained (i.e., the separation probability is less than 70%) when the video frame rate is higher than 26.7 Hz. Hence, to operate at an 8-bit phase precision with a total modulation depth of 2π at λ=1550 nm, the video frame rate must be less than 26.7 Hz at 1550 nm for the current LCOS device.

4. EFFECTS OF PHASE FLICKER AT APPLICATION LEVEL

After exploring how the phase flicker limits the system performance at device level, we can now move on to the application side. The existing studies mentioned previously used either model-approximated phase noise as phase flicker input or the flicker data without covering the temporal phase fluctuation for all gray levels in the simulations for application performance. Unlike those, this section simulates and evaluates the impact of phase flicker on fundamental multilevel phase elements, in terms of blazed gratings and holograms of binary images, in a more accurate way, with fully characterized phase flicker profiles of the 8-bit phase-only LCOS device used in this work.

A. Methodology

The basic idea of the simulation is to add phase flicker noise at the hologram or grating plane and investigate the noise effect at the replay field. The procedure is illustrated in *Fig. 9*. We can assume that there is a phase hologram or a phase grating to be loaded onto the phase-only LCOS device, the pixel values of which are in gray levels. According to the gray level of each pixel, the phase of the incident light can be modulated to reach a certain level.

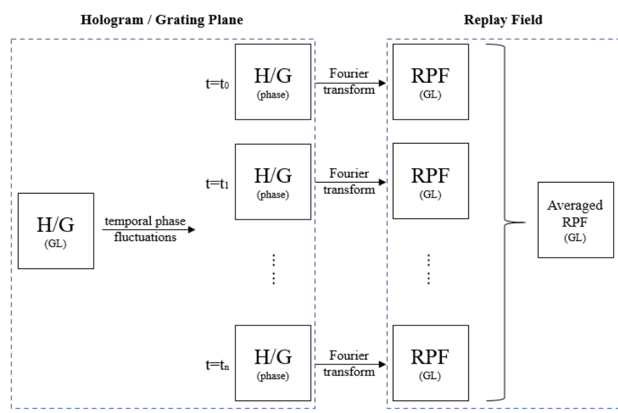

Fig. 9 Simple illustration of the phase flicker simulation with H/G referring to hologram/grating and RPF referring to replay field.

However, given the existence of phase flicker, the modulated phase depth oscillates over time with the mean value of the fluctuation equal to the desired phase level. In this case, we can set up a lookup table of phase noise forming by the temporal phase variation at each gray level. At each time point, the hologram or grating in gray levels can be mapped into the one in phase values based on the lookup table, and the Fourier transform of the hologram or grating is calculated to produce the instantaneous replay field. After repeating the steps in a specific time period, we can then get the static averaged replay field from all the instantaneous values and the dynamic variation of it.

Before the simulation, temporal phase fluctuations in one frame time (i.e., 4.2 ms) of 256 gray levels are experimentally measured at λ=1550 nm and T=30 °C from the LCOS device used in this work, showing an averaged phase flicker over all addressed levels of ~0.0035π. The phase variation profiles are then scaled by different factors to represent different phase flicker performances. The scaling means to amplify or attenuate the amplitude of the fluctuation but maintaining the same mean phase level at each gray level. *Fig. 10* shows an example of such amplifications at gray level 120, with the desired phase level of 0.9679π and scaling factors of 10, 20, and 30.

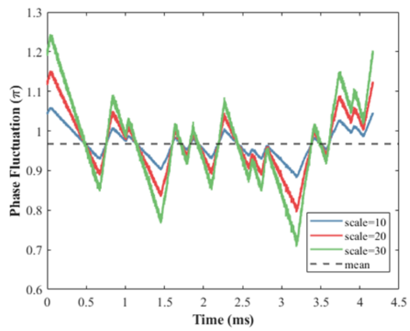

Fig. 10 An example of amplifying the phase fluctuation profile at gray level 120 with the scaling factors of 10, 20, and 30.

B. Blazed grating

Blazed grating, which is a type of the multilevel phase elements, is analysed. An ideal blazed grating has a sawtooth thickness profile as shown in *Fig. 11*. However, in the context of using an 8-bit LCOS, such ideal blazed gratings do not exist. If the peak-to-peak phase variation of the grating is 2π, then 2π is firstly quantized into 256 discrete levels to approximate the continuous profile, from which we can then select *p* levels for a grating pitch of *p*. First order diffraction efficiency is selected to quantify the performance of the blazed grating, as it can closely related to the device level crosstalk in some applications, i.e., the higher diffraction efficiency of first order indicates a lower power of other orders and hence lower crosstalk for the system [1].

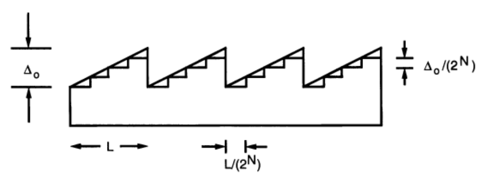

Fig. 11 Ideal sawtooth thickness profile for a blazed grating, and binary optic approximation of that profile (N=2) from [22].

The far field diffraction pattern of a 1D blazed grating with a length of 1920 pixels is simulated with an incident wavelength of 1550 nm and a propagation distance of 50 cm. How first order diffraction efficiency can be affected by the phase flicker is as shown in *Fig. 12*(a), with *p* referring to the grating pitch. We can see that as the phase flicker increases, the diffraction efficiency drops. For the same level of phase flicker, the diffraction efficiency decreases as the grating pitch decreases, which is as expected as the grating pitch essentially introduces a second quantization other than the first quantization of 8-bit modulation. For comparison, we can calculate how first order diffraction efficiency changes with different quantization levels for an ideal blazed grating with a continuous sawtooth profile by using the equation [22]

$$\eta_1 = \left(\frac{\sin\left(\frac{\pi}{q}\right)}{\frac{\pi}{q}} \right)^2 \tag{2}$$

where q is the quantization level. As can be seen from *Fig. 12* (b), the biggest increment of efficiency happens when the quantization level increases from binary to multilevel. In *Fig. 12* (a), the averaged reduction of the diffraction efficiency with different grating pitches is ~13% when phase flicker increases from ~0.004π to ~0.18π. A similar amount of efficiency is lost when the quantization level reduces from 8 to 4.

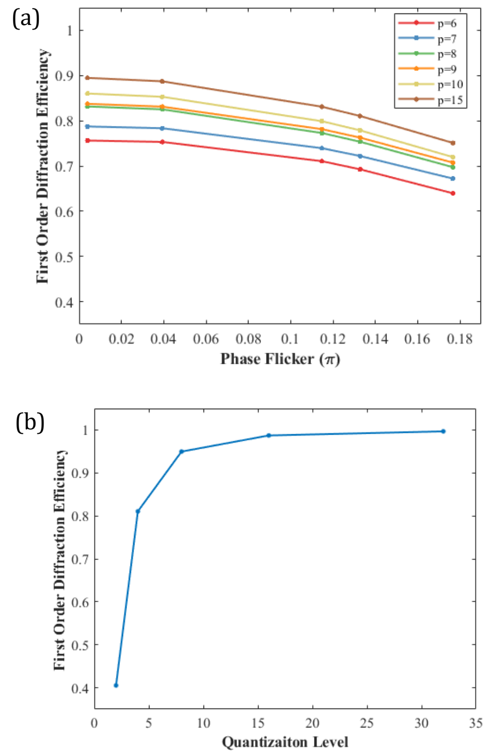

Fig. 12 Impact of (a) phase flicker and (b) quantization level on the first order diffraction efficiency of blazed gratings.

C. Hologram of binary image

The target image is designed to be binary rather than multilevel to avoid the effect of phase flicker convoluted by a large number of different gray levels. The 100×100 pixels image is divided into two identical areas as shown in *Fig. 13*, with the bright area filled with gray level *A* and the dark area filled with gray level *B*. Gerchberg-Saxon algorithm [23] is used to generate the corresponding phase holograms.

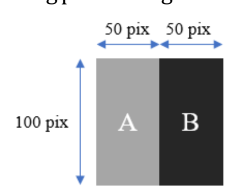

Fig. 13 Structure of a gray level pair, i.e. a binary target image with two identical regions filled with gray levels A and B, respectively.

The reconstructed image is evaluated by the contrast ratio, which is one of the commonly used estimators in image quality assessment and is the bright-to-dark intensity ratio as defined in Equation 3.

$$contrastratio = \frac{\overline{I}_{brightarea}}{\overline{I}_{darkarea}} \tag{3}$$

The results are shown in *Fig. 14*(a) with A and B referring to the gray levels. As the phase flicker increases, the contrast ratio decreases, indicating the degradation of the image quality. To better understand how the effect of phase flicker compares with common amplitude noise, Gaussian white noise with zero mean and variance of 0 to 25 gray levels is directly added to the target image at pixel level, as the so-called gray level pair, in *Fig. 13* without including any diffraction process. The contrast ratio of the resultant noisy image for different gray level pairs is shown in *Fig. 14*(b). As the variance increases, the contrast ratio shows a similar decreasing trend as the previous phase flicker case. For each gray level pair, we can calculate how much the contrast ratio drops as the phase flicker increases. Then the decrements for different pairs are averaged to represent the overall decreasing trend. The average drop in contrast ratio of ~0.66 roughly matches with the drop when the variance of the Gaussian noise increases from 0 to ~10 gray levels. We can see in *Fig. 14*(b), the starting points of the contrast ratio (i.e., without Gaussian noise) match with their theoretical maximum values that appeared in the target images, e.g., 5 for the gray level pair of 250 and 50. However, as the trend shown in *Fig. 14*(a), it can be expected that even without any flicker noise, the maximum contrast ratio would still be lower than that of the target image. The discrepancy is reasonable as the GS algorithm also introduces a considerable amount of error during the hologram generation process, and hence the reconstructed image will never be a perfect match with the target image in the first place.

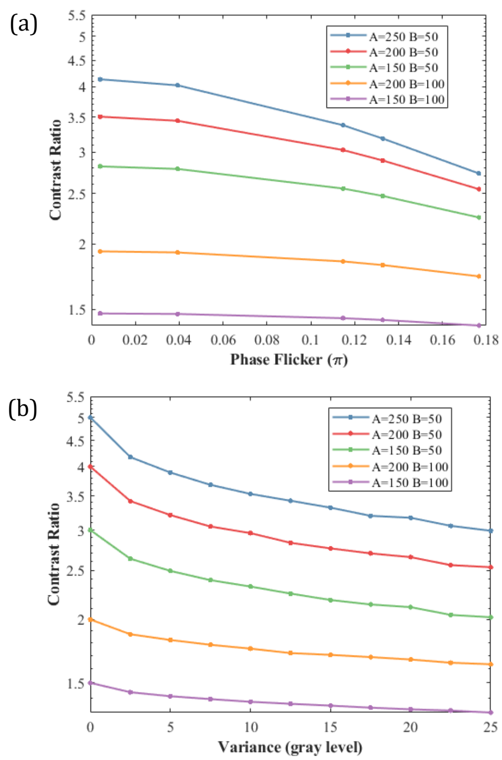

Fig. 14 Impact of (a) phase flicker and (b) Gaussian noise on the contrast ratio of the resulting image, with identical region sizes of A and B in the target image.

Although the contrast ratio defined in Equation (3) is normalized by region size, which means it is independent of the region size of gray level A and B in the target image, this independence is not guaranteed for the image with flicker or amplitude noise. *Fig. 15* shows the impact of the phase flicker and amplitude noise on the contrast ratio of the resulting images, with 25% and 75% region size of gray A in the target image, respectively. Similar trends between contrast ratio and noise can still be observed as the ones identified in the identical region size case.

5. OPTIMIZATION OF PHASE FLICKER

Being aware of the effects of phase flicker, how to suppress it in digitally driven LCOS devices becomes a challenging topic and there have been several works trying to achieve the goal. Relevant studies are briefly discussed here and details should be referred to the individual papers.

The existing approaches fall into two categories. The first category is based on the understanding of the influence of the LC viscosity on the time response of LC, i.e., increasing the viscosity means a slower time response as a result of increased damping, and hence a lower phase flicker produced. For example, García-Márquez *et al.* [24] presented a method to reduce the phase flicker by reducing the temperature of the LCOS device.

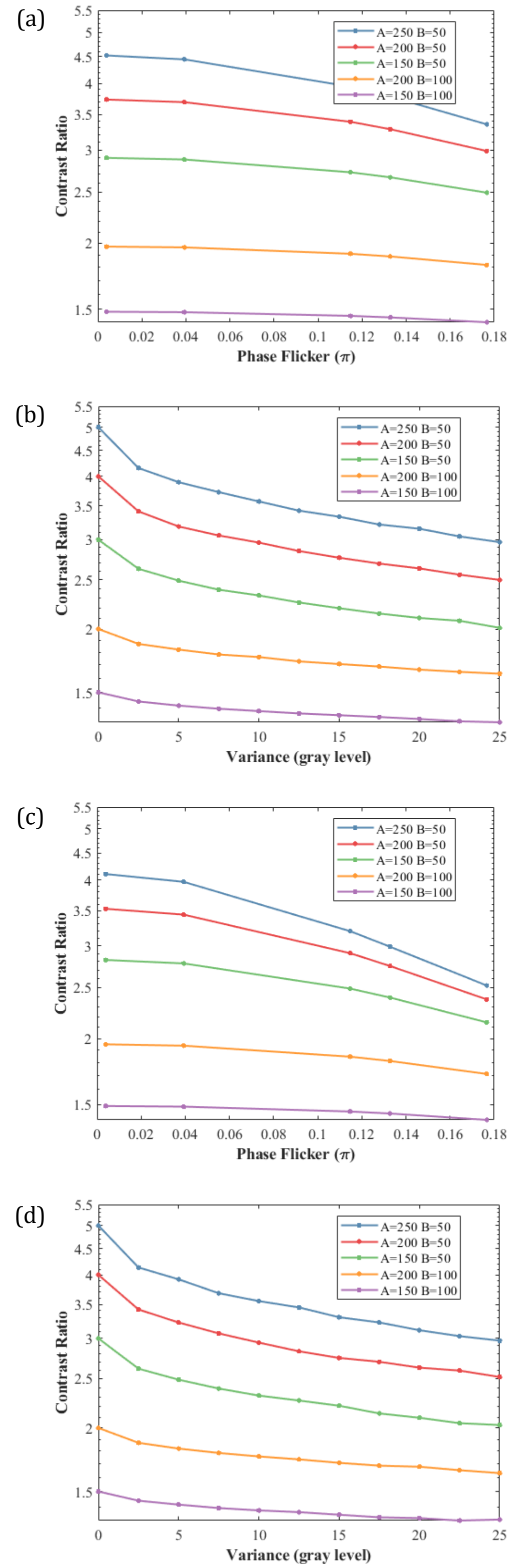

Fig. 15 Impact of phase flicker and Gaussian noise on the contrast ratio of resulting image, with (a)-(b) 25% and (c)-(d) 75% region size of gray A in the target image.

A reduction of up to 80% of the flicker initial value had been demonstrated when the LCOS was brought to −8 °C. Chen *et al.* [25] manufactured two LCOS devices in house, which were filled with the same LC material but different cell gaps. It was proved that a lower phase flicker could be achieved with a thicker LC layer. However, it should be noted that the increase in viscosity means the sacrifice in the switching speed, i.e., this technique is not advantageous for any applications with critical requirements on device speed.

The second category is to minimize the phase flicker through optimizing the driving waveforms of the LCOS device. Yang *et al.* [26] quantitatively analysed how LC responded to the ON and OFF pulses in the driving signal, and then constructed a model to predict the temporal phase response of the LC to any PWM driving waveforms based on this rise and decay characteristics. This method provided a reliable way for phase flicker prediction but requires measurement of LC response to the pulses at each phase level, which might be time-consuming. The author previously proposed two different methods to optimize the waveforms [9,21]. The first one was based on a strategy of splitting selected long pulses and distributing them in a uniform manner, enabling a meaningful increase of phase levels from 8 bits to 9 bits. However, this method was based on manual selection for individual LCOS devices, which is not easy to apply in general. The second method overcame this problem and was based on a deep learning model built with fully connected layers, making it possible to practically realize 10-bit phase modulation for digitally driven LCOS devices.

6. CONCLUSIONS

The effects of phase flicker have been analysed quantitatively at both the device level and the application level. On the device side, phase flicker can limit the phase modulation resolution by introducing overlapping between adjacent phase levels. Only when the phase flicker is low enough, can the temporal fluctuations be clearly separated to create meaningful phase levels. The requirements of phase flicker for different phase modulation resolutions were given, to advise the tolerance of the overlapping at a separation probability of 70%. Except for the modulation level, phase flicker also introduces constraints on the input frame rate of the LCOS device. The optimal performance of both phase flicker and LC response (i.e., relatively minimized phase flicker and fast LC response time) for the phase modulation depth of 2π was investigated for dynamic display of the hologram. Any dynamic holograms displaying at a frequency higher than 33.4 Hz at λ=1550 nm would cause an inadequate LC response so that a 2π phase modulation could not be reached. To operate at an 8-bit phase precision with a total modulation depth of 2π at λ=1550 nm, the video frame rate must be less than 26.7 Hz at 1550 nm for the current LCOS device.

On the application side, the impacts of phase flicker on the diffraction efficiency of blazed gratings and the contrast ratio of holographic binary images have been investigated by using temporal phase fluctuation profiles experimentally measured from the 8-bit LCOS device used in this work. For a 1D blazed grating, the averaged reduction of the first order diffraction efficiency with the grating pitch of 6 to 20 pixels is about ∼13% when phase flicker increases from ∼0.004π to ∼0.18π. A similar amount of efficiency is lost when the quantization level of the sawtooth profile of the grating reduces from 8 to 4. For the holographic image reconstructed by a binary target image, the averaged decrement in contrast ratio for different gray level pairs is ∼0.66 as the phase flicker increases, which roughly matches with the drop when the variance of the added Gaussian noise increases from 0 to ∼10 gray levels. In conclusion, the effects of phase flicker on the performance of blazed gratings and image holograms are shown to be comparable to that introduced by phase quantization and amplitude noise.

In summary, this work firstly reviewed how existing studies simulated the effect of phase flicker in different holographic systems, as only how other people optimized phase flicker was discussed in our previous work [9]. The experimental setup and the characterization technique remain the same, as they have been proved to be the most efficient and precise way to get phase flicker profiles. Subsequently, critical results showing the phase flicker tolerance for different phase modulation resolutions was demonstrated via a new table, *Table 2*. This part of results is very important as most of the LCOS users are unaware of how the overlapping caused by phase flicker can practically affect the effective modulation level of their devices. And the numbers can also help the readers understand why the phase levels in analogue LCOS devices can be up to 10 or even 12-bit (as described in the text before *Table 2*). The phase flicker of Santec's analogue LCOS is <0.001π [17], which just matches the flicker requirement listed for 10-bit in *Table 2*. Critical results about the balance between low flicker and fast LC response for fast frame rates were also new. Again, most of the LCOS users might not even know there is a trade-off between these two features. Nevertheless, it is still very significant especially when it comes to dynamic holographic applications. It is definitely beneficial to have relatively high modulation resolution and fast switching at the same time. Finally, it was shown that the effect of phase flicker could be analysed separately. The impact of phase flicker only on multilevel phase elements was simulated and evaluated using blazed gratings and holograms of binary images, to illustrate the limitation introduced by phase flicker on system performance at device level.

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