Transient Crosstalk in Holographic Optical Switching Based on Wavefront Encoding

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***Abstract*— This work demonstrates that wavefront encoding technique can be used reduce the peak transient crosstalk by >10 dB in holographic optical switches based on the liquid crystal on silicon (LCOS) technology, when compared with switches based on the conventional Fourier transform optical setup. At the same time, this technique also reduces the switching time, without any modifications needed to either the LCOS device or its driving circuits.**

***Index Terms*—Optical switching, holography, transient crosstalk, wavefront encoding, liquid crystal on silicon**

I. Introduction

Optical switches [1] are widely used in modern telecom networks [2], [3] and datacentre interconnecting networks [4]. They allow real-time remote control of optical signal provisioning in multi-degree networks. Since optical switching technology eliminates the need for the electrical-optical-electrical (OEO) conversion process, it significantly reduces the power consumption of the network. In addition, optical switching is insensitive to the data modulation formats used by the signals. Therefore, it enables service providers to build future-proof networks. Recently, phase-only liquid crystal on silicon (LCOS) [5] spatial light modulators (SLMs) have become the technology of choice for optical switches including wavelength selective switches (WSSs) [6]–[8], wavelength crossconnects (WXCs) [9], [10], and N×N space switches [11]. This is mainly because LCOS technology is able to support advanced switching features including flex-grid switching [12], [13], multi-casting and broadcasting [14]–[16], etc.

LCOS-based optical switches operate on the principle of holographic beam steering [17], [18]. The beams of the input optical signals hit different areas of the LCOS device, where the corresponding beam-steering phase holograms are displayed. In most cases, the holograms are in the form of blazed gratings, which are able to steer the optical beam in different directions according to its period. However, sophisticated computer algorithms [19] can also be used to generate more complex holograms, which are capable of directing the beam into multiple output ports at the same time [20]. Since the operators are able to display phase holograms of any forms or shapes at any position on the LCOS device, optical switches based on LCOS technology are less sensitive to alignment errors. The holographic nature beam steering scheme also makes such switches more tolerant to the failure of individual pixel electrodes on the LCOS backplane.

One of the key challenges for optical switches based on the LCOS technology is the management of crosstalk [22-24]. Due to the viscosity of liquid crystal material [25] and the fringing field effect [26]–[28], the LCOS device is not able to display the design beam-steering hologram perfectly, especially in areas where there are abrupt phase changes between neighbouring pixels. As a result, some of the input signal beam is diffracted into higher diffraction orders and subsequently coupled into unintended output ports. This gives rise to static crosstalk. The static crosstalk can be effectively suppressed by advanced hologram design [24], [29] or simply by using higher quality LCOS devices [30]. In our previous works [15], [16], [31], we intentionally introduced defocus into the optical switching system and therefore the optical arrangement was no longer based on the conventional Fourier transform setup. Holograms in the form of an off-axis Fresnel lens were used to compensate for the defocus and efficiently steer the beam into its target ports. At the same time, the un-wanted diffraction orders remained to be defocused at the output plane and therefore had reduced coupling efficiency to the unintended ports. This technique, which is referred to as wavefront encoding, is able to reduce the worst-case static crosstalk by more than 6 dB.

The transient crosstalk in the LCOS-based optical switches only appears when the switching configuration is being updated, i.e. when the beam-steering hologram displayed by the LCOS device is changing. Network operators used to turn off the wavelength signal before the switching in order to manage the transient behaviour of the optical switches. However, optical switches without transient crosstalk become desirable in recent years since it can simplify the switching process. The transient crosstalk is caused by the intermediate holograms displayed by the LCOS device when it is switching from the starting hologram to the ending one. The characteristics of transient crosstalk depend on the dynamic response of the

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LCOS device as well as the starting and ending holograms. Although several advanced LC driving schemes [32], [33] have been developed to address the response time of the LCOS devices, none of them give control over the intermediate phase holograms. In our previous works [34], [35], two methods were proposed to ensure that the intermediate holograms displayed by the LCOS device during switching have non-periodical structures. Therefore, the transient crosstalk can be reduced in the LCOS-based optical switches using the conventional Fourier transform arrangement. However, these two methods would either double the switching time or require prior knowledge of the LCOS device in use.

This work studies the characteristics of the transient crosstalk in the optical switches using the wavefront encoding technique, with a particular emphasis on the intermediate phase holograms. The experimental results on the transient crosstalk and the switching time are presented and analysed.

II. Experimental Setup

Figure 1 shows a standard LCOS-based optical switch using the conventional Fourier transform arrangement. The LCOS device and the fibre collimating array are placed at the front and back focal planes of a Fourier transform lens, i.e. Lens 1, respectively.

The input optical beam is launched into this system via the input fibre collimator port and passes through the Fourier transform lens before hitting the LCOS device. The LCOS device displays a phase hologram in the form of a blazed grating to impart a wavefront tilting of the beam. On the way back, the Fourier transform lens translates this wavefront tilting into a positional offset with respect to the optical axis. As result, the beam will be diffracted into a position that corresponds to the target output port at Plane F shown in Fig. 1. If the LCOS device were able to display a perfect blazed grating hologram, all the optical power would be diffracted into the +1st diffraction order. As mentioned previously, however, higher diffraction orders will occur due to the inaccurate display of the blazed grating by the LCOS device. These diffraction orders will have different offset with respect to the optical axis at Plane F due to their different diffraction angles. Since Plane F and the LCOS device are placed at the front and back focal planes of the Fourier transform lens, respectively, all the diffraction orders are in focus at Plane F, i.e. matching the mode characteristics of the output ports. Therefore, some of the higher diffraction orders could be coupled into the unintended output port with high efficiency if they have the same off-axis position. This would lead to high static crosstalk. Our previous works [34], [35] have also shown that transient crosstalk also needs to be carefully managed in optical switches based on the conventional Fourier transform configuration. It should be noted that a photodiode array with apertures was used at the output positions to emulate the collimated output fibre ports. The aperture size is 0.15 mm. This emulated the effect of reduced fibre coupling efficiency for those higher diffraction orders, assuming the Gaussian beam waist of the collimated fibre ports is 0.05 mm.

In this work, the wavefront encoding technique is proposed to address the transient crosstalk in LCOS-based optical switches. Fig. 2 shows an optical switching setup using the wavefront encoding technique. In this setup, the fibre collimator array and the LCOS device were kept at the same positions as in the conventional setup shown in Fig. 1. Lens 1

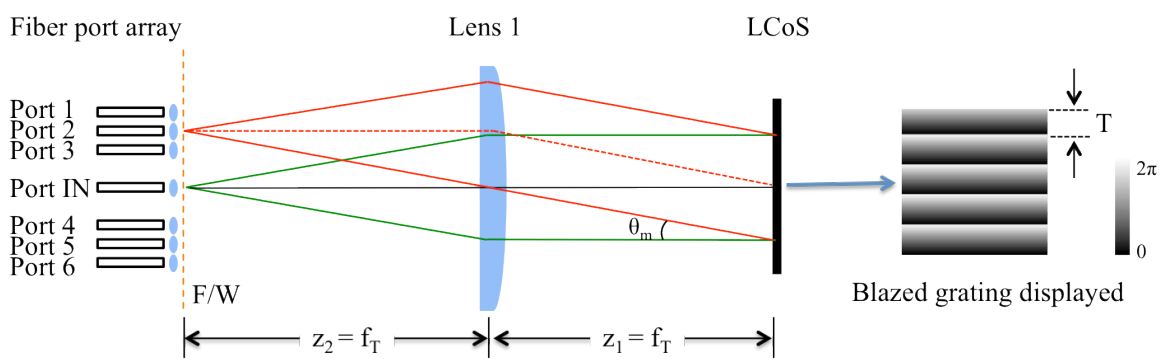

Fig. 1. An LCOS-based optical switch using conventional Fourier transform setup

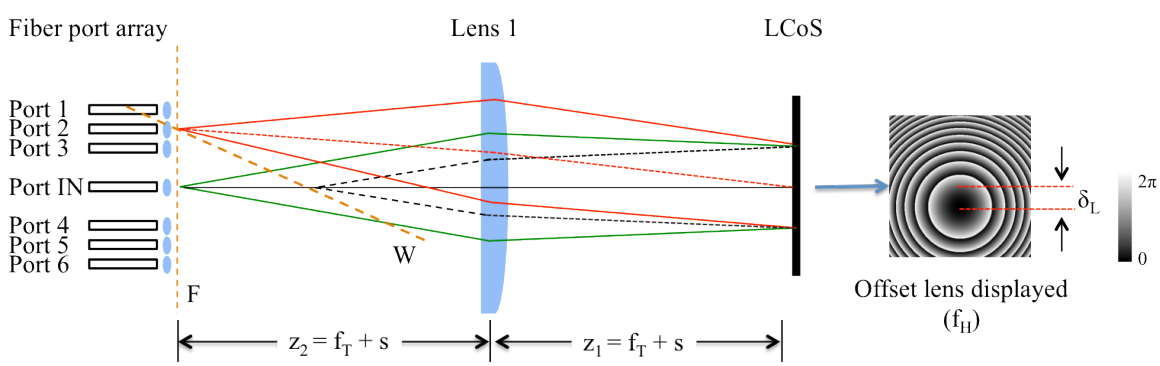

Fig. 2. An LCOS-based optical switch using the wavefront encoding technique

TABLE I
THE POSITIONS AND HOLOGRAM PARAMETERS FOR OUTPUT PORTS

Port	Position	Period (T)	Offset (δ_L)
1	-1400	-96.3	-2100
2	-1050	-128.4	-1575
3	-700	-192.6	-1050
4	700	192.6	1050
5	1050	128.4	1575
6	1400	96.3	2100

Unit: um

was replaced by a new lens with shorter focal length. In this case, both the fibre collimator array and the LCOS device were moved away from the focal planes of Lens by a distance of s. A defocus was intentionally introduced into the optical switching system. Instead of blazed gratings, the phase holograms in the form of an off-axis Fresnel lens are used to steer the beam into the target output port. The off-axis Fresnel lens will not introduce a positional offset to the diffracted beams but also compensate for the defocus for the $+1^{st}$ diffraction order. Higher diffraction orders will be focused along Plane W instead of Plane F as shown in Fig. 2. Therefore, these higher diffraction orders would be defocused at Plane F. As a result, only the $+1^{st}$ diffraction can be coupled into the fibre port with a high efficiency. This reduces the static crosstalk. This work aims to investigate the effect of the wavefront encoding technique on the transient crosstalk in LCOS-based optical switches.

In both configurations, the input signal comes from a fibre-coupled laser diode located on the optical axis. There are six output ports located at ±700, ±1050 and ±1400 μm from the optical axis. The distance between the input plane and the LCOS device was kept at 400 mm. In this case, the focal length of the Fourier transform lens was 200 mm in the conventional setup. In the setup using the wavefront encoding technique, however, a lens with a focal length of 150 mm was chosen to introduce the defocus into the switching system. Correspondingly, the LCOS device should display a Fresnel lens hologram with a focal length of -200 mm in order to compensate for the defocus for the $+1^{st}$ diffraction order. The periods of the blazed gratings in the conventional optical switching system and the offset of the diffractive lens patterns on the LCOS device in the wavefront encoding based system are listed in Tab. I for each port. It should be noted that, for the proof of concept, this work used the wavelength of 674 nm. The higher diffraction orders in the wavefront-encoded system were defocused at the output plane and therefore were clipped by the apertures before hitting the photodiode. This emulated the effect of reduced fibre coupling efficiency for those higher diffraction orders, assuming the Gaussian beam waist of the collimated fibre ports is 0.05 mm. The LCOS device used in this work was assembled in-house using a process developed by the group. It had 1280×720 pixels at a pitch of 15 μm, with a 0.5 μm gap between pixels. The nematic liquid crystal material was parallel-aligned in this device. It should be noted that the front coverplate of this LCOS device was not anti-reflection (AR) coated. The long axis of the LCOS device is aligned to the switching axis of the system in this work. A manual polarisation controller was used in this work to ensure the beam launched into the system has the correct polarisation for the LCOS device.

III. RESULTS

Since the test system had six output ports, there were 30 possible combinations of starting port and ending port in total when all switching scenarios are accounted for. During each switching scenario, the remaining four output ports may be affected by the transient crosstalk. Therefore, there were 120 responses of transient crosstalk to be measured. We set the transient crosstalk threshold at -25 dB.

Fig. 3 shows the transient response at all the output ports when the signal was switched from Port 5 to Port 3. The values in these plots are referenced to the power measured at Port 5 before the switching. This constitutes a typical transient response in this experiment. The solid lines represent the experimental results measured in the optical switch based on the conventional setup and the dashed lines correspond to the results for the wavefront-encoded system. It can be seen that a peak transient crosstalk of ~-10 dB was detected at Port 2 and Port 6 in the conventional optical setup based on the Fourier transform arrangement. The wavefront encoding technique effective eliminated the transient crosstalk at these two ports. Port 4 was affected by the transient crosstalk in both setups. However, the wavefront encoding technique was able to reduce the peak transient crosstalk by >15 dB. Port 1 was primarily affected by the static crosstalk. A reduction of 5 dB was achieved in the system using the wavefront encoding technique, which was consistent with our prior work on the static crosstalk.

It can also be seen in Fig. 3 that it took ~80 ms for the signal to reach within -0.5 dB range of the final power level at Port 3 in both setups. The transient crosstalk at Port 6 in the optical switch using the conventional setup was still above -25 dB after >100 ms. Therefore, it is the transient crosstalk that ultimately restricts the switching speed of an LCOS-based optical switch using the Fourier transform setup. When the wavefront encoding technique was implemented, the duration of the transient crosstalk was significantly reduced. Although it is possible that the transient crosstalk was partially lost in the background of the photo detector system, however, the target crosstalk level for LCOS-based optical switches, especially the wavelength selective switches, is usually -30 dB, which is higher than the background level in this work. Therefore, it can be concluded that the wavefront encoding technique can also improve the switching speed of the switch.

As described in the first paragraph of this section, there were 120 responses of the transient crosstalk to be measured at different ports in different combinations of starting and destination ports. Histograms of the peak transient crosstalk values in these 120 responses are shown in Fig. 4 and Fig. 5 for the two setups respectively. In the conventional switching system, the peak transient crosstalk exceeded -25 dB threshold in 80 out of the 120 cases. In the wavefront encoded system, only 34 cases exceeded this threshold, with only one being above -15 dB. The worst-case peak transient crosstalk was

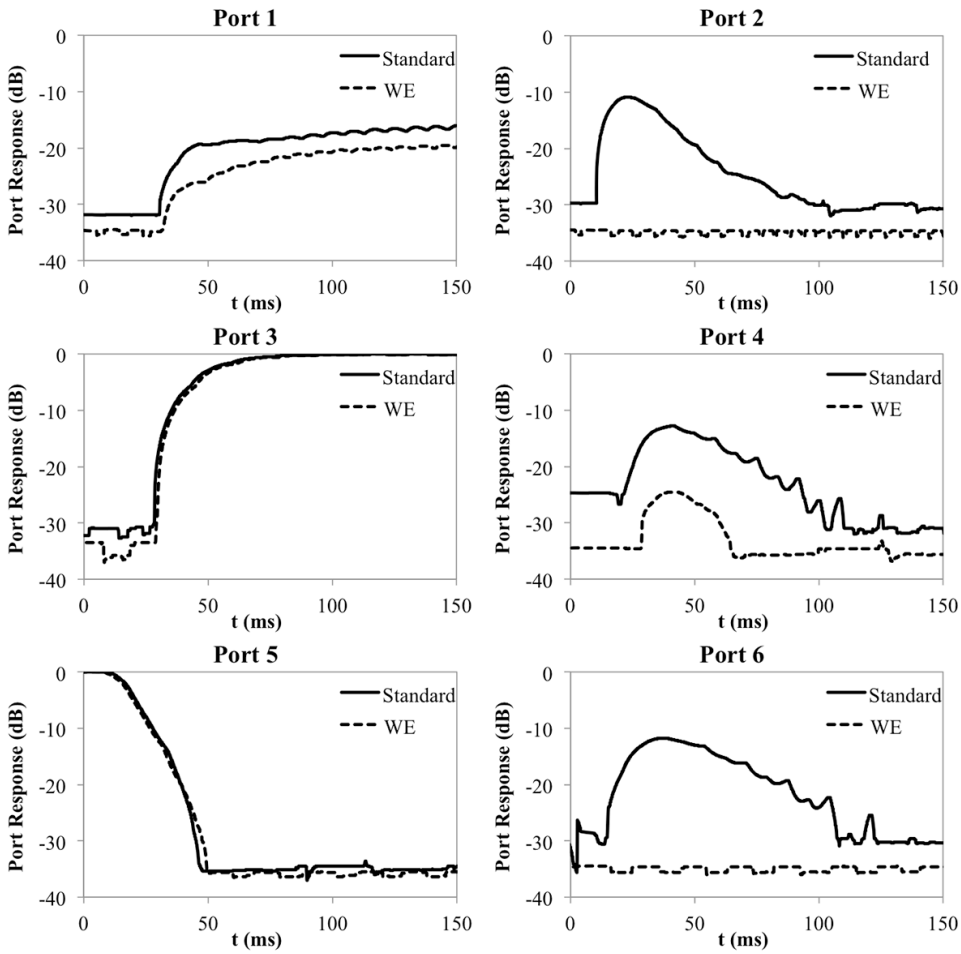

Fig. 3. The transient responses when the signal is switched from Port 5 to Port 3.

reduced by 11.46 dB from -3.33 dB in the conventional system to -14.79 dB in the wavefront encoding based system.

Tab. II lists the worst-case peak transient crosstalk for all the 30 possible switching scenarios in a conventional optical switch using the Fourier transform setup. The ports that were affected by transient crosstalk in each switching scenario are also denoted in this table. Only four switching scenarios were completely free of transient crosstalk, i.e. the peak transient crosstalk was below our -25 dB threshold. In these four scenarios, the starting and destination ports are symmetrical with respect to the optical axis, i.e. switching between Port 1 and Port 6, or between Port 2 and Port 5. Although switching between Ports 3 and 4 is also symmetrical with respect to the optical axis, transient crosstalks of around -13 dB were observed at Port 1 and Port 6, which corresponds to the position of the +2nd diffraction order of the blazed grating for either the starting or ending beam steering holograms. This is mainly due to the static crosstalk of the +2nd diffraction order as a result of imperfect display of the phase holograms in the form of the blazed gratings and multiple reflections caused by the non-AR coated coverplate of the LCOS device.

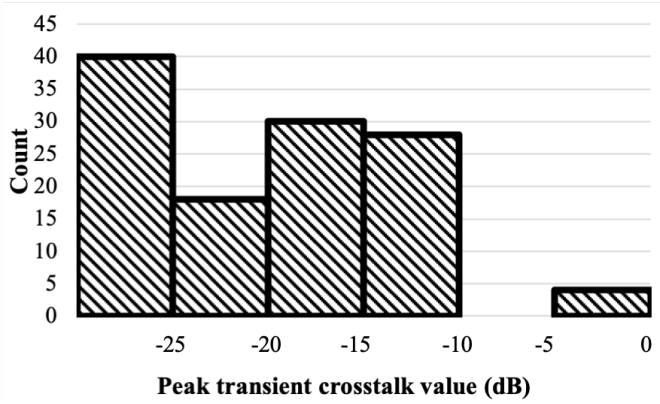

Fig. 4. Histogram for the peak transient crosstalk values in the conventional switching system.

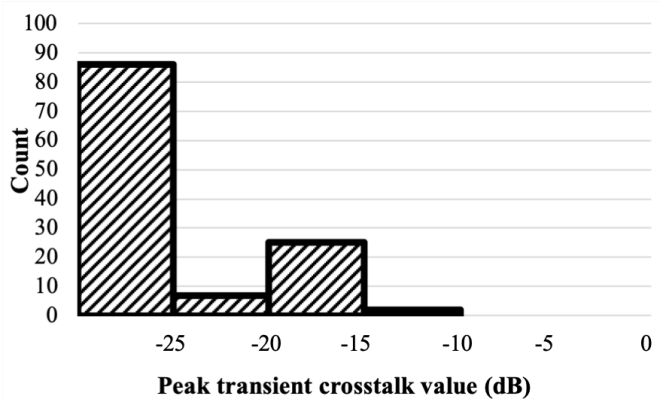

Fig. 5. Histogram for the peak transient crosstalk values in the wavefront encoded switching system.

TABLE II
WORST-CASE PEAK TRANSIENT CROSSTALK (IN DB) MATRIX MEASURED IN THE OPTICAL SWITCH USING THE FOURIER TRANSFORM ARRANGEMENT

		Destination Port					
		1	**2**	**3**	**4**	**5**	**6**
Starting Port	**1**	N/A	**-14.54 (6)**	-16.00 (6)	**-3.57 (3)**	**-13.35 (2/6)**	< -25
	2	**-14.44 (6)**	N/A	**-14.05 (1)**	**-11.98 (1/3)**	< -25	-15.14 (1/3)
	3	-16.03 (6)	**-14.61 (1/3)**	N/A	**-12.59 (1/6)**	**-10.85 (1/2/6)**	**-3.32 (4)**
	4	**-3.33 (3)**	**-11.58 (3)**	**-13.97 (1/6)**	N/A	**-14.08 (6)**	-16.22 (1/3)
	5	**-13.07 (2/6)**	< -25	**-10.90 (2/4/6)**	**-13.88 (6)**	N/A	-16.08 (1/2/3)
	6	< -25	**-14.42 (1/3)**	**-3.30 (4)**	-16.01 (1/3)	-15.69 (1/2/3)	N/A

* Numbers in parentheses represent the corresponding ports where peak transient crosstalk is observed. Bold denotes peak transient crosstalk >-15 dB. Bold underlined denotes peak transient crosstalk >-5 dB.

TABLE III
WORST-CASE PEAK TRANSIENT CROSSTALK (IN DB) MATRIX MEASURED IN THE OPTICAL SWITCH USING THE WAVEFRONT ENCODING TECHNIQUE

		Destination Port					
		1	**2**	**3**	**4**	**5**	**6**
Starting Port	**1**	N/A	<-25	-18.86 (4)	**-14.93 (3)**	-19.41 (3)	<-25
	2	<-25	N/A	-19.45 (1)	-18.49 (1/6)	<-25	-24.58 (4)
	3	-18.61 (4)	-19.42 (1/4)	N/A	-18.51 (1/6)	-19.39 (1/4)	-16.25 (4)
	4	**-14.79 (3)**	-18.66 (3/6)	-18.66 (1/6)	N/A	-18.69 (6)	-18.43 (3)
	5	-18.91 (3)	<-25	-19.34 (1/4)	-18.58 (6)	N/A	<-25
	6	<-25	-24.87 (4)	-15.11 (4)	-18.87 (3)	<-25	N/A

* Numbers in parentheses represent the corresponding ports where peak transient crosstalk is observed. Bold denotes peak transient crosstalk >-15 dB. Bold underlined denotes peak transient crosstalk >-5 dB.

The highest level of transient crosstalk in the conventional setup was observed at Port 3 (when switching between Port 1 and Port 4) and Port 4 (when switching between Port 3 and Port 6). In both cases, the grating period for the starting grating was either twice or half of that for the ending grating. The slopes of these two blazed gratings were also in opposite directions. The position of the port where high transient crosstalk was detected coincides with the -1st diffraction order of either the starting or ending gratings. This is consistent with the analysis in our previous work [34], [35]. High transient crosstalk usually occurs when the period of the starting grating (T_s) and that of the ending grating (T_e) hold a negative integral relationship, i.e. when $T_s \approx n*T_e$ or $T_e \approx n*T_s$, where n = -1, -2, …; a high level of transient crosstalk occurs at the $m \neq +1^{st}$ order position of either the starting or ending grating. As mentioned above, the high transient crosstalk detected in these switching scenarios originated from the intermediate phase holograms with periodical structures that can be displayed by the LCOS device during switching.

Tab. III lists the worst-case peak transient crosstalk in the optical switch using the wavefront encoding technique. There were eight switching scenarios that were free of transient crosstalk >-25 dB. In the majority of cases, the peak transient crosstalk was reduced to about -19 dB. The transient crosstalk measured when switching between Port 1 and Port 4, or between Port 3 and Port 6 remained relatively high when compared to the other switching scenarios. When compared to the results obtained in the conventional setup, however, the wavefront encoding technique reduced the peak transient crosstalk by ~10 dB in those cases. It is expected that the peak transient crosstalk could be further reduced if the LCOS device has a proper AR coating on its coverplate.

The mechanism behind the reduction in the transient crosstalk was also investigated through the intermediate phase patterns displayed during switching. Taking the switching from Port 5 to Port 3 for example, the phase pattern displayed on the LCOS device changes from the one shown in Fig. 6(a) to the one shown in Fig. 6(b) during this process. Based on the test procedure developed in our previous work [34], [35], a series of intermediate phase holograms displayed during switching can be numerically calculated on a pixel basis, according to the measured switching behaviours of the LC material between different phase levels. Fig. 6(c) shows the calculated intermediate phase hologram that corresponds to the peak transient crosstalk in this case. It can be seen that this phase pattern is basically a mix of the starting and ending holograms plus some high-frequency structures. The replay field of this intermediate hologram was simulated using the fractional Fourier transform [36] and is shown in Fig. 6(d). Strong diffraction orders only appeared at the positions of the starting and ending ports in this replay field. Weak transient diffraction orders also appeared during the switching process. Their positions corresponded to the positions of higher diffraction orders of either the starting or ending holograms. They contributed to the transient crosstalk measured in this work. However, the wavefront encoding technique further defocuses these weak transient orders at the output plane. Therefore, the transient crosstalk is significantly suppressed. If an asymmetric port arrangement was used, the static and transient crosstalk would be further reduced in both setups. However, it would not affect the comparison between them.

IV. DISCUSSION

In LCOS-based optical switches using the conventional Fourier transform configuration, all the beam steering holograms are in the form of blazed gratings and therefore have periodical structures. The intermediate phase holograms displayed by the LCOS device during the switching are likely to have periodical structures too. Such intermediate holograms could form multiple relatively strong diffraction orders. These diffraction

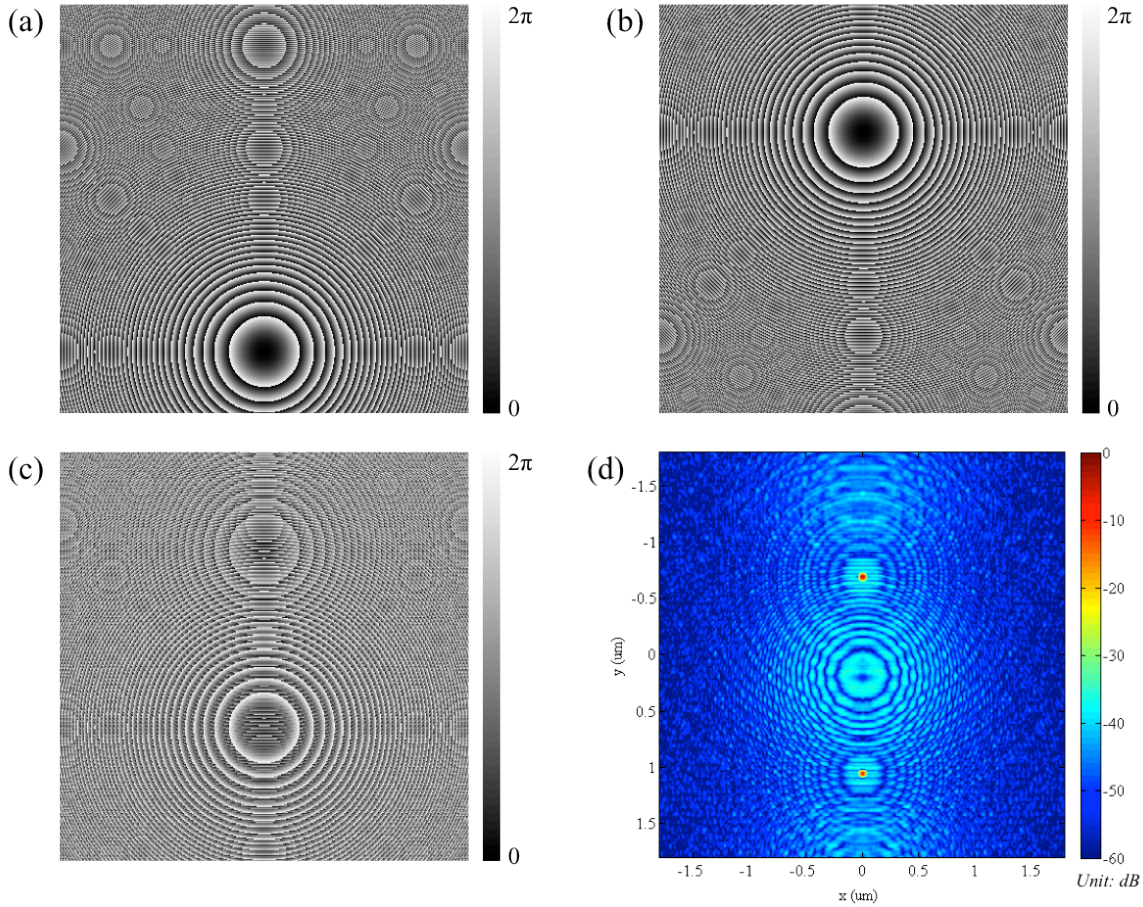

Fig. 6. Switching from Port 5 to Port 3; (a) the starting hologram for Port 5; (b) the ending hologram Port 3; (c) the calculated intermediate phase hologram corresponds to the peak transient crosstalk; (b) the corresponding replay field at the output plane of this intermediate hologram.

orders will be in focus at the plane of the output ports and could have an efficient coupling to unrelated output ports if their positions overlap with each other. This would lead to high transient crosstalk.

In contrast, a complex off-axis Fresnel lens pattern is required to ensure that one of the diffraction orders has an efficient coupling to the output port in the LCOS-based optical switches using the wavefront encoding technique. It is highly unlikely that the intermediate phase holograms displayed by the LCOS device during the switching will such characteristics. Therefore, the intermediate phase holograms are less likely to cause high transient crosstalk at unrelated ports when the wavefront encoding technique is implemented. Based on our analysis of the intermediate phase holograms in the wavefront-encoded LCOS optical switches, the intermediate phase holograms are more likely to contain some high-frequency structures, which will only scatter the light around the background, without introducing strong transient diffraction orders at a specific output port position.

Although the wavefront encoding technique doesn't affect the response time of the LCOS device, however, it can significantly shorten the duration of the transient crosstalk when it is above a specified level. This leads to a significant improvement of the switching speed in LCOS-based optical switches without any changes to the LCOS device and its driving circuitry. It is expected that the switching speed could be further improved by using a specialised liquid crystal material or by using advanced driving schemes that would improve the speed of the LCOS device itself.

The transient crosstalk in the wavefront-encoded optical switches can be further suppressed by increasing the defocus of the system. In general, this has little impact on the number of pixels required. If not properly designed, however, larger defocus could lead to excessive insertion loss at outer ports, which would ultimately restrict the port count for a given number of pixels. Therefore, the crosstalk reduction and port count need to be carefully balanced in the design process.

V. Conclusion

It was experimentally demonstrated in this paper that the wavefront encoding technique can achieve >10 dB reduction in the worst-case transient crosstalk in LCOS-based optical switches. The analysis showed that the intermediate phase holograms during switching in the wavefront-encoded optical switches were less likely to form strong diffraction orders that could be coupled into the unrelated ports with high efficiency. It was also identified that it is the presence of the transient crosstalk that fundamentally limits the switching speed of the LCOS-based optical switches. The wavefront encoding technique is also able to shorten the duration of the transient crosstalk and therefore improve the switching speed in LCOS-based optical switches. The performance achieved in this work

has the potential to be further improved with an AR coated LCOS device. As a result, hitless switching protection could be further simplified with improved switching speed.

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