Spatiotemporal Multiplexing and Streaming of Hologram Data for Full-Color Holographic Video Display

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We propose a new approach to spatiotemporally multiplex sub-holograms and stream hologram data in parallel by using multiple spatial light modulators (SLMs) to increase the spatiotemporal resolution of holographic display system. With the proposed approach, we have achieved a spatiotemporal resolution of 4.5×10^{10} pixel/s, as compared with 1.89×10^{9} pixel/s of a single SLM. Each frame of computer-generated hologram video has a pixel count of 378 Mpixels and is divided into 288 sub-holograms, each of 1.31 Mpixels. During the playback of holographic video, these sub-holograms are spatiotemporally multiplexed and streamed in parallel to form the integrated hologram within 16.67 ms, which enables full-color holographic video display with a 10-in. diagonal at a hologram data frame rate of 60 frames per second (fps). New SLM devices with higher spatiotemporal resolution need to be developed in order to meet the data bandwidth requirement of about $10^{12} \sim 10^{14}$ pixel/s for future 3D holographic displays.

KEYWORDS: holographic display, full-color, computer-generated hologram, spatiotemporal multiplexing, data streaming, bandwidth

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1. Introduction

Holographic display is considered as a true three-dimensional (3D) display because it provides all depth cues required by human visual system such as binocular parallax, motion parallax, accommodation and convergence. It is glasses-free and does not cause eye fatigue induced by accommodation-convergence mismatch. In the past years, various types of electro-holographic display systems have been proposed and investigated by different research groups in the world.[1-8)]

Recently, our research team has demonstrated a dynamic full-color full-parallax 3D holographic display with 10-inch diagonal by using a spatiotemporal multiplexing method.[9)] The optical system is schematically shown in Fig. 1. Twenty-four spatial light modulators (SLMs) were physically tiled on two plates, with 12 SLMs on each plate. They were combined with a beam combiner into an SLM array (8 rows × 3 columns) as shown in Fig. 1. The SLM array was then scanned for optical scan tiling with a one-axis 12-mm scanning mirror along horizontal direction. An optical demagnification of 0.5× was realized by using two parabola mirrors. The expanded and collimated RGB laser beams were combined with two X-cubes and a beam combiner.[9)] The viewing zone of our display system is almost collimated and has a viewing field of about 3 inch in height and 10 inch in width. The viewing angle is limited to be around 5° due to the large pixel pitch of 13.62 μm of SLM devices used in the system.

For full-parallax holographic displays with a diagonal of 10-40 in. and a viewing angle of 30-90°, a display device that is capable of presenting about $10^{12} \sim 10^{14}$ pixel/s is required.[10)] Submicron pixel pitch is also required to achieve such a large viewing angle. The limited spatiotemporal resolution of about 10^{10} pixel/s of a single SLM device has become a critical issue for practical holographic display applications. In this paper, we propose to spatiotemporally multiplex sub-holograms and stream hologram data in parallel by using multiple SLMs in order to increase the spatiotemporal resolution or bandwidth of the whole display system. We will present how to multiplex sub-holograms to form a single integrated hologram video frame and report the bandwidth required for streaming hologram data to play back 10-in. full-color holographic video at a hologram data frame rate of 60 frames per second (fps). We will also discuss the data bandwidth limitations in the development of our holographic display system.

2. Spatiotemporal Multiplexing of 288 Sub-holograms

The SLM that we used to display hologram data is a ferroelectric liquid crystal on silicon (FLCoS) device with a pixel count of 1.3 Mpixels (1280 × 1024) and a pixel pitch of 13.62 μm. In order to increase the pixel count of displayable holograms, we developed physical and optical scan tiling techniques for our 10-in. display system.[9,11] We first physically tiled 24 FLCoSs into an SLM array (8 rows × 3 columns) to achieve a pixel count of 31.5 Mpixels. Each column consisted of 8 FLCoSs seamlessly tiled along vertical direction, with a gap of one FLCoS width between two adjacent columns. The gap was then filled by optical scan tiling using a one-axis scanning mirror along horizontal direction, as schematically shown in Fig. 2. The total pixel count of a displayable hologram was further increased from 31.5 Mpixels to 378 Mpixels with 12 scan steps, which could support the display of 3D objects with a 10-in. diagonal.

The 378-Mpixel hologram was pre-computed with our split look-up table (S-LUT) algorithm using the graphics processing unit (GPU) cluster with 32.5 Tflop/s computing ability.[12] It was converted from complex values to phase values, and then binarised into 0s and 1s. After that, it was divided into 288 sub-holograms, each of 1.3 Mpixels, and grouped into 12 groups. Each group contained 24 sub-holograms, which were spatially multiplexed for 24 physically tiled FLCoSs (Fig. 2). These 12 groups were spatiotemporally multiplexed by optical scan tiling from positions 1 to 12 (Fig. 2). The time needed to form such an integrated hologram is 16.67 ms (corresponding to 60 fps) which is shorter than the time resolution for human eye (20-25 Hz).

We used a new space division multiplexing (SDM) technique to achieve color mixing.[9] The hologram was computed for three portions randomly distributed on the hologram plane with a color selective matrix, each corresponding to one of the red (R), green (G), and blue (B) components of the color object. Such a single hologram generated with SDM contains all the RGB color components. During reconstruction, each portion of the hologram was only illuminated with a masked laser beam of the corresponding color. As a result there was no extra data processing or additional bandwidth required for hologram data streaming in order to achieve full-color holographic video display. Figure 3 shows how the hologram was computed and multiplexed with the SDM technique. For each 378-Mpixel hologram frame, the computing time of 7.17 s was achieved for the color 3D object with 4.35×10^5 sampling object points.

3. Streaming of Hologram Data for Full-Color Holographic Video Display

Our display system combined two tiling techniques to form the 378-Mpixel binary hologram, i.e. the physical tiling of 24 FLCoSs and 12-step optical scan tiling of 24 physically tiled FLCoSs.[9,11] The 24 physically tiled FLCoSs were controlled by 6 hologram launching units (Fig. 4). Each launching unit controlled 4 FLCoSs which were connected to 2 GPUs, and these 2 GPUs were linked by one G-Sync card. All 24 FLCoSs on 12 GPUs were hardware-synchronized by 6 G-Sync cards. Actually, for controlling individual FLCoS only, we do not need high performance GPU. However, in order to synchronize all the DVI frames, we need the GPUs with a frame-lock function. In our system we used the nVidia Quadro 5000 GPUs. The 6 launching units were linked to 3 hologram loading units via high speed network switches, and software-synchronized with a control program. The 12 sets of 24 sub-holograms launched onto the 24 FLCoSs were synchronized with 12 optical scan steps by using field-programmable gate array (FPGA).[11]

In our launching platform (Fig. 4), the 4 FLCoSs connected to a launching unit via 4 DVI cables were arranged in the same half column such as A1, A2, A3 and A4 in Fig. 5(a), and treated as a single connected 5120×1024 display screen in software program. According to the spatiotemporal multiplexing requirements, the 378-Mpixel hologram was divided into 288 sub-holograms, and arranged into 72 portions as shown in Fig. 5(b). Each portion contained 4 sub-holograms displayed on 4 connected FLCoSs. The FLCoS device accepts binary bit-plane data in a 24 bit DVI frame format. To fully utilize this feature, each FLCoS was hardware-locked and synchronized to show 24 binary bit planes of 1280×1024 pixels within a 60 Hz DVI frame duration (16.67 ms). For storing the hologram data, the sequence of 12 scan steps were used to put the binary pixel values of corresponding sub-holograms into an even bit plane position (0, 2, 4, …, 22), as shown in Fig. 5(b), so that no extra data processing was required during the playback of holographic video. Twelve duplicated binary bit planes were added to the 12 sub-holograms at the odd bit plane position (1, 3, 5, …, 23) for each DVI frame of a single FLCoS in order to fit into the 24 bit DVI format, which doubled the bandwidth requirement. 24-step scan tiling can be implemented to further increase the displayed image size by replacing the 12 duplicated binary bit planes with sub-holograms if faster and larger scan-angle scanning mirrors are available.

During the playback of holographic video, the hologram data were streamed in parallel from hologram loading platform to hologram launching platform and output to the physically tiled 24 FLCoSs devices. The flowchart of parallel hologram data streaming is shown in Fig. 4. The pre-formatted and stored hologram data were read from 6 solid state drives (SSDs) in 3 loading units, transmitted to 6 launching units via network, and launched onto the 24 FLCoSs for reconstruction. The 12 GPUs in our 6 launching units were used to output the hologram data via 24 DVI interfaces required by 24 FLCoS drivers, and to lock the 24 FLCoSs on the same phase. The FLCoS driver decoded a DVI frame into 24 binary bit planes and launched them in a fixed sequence, and the starting of these 24 bit planes was linked to the starting of DVI frame. If we used normal DVI outputs without synchronization, the 24 DVI signals would not start a frame at the same time and we could not do any optical scan tiling. The 12 GPUs we selected have a Gen-Lock function to lock the starting of DVI frame from these 24 outputs by hardware, so we could ensure bit plane 0 was shown on all the 24 FLCoSs synchronously, followed by bit plane 1, and so on, which enabled us to do synchronized scan tiling.

The hardware bandwidth and the bandwidth requirements for the playback of 378-Mpixel hologram data at 60 fps are shown in Fig. 6. It can be seen that our system requires a total bandwidth of 45 Gbps, corresponding to 4.5×10^{10} pixel/s. The time measured for transmitting 1000 holographic video frames was 34.215 s, corresponding to a video frame rate of 29.23 fps. Since the same hologram data of each video frame was scanned twice to meet the requirement of 24 bit DVI format, the actual hologram data frame rate should be 58.46 fps, corresponding to a data throughput of 44.14 Gbps, which was supported by our system bandwidth of 45 Gbps.

Figure 7 presents the flowchart of hologram data generating, processing, formatting, spatiotemporal multiplexing and streaming for our full-color 3D holographic video display. With the above proposed approach to spatiotemporally multiplex sub-holograms and stream hologram data in parallel by using multiple FLCoSs, we have increased the spatiotemporal resolution of our 3D holographic display system from a single FLCoS of 1.89×10^{9} to 4.5×10^{10} pixel/s. With such a system we achieved full-color holographic video display with a 10-in. diagonal at a hologram data frame rate of 60 fps. Figure 8 shows snapshots of the reconstructed holographic video of three animated color magic cubes, each rotating around its vertical axis. The storage capacity required for such hologram video data with 378 Mpixels per frame is 340 Gbyte for a one-minute video.

For full-parallax holographic displays with a diagonal of 10-40 in. and a viewing angle of 30-90°, a display device that is capable of presenting about $10^{12} \sim 10^{14}$ pixel/s is required.[10)] To meet this requirement, the bandwidths of all the involved hardware devices, such as SSDs, optical fibers and SLMs, need to be increased significantly. Table 1 lists some characteristics of various types of SLM devices reported.[10,13-16)] The SLM device used in our current system is the FLCoS presenting 1.89×10^9 pixel/s. Recently, ForthDD has shipped new QXGA-R9 FLCoS device featured with 2048 × 1536 pixels and binary bit-planes up to 5.7 kHz.[15)] It can provide a maximum spatiotemporal resolution of 1.79×10^{10} pixel/s, similar to that of DMD (see Table 1) which is still much less than the above mentioned system target by two to four orders of magnitude. It is shown that the limited spatiotemporal resolution of single SLM device is a critical issue for practical holographic display applications. New SLM devices with higher spatiotemporal resolution need to be developed, while using the approach of spatiotemporal multiplexing of sub-holograms and streaming hologram data in parallel with multiple SLM devices to increase the spatiotemporal resolution of the display system.

4. Conclusions

Spatiotemporal multiplexing of sub-holograms and streaming of hologram data in parallel by using multiple SLMs are proposed to increase the spatiotemporal resolution of 3D holographic display system for full-color holographic video display. The 378-Mpixel binary hologram containing RGB components multiplexed with SDM is divided into 288 sub-holograms, which are pre-formatted and stored according to the spatiotemporal multiplexing requirements of the system. These sub-holograms are spatiotemporally multiplexed to form an integrated binary hologram with 378 Mpixels per frame within 16.67 ms during the playback of a full-color holographic video at a hologram data frame rate of 60 fps. For a 10-in. diagonal holographic video display, a total bandwidth of 45 Gbps is required to stream the hologram data, which corresponds to a spatiotemporal resolution of 4.5×10^{10} pixel/s. Although the spatiotemporal multiplexing of more sub-holograms is an effective way to increase the displayed image size, it is limited by the spatiotemporal resolution of the SLM devices. The development of new SLM devices with higher spatiotemporal resolution and smaller pixel pitch is essential in order to meet the requirement for full-parallax holographic displays with bigger size and larger viewing angle.

Acknowledgments

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Table 1.

Table 1. Some characteristics of various types of SLM devices.

Type	LCD	LCoS	FLCoS	DMD
Resolution (pixels)	4096 × 2160	8192 × 4320	2048 × 1536	1920 × 1080
Frame rate (fps)	60	60	5.7×10^3	24×10^3
Pixel format	8-bit greyscale	8-bit greyscale	24-bit video and binary bit-planes	Binary
Spatiotemporal resolution (pixel/s)	5.3×10^8	2.1×10^9	1.79×10^{10}	4.97×10^{10}

Caption of Figures

Fig. 1. (Color online) Schematic drawing of the holographic display system: P1 and P2 are two plates, each with a physically tiled SLM array (4 rows × 3 columns); A, B and C are the top view of 3 columns of SLMs on P1 and P2; BS/BC is a beam splitter or beam combiner; M is a plane mirror; PM1 and PM2 are parabola mirrors; SM is one-axis scanning mirror.

Fig. 2. (Color online) Sketch of spatiotemporally multiplexed 288 sub-holograms.

Fig. 3. (Color online) Computing process of the hologram with RGB components multiplexed by SDM.

Fig. 4. (Color online) Flowchart of hologram data streaming in parallel by using 24 SLM devices. The SLM used here is FLCoS, represented by FLC.

Fig. 5. (Color online) (a) Connection of 24 physically tiled FLCoSs; (b) Arrangement of 72 portions for a 378-Mpixel hologram.

Fig. 6. (Color online) Hologram data streaming and bandwidth analysis.

Fig. 7. Flowchart of generating, processing, formatting, spatiotemporal multiplexing and streaming of hologram video data.

Fig. 8. (Color online) Snapshot of a full-color 3D holographic video, showing 3 reconstructed magic cubes captured with a camera focused on (a) left and right ones at the front depth, and (b) central one at the back depth.

Fig. 1.

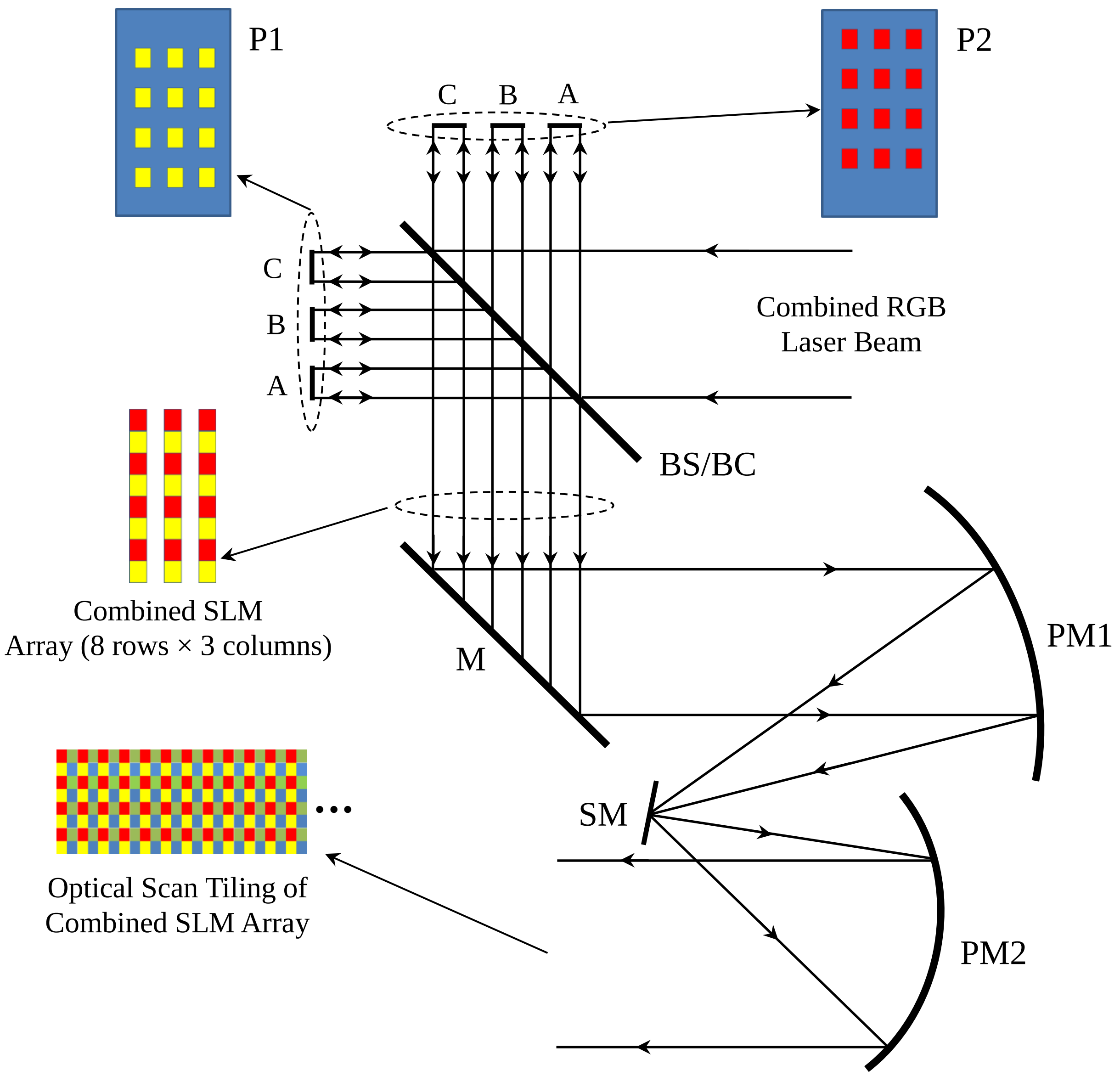

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Fig. 2

9	10	9	10	9	10	8	11	8	11	8	11	7	12	7	12	7	12	6	1	6	1	6	1	5	2	5	2	5	2	4	3	4	3	4	3
9	10	9	10	9	10	8	11	8	11	8	11	7	12	7	12	7	12	6	1	6	1	6	1	5	2	5	2	5	2	4	3	4	3	4	3
9	10	9	10	9	10	8	11	8	11	8	11	7	12	7	12	7	12	6	1	6	1	6	1	5	2	5	2	5	2	4	3	4	3	4	3
9	10	9	10	9	10	8	11	8	11	8	11	7	12	7	12	7	12	6	1	6	1	6	1	5	2	5	2	5	2	4	3	4	3	4	3
9	10	9	10	9	10	8	11	8	11	8	11	7	12	7	12	7	12	6	1	6	1	6	1	5	2	5	2	5	2	4	3	4	3	4	3
9	10	9	10	9	10	8	11	8	11	8	11	7	12	7	12	7	12	6	1	6	1	6	1	5	2	5	2	5	2	4	3	4	3	4	3
9	10	9	10	9	10	8	11	8	11	8	11	7	12	7	12	7	12	6	1	6	1	6	1	5	2	5	2	5	2	4	3	4	3	4	3
9	10	9	10	9	10	8	11	8	11	8	11	7	12	7	12	7	12	6	1	6	1	6	1	5	2	5	2	5	2	4	3	4	3	4	3

Fig. 2. (Color online) Sketch of spatiotemporally multiplexed 288 sub-holograms.

Fig. 3

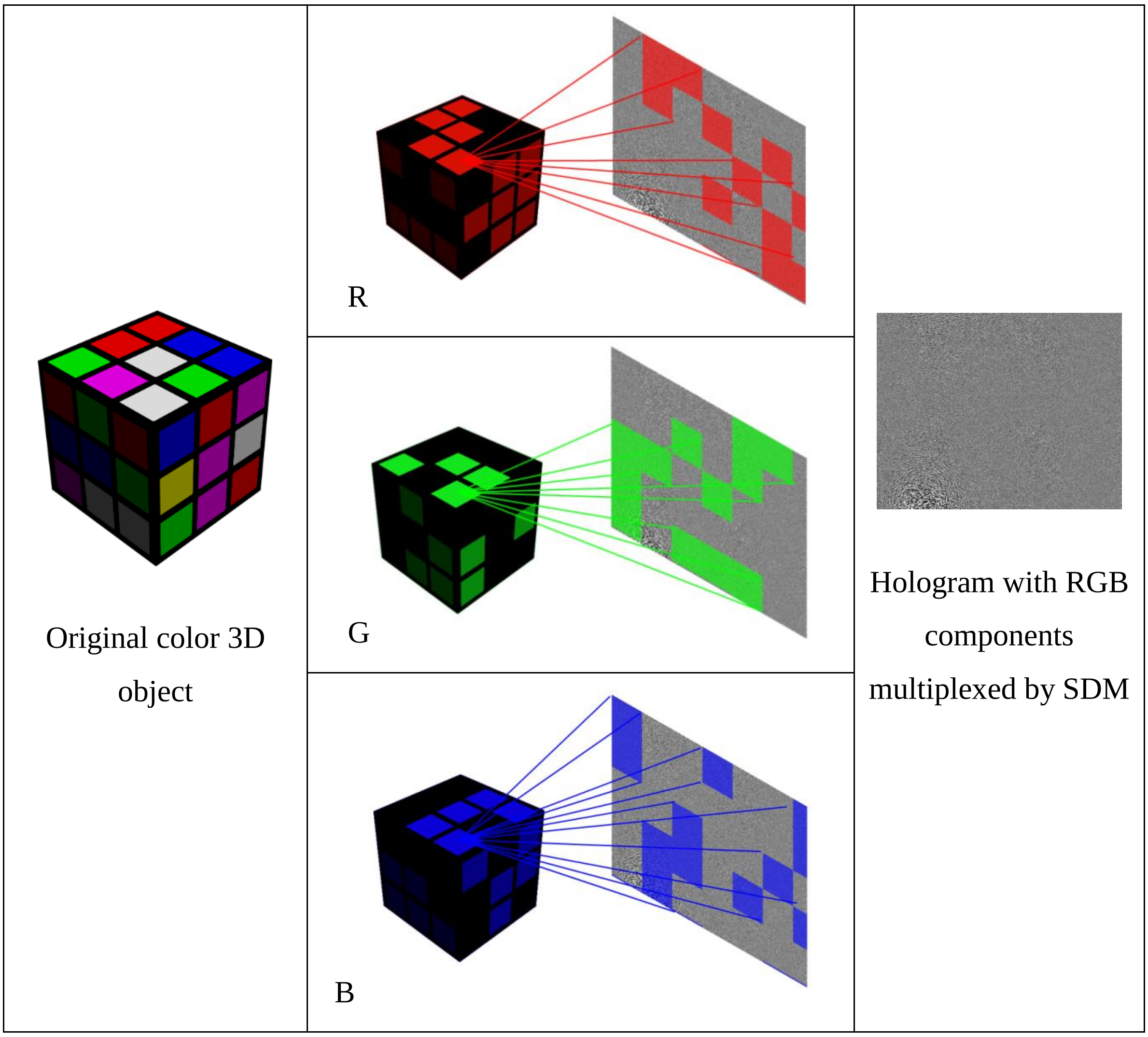

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Fig. 4

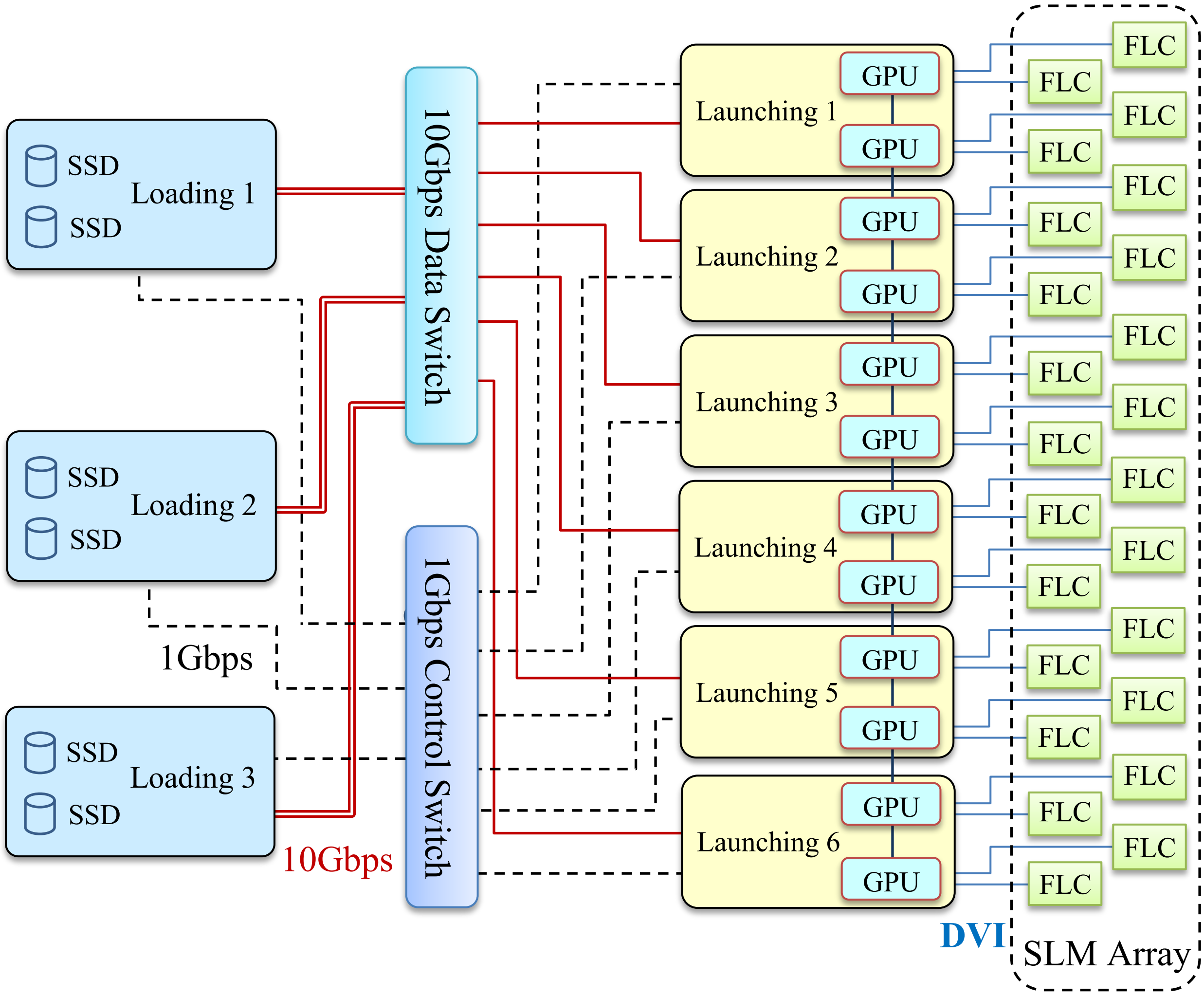
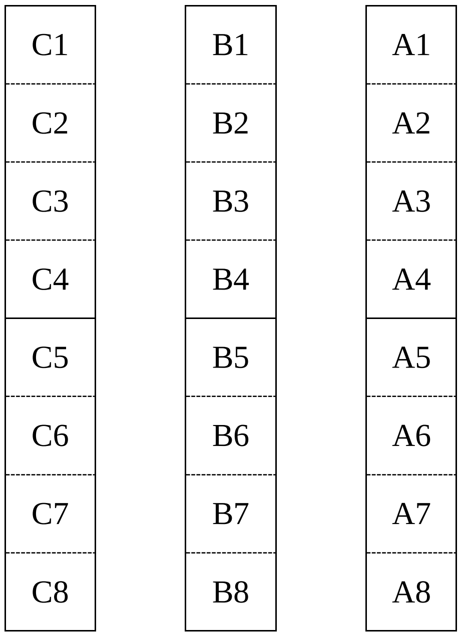


Fig. 4. (Color online) Flowchart of hologram data streaming in parallel by using 24 SLM devices. The SLM used here is FLCoS, represented by FLC.

Fig. 5.



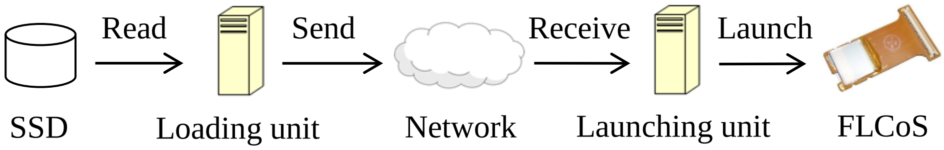
(a)

Scan steps	9	10	9	10	9	10	8	11	8	11	8	11	7	12	7	12	7	12	6	1	6	1	6	1	5	2	5	2	5	2	4	3	4	3	4	3
4 FLCoSs per half column	C1 C2 C3 C4	C1 C2 C3 C4	B1 B2 B3 B4	B1 B2 B3 B4	A1 A2 A3 A4	A1 A2 A3 A4	C1 C2 C3 C4	C1 C2 C3 C4	B1 B2 B3 B4	B1 B2 B3 B4	A1 A2 A3 A4	A1 A2 A3 A4	C1 C2 C3 C4	C1 C2 C3 C4	B1 B2 B3 B4	B1 B2 B3 B4	A1 A2 A3 A4	A1 A2 A3 A4	C1 C2 C3 C4	C1 C2 C3 C4	B1 B2 B3 B4	B1 B2 B3 B4	A1 A2 A3 A4	A1 A2 A3 A4	C1 C2 C3 C4	C1 C2 C3 C4	B1 B2 B3 B4	B1 B2 B3 B4	A1 A2 A3 A4	A1 A2 A3 A4	C1 C2 C3 C4	C1 C2 C3 C4	B1 B2 B3 B4	B1 B2 B3 B4	A1 A2 A3 A4	A1 A2 A3 A4
4 FLCoSs per half column	C5 C6 C7 C8	C5 C6 C7 C8	B5 B6 B7 B8	B5 B6 B7 B8	A5 A6 A7 A8	A5 A6 A7 A8	C5 C6 C7 C8	C5 C6 C7 C8	B5 B6 B7 B8	B5 B6 B7 B8	A5 A6 A7 A8	A5 A6 A7 A8	C5 C6 C7 C8	C5 C6 C7 C8	B5 B6 B7 B8	B5 B6 B7 B8	A5 A6 A7 A8	A5 A6 A7 A8	C5 C6 C7 C8	C5 C6 C7 C8	B5 B6 B7 B8	B5 B6 B7 B8	A5 A6 A7 A8	A5 A6 A7 A8	C5 C6 C7 C8	C5 C6 C7 C8	B5 B6 B7 B8	B5 B6 B7 B8	A5 A6 A7 A8	A5 A6 A7 A8	C5 C6 C7 C8	C5 C6 C7 C8	B5 B6 B7 B8	B5 B6 B7 B8	A5 A6 A7 A8	A5 A6 A7 A8
Bit position	16	18	16	18	16	18	14	20	14	20	14	20	12	22	12	22	12	22	10	0	10	0	10	0	8	2	8	2	8	2	6	4	6	4	6	4

(b)

Fig. 5. (Color online) (a) Connection of 24 physically tiled FLCoSs; (b) Arrangement of 72 portions for a 378-Mpixel hologram.

Fig. 6



Interface	SSD	Fiber	Fiber	DVI
Number of interfaces	6	6	6	24
Hardware bandwidth	8.8 Gbps	10 Gbps	10 Gbps	1.89 Gbps (60Hz)
Bandwidth requirement (total)	1280 × 1024 × 24 bit × 24 × 60 Hz = 755 Mbit × 60 Hz = 45 Gbps			
Bandwidth requirement (per interface)	7.5 Gbps	7.5 Gbps	7.5 Gbps	1.89 Gbps (60Hz)

Fig. 6. (Color online) Hologram data streaming and bandwidth analysis.

Fig. 7

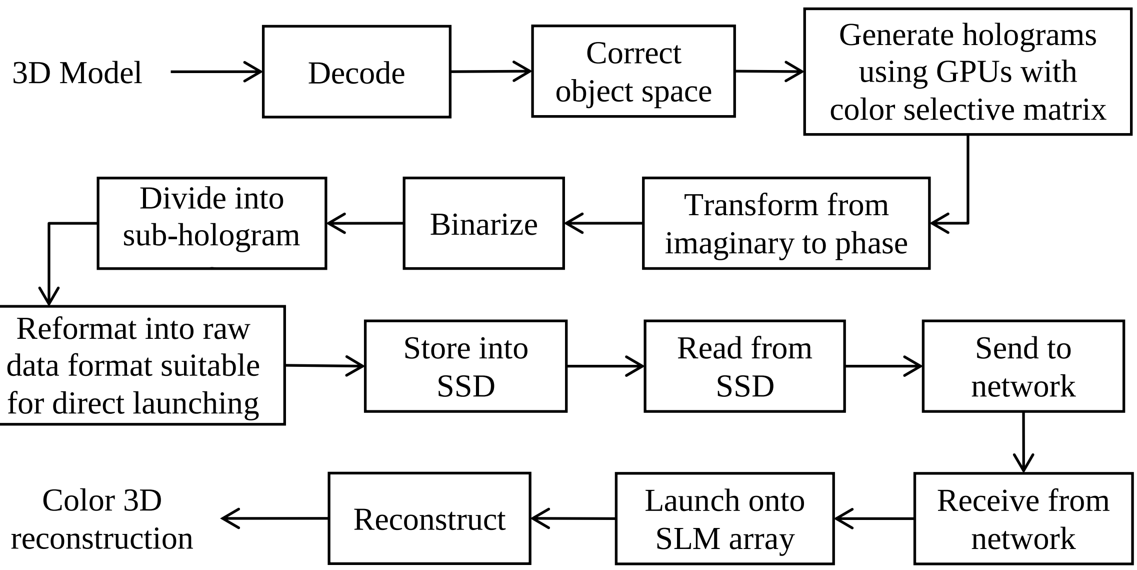
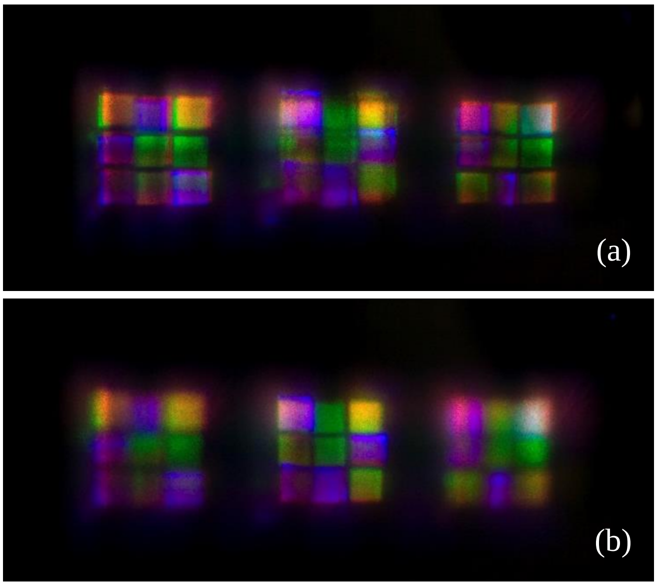


Fig. 7. Flowchart of generating, processing, formatting, spatiotemporal multiplexing and streaming of hologram video data.

Fig. 8



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