Experiments on a multichannel holographic optical switch with the use of a liquid-crystal display

Hirofumi Yamazaki and Masayasu Yamaguchi

NTT Communication Switching Laboratories, 3-9-11, Midori-cho, Musashino-shi, Tokyo 180, Japan

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A new configuration of holographic switches is proposed and verified for multichannel optical switching. Experimental 1 × 64 and 2 × 32 switching is achieved by using real-time binary phase-only holograms generated by a twisted nematic liquid-crystal display. This holographic free-space switching is applicable to photonic switching systems and optical interconnections.

Most $N \times N$ optical switches, whether they are waveguide types[1] or free-space types,[2] consist of multiple 2 × 2 switches. When large-scale switches are made, the cascade connections of many 2 × 2 switches cause the accumulation of loss and cross talk. On the other hand, holographic $N \times N$ optical switches are constructed from $1 \times N$ switches arranged in parallel and do not need cascade connections. Therefore they have no accumulation of loss and cross talk and thus are suitable for large-scale switches.

Holographic switches that use photorefractive materials or acousto-optic Bragg cells have been demonstrated.[3,4] These switches, however, have drawbacks. Generation of real-time holograms with high diffraction efficiency and fast speed in photorefractive materials generally requires high voltages (of the order of a kilovolt).[5] Acousto-optic Bragg cells can steer light beams only one dimensionally and require cascade connections for two-dimensional beam steering. On the other hand, liquid-crystal displays (LCD's) can renew holograms with low driving voltages (5 V in our experiments) and can steer light beams two dimensionally. But the LCD's also have a drawback, i.e., low spatial resolution owing to the pixel size, which results in a smaller angle for beam steering. The pixel size is, however, expected to be reduced to an acceptable size (e.g., 10 μm) in the future. We previously demonstrated 4 × 4 holographic optical switching by using an LCD as a binary phase-only modulator.[6] In this Letter a new configuration of holographic switches is proposed for easy implementation of multichannel switching, and 1 × 64 and 2 × 32 optical switching is demonstrated experimentally.

Figure 1 shows a schematic diagram of the proposed switch. The LCD is divided into sections, and each section is assigned to a corresponding input port. Holograms are calculated and stored in the memory of a controller before the switch is operated. A hologram is written independently on each section with electrical signals from the controller. A phase hologram on each section bends an input beam in the desired direction, and the lens feeds the deflected beams at the same angle to the corresponding output port. A signal light is switched by renewing the hologram on the corresponding section.

The configuration that we used for 4 × 4 switching requires different holograms for different input ports to be connected with an output port. Therefore strictly nonblocking $N \times N$ switching is achieved with N^2 types of holograms in general. As the positions of unwanted diffracted lights (e.g., minus-order or higher-order diffracted light) on the output plane vary according to the input positions, the optical design for removing the unwanted lights becomes difficult when the number of inputs is large. Our proposed configuration associates a hologram with an output port as mentioned above. It requires only N types of holograms for $N \times N$ switching and makes it easy to remove unwanted diffracted light.

The 1 × 64 switching with the LCD was studied to determine the factors restricting the number of output ports. In the experiment, optical switching was achieved by using binary phase-only modulation with a twisted nematic LCD. The display used was an active-dot-matrix type for an overhead projector. It has 640 horizontal and 400 vertical pixels, and its pixel size is 0.33 mm × 0.33 mm. Measurements showed that the phase-modulation depth of the light through the LCD was $\pi/3$.[6]

Figure 2 shows the optical setup that we used.[7] The light source is a He–Ne laser with a wavelength

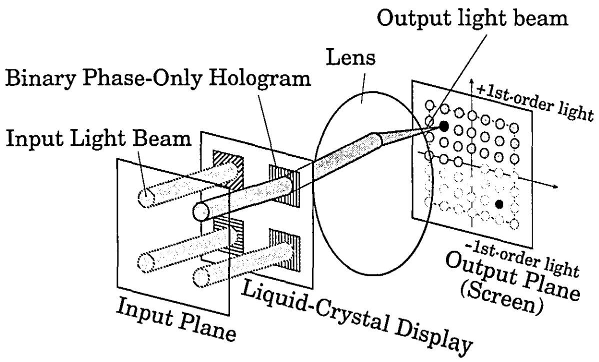


Fig. 1. Schematic diagram of the proposed holographic switch that uses an LCD.

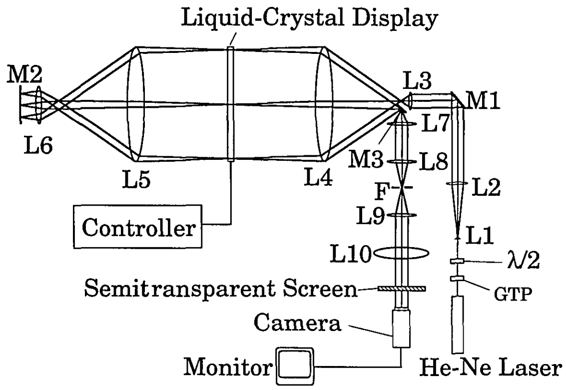


Fig. 2. Experimental setup for free-space optical switching by using binary phase-only modulation with an LCD.

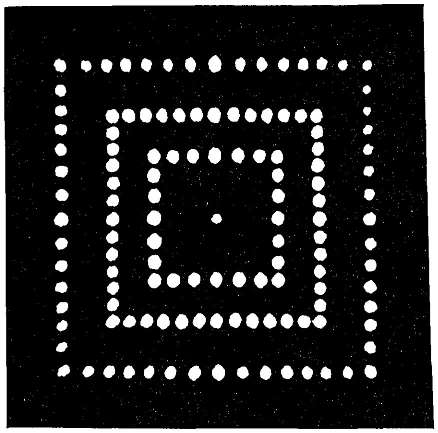


Fig. 3. Output light spots from 1 × 64 switching. The light sequentially switched to any one of 64 output positions is shown by multiple exposure.

of 633 nm. The polarization of the input light is aligned parallel with the liquid-crystal molecule director at the front of the display by using a Glan–Thompson polarizing prism (GTP) and a $\lambda/2$ plate. The light beam goes through lenses L1–L6 and the LCD. It is reflected by mirror M2 and returns to mirror M3. The light extracted by mirror M3 reaches the semitransparent screen through lenses L7–L10 and spatial filter F. The output light on the screen is monitored by the camera.

The light beam is sent through the LCD twice for two purposes. One is to match the polarizations of the lights through the off-state and on-state pixels. The polarization of the light through the off-state pixels is at 90 deg to the light through the on-state pixels because the twisted nematic LCD rotates the polarization of the light through the off-state pixels by 90 deg. This right-angle polarization difference between the lights through the off- and on-state pixels disables the optical interference that is necessary for the holographic beam steering. However, by introducing the double-passage configuration, the 90-deg polarization rotation through the off-state pixels can be canceled, and the lights through the off- and on-state pixels can be made to interfere with each other. The other purpose is to make the phase-modulation depth of the LCD closer to π, which is necessary to suppress the unwanted diffracted light and to maximize the first-order diffracted light.[8] The phase-modulation depth of the light through the LCD becomes $2/3\pi$ (doubled) after two passes.

The diameter of the input beam is 3 mm. The light beam is expanded by lenses L3 and L4 and reduced by lenses L4 and L7 so that the light passes through more pixels to obtain higher spatial resolution. The diameter of the light is expanded to 27 mm on the LCD and reduced to 1/70 on the way from the LCD to an output port. Lenses L8 and L9 and the spatial filter F extract the zeroth-order beam from the diffracted light generated by the effect of the regular grid structure of the LCD.[9] The light from the lens L9 is bent in a direction determined by the hologram. Lens L10 collects the deflected lights at the same angle to an output port.

Figure 3 shows the experimental result for 1 × 64 switching. The output light is switched to any one of 64 output ports, and the figure shows all of them by multiple exposure. There are 129 spots in the figure: 64 positive first order (the upper half), 64 negative first order (the lower half), and 1 zeroth order (the center). Therefore, in practice, the number of selectable ports is 64. The positive and negative orders are generated because holograms on the LCD are simple phase-only gratings. The center spot (zeroth order) appears owing to two factors. One is that the original light reaches the screen when the hologram is erased for switching. The other is that the phase-modulation depth is less than π rad.

This experiment used simple holograms (64 types of one-dimensional grating) because they do not require much calculation time to generate or much memory to store. The 64 gratings are obtained by rotating three one-dimensional gratings having line pitches of 2, 3, and 5 pixels. The three sets of gratings with different pitches diffract the lights and generate three square arrays of the light spots on the output plane as shown in Fig. 3. The largest, middle, and smallest squares correspond to the gratings with the line pitches of 2, 3, and 5 pixels, respectively. These line pitches change slightly during the rotation of the gratings owing to the algorithm for generating the gratings. This pitch variation gives the square arrangement of the light spots instead of the circular arrangement.

The pixel size mainly restricts the number of out-

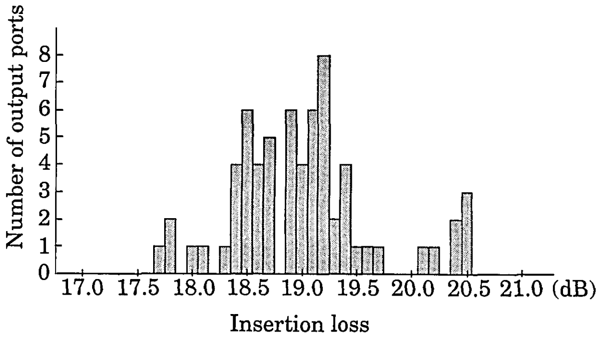
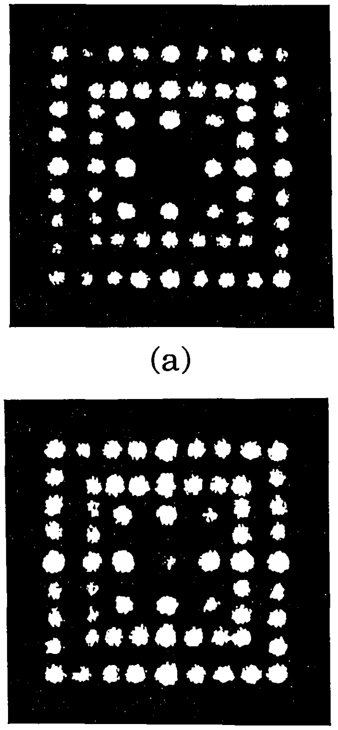


Fig. 4. Loss distribution of the 1 × 64 holographic switch.



(a)

(b)

Fig. 5. Output light spots of the 2 × 32 switching. The light sequentially switched to any one of 32 output positions is shown by multiple exposure. (a) Output light when one input beam is incident upon the optical setup. (b) Output light when two input beams are incident upon the optical setup.

put ports in the experiment. It determines and quantizes the square size of the output spot arrays in Fig. 3. The number of output ports on the sides of the squares is determined by the square size and the spot size. If the pixel size were smaller, the square size and the number of the available spot squares could be increased, and then the number of output ports also could be increased.

Figure 4 shows the loss distribution of the 1 × 64 switch. The average, maximum, and minimum of the loss are 19.3, 20.5, and 17.7 dB, respectively. The loss dispersion is within 3 dB. Most of the loss is caused by reflections at the LCD, which has no antireflection coating, and at the many lenses. If we used an antireflection-coated LCD with smaller pixels and eliminated the beam-expansion and beam-reduction system, the loss would decrease remarkably.

The 2 × 32 switching was demonstrated to verify that a hologram can direct the light beams from different input ports to the same output port. The optical setup shown in Fig. 2 was used, and two parallel light beams are incident upon the LCD as inputs. In this setup, the aberration increases if the distance from the optical axis becomes longer, which results mainly from the optical system for expansion and reduction of the light beam. Therefore, to suppress the aberration, the diameter of the input beams was reduced to 1 mm, and the input positions were moved closer to the optical axis. Furthermore the beam-reduction ratio on the way from the LCD to an output port was changed from 1/70 to 1/35. These changes approximately halve the diffraction angle of the output lights compared with that of the 1 × 64 switching. Therefore the number of output ports decreases to 32, and the spot diameters are larger than in Fig. 3. Figure 5 shows the experimental result for 2 × 32 switching, which is taken by multiple exposure. Figure 5(a) shows that the output light is switched to any one of 32 output ports when one input beam is incident, and Fig. 5(b) shows the output spots when two input beams are incident. These figures prove that the two inputs from different input ports are directed to the same output ports by the optical setup.

In this Letter we have proposed a new configuration of holographic switches that facilitates multichannel switching that uses an LCD. Whereas the previous configuration needed N^2 types of holograms for strictly nonblocking $N \times N$ switching, the proposed configuration requires only N types of holograms, which is equal to the number of output ports. Furthermore the proposed configuration makes it easy to remove unwanted diffracted light. The 1 × 64 switching showed that the main factor restricting the number of the output ports is the pixel size. The 2 × 32 switching verified that the configuration can handle multichannel switching. The aberration of the expansion and reduction optical system restricted the number of input ports to one or two in the experiment. But if an LCD had 640 × 400 pixels (pixel size 5 μm × 5 μm) and 80 × 80 pixels were assigned to each input, the expansion and reduction system would not be necessary, and the number of inputs would be 40. In this case, the number of pixels on the LCD would determine the number of inputs. If the twisted nematic LCD were changed to a homogeneous LCD and the thickness of the liquid-crystal layer were optimized to obtain the phase-modulation depth of π, a single-path optical system through the LCD would be sufficient to switch the light beam, and the switch configuration could be simple, as shown in Fig. 1.

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