Planar optical dynamic crossbar switch

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Abstract. A compact dynamic crossbar switch, based on a planar optics configuration, is presented. It consists of a pair of identical planar holographic cylindrical telescopes, each recorded on a single substrate, and a two-dimensional array (8×8) ferroelectric liquid crystal spatial light modulator. The crossbar switch can direct the light from any particular source in a one-dimensional array of 8 sources to a particular detector in a one-dimensional array of 8 detectors. The design of the overall configuration is presented along with experimental results. [S0091-3286(99)01108-3]

Subject terms: holographic optical elements; optical interconnects; spatial light modulators.

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1 Introduction

Crossbar interconnection switches are essential components in a variety of applications such as communication networks and parallel computation.[1,2] These switches have been incorporated into free-space optical configurations for performing dynamic vector matrix multiplication and arbitrary interconnection between N inputs to N outputs.[3–7] Such configurations consist of several discrete conventional lenses and a dynamic spatial light modulator (SLM). Unfortunately, the combination of discrete elements and free-space optics often leads to excessive weight and volume. Moreover, the needed accurate alignment between individual elements in these configurations is extremely difficult and often impractical.

The problems associated with discrete elements and free space configurations can be alleviated by using planar optics configurations.[8–10] In these, several diffractive optical elements are recorded on a single substrate. The light between the different optical elements propagates inside the substrate, as a result of either total internal reflection or reflective coatings on the substrate surfaces. The alignment between the various diffractive elements that are recorded on one substrate can be done with relatively high accuracy during the recording stage, rather than operation stage. In previous work, we presented a planar optical configuration for a passive crossbar switch implementing a two-dimensional array of binary masks.[11] In this paper we present a similar planar optical configuration for implementing a *dynamic* and compact crossbar switch, that includes an electronically controlled SLM of relatively high switching rates. The SLM is a ferroelectric liquid crystal spatial light modulator (LCSLM) that has a response time of about 7–8 μsec and can support[12] switching rates of about 40 KHz.

2 Crossbar Switch Design and Limitations

For the operation of the planar optical crossbar switch, the light from every element in a linear array of sources is first spread out towards a specific row of the two-dimensional LCSLM array by means of a holographic cylindrical telescope. Then, the light from every column of the LCSLM array is collected to a specific element in a linear array of output detectors, by means of an identical holographic cylindrical telescope that is rotated by 90° with respect to the first one. The configuration of the planar holographic cylindrical telescope for spreading out the light is schematically shown in Fig. 1. It consists of two holographic cylindrical lenses (HLs), each of which is recorded on an opposite side of a single substrate; an alternative configuration could have both lenses recorded on the same side of the substrate. The first HL is a negative cylindrical lens which spreads the light from an adjacently placed one-dimensional array of light sources. The other HL is a positive cylindrical lens which collimates the spread light and directs it towards an adjacently placed LCSLM with a two-dimensional array of binary, transparent and opaque subareas (pixels). In essence, such a planar configuration operates as a cylindrical Galilean telescope,[13] for expanding a one-dimensional beam. The planar configuration for collecting and directing the light from the LCSLM towards the linear array of output detectors is identical to that shown in Fig. 1, except that the input light from the LCSLM is incident at the positive lens. Thus, the light transmitted through each column of the LCSLM is summed up at the appropriate detector. The two planar cylindrical telescopes and the LCSLM may be at-

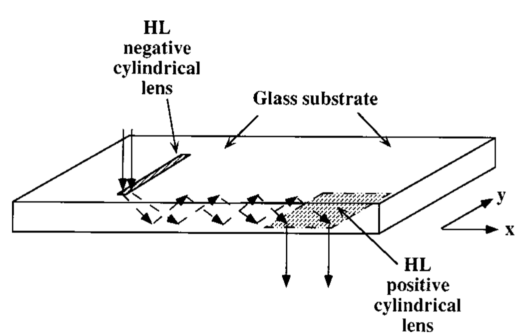


Fig. 1 Planar configuration of the holographic cylindrical telescope.

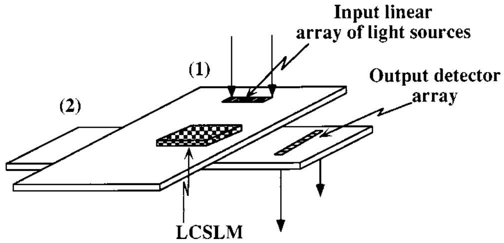


Fig. 2 Planar configuration of an optical crossbar switch.

tached together to form a single substrate, that would be insensitive to relative movements of the individual elements.

The overall configuration of the planar optical crossbar switch, that includes the two identical planar telescopes, is shown schematically in Fig. 2. The upper and lower planar telescope configurations are denoted by the indices 1 and 2, respectively. In this optical crossbar switch, the interconnection between arbitrary elements of the input to those of the output detector is according to whether a particular element of the LCSLM array is ON (transparent) or OFF (opaque). For example, when a signal from the ith source in the input array should be connected to the jth detector in the output array, the value of the $\{i,j\}$ element of the LCSLM array should be ON, i.e., this element is transparent.

The geometry for recording the planar holographic lenses of the cylindrical telescopes is presented in Fig. 3. Figure 3(a) shows an off-axis unfolded recording geometry which is given merely to explain the recording procedure, whereas Fig. 3(b) shows the total actual geometry for recording the planar holographic lenses. In Fig. 3(a), the ''object'' wave for both HLs is an off-axis cylindrical wave converging towards the point P, and the ''reference'' beams are normal incident plane waves. As shown, the off axis angle between the object waves and reference waves is θ. It is important to note that the ''object'' wave for the second HL passes through the first HL, so that all the aberrations introduced by the $HL1$ and the medium between $HL1$ and $HL2$ are cancelled in operation. Specifically, a perfect input plane wave will result in a perfect output plane wave. Now, when recording the planar HLs, it is necessary to ensure that the off-axis angle θ for the chief ray of the object wave, inside the substrate, is sufficiently large so that the entire cylindrical wave will be trapped inside the substrate by total internal reflection, i.e., $\theta > \sin^{-1}(1/n)$, where n is the refractive index of the substrate. This can be conveniently done, as depicted in Fig. 3(b), with a prism having the same refractive index as the substrate. The converging cylindrical object is coupled into the glass substrate through the prism, so that after one bounce inside the substrate it extends beyond the prism surface and continues to propagate in the substrate until reaching the location of $HL2$. The reference waves, which are normally incident plane waves, are set at the appropriate position to interfere with the cylindrical waves at the locations of $HL1$ and $HL2$.

An important criterion of optical crossbar switching is how many elements can be interconnected through it. In

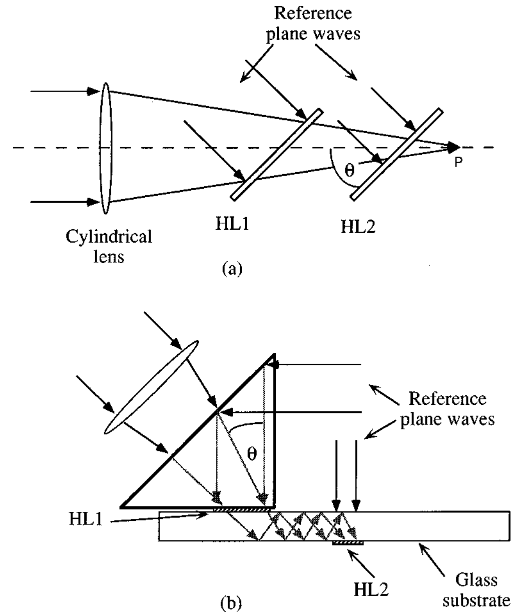


Fig. 3 Recording geometry for the holographic cylindrical telescope: (a) unfolded geometry, (b) planar geometry.

our crossbar switch configuration, the maximum number of elements M_{max} is limited by the diffraction of each element in the y direction. The diffraction is negligible in the x direction where the optical power of the cylindrical lens is dominant. Our crossbar switch behaves as a space variant system,[14,15] so the maximal number of elements M_{max}, that can be interconnected is $M_{max} \approx \sqrt{S/2\lambda F^{\#}}$, where S is the length of the one-dimensional array of sources or detectors, λ is the operating wavelength and $F^{\#}$ is the characteristic F number of the planar telescope configuration. This leads to a realistic limiting value for M_{max} of approximately 30 along each coordinate in our system. However, it is possible to modify the configuration, so as to obtain a space invariant system behavior by inserting an imaging lens between the two lenses of each cylindrical telescope. This will increase the maximal number of possible interconnect elements to be[16] $M_{max} \approx S/\lambda F^{\#}$, so the limiting factor would no longer be diffraction, but rather aberrations of the lenses and the size of each element of the SLM.

Another criterion is the cross-talk between adjacent elements. Such cross-talk can arise from diffraction and scattering or spurious reflections inside the substrate. The dominant cause for cross-talk is diffraction. In our case, a one-dimensional analysis is sufficient, since the diffraction is negligible in the direction where the cylindrical lens has optical power. For the analysis, we calculated the Fresnel diffraction from a mask simulating a LCSLM, having an array of elements each of 450 μm with a distance of 550 μm between centers of adjacent elements. The results revealed that the cross-talk is approximately 1% (calculated as the portion of the energy received by the neighboring element). This value can be significantly reduced by optimizing the dimensions of the elements, and the distances between them.[17] The cross-talk due to scattering or spurious reflections is less problematic. Specifically, even if we assume 10 reflection planes with 0.5% of the incident

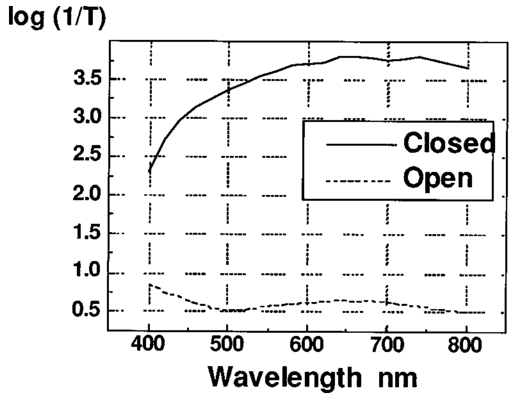


Fig. 4 The transmittance, at ON and OFF positions, of a single pixel of the LCSLM as a function of the illumination wavelength.

power scattered in each reflection, the cross-talk is less than 0.05%; this is due to the fact that the scattering angle from each element is relatively small.

In practice, the input wave may be derived from an array of light emitting diodes or lasers, that emit non-planar wavefronts. In such a case it is necessary to replace the HL, that is adjacent to the input array, with a lenslet array so that the light from each element will be transformed to a diverging cylindrical wavefront inside the substrate. It is also possible to replace the HL, that couples the light out of the substrate, with a holographic lenslet array, so that the output light will focus efficiently onto each element of the detector array. In a typical situation, the operating wavelength differs from that of recording, for example, when the needed operating wavelength is at near infra-red where no holographic recording materials are available. In such a case, it would be necessary to resort to recursive design and recording methods[9] in order to compensate for inherent chromatic aberrations and diffraction efficiency changes.

3 Experiments

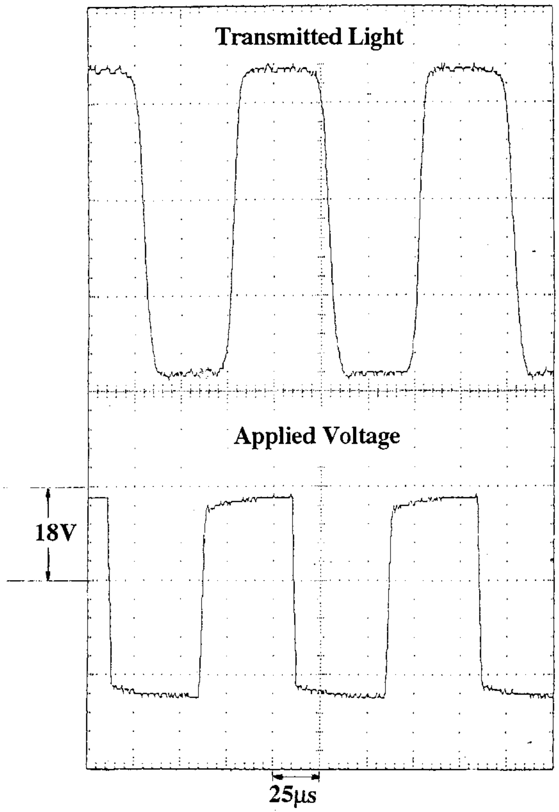
In order to experimentally evaluate our planar crossbar switching configuration, we first recorded two identical planar holographic cylindrical telescopes. The individual cylindrical HLs were recorded according to the arrangement shown in Fig. 3. We used a recording wavelength of 514.5 nm derived from an Argon laser, glass substrate thickness of 7 mm, off-axis angle θ inside the substrate of $\theta = 50°$, and lateral distance between the centers of the cylindrical lenses of about 30 mm. The HLs were recorded on photopolymer materials, Du-Pont HRF-600 10, that were attached to the top and the bottom sides of the glass substrates. Then, we incorporated the LCSLM in between the two planar telescopes. For the experiments, the array of input light sources was simulated with a mask having a linear array of transparent areas that were illuminated with a collimating beam. The light transmitted through the input array was directed towards the output in accordance to how many of the LCSLM pixels were transparent or opaque. The output intensity distribution was detected and monitored with a CCD camera.

We first measured the transmittance in the ON and OFF positions (contrast ratio) and the switching rate for individual pixels of the LCSLM. Representative results are presented in Figs. 4 and 5. Figure 4 shows the measured transmittance at ON and OFF positions, for a single pixel, as a function of the illuminated wavelength. These results indicate the change in transmittance can be as much as 1000 to 1. To determine the switching rates that are possible with each pixel in an LCSLM, we applied an alternating square voltage of ± 40 V, at different frequencies, and monitored the transmitted light. The results for two different frequencies are shown in Fig. 5. Figure 5(a) shows the applied voltage square wave and corresponding transmitted light at a frequency of 10 KHz, and Fig. 5(b) those at a frequency of 40 KHz. These results indicate that as the frequency increases the transmitted light will no longer duplicate the shape of the applied voltage. This is due to the fact that at the higher frequencies only part of the liquid crystal molecules reach a stable state while the others start to rotate back.[18] These results imply that the switching rates are limited, but can handle 40 KHz adequately.

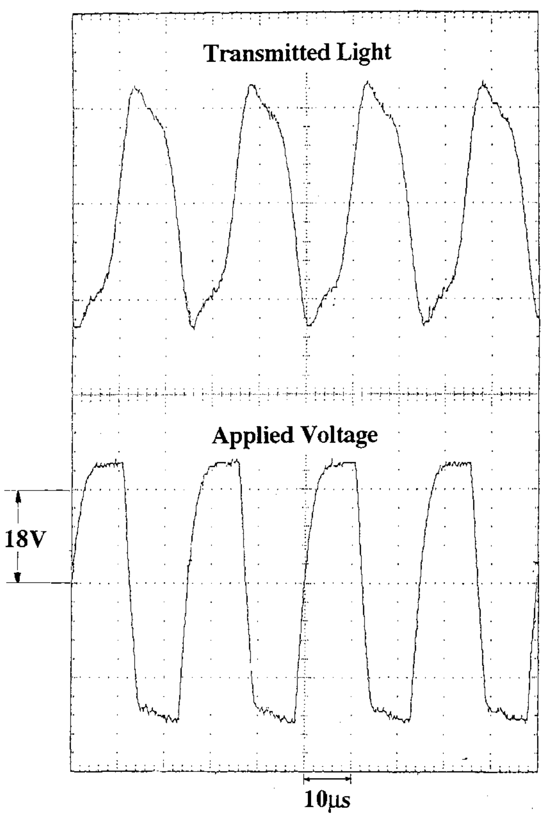
We also measured the cross-talk that would occur between two adjacent elements of the SLM. In the experimental setup, we illuminated a single element of a mask having an array of elements and focused the light from this element by means of the planar cylindrical telescope. The focused output intensity distribution of two adjacent elements (one ON and one OFF) was detected with a CCD camera. The results are shown in Fig. 6. Figure 6(a) shows a photograph of the output intensity distribution, with the dashed line marking the border between adjacent elements. Figure 6(b) shows the corresponding cross section through the maximum intensity line. The measured cross-talk, calculated as the ratio of the total energy in each of the two adjacent elements is 1%, in good agreement with the theoretical value. Since most of the undesired energy originates near the edges, it is possible to reduce the cross-talk by simply placing an aperture (a mask) in the center of each element. With the apertures shown by the white frames in Fig. 6(a), the cross-talk was reduced to 0.06%, which is even lower than the contrast ratio of the actual LCSLM. The maximal cross-talk would occur when all elements of the input mask are ON and only one element is OFF. This cross-talk would be 0.4%.

To illustrate the operation of our dynamic crossbar switch, the input was a linear array of eight light sources, the output a corresponding linear array of eight detectors, and the pixels of the LCSLM were so arranged as to perform a fan-out interconnection. The expected and actual experimental results are presented in Fig. 7. The expected interconnections are shown in Fig. 7(a), and the corresponding experimental intensity distribution is shown in Fig. 7(b). As evident, the correct fan-out of the input light was obtained and there is a good discrimination between the ON and OFF pixels. The differences in the intensities among the elements of the output array are due to nonuniform diffraction efficiencies of the HLs and the differences of light transmittance through different SLM pixels.

The average diffraction efficiency for each HL was only about 70%. This reduction from a theoretical value of 100% is due to shrinkage of the photopolymer recording material during the development process, that changes the local Bragg condition. In addition, the transmittance through the photopolymer material was about 80%, so the diffraction efficiency for each HL was about 55%. Thus,

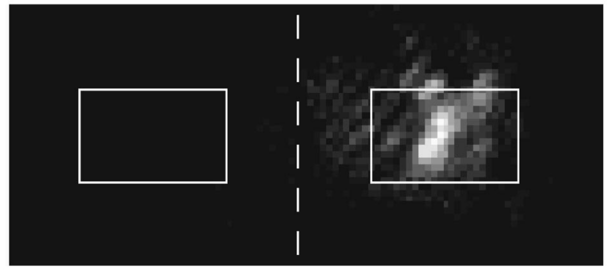


(a)

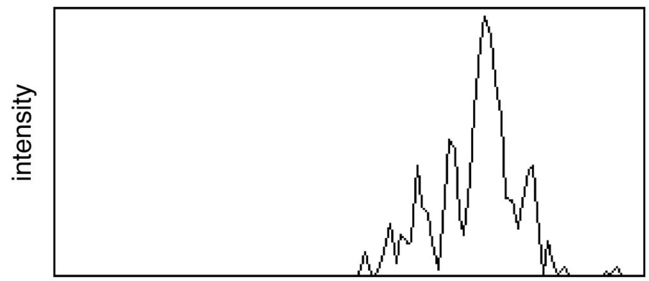


(b)

Fig. 5 The transmitted light through an individual pixel of the LCSLM as a function of applied voltage at different frequencies: (a) 10 kHz, (b) 40 kHz.

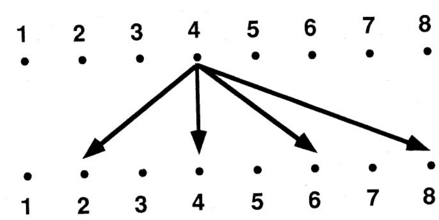


(a)

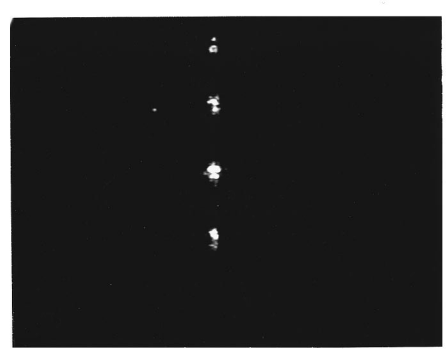


(b)

Fig. 6 Output intensity distribution of two adjacent elements−one ON and one OFF. (a) Intensity distribution, where the dashed line represents the border between two adjacent elements and the white frames represent the reduction of apertures. (b) Cross section at the maximum intensity line.



(a)



(b)

Fig. 7 Experimental results of the planar crossbar switch: (a) the expected fan-out interconnections, (b) the experimental light distributed at the output.

the overall efficiency for the four *HL*s was about 9% and the amount of light that reached every element in the output was about 1% of the input light. The local changes in the Bragg condition cause non-uniformities in output beam that can be observed by the non-uniform output intensity in Fig. 7(b). These problems can be alleviated by using other recording materials, such as dichromated gelatin, which have higher diffraction efficiencies and improved transmittance.

4 Conclusions

We have designed and demonstrated a compact, planar, dynamic and modular optical configuration that can operate as a crossbar switch. The alignment between the planar holographic cylindrical lenses, the one-dimensional array of input light sources, the one-dimensional array of output detectors, and the two-dimensional LCSLM is relatively simple. The cross-talk between different elements of the output arrays is very low and is limited by the contrast ratio of the LCSLM. We believe that it is possible to design and fabricate a LCSLM having equal light transmittance through each pixel and yet retain the high modulation rates. Possible applications for the dynamic crossbar switch could be in dynamic optical signal processing[19] and dynamic optical interconnects.[20] The fan-out interconnections is but one example for our planar crossbar switching configuration. Other interconnection arrangements can readily be implemented with different choice of the pixel distribution in the LCSLM, so as to fit a specific application.

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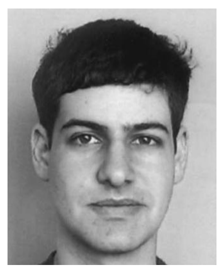

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