Liquid Crystal Spatial Light Phase Modulator and its Applications

Tsutomu Hara

Central Research Laboratory, Hamamatsu Photonics K.K.

5000 Hirakuchi, Hamakita-city 434-8601, Japan

Phone: +81-53-586-7111, E-mail: hara@crl.hpk.co.jp

Abstract

The optically addressed and electrically addressed spatial phase only light modulators without pixelized structures have been developed. A sufficient phase modulation capability and a high diffraction efficiency of these devices are useful for practical applications.

1. Introduction

Two dimensional phase only light modulation has drawn a great deal of interest in applications for optical correlation, optical interconnection, laser processing, adaptive optics and so forth. Therefore a spatial phase only light modulator is highly desired for these applications.

In order to realize a practical device, a nonpixelized, optically addressed, parallel aligned nematic liquid crystal spatial light modulator (PAL-SLM) has been developed [1]. We have obtained a large depth of phase only modulation based on the electro-optical characteristics of a parallel aligned nematic liquid crystal layer.

Moreover, a phase only modulator is required to be controllable by a computer for real time display of computer-created patterns. Therefore a nonpixelized electrically addressable spatial light phase only modulator has been developed [2,3]. The device consists of the PAL-SLM, coupling optics, an XGA liquid crystal display (LCD) which serves as an accurate addressable mask for the PAL-SLM, a laser diode (LD) for illuminating the LCD and collimating optics for the LD.

2. PAL-SLM

The PAL-SLM has a sandwich structure consisting of an undoped hydrogenated amorphous silicon (a-Si:H) photoconductive layer used for addressing, a dielectric mirror, and a parallel aligned nematic liquid crystal layer for modulating between the two transparent conductive electrodes (ITO)• as shown in Fig.1. By illuminating the a-Si:H layer with write-in light, voltage is supplied to the liquid crystal layer. This causes the liquid crystal molecules to tilt and readout light is modulated corresponding to the write-in light information.

The phase shift of over 2π radians (680nm) can be accomplished with write-in light intensity of 200• • W/cm^2 (680nm) when the applied voltage is 3.0V, in the case of the readout laser light polarized parallel to the molecular axis of the liquid crystal. The response time was measured to be 30msec, when the phase modulation depth was π radians.

Figure 2 shows the diffraction efficiency of the device in which a sinusoidal grating was written. At low spatial frequencies (<5 line pairs/mm), the diffraction efficiency was 31%, which was very close to the theoretical maximum of Raman-Nath diffraction(33.9%).

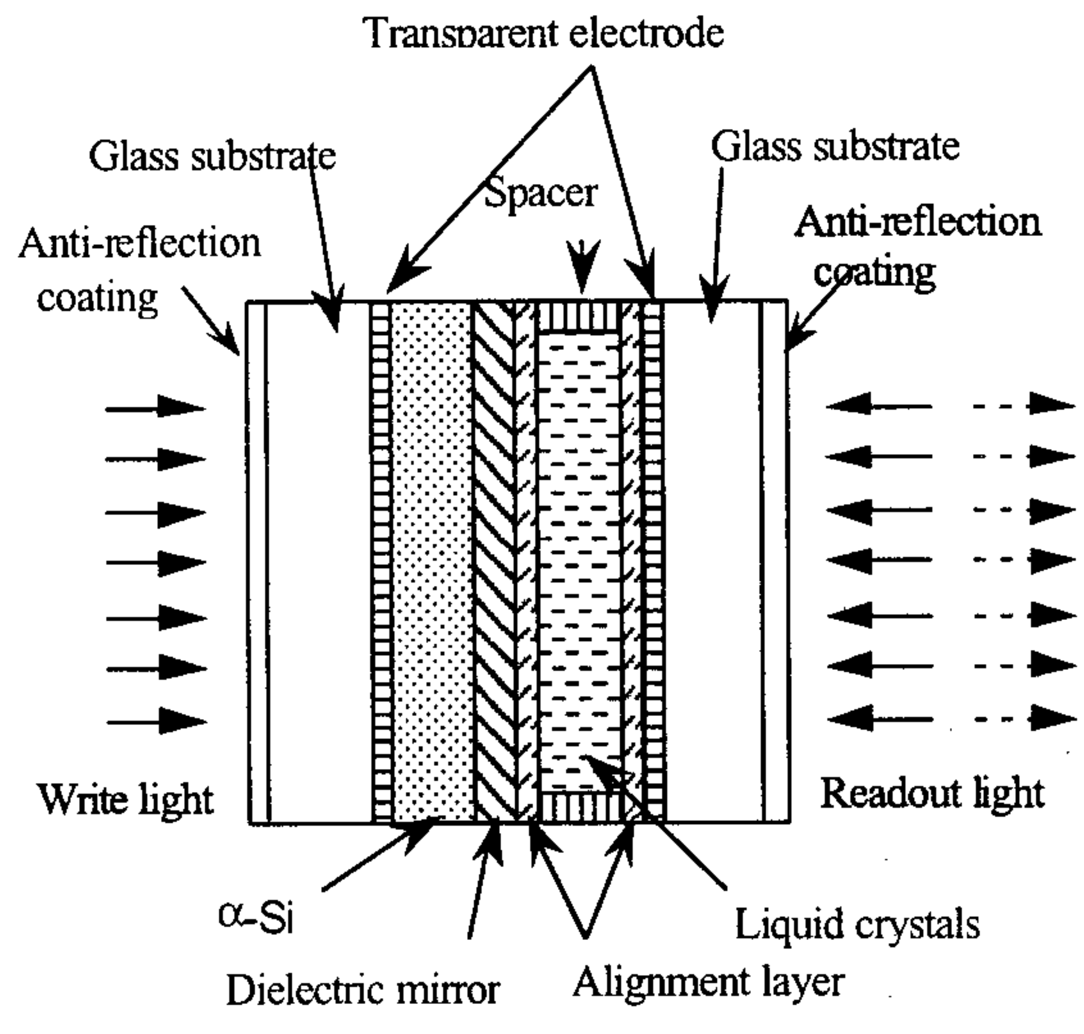


Figure 1 Structure of PAL-SLM.

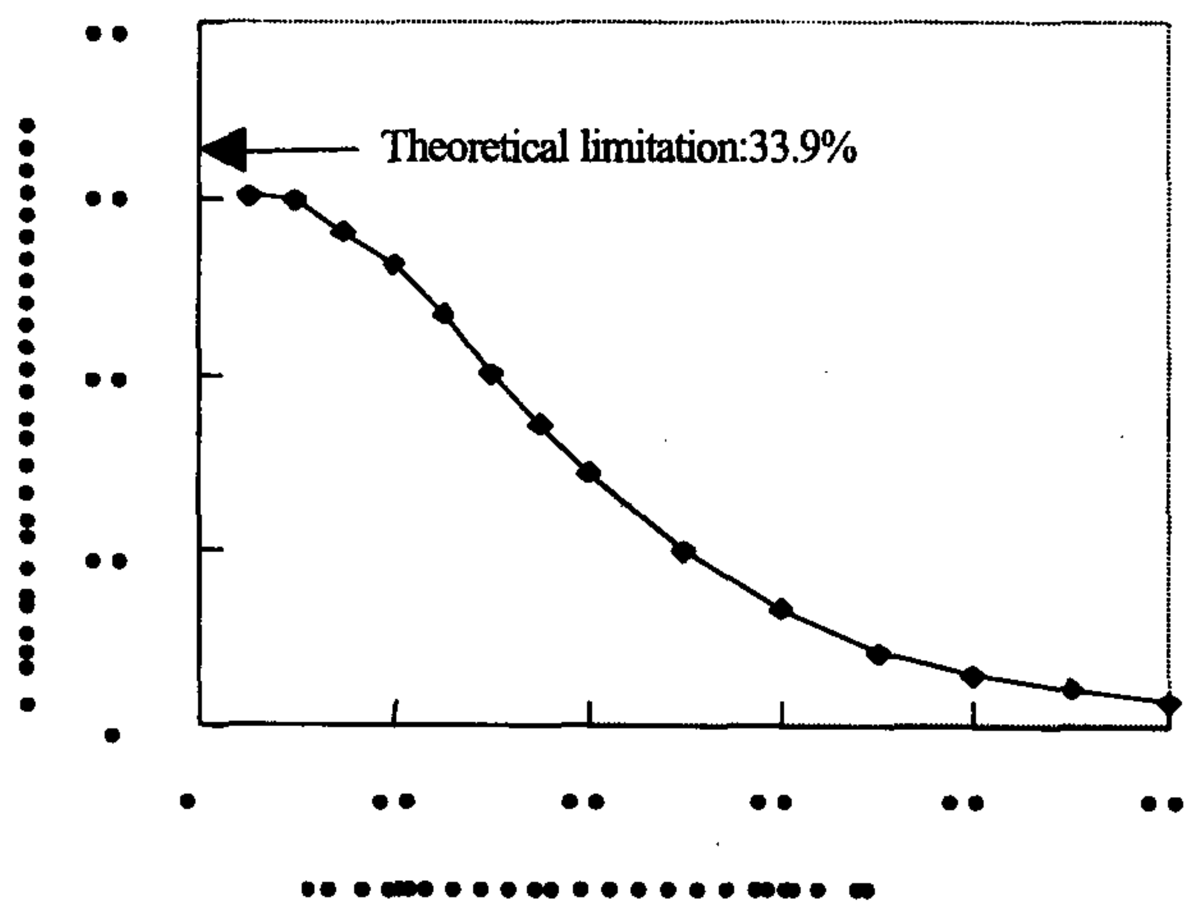
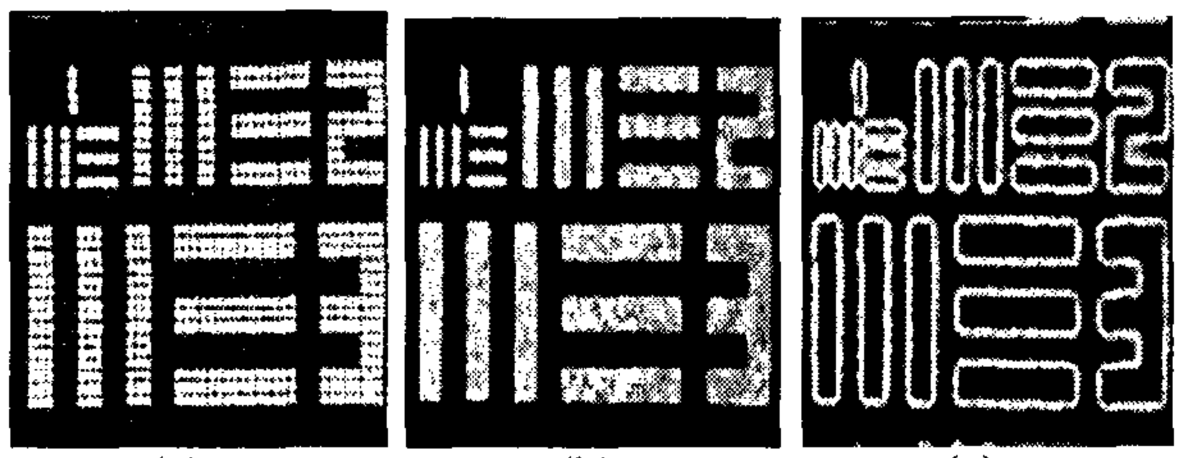


Figure 2 Diffraction efficiency of PAL-SLM.



(a) (b) (c)

Figure 3 Readout images. (a)An output image of the LCD alone. (b)An output image of the module at π radian phase modulation. (c) An output image of the module at 2π radian phase modulation.

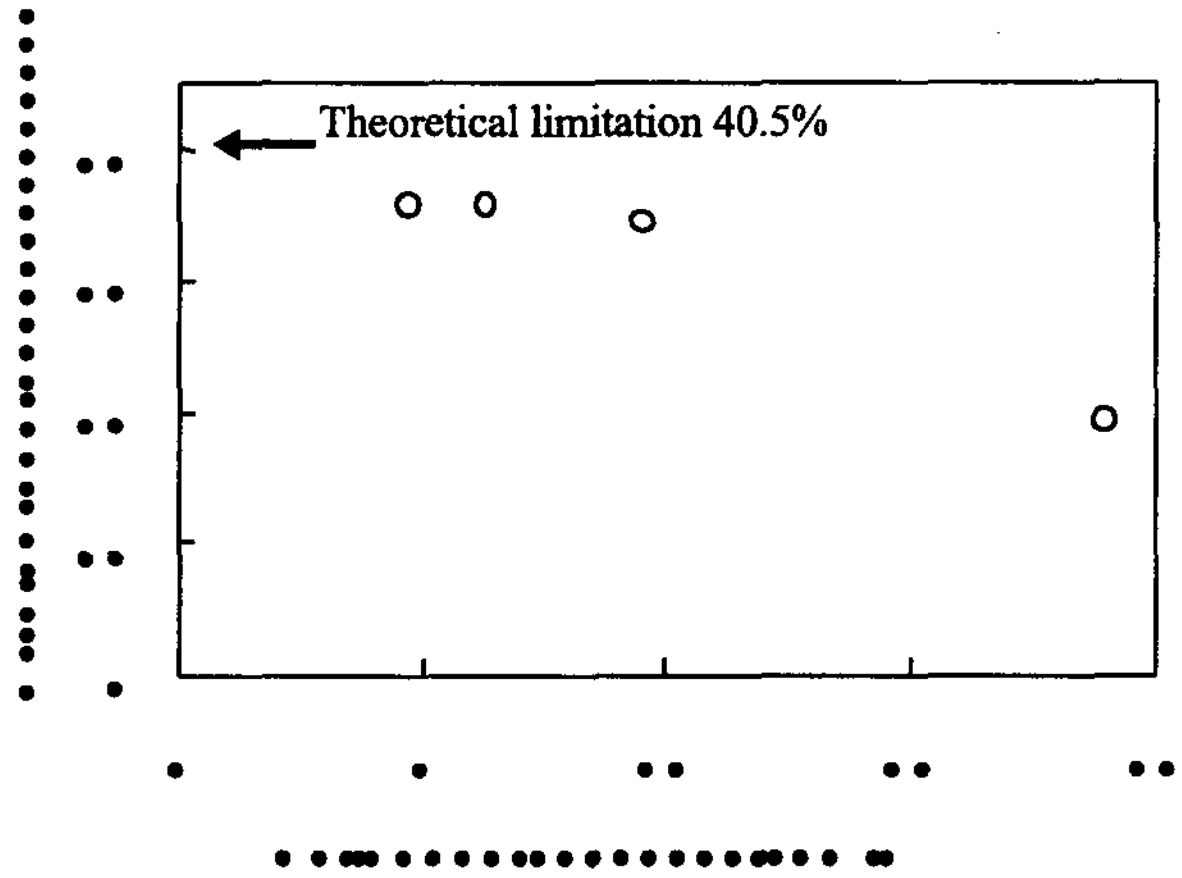


Figure 4 Diffraction efficiency from binary grating of the module.

3. LCD coupled PAL-SLM module

The XGA-LCD and the PAL-SLM were coupled by a set of lens for 1:1 imaging. We designed a new set of lenses so as not to transfer the pixel structure of the LCD as shown in Fig.3. Therefore a surplus diffraction light (diffraction noise) caused by the pixelized structure was reduced to less than 3% by the coupling optics, comparing with almost 50% occurring in the LCD alone.

The transfer characteristic was measured. Uniform patterns of each gray level were displayed on the LCD and the amount of the phase modulation of the PAL-SLM was measured as a function of the gray level. The relation between the phase modulation and the gray level was almost linear and more than 2π radian modulation was achieved.

Diffraction efficiency of the device was also measured as shown in Fig.4. The device has a high diffraction efficiency of greater than 35% at the spatial frequency of 10 lp/mm of binary (0, π) grating. Also when a multilevel (0, 0.5π, π, 1.5π) grating was written in the device, a diffraction efficiency of greater than 70% at the spatial frequency of 10 lp/mm was obtained.

4. Optical Computing

We have designed and constructed a compact Joint Transform Correlator (JTC) system[4,5] as shown in Fig.5. It consists of a liquid crystal display (LCD) to display the input image, two Fourier transforming lenses, a PAL-SLM in the joint Fourier transform plane, a CCD camera to detect the correlation signal, and a laser diode(LD) as readout light source. The parallelism of optical processing enables the system to provide a correlation signal in less than 0.1 seconds in the case the input image is 512×512×8 bits. For the first step, we have applied the correlator to fingerprint identification.

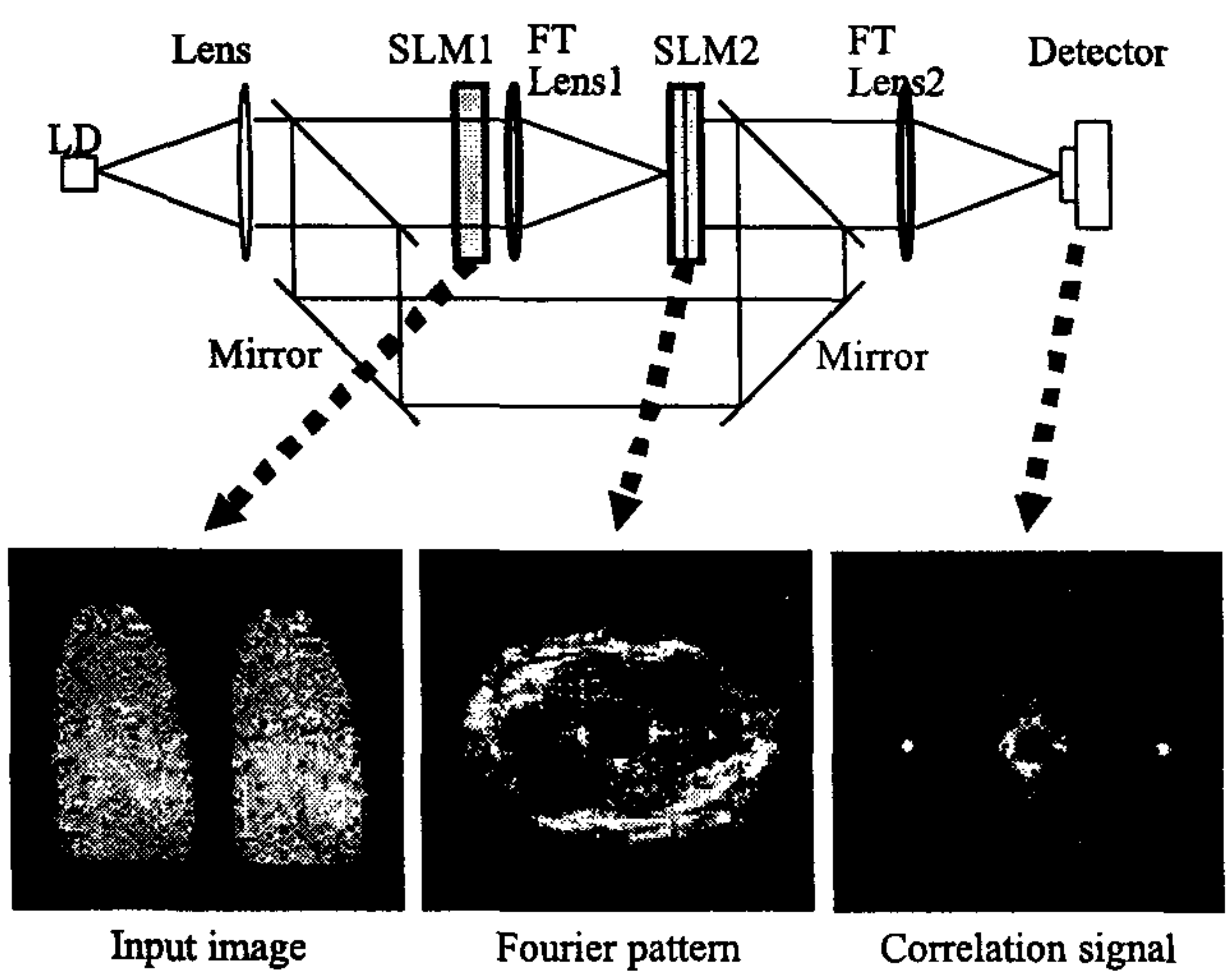


Figure 5 JTC system for fingerprint identification.

5. Optical interconnection

We have realized a reconfigurable free space optical interconnection module[6] that connects LSI chips with parallel optical input and output channels. Figure 6 shows the principle of the system. The interconnection topology is reconfigurable by modifying a computer generated hologram (CGH) written on a PAL-SLM, and located at the Fourier plane of the module. The appropriate interconnection topology can therefore be built to meet the requirements of a given application. For example, a light from an LD on LSI chip can be transmitted to several photo diodes(PDs) simultaneously.

6. Optical waveform shaping

Figure 7 shows the experimental results of laser waveform shaping. In this application a computer generated hologram (CGH) is designed with a computer and is written in the SLM. The readout light is modulated in the SLM as designed. A Gausian shaped beam from a laser can be changed to a circular shaped beam, a rectangular shaped beam, a star shaped beam etc. without energy loss. This technology can be applied to a laser processing system, a laser printing system and so on.

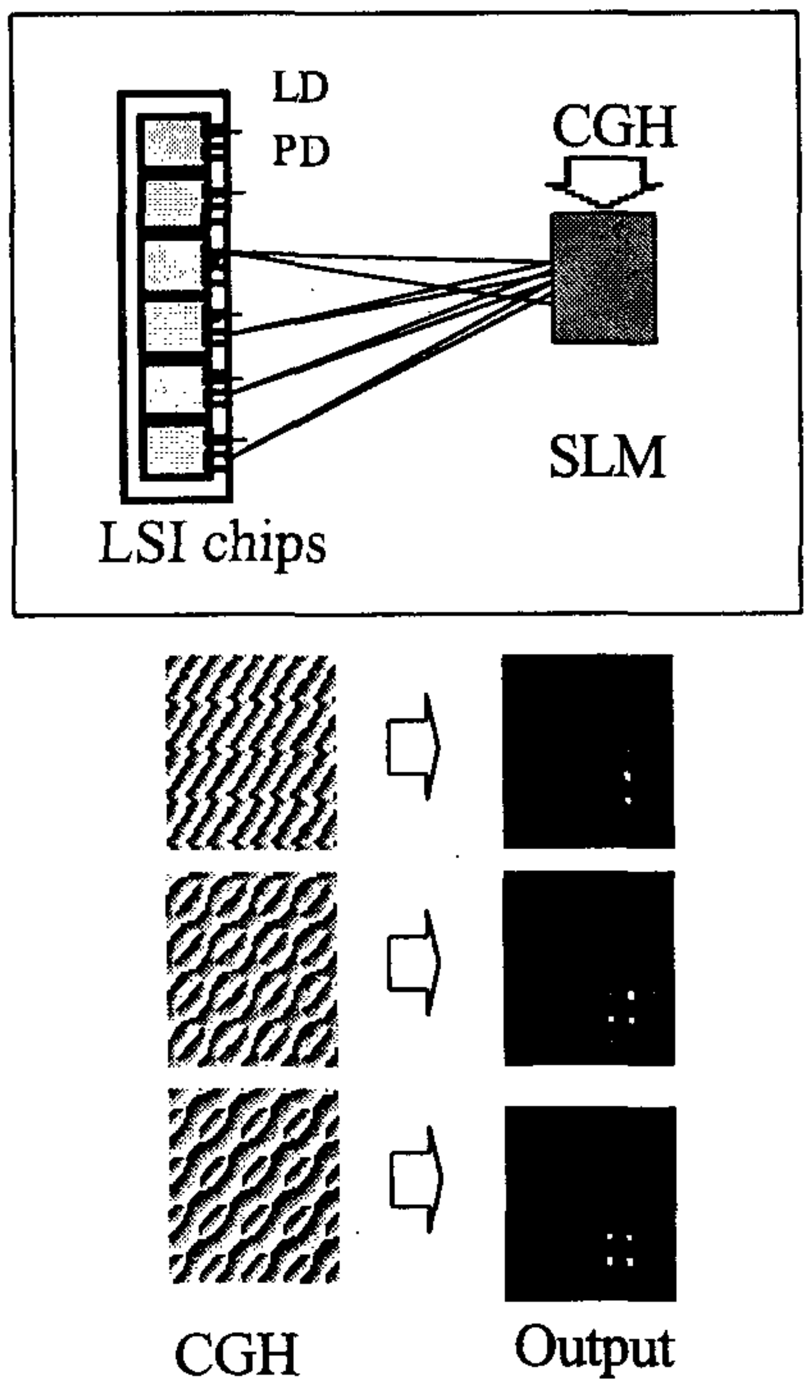


Figure 6 Reconfigurable optical interconnection.

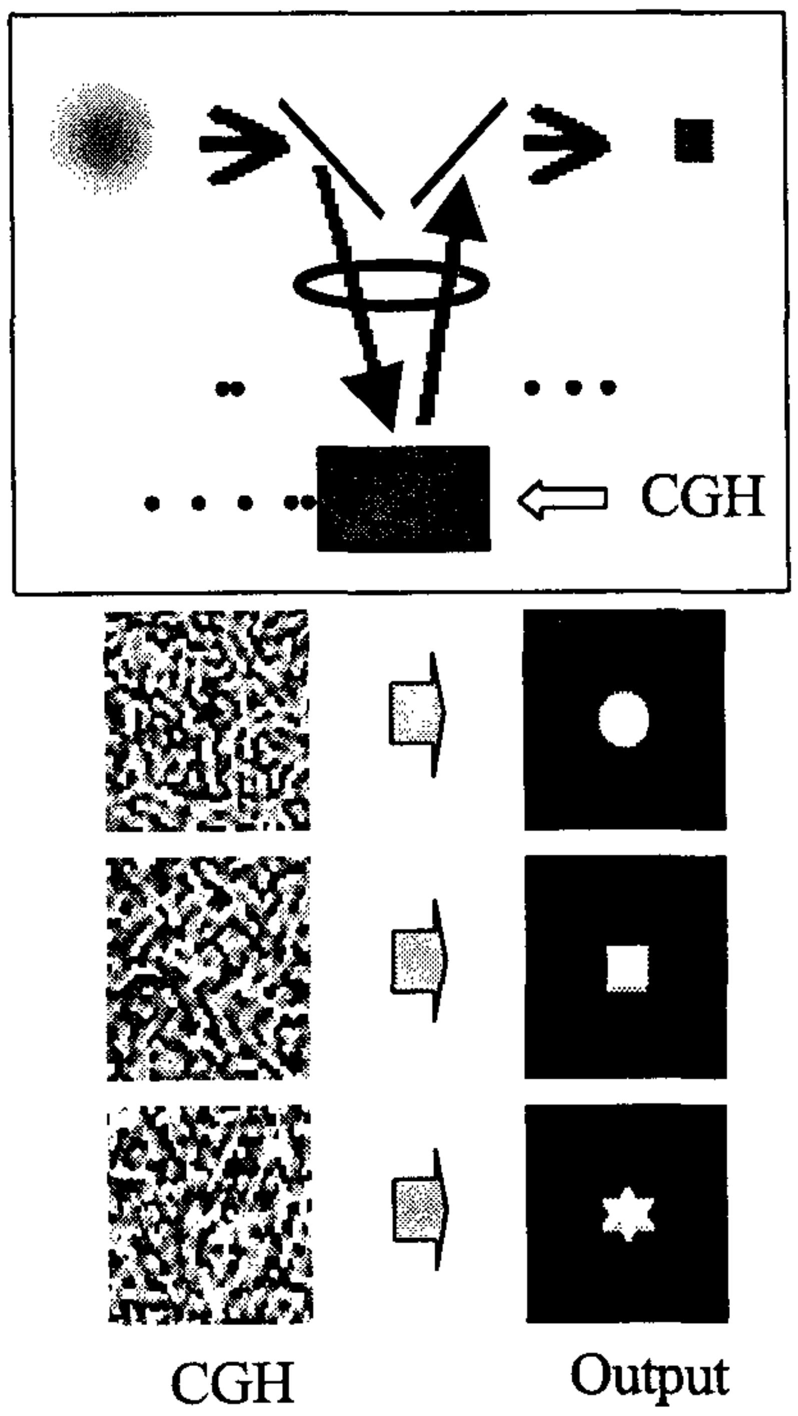


Figure 7 Laser waveform shaping.

7. Optical wavefront compensation

Figure 8 shows the experimental system for a wave-front compensation. Distorted optical wave cannot be focused at a focal plane of a lens. By detecting the distortion with an interferometer and operating the PAL-SLM by the signal from the interferometer, the optical wave front is corrected and can be focused as shown in the photograph in Fig.8. This technique[7] can be applied to laser processing, a telescope[8], and vision science[9] such as ophthalmology and so on.

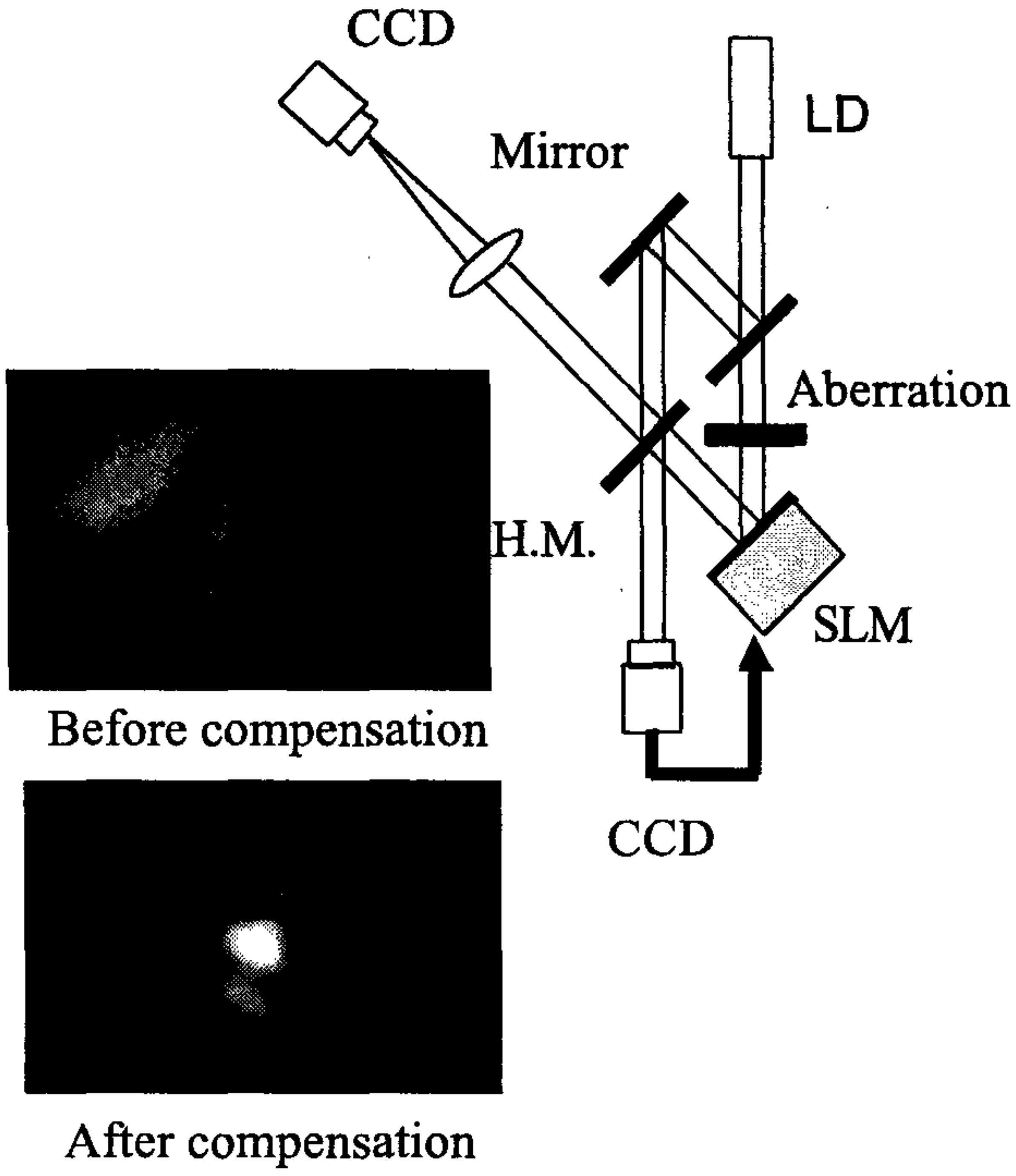


Figure 8 Optical wavefront compensation.

8. Conclusion

The optically addressed and electrically addressed spatial phase only light modulators without pixelized structures have been developed. These devices have a sufficient phase modulation capability and a high diffraction efficiency. We have demonstrated that these characteristics are useful for several applications where a two-dimensional optical phase control is required. These continuous efforts will bring us to realization of practical applications.

9. References

[1] N.Mukohzaka, N.Yoshida, H.Toyoda, Y.Kobayashi, and T.Hara, "Diffraction efficiency analysis of a parallel-aligned nematic-liquid-crystal spatial light modulator," Appl.Opt., **33**, (14), p.2804 (1994).

[2] Y.Igasaki, F.Li, N.Yoshida, H.Toyoda, T.Inoue, N.Mukohzaka, Y.Kobayashi, and T.Hara, "High Efficiency Electrically-Addressable Phase-Only Spatial Light Modulator," Opt.Rev.,**6**, p.339 (1999).

[3] T.Hara, N.Fukuchi, Y.Kobayashi, N.Yoshida, Y.Igasaki, and M.H.Wu, "Electrically-addressed spatial light phase modulator," Proc.SPIE, **4470**, p.114 (2001).

[4] Y.Kobayashi, H.Toyoda, N.Mukohzaka, N.Yoshida, and T.Hara, "Fingerprint Identification by an Optical Joint Transform Correlation System," Opt.Rev., **3**, p.403 (1996).

[5] H.Toyoda, Y.Kobayashi, N.Mukohzaka, T.Hara, and T.Ohno, "Frame-Rate Displacement Measurement System Utilizing an Ultra-High-Speed Shutter Camera and an Optical Correlator," IEEE Trans. Instrumentation and Measurement, **44**, p.755 (1995).

[6] H.Toyoda, Y.Kobayashi, N.Yoshida, Y,Igasaki, T.Hara, and M.Ishikawa, "High efficient electrically-addressable spatial light modulator for reconfigurable optical interconnection," OSA Snowmass Meeting, SLM'99 technical digest, SMB3(1999).

[7] T.Shirai, T.H.Barnes, and T.G.Haskell, "Adaptive wave-front correction by means of all-optical feedback interferometry," Opt. Lett., **25**, p.773 (2000).

[8] M.T.Gruneisen, T.Martinez, D.V.Wick, J.M.Wilkes, J.T.Baker, and I.Percheron, "Holographic Compensation of Severe Dynamic Aberrations in Membrane-Mirror Based Telescope Systems," Proc.SPIE, **3760**, p.142 (1999).

[9] J.Liang, D.R.Williams, and D.T.Miller, "Supernormal vision and high-resolution retinal imaging through adaptive optics," J. Opt. Soc. Am., **A14**, p.2884 (1997).