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자유공간 광학계를 소규모로 집적하기 위한
마이크로광학 기술개발과 광교환용
평면광학계 구현

Microoptics technology and planar optical integration of
free-space optical switching systems



한국전자통신연구원

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광교환 및 광정보처리를 위한 3차원 자유공간 광학계의 장점인 초고속, 대용량 병렬 정보처리 능력은 널리 알려져 있으나, 지금까지는 자유공간 광학계의 큰 규모와 시스템 구성의 어려움 및 정렬상태의 불안정 등, 실제시스템으로 구현되기까지는 많은 어려움이 있는 것으로 알려왔습니다.

이 보고서는 자유공간 광학계의 이러한 어려움을 극복하기 위한 연구에 관한 것으로서, 마이크로 광신호연결의 한계연결효율을 추출하고, 이를 토대로 광교환용 평면집적 광학계의 3차원 연결구도제안 및 연결용량을 분석하는데 중점을 두고 있습니다. 마이크로 광학부품을 광학수차 없이 제작하기 위한 장치제작과, 마이크로 렌즈어레이의 광학적 성능분석용 장치 등이 연구결과로서 얻어졌으며, 새로운 광교환용 병렬연결구도의 제안 및 분석도 중요한 연구결과라 하겠습니다.

여기에 기술된 연구결과가 많은 사람들에게 유익하게 사용될 수 있기를 기대하며, 끝으로, 기초기술연구를 선도하고 있는 기초기술부연구부장 이일항 박사 및 연구에 참여한 연구진의 노고와, 연구재정을 지원해 주신 한국통신 및 관계부처 여러분들에게 심심한 사의를 표합니다.

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한국전자통신연구소장 양 승 택

제 출 문

본 연구보고서는 기초연구과제인 “자유공간 광학계를 소규모로 집적하기 위한 마이크로광학 기술개발과 광교환용 평면광학계구현”의 1차년도 연구결과로서, 본 과제에 참여한 아래의 연구팀이 작성한 것입니다.

사업책임자 : 책임연구원 이 일 항 (기초기술연구부)
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요 약 문

I. 제 목

자유공간 광학계를 소규모로 집적하기 위한 마이크로광학 기술개발과 광교환용 평면광학계 구현

II. 연구의 목적 및 중요성

본 과제에서는 지금까지 제안되어 왔던 광스위칭 네트워크 용 자유공간 광학계(free-space photonic switching network system)를 한장의 광학기판에 집적하기위한 마이크로 광신호 연결기술 개발과, 이를 기반으로 한 평면광학적 연결구도(planar optical interconnection schemes)창출을 목적으로 한다.

이러한 연구는 자유공간 광학시스템의 단점을 극복하기 위해서는 전체 시스템의 크기를 OEIC와 유사한 wafer 규모로 하나의 광학기판 (유리, 실리콘, GaAs 등)에 집적하여, 기존의 광 교환소자 혹은 OEIC와 동일한 규모로 구성할 수 있어야만이 실용화가 가능하므로, 광교환 시스템, 혹은 병렬광신호처리계를 위한 중요한 기초기술이라 할 수 있다.

Ⅲ. 연구내용 및 범위

연구내용은 크게 두가지로 분리할 수 있는데, 첫째는 마이크로 렌즈 어레이, 마이크로 프리즘 어레이, CGH(computer-generated hologram)등을 제작하기 위한 laser direct writing (LDW)장치의 구성이며, 둘째는 3차원 crossover 및 perfect shuffle 등의 다단계연결망(multiple-stage interconnection networks) 구조를 갖는 평면광학계(planar optics)의 고안 및 성능분석(performance analysis)이다.

연구범위로는, 마이크로 광학부품을 제작하기 위한 laser direct writing 장치를 구성(mm 정도의 resolution 1mm writing diameter), 이 장치를 이용한 마이크로 광학부품 (렌즈어레이, 프리즘, grating) 제작 및 광학적 특성평가, 그리고, 3차원 MIN 연결망인 crossover 및 perfect shuffle interconnection의 광 신호연결 용량 추출 등이다.

Ⅳ. 연구결과 및 활용방안

주요 연구 결과로는

- . Laser writing 장치 제작완료.
- . 마이크로 렌즈등의 핵심부품 어레이 제작.
- . 마이크로 광학부품의 성능평가 위한 이론 및 프로그램 완성.
- . Perfect shuffle 광연결용 planar optics 제안 및 연결용량 추출.
- . Crossover 광연결용 planar optics 제안 및 연결용량 추출.

이러한 연구결과의 활용방향으로는,

- 마이크로 광학부품의 제작기술 확보로 일반적인 마크로 광학부품을 사용하는 광학계를 마이크로 광학부품으로 대체할 수 있기 때문에, 수 μm 이하의 정확도를 갖고 광학 시스템을 구성할 수 있다.
- 또한, 평면광학계(planar optics)를 이용한 광스위칭 네트워크 구현기술은 시스템의 정렬(alignment) 안정성과 OEIC와 직접 접속될 수 있는 규모로 광연결시스템(optical interconnection system)을 구현할 수 있게 되어, 광 신호접속 뿐만아니라 광교환용 다단계 연결망 구조를 갖는 광 스위칭 네트워크의 실용화 가능성을 높여줌.
- 따라서, 현재 자유공간 광학계가 갖고 있는 최대단점인 큰 규모와 정렬의 불안정성이 해결될 수 있으므로, 광통신 및 병렬 정보처리 프로세서 개발에 주는 파급효과가 큼.

ABSTRACT

I. Title

Microoptics technology and planar optical integration of free-space optical switching systems

II. The objectives

The objective of this project is to investigate novel ways to implement microoptical interconnections for photonic switching. The purpose of this year project is to evaluate planar optical interconnects with space-division switching configurations, and to develop a laser writing system for the fabrication of microoptical components, such as microlenses, Fresnel lenses, microprisms, and so on.

III. Results

As the results in this year, there are two main results of the laser writing system and the planar optical schemes for switchings. The laser writing system has been set up with the fabrication accuracy of laterally less than $1\mu\text{m}$ and vertically less than 0.1λ . Several types of microoptics of spherical and toric lenses, diffractive gratings, and a special microlens array for perfect shuffle interconnects, have been fabricated and evaluated. Two types of space-division switching nets, perfect shuffling and crossovers, have been implemented, and investigated their performances with some preliminary experimental results.

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제 1 장 서 론

제 1 장 서 론

통신용 교환망 및 병렬프로세서등에 이용되는 스위칭 네트워크는 주로 균일한 구조를 갖는 다단계 연결망(multi-stage interconnection networks : MIN)인 crossover, perfect shuffle Banyan등의 여러가지 공간분할 방식의 구조가 널리 연구되고 있다. 이는 MIN의 switching node가 갖는 간단한 기능 (2 input-2 output), 확장성(extendibility), 그리고 높은 공간대역폭 (spatial bandwidth) 등의 특성 때문이다. 이러한 특성은 일반적으로 쓰이는 광학부품(렌즈, 거울, 프리즘, beam, splitter, waveguide 등)을 이용하여 MIN을 구현하는 것을 가능하게 해주며, 특히 2차원 배열의 신호를 공간적으로 전달할 수 있는 자유공간 광학계를 이용함으로써, 신호전달 및 병렬신호 처리능력을 극대화 시킬 수 있다. 즉, 자유공간 광학계를 이용한 3차원 광교환 스위칭네트워크 구현이 가능하게 된다.

그러나, 자유공간 광 스위칭 시스템은 광소자간의 정렬 (alignment) 및 이미 정렬된 상태의 유지가 매우 어려워 전체적으로 시스템의 견고성이 부족하며, bulk한 광학소자를 사용하기 때문에 시스템의 규모가 크다는 단점을 갖고 있다. 또한 기존의 광통신용 OEIC(opto-electronic integrated circuit) 등과의 접속 (interface)도 서로 상이한 규모때문에 큰 효율성이 없는 등, 자유공간 광 스위칭 시스템의 큰 장점들(3차원 정보전달 $\sim 10^6$ 입력수/mm²의 공간 대역폭, 낮은 신호 간섭성, 전달매체의 불필요성 등)에도 불구하고, 그 실용화 가능성이 의문시 되고 있다.

따라서, 위와 같은 자유공간 광 스위칭 시스템의 단점을 극복하기 위해서는 전체 시스템의 크기를 축소시킬 수 있도록 광학소자들을 μm 단위로 제작할 수 있는, 마이크로 광학 (micro-optics) 기술이 필요하다. 그리고, 전체 시스템의 크기를 OEIC와 유사한 wafer 규모로 하나의 광학기판 (유리, 실리콘, GaAs등)에 집적하여, 기존의 광 교환소자 혹은 OEIC와 동일한 규모로 구성할 수 있어야만이 실용화가 가능하다. 즉, 그림 1에 도시된 바와 같이 3차원 자유공간 광학계를 한장의 광학기판에 그대로 집적하는 평면광학계 (planar optics)구성기술은 광교환 시스템을 위한 하나의 핵심기반기술이라 할 수 있다.

본 연구는 마이크로 광학부품을 제작할 수 있는 장치 및 제작기술을 확보하고, 이를 바탕으로 3차원 자유공간 광학계의 장점인 높은 공간 대역폭, 병렬 신호처리능력등을 최대로 유지하며, 자유공간 광학계의 단점인 정렬 불안정성 및 큰 규모등을 해결하기 위해, 한장의 광학기판에 시스템을 집적하는 평면광학(planar optics) 기술개발과, 균일한 MIN구조를 갖는 광스위칭 네트워크를 구현하기위한 평면 광스위칭 시스템의 제안 및 이들에 기반이 되는 planar optical interconnection에 대한 실험결과를 보였다.

제 2 장에서 MIN중의 하나인 퍼펙트셔플을 위한 평면 광연결구도에 관한 제안 및 실험결과를 보였으며, 제 3 장에서는 제 2 장의 퍼펙트셔플과 동일한 기능을 갖는 크로스오버 연결을 위한 평면 광연결구도에 관하여 논하였다. 제 4 장은 laser writing system에 관한 것으로서, 마이크로 광연결용 광학계, 특히 앞서 설명된 평면광학계에 필요한 마이크로 광학부품등을 정밀하게 제작하기 위한 장치이다.

제 2 장 퍼펙트셔플 연결망을 갖는 광고환용 평면광학계

제 2 장 퍼펙트셔플 연결망을 갖는 광고환용 평면광학계

MIN(multiple-stage interconnection network) 연결방식중의 하나인 perfect shuffle network 은 통신 뿐만아니라 병렬 컴퓨팅을 위한 프로세싱 알고리즘으로서도 이론적으로 제안되어 왔으며[5], crossover network을 이용한 입력 신호간의 sorting 알고리즘등도 널리 연구되고 있다[6]. 또한, 이들을 3차원 MIN구조로 확장함으로써 보다 큰 신호전달 및 처리능력을 얻을 수 있다 [7]. 그러나, 3차원 MIN은 전자회로적으로는 전기배선에 의한 연결망 구성이 매우 어렵기 때문에 광학적 구현연구가 매우 중요하다고 할 수 있다.

그리고, 3차원 perfect shuffle MIN은 multiple imaging이 가능한 CGH(computer-generated hologram), 혹은 여러개의 렌즈를 적절히 배치함으로써 평면광학계로의 구현이 가능하다[9]. 특히 CGH의 사용은 다음과 같은 장점을 갖고 있다. 즉, 여러개의 렌즈를 이용하는 방식에 비해 입력광신호의 채널크기를 절반이하로 줄어 공간대역폭을 늘릴 수 있으며, 렌즈수차등의 잡음효과 및 제작과정에서 오는 오류 등이 감소되고, 다른 마이크로 광학부품들과 동일한 lithography 과정으로 만들 수 있는 등 제작이 간편하다. 또한, CGH의 이용은 기타 다른 구조의 MIN이나 광정보처리계등을 위한 평면광학계의 실현도 가능하게 해줄 수 있다.

그림 2-1은 8개의 입력신호를 8개의 출력채널로 연결하는 1차원 perfect shuffle interconnection network의 개략도이다. 각 switching node stage 마다 4개의 switching node들이 있으며, switching node는 bypass-exchange기능을 갖고 있다. 따라서, 임의의 입력신호는 출력단인 마지막 node stage의 임의의 switching node들로 연결될 수 있다.

이러한 1차원 perfect shuffle 망을 2차원으로 확장하면 그림 2-2와는 배열로 된다. 각 4분면에 있는 채널들은 골고루 섞여 서로서로 이웃하여 변환되는데, 이러한 연결망은 3차원 공간을 이용하는 자유공간 광학계로써 구성될 수 있다.

1-D PERFECT SHUFFLE NETWORK (N=8)

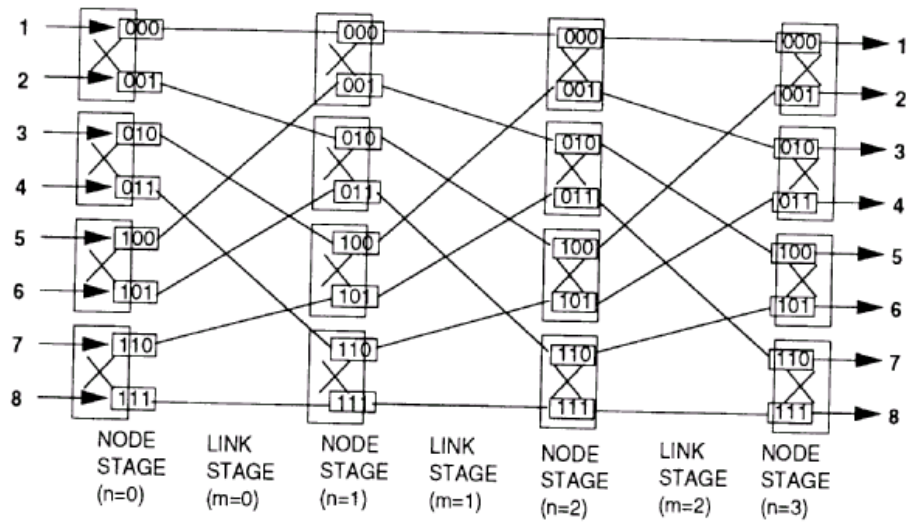


그림 2-1. 1차원 퍼펙트 셔플 연결망.

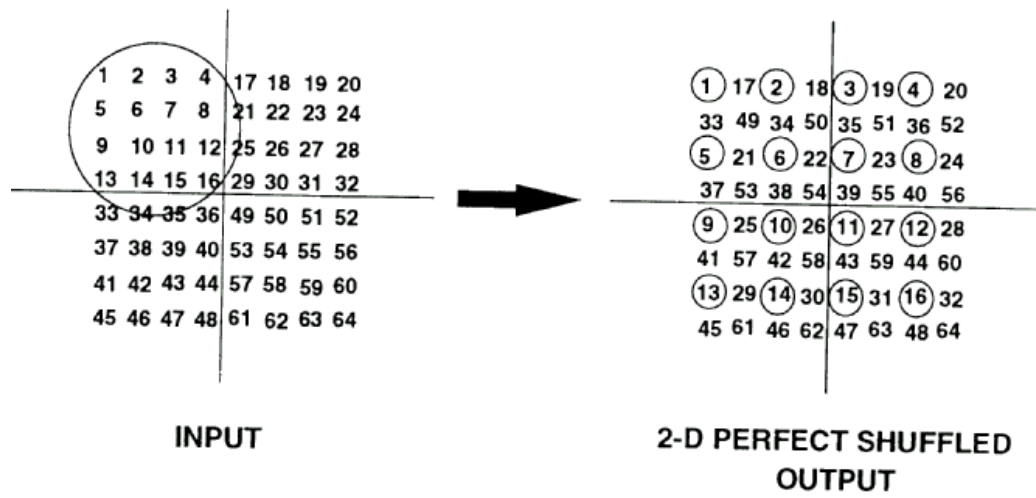


그림 2-2. 2차원 퍼펙트 셔플링의 설명도.

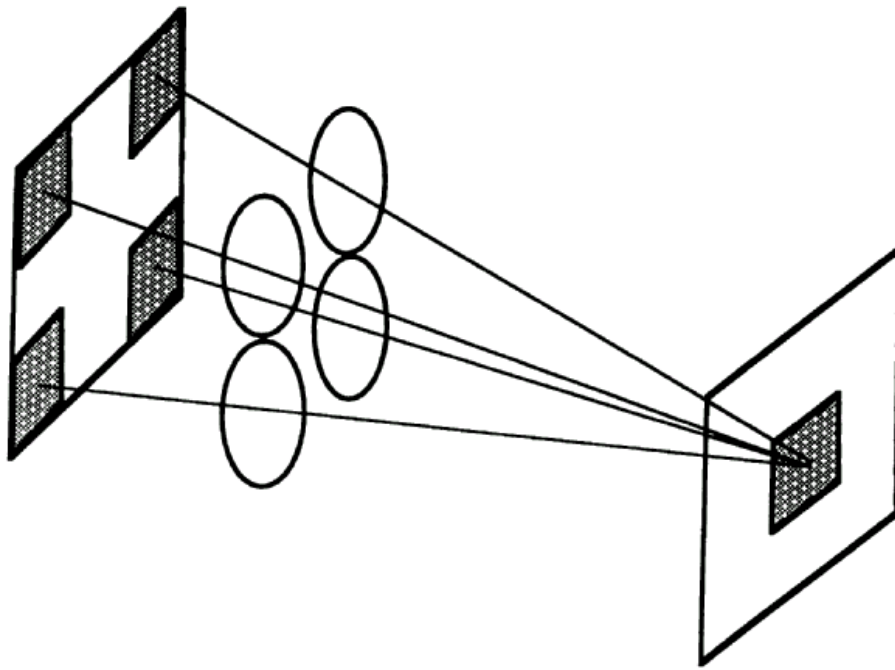


그림 2-3. 2차원 퍼펙트 서플링을 위한 광학계.

그림 2-3에 4개의 렌즈어레이를 사용한 3차원 perfect shuffling의 개략도가 도시되어있다. 각 4분면에 있는 신호배열들은 하나의 렌즈에 의해 출력단의 가운데로 전달되어, 결국 골고루 섞인 결과가 된다.

그런데, 그림 2-3과 같이 4개의 렌즈어레이를 사용하는 자유공간 광학계의 경우, 렌즈간의 정확한 정렬, 입출력단과 렌즈들간의 정확한 위치정렬등에 매우 많은 시간과 노력을 필요로 한다. 따라서, 이러한 문제점을 극복하기 위해서는 평면광학계로의 구현이 필요하다. 즉, 한 장의 광학기판에 모든 광학부품을 동일 제작과정으로 만들어, 각 부품간의 정렬을 lithography 기술이 갖는 $1\mu\text{m}$ 이하의 정확도로 이룩할 수 있게된다.

[부록 2-1]에 이와 같은 planar optics를 이용한 perfect shuffle interconnects에 관하여, 기본 개념 및 구성방식, 그리고, 실험결과등에 관하여 논의되어 있다. 4개의 독립적인 렌즈를 사용하는 경우에 비해, 4개의 렌즈 역할을 하는 1개의 CGH(computer-generated hologram)를 사용하였는데, 이러한 구도가 갖는 planar optics의 장단점도 논의되어 있다.

[부록 2-2]는 perfect shuffling 용 CGH 렌즈어레이의 광학수차(optical aberration)를 분석하고, 이를 토대로 planar optical perfect shuffle interconnector가 갖는 연결용량이 도출되어 있다.

부록 2-1

Optical perfect shuffle interconnection using a computer-generated hologram

[Applied Optics,,Vol.32, No.26, 5022(1993)]

[부록 2-1]

Optical perfect shuffle interconnection using a computer-generated hologram

Abstract

We propose using a computer-generated hologram that combines a fanout and focusing element can be used to perform an optical perfect shuffle interconnection. The hologram is designed by calculating the interference fringes between diverging waves from four point sources and a reference plane wave. With this element, we have shown experimentally the resulting perfect shuffle pattern. The use of the computer-generated hologram makes it easy to implement a planar optical perfect shuffle interconnect, which is compact, has low aberrations, and is easy to align. The planar optics configuration for a perfect shuffle interconnection network is also discussed.

I. Introduction

The perfect shuffle network is one of the regular multiple-stage interconnection networks with wide applications for telecommunications and parallel computing processors.^[1] The implementation of the perfect shuffle interconnections has been achieved by the use of the free-space optics so far.^[2-6] Conventionally, these approaches have relied on the alignment of discrete optical components, such as lenses and prisms, together in a system and have performed 1-D and 2-D perfect shuffle operations, which are defined by the array format of the input signals. The 2-D perfect shuffle has been implemented by the free-space optics using a set of four lenses^[5,6], so that the input data is separated into four quadrants, each quadrant is magnified to the original size and shifted for interlacing, and then the quadrants are recombined into a single image. Recently, an approach for implementing the perfect shuffle operation with four sub-holographic lenses was also proposed^[7], where the four holograms are used as the four lenses.

In this paper, we propose an optical implementation of a 2-D perfect shuffle using a single interferogram-type binary CGH, and its planar optical configuration. The CGH which combines imaging and fanout, is designed as an interferogram, calculated from the interference between diverging waves from four point sources and a reference plane wave. This CGH is the superposition of the four interference fringes, so that it generates four focal spots in the presence of a plane incident light. Therefore, the CGH can replace the four discrete lenses of the systems mentioned to implement the perfect shuffle. Simple preliminary experimental results are also presented for the case of the folded perfect-shuffle interconnections^[6].

II. Computer-generated hologram

The main features and some of the advantages of this CGH approach are discussed. Primarily, it offers the potential to implement a perfect shuffle network with larger spatial bandwidth, which is defined as the number of channels to be integrated in a given I/O plane. Since the whole area of the CGH acts as the lens aperture, the resolving power of the CGH is at least two times greater than that of the four-lens approaches mentioned above, resulting in increased spatial bandwidth. In the four-lens case, the lens spacing and lens properties are required to be identical, but by using the CGH these design parameters are much less constrained. The uniformity of the incident beam on the lens plane is also less critical in the CGH approach compared with the four-lens system because the CGH will image light from any area of the CGH to each focal spot. Even if only part of the CGH is illuminated by incident light, then it will still function as 4 lenses to produce 4 uniform spots at the focal plane.

This should maintain a more constant signal level at the perfect shuffled output plane. Also the use of CGH over other bulk-optical imaging methods, has certain advantages in terms of ease of miniaturization and compatibility with the lithographic device production process, and aberration-free imaging as well, therefore the planar integration of the perfect shuffle interconnects can be achieved easily. The diffraction efficiency of the CGH could be a disadvantage, however, the fabrication technique of binary phase holograms with multiple phase structure would increase the efficiency up to 95%, for an 8-level hologram.^[8]

The interferogram-type binary CGH is designed by first calculating the interference fringe between diverging waves from four point sources and a reference plane wave, and then by clipping it to make a binary hologram. For normal incidence of the reference wave onto the hologram plane, the interference term that contributes to the fringe pattern is given by^[9],

$$\Delta I(x, y, 0) = \sum_i \frac{1}{z_i} \cos \left(\frac{\pi}{2\lambda z_i} \left\{ (x - x_i)^2 + (y - y_i)^2 + z_i \right\} \right) \quad (1)$$

where λ is the wavelength, and (x^i, y^i, z^i) for $i=1$ to 4 are the coordinates for the i th point source, and $z^i=f$ for all values of i . It is assumed that all the light amplitudes are unity. Figure 1(a) shows the CGH interferogram given by Eq.(1) with its binary levels of zero (or black) for negative DI, and one (or white) for positive phase. It was designed with a diameter(d) of 4mm, a focal length(f) of 13cm at $\lambda=633$ nm and a spacing(S) of 125m between the four spots produced by the CGH at the focal plane. Figure 1(b) shows the photograph of the four spots focused on the focal plane by an incident plane wave. The diameter of each Airy disk was measured to be 52m, which is close to the diffraction limit size of 50.2m, and the spot spacing(S) was measured to be 126m. In the experiment, the diffraction efficiency of the reflection-type binary CGH has been measured close to the theoretical maximum of 26%, and the uniformity also measured to be 98%.^[9]

If we produced these four spots by using 4 lenses, then lenses with a diameter and lens spacing of $125m$ would be required, resulting in the diameter of the Airy disks becoming ten times larger than the spot spacing. The field angle of a lens is described as twice the angle at the object point between the principle axis and outer ray of the entrance pupil. In the CGH design this is just the object point distance to the outer radius, so this can be designed for most conditions. The optical configuration for the perfect shuffle case, therefore, can offer greater field angle, that is larger spatial bandwidth, than conventional systems using 4 discrete lenses.

III. Perfect shuffle interconnection with CGH

Figure 2 shows the schematic diagrams which explain the basic idea of implementing the perfect shuffle using the CGH of Fig.1(a). The $2S$ -spaced four point sources at the input plane, which are separated by a distance $2f$ from the CGH, are imaged onto the output image plane as shown in Fig.2(a). Each point source is imaged into four spots, and four spot images from the four different point sources are superposed at the center of the image plane. In the diagram of Fig.2(a), the four spot images superposed at the center are depicted as being slightly shifted to each other in order to simplify the diagram. Since this on-axis optics is an imaging setup with unity magnification, the spacing between spots, $2S$, is maintained. As shown in Fig.2(b), if we put an Input pattern which consists of four quadrants with the $2S$ center spacing and special pixels (or point sources) arranged to give the input format of the folded perfect shuffle^[6], then we would get the result of the folded perfect shuffle at the center block of the output plane. The pixel arrays shaped with different patterns are interleaved, that is, perfect-shuffled at the center. The remainder of the output patterns, imaged onto the other eight blocks represent an optical loss, however this is the same as in the perfect shuffle 4 lens setup.

Figure 3 shows the experimental results obtained from the optical configurations of Fig.2. The binary CGH fabricated on a photographic film was used in the experiment. The output obtained from the configuration of Fig.2(a) is shown in Fig.3(a), where the spot spacing is $252\text{m}(=2S)$. The four spots from each of the different sources are superposed at the center of the output. Since the optical setup was slightly mis-aligned in order to emphasize the superposition, the superposed spot size at the center looks larger than the others as shown in Fig.2(a). Figure3(b) shows the input pattern of the folded perfect shuffle and Fig2(b) shows its position in the system. Each pixel size is $(50\text{m})^2$, which is nearly the same as the diffraction limited spot size $(50\text{m})^2$ of the CGH, and the pixel spacing (or center-to-center distance) is $125\text{m}(=S)$. The desired output and experimental output of the folded perfect shuffle are shown in Fig.3(c) and Fig.3(d), respectively. The central region of Fig.3(c) shown within the dashed line box represents the desired perfect shuffle output as indicated in Fig.2(b). The experimental result shown in Fig.3(d) was obtained using a CCD camera image capturing system with objective lens(x20) and was then photographed from a TV monitor. The 4×4 pixel array shown in the central region of the experimental result is the folded perfect shuffle output, and It can be seen to be the same as the desired output pattern shown in Fig.3(c). The merging of the pixels is due to the fact that the pixel size (50m) remains constant but the pixel spacing after the shuffling is reduced to $62.5\text{m}(=S/2)$. The non-uniformity of intensity and imaged pixel size is due to the lens and camera imaging system. It is worth noting that, if we use the 4-lens perfect shuffle system with the same input of Fig.3(b), we can not obtain the result because the diameter of the lenses should be less than 125m, and the diffraction-limited spot size of them should be larger than 1.6mm. To resolve the 50m pixels in the 4-lens system, the diameter of the lenses must be larger than 1mm, so that the total size of the perfect shuffle setup will be increased by the enlarged lenses and I/O areas. Therefore, the approach using the interferogram-type CGH, enables us to implement a perfect shuffle interconnect with a higher spatial bandwidth.

The CGH makes it practical to implement the perfect shuffle in a compact and vibrationally robust manner by using the technology of planar integration of free-space optical components. In Fig.4 we propose a planar optical configuration of the perfect shuffle interconnection using an off-axis CGH. It consists of two substrates aligned to each other by the flip-chip solder bonding technique^[12,13]. The glass substrate consists of the focusing elements, with two blazed gratings designed to deflect the beams, and the CGH designed for the off-axis case, are fabricated on both surfaces as shown in the figure. On the other substrate, the optoelectronic components are made using a Si or GaAs wafer. It is envisaged that the input and output optoelectronic components, such as a 2-D surface-emitting laser array(input) and a 2-D detector array (output), are fabricated on one side of the wafer. The light beams from the laser array are reflected from the blazed grating with the correct angle and imaged onto the detector array by the CGH, resulting in the perfect-shuffle output. The off-axis CGH is designed by the interference of four diverging waves and plane wave with correct angle between them, and fabricated on the bottom surface of the substrate by using a lithographic etching technique, so the CGH fabricated is a surface-relief binary phase hologram. The blazed gratings are also etched on the top of the substrate, however, the alignment of them is not critical. A high accuracy for alignment is only required between the CGH and I/O optoelectronic components, and this alignment can be done by the solder-bonding technique^[10,11] and the lithographic mask aligning process. One extension would be to cascade the interconnect and to use the optical logic device arrays with read-out beam arrays, such as SEED (self-electro-optic effect device) or AFPM(asymmetric Fabry-Perot modulator) arrays, instead of the laser and detector arrays.

The binary CGH shown in Fig.1(a) is divided into many blocks by the 2-D grid lines and the contrasts between adjacent blocks are opposite. The pitch of the lines is matched to the grating diffraction condition for generating the four focal spots at the focal plane. Therefore, the binary CGH can be considered as a superposition of a Fresnel zone plate (FZP) and the 2-D grating with a checker-board format, so that a spot to be produced by the FZP would be diffracted into the four spots. This consideration makes it easy to derive the maximum spatial bandwidth of the perfect shuffle interconnection shown in Fig.2(b). After the simple calculation with the equations for the Fresnel zones and Airy disk, and with the limitation of e-beam lithographic technique (1m), the minimum pixel size to be resolved was found to be 2.44m. Therefore the maximum number of pixels (or spatial bandwidth) of the perfect shuffle interconnection is given by dividing the total area of the input plane ($4S=500\text{m}$) with the minimum pitch of the input pixels ($2\times 2.44\text{m}$), resulting in 100×100 pixels. It is possible to increase the spatial bandwidth by using the CGH with larger spot separation(S), but it will be limited by the aberrations of the CGH, such as field of curvature and astigmatism. In the folded perfect shuffle setup shown in Fig.2(b), the pixel arrays in four quadrants should be shifted to each other, and an input device array, specifically designed would be required.

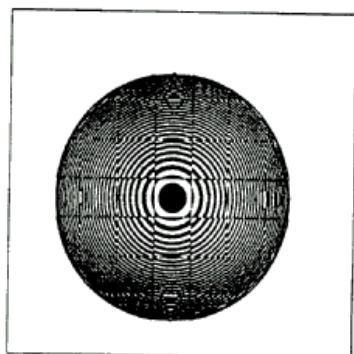
IV. Summary

In conclusion, we have proposed an optical implementation of 2-D perfect shuffle interconnects using a single interferogram-type CGH, and we have shown some experimental results. The use of the CGH element offers the advantages of having higher spatial bandwidth, low optical aberration, and more flexible to system design, than the case of conventional systems using four individual lenses. The design flexibility also gives us the potential to implement a planar optics for the perfect shuffle interconnects.

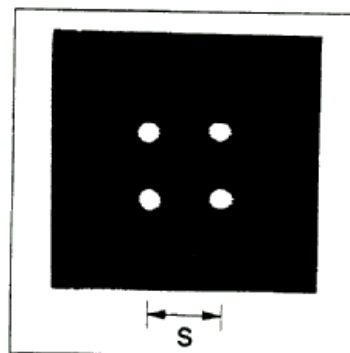
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(a)



(b)

Figure 1.(a) The interferogram-type binary CGH. (b) Four focal spots generated by the CGH.

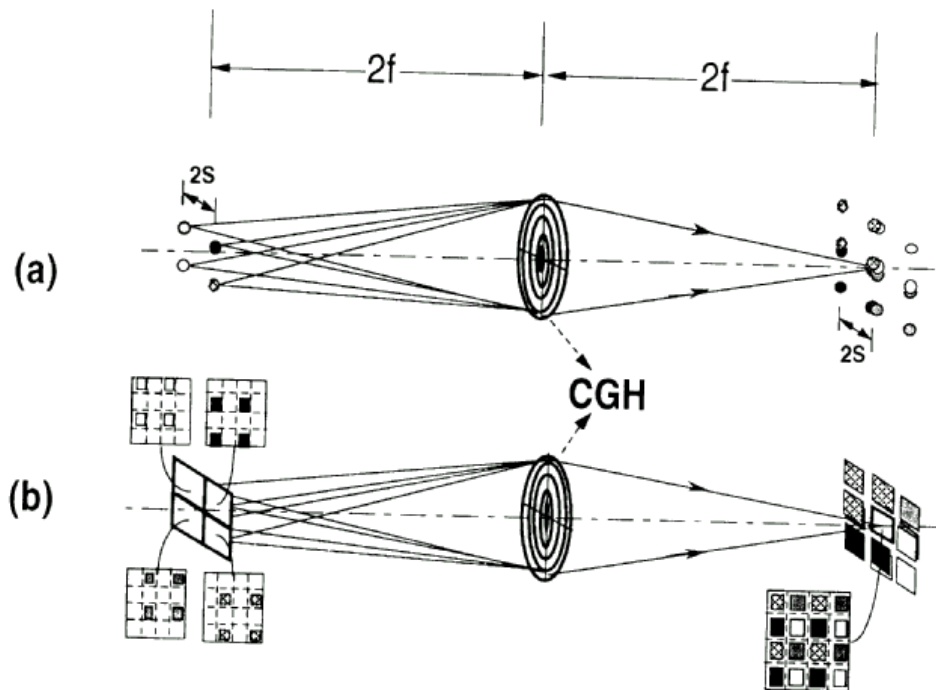


Figure 2. The folded perfect shuffle interconnection using the CGH shown in Fig.1(a).
 (a) Imaging property of the CGH. (b) Folded perfect shuffle.

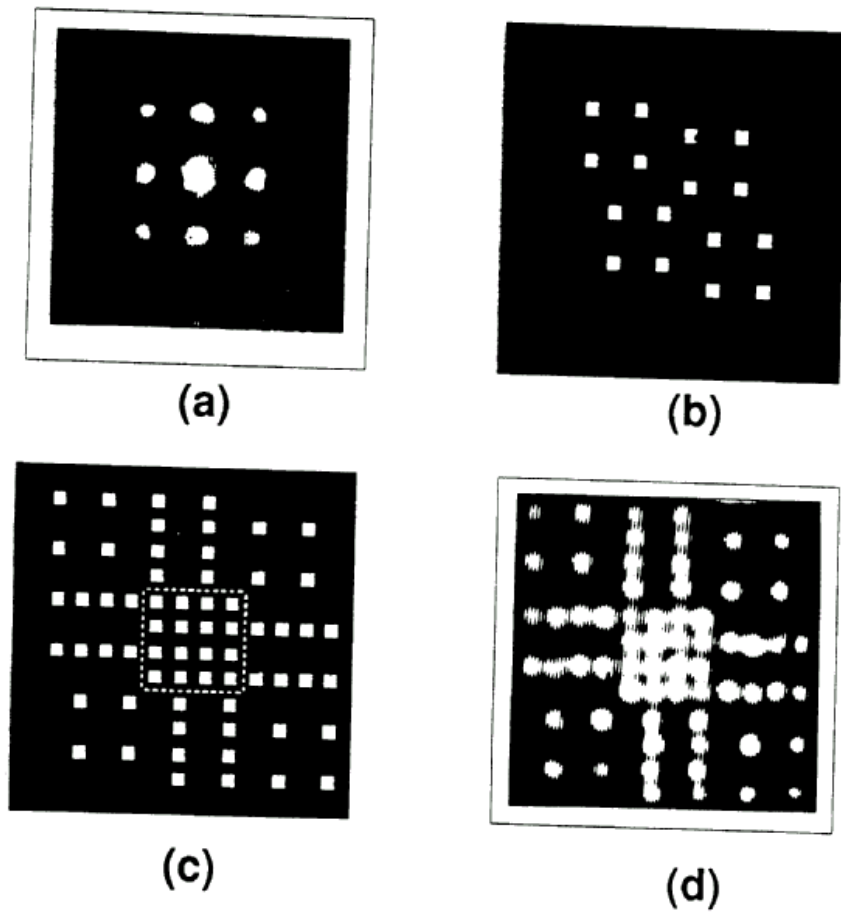


Figure 3. Experimental results. (a) Output image of the configuration shown in Fig.2(a).
 (b) Input pattern, (c) desired output, and (d) experimental output of the folded perfect shuffle configuration shown in Fig.2(b).

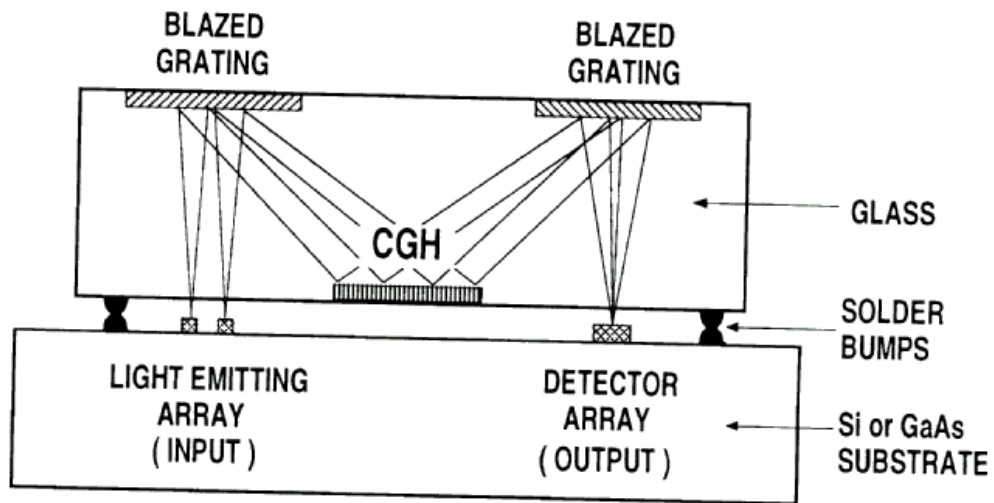


Figure 4. Planar optical configuration of the perfect shuffle interconnects using an off-axis CGH.

부록 2-2

Holographic Perfect shuffle interconnections for planar optics

[Technical Digest of OSA Topical Meeting on Photonics in Switching,
Palm Springs, CA, USA, March 15-17, 1993, paper of PTuD1.]

[부록 2-2]

Holographic Perfect shuffle interconnections for planar optics

ABSTRACT

For perfect shuffle interconnections, a planar optical configuration with two double-imaging deflective-reflective holograms is proposed. Interconnection capacity is derived from an aberration analysis.

I. Introduction

The perfect shuffle network is one of the regular multiple-stage interconnection networks with wide applications for telecommunications and parallel computing processors.[1] Optical implementation of the perfect shuffle interconnects has been mainly achieved by the use of free-space optical components, such as lenses, prisms, or holograms.[2,3] In order to implement the interconnects in a compact, robust, and alignment-free manner, technologies of planar integration of the free-space optical components[4] are required. In this summary, we propose a planar optical configuration which can carry out the perfect shuffle interconnects, and it is suitable to link areas of a wafer scale integrated circuit together by means of computer-generated holograms(CGH). Two double-imaging diffractive-reflective CGHs are used as key components acting as a set of four lenses in the free-space configuration of Ref.3. Interconnection capacity of the proposed planar system and the optimum number of internal reflections in an optical substrate are also derived by analyzing aberrations of CGH s.

II. Perfect shuffle using a computer-generated hologram

In the folded perfect shuffle implementation[3] using a set of four conventional lenses or four holographic lenses, the input data are separated into four quadrants. Each quadrant is magnified to the original size and shifted for interlacing, and the quadrants are recombined into a single imaging pattern. The use of hololenses generated by computer is known as a more practical approach for integration to an optical substrate, since we can make them as surface relief holograms by lithographic techniques. Also It is possible to replace the four lenses with a multiple-imaging CGH. This CGH can be designed as an interferogram from the interference between diverging wavefronts from four point sources and a converging wavefront, so that it produces four images in the present of one input pattern[5].

Figure 1(a) shows the schematic diagrams to implement the folded perfect shuffle using the CGH. The input pattern consists of four quadrants, and each quadrant has the 2×2 pixels arranged to give an input format of the folded perfect shuffle. This would give the folded perfect shuffle in the center block of the output plane. the pixel arrays shaped with different patterns are interleaved, that is perfectly shuffled at the center. In the experiment, Fig.1(b) and fig.1(c) show respectively an input with pixels of size $(50\mu\text{m})^2$ and the experimental output obtained from the monitor screen. The 4×4 pixel array shown at the central region of fig.1(c) is the result of the folded perfect shuffle interconnection.

III. Planar optics implementation

It is known that the planar integrated system which consists of an even number of diffraction gratings suffers less from wavelength dependence, since the diffraction angle relating to the different wavelength can be compensated exactly[6]. Therefore, when we implement a planar optical system based on the configuration shown in Fig.1(a), it is better to use two double-imaging CGH s, instead of the single multiple-imaging CGH of Fig.1(a). The planar configuration proposed here is depicted in Fig.2(a), and its equivalent diagram of an unfolded optical system is shown in Fig.2(b). The planar system of Fig.2(a) consists of two substrates, optical and optoelectronic integrated circuit(OEIC) embedded substrates, interfaced by the solder-bump bonding technique in order to achieve an alignment accuracy of less than 2 μ m[7]. The two double-imaging CGH s, CGH-Z and CGH-Y, are surface-relief phase holograms designed as an interferogram from interference between diverging wavefronts from two point sources and a converging wavefront with an angle, q . They make, respectively, two images of the input object of laser diode array(LDA) onto the positions of P, and four images onto the photodiode array(PDA) as shown in Fig.2(b), via multiple internal reflections in the optical substrate. That is, the CGH-Z produces two identical patterns shifted with respect to each other in the direction of z-axis, and the patterns are again doubly imaged in the y-axis by the CGH-Y resulting in a 4x4 array format on the PDA.

IV. Interconnection capacity

The interconnection capacity, which is defined as the maximum number of input channels (laser diodes) to be connected by the planar optical system of Fig.2(a) to the same number of detectors, would be restricted by the aberrations of the double-imaging CGH s and by the choice of architecture. The third order coefficients of spherical aberration(S), coma(C), and astigmatism(A) of the Brandt-type hololens[8] are considered here to obtain the interconnection capacity. When the Gaussian beams($\exp[-x^2/w_0^2]$) emitted from the LDA pass through the interface between air and the optical substrate, refraction occurs. Therefore, we can consider the effective optical path length from LDA to CGH-Z to be $R_0 = n(Z_0 + t)$ [9], where n and t are the refractive index

and thickness respectively of the optical substrate. The air gap Z_0 between the substrates is assume to be uniform and equal to 20m, the height of the solder-bump[7]. The path length from the CGH-Z to point P is also given by $RR=n(bt/\cos q)$, where b is the number of reflections when the beams propagate from LDA to P($b=3$ in the Fig.2). The total aberration can be derived by[8]

$$|\Delta| = -\frac{D_c^4}{8\lambda}S + \frac{D_c^3}{2\lambda}C + \frac{D_c^2}{2\lambda}A, \quad (\text{in unit of } \lambda)$$

where,

$$S = 0,$$

$$C = \left(\frac{1}{R_o^2} - \frac{1}{R_R^2} \right) \sin \alpha,$$

$$A = \left(\frac{1}{R_o} - \frac{1}{R_R} \right) \sin^2 \alpha - \left(\frac{2 \sin \theta}{R_R} \right) \sin \alpha,$$

$$\sin \alpha = \left(\frac{\delta_x}{R_o} \right), \quad D_c = 2k \sqrt{1 + \left(\frac{\lambda R_o}{n\pi\omega_o^2} \right)^2}.$$

D_c is diameter of the CGH-Z, the constant k is the ratio of $D_c/2$ to the Gaussian beam waist at the CGH-Z plane, and dx is the half width of the input object (LDA). Figure 3(a) shows the total aberration (in units of 1) of Eq.(1) as a function of dx (in units of m) for different beam waists, ω_o , at LDA, when $l=0.85$ m, $t=10$ mm, $k=1.52$, $q=150$, $Z_0=20$ m, $n=1.5$, and $b=3$. As ω_o increases from 5m to 20m, the aberration decreases from 0.51 down to 0.11 when $dx=500$ m. It is noted that the resolution limit of CGH-Z, which is defined by $1.21f/D_c$, is 4.7m when $\omega_o=5$ m, and 18.4m when $\omega_o=20$ m. Therefore the value of ω_o can be taken as a minimum pixel size of the input channels imaged by the CGH-Z. If we take $|D|=1/4$ as a maximum aberration to be tolerated in the planar system, and define R_x to be the smaller magnitude between positive and negative dx when $|D|=1/4$, then the maximum number of input channels (N) can be obtained by dividing $2R_x$ with the channel spacing (or center-to-center spacing of the laser diodes), $2x(2k\omega_o)$. As an example, when $\omega_o=5$ m, R_x is given by 360m, and so $N=23$. In the case of 2D array, the interconnection capacity (or the number of input channels) are $N^2=23^2$. For a larger ω_o than 5m, N becomes smaller.

Therefore at least 16×16 input channels are possible in the planar system of Fig.2(a), with the physical dimensions of the laser diode diameter; $2kwo=15.2m$, the glass thickness; $t=10mm$, and $Zo=20m$. Figure 3(b) shows the $|D|$ according to the number of reflections, b , for the case of $wo=5m$. When $|D| \leq 1/4$, $R_x=360m$ for $b=3$, $R_x=340m$ for $b=4$, and R_x becomes much smaller for the other cases of b . Therefore, we can choose the $b=3$ as an optimum number of internal reflections in the optical substrate.

In conclusion, by using two double-imaging CGH s we have proposed and analyzed a planar optics configuration for 2D perfect shuffle interconnections. It has been found that at least 16×16 2D input channels can be connected by the proposed planar system, when the beam waist, wo , at the LDA is 5m and the number of internal reflections, b , is 3.

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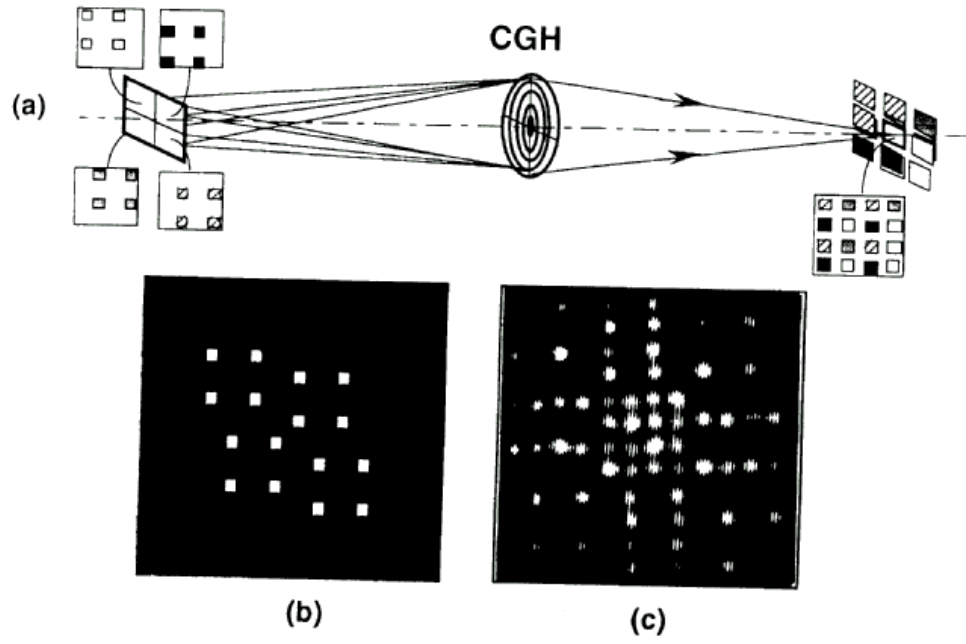


figure 1. Folded perfect shuffle interconnection using a multiple-imaging CGH. (a); schematic diagram, (b); input with 4×4 pixel array (50m 2pixels), (c); experimental result of the perfect shuffled output shown at the center region of 4×4 pixel array.

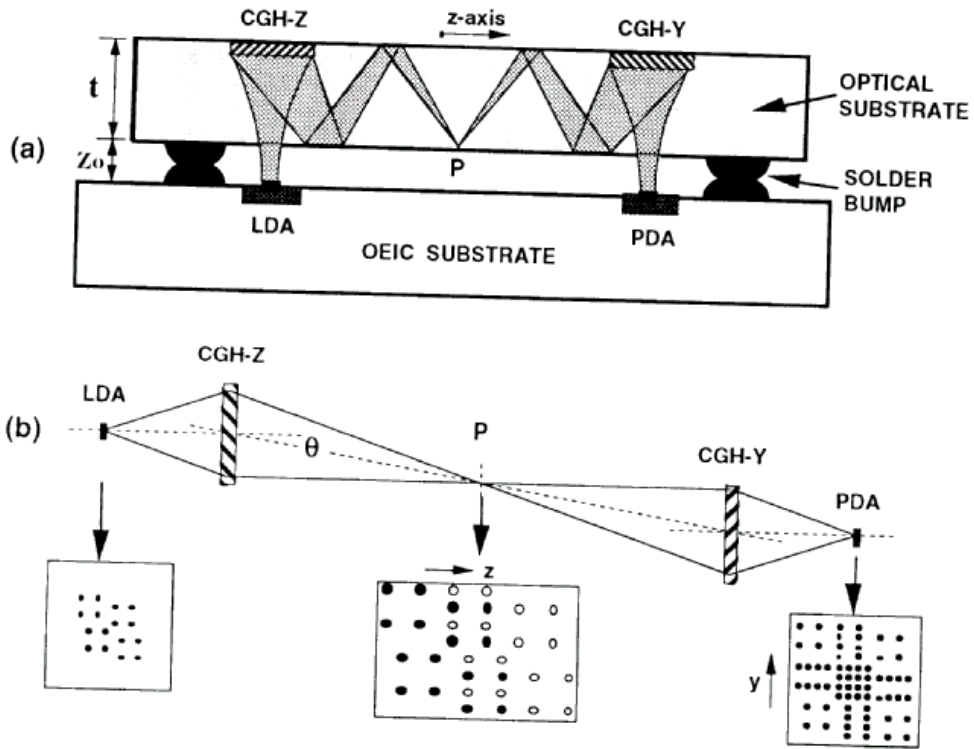


figure 2. (a); planar optics configuration for the perfect shuffle interconnects using two double-imaging computer-generated holograms, CCH-Z and CGH-Y. (b); schematic diagram equivalent to the planar system of(a).

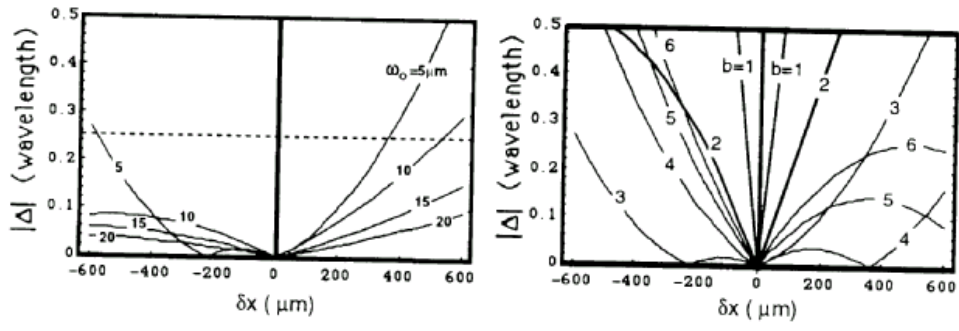


Figure 3. Total aberration, $|\Delta|$, as a function of δx for the different beam waists, w_0 , in (a), and for the different number of reflections, b , in (b).

제 3 장 크로스오버 연결망을 갖는 광고환용 평면광학계

제 3 장 크로스오버 연결망을 갖는 광교환 평면광학계

본 장에서는 MIN 중의 하나인 crossover interconnection에 관한 것으로서, 우선 기존의 마이크로 프리즘 어레이를 이용한 crossover MIN용 자유공간 광학계에 대해 논의한 후, 이를 평면광학계로 구현하기 위한 새로운 구조 및 crossover MIN 평면광학계의 핵심소자인 예각 마이크로 프리즘 어레이에 대해 설명코자 한다.

그림 3-1(a)은 Crossover interconnection(입출력 채널이 4개인 경우)의 개략도이다. 각 switching node들로부터 나가는 신호광은 bypass 또는 crossconnect 연결이 되어 다음 node stage로 전달된다. 이러한 croosovering은 앞장에서 설명된 perfect shuffling과 동일한 node 수 및 기능을 하는 것으로 증명되어있다. 따라서, 응용하고자 하는 광 시스템의 하드웨어에 따라 MIN 구조를 선택할 수 있다.

그림3-1(b)은 마이크로 프리즘어레이를 이용하여 crossover interconnection을 수행하는 기본 개념도이다. 우선 첫번째 node stage에서는 전체 입력신호가 모두 crossconnect 되는데, 이때 한개의 직각 프리즘을 사용하면 그림에서와 같이 입출력 신호의 배열이 변환된다. 마찬가지로, 두번째 node stage에서도 두개의 프리즘에 의해 입력신호들이 양분되어 각각 crossovering이 이루어 진다.

그림 3-2는 위의 기본개념을 이용하여 입력신호를 출력단(optical logic array)에 crossover 연결하는 구성도이다. 마이크로 프리즘어레이, interconnection mask, 편광 beam splitter, switching node인 optical logic array등이 사용되어 있다. 입력 광신호는 편광 beam splitter에서 양분되어, 연결 mask에서 일부 반사된 후 optical logic array에 입사하는 bypass connection, 그리고, 편광 beam splitter에서 반사된 신호는 프리즘 어레이를 거친 후 logic array에 도달함으로써, crossconnect interconnection을 이룬다.

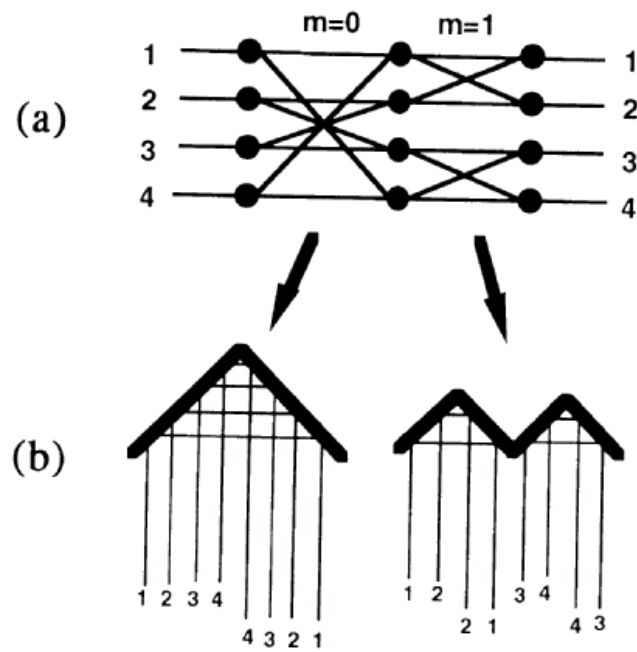


그림 3-1. (a)크로스 오버 연결망, (b) 프리즘을 이용한 crossconnection.

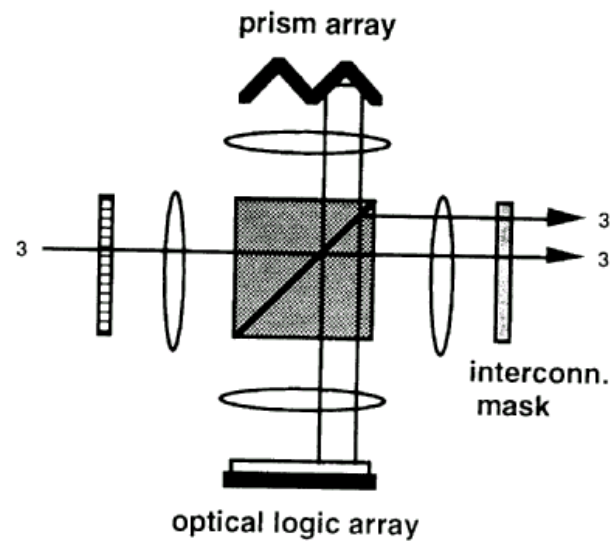


그림 3-2. 크로스 오버 연결을 위한 자유공간 광학계.

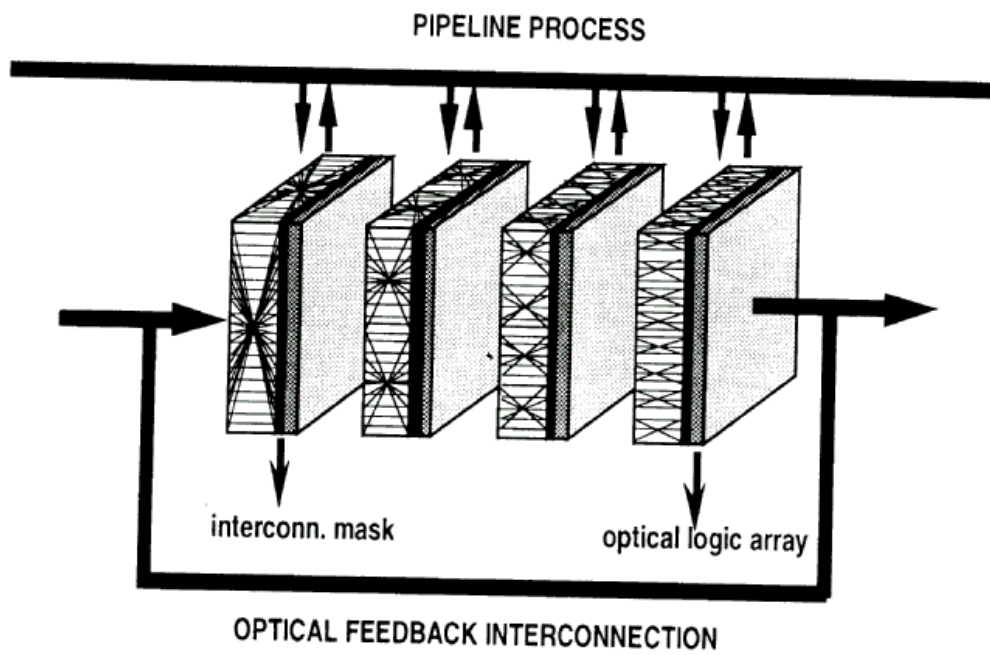


그림 3-3. 3차원 크로스 오버 연결망.

이러한 crossover interconnection 망은 3차원 자유공간 광학계로써 구성될 수 있는데, 그림 3-3에 다단계 연결망을 보였다. 각 switching node stage간에는 pipeline을 통하여 제어되며, 한 node stage에 있는 각각의 node들은 동시에 switching 역할을 하는 병렬 프로세싱이 가능하다.

그런데, 그림 3-2와 같은 자유공간 광학계는 시스템정렬 및 구성의 어려움을 갖고 있다. 따라서, 제 2 장의 평면광학계 구성방식과 같이 crossover interconnection용 광학계를 평면 광학계로 구현하는 것은 광교환 시스템의 실용화에 큰 의미가 있다고 할 수 있다.

[부록 3-1]은 crossover interconnection용 자유공간 광학계를 평면광학계로 구현하는 기본 개념과 실험결과를 설명한 것이다.

[부록 3-2]는 crossover interconnection용 평면광학계의 최대 연결용량을 구성 방식에 따라 유도한 것으로써, 입출력 소자 및 프리즘등 광학부품간의 배열구조에 따라 연결용량이 크게 좌우되었다.

부록 3-1

Planar optical implementation of crossover
interconnects

[Optics Letters, Vol.17, 1253(1993)]

[부록 3-1]

Planar optical implementation of crossover interconnects

Abstract

We propose a planar optical configuration for implementation of crossover interconnects. The planar overlay allows 2-D pixel arrays located on a wafer scale integrated circuit to be interconnected in a compact and vibrationally robust configuration. By using an acute-angle microprism array with apex angles of 70.52 degrees formed using silicon V-groove technology, we have demonstrated the crossover interconnections. Some practical limits of the planar optical crossover interconnections are also discussed. Switching networks, such as crossover, perfect shuffle, and Banyan, are being widely considered for use in regular multistage interconnection topologies for telecommunications and in multiprocessor computers for shared memory access, because of their simplicity, extendibility, and high throughput[1]. As an example, the crossover network has been demonstrated by AT&T Bell Laboratories[2,3]. This network was implemented by using free-space optics, which contained rectangular angle prism gratings and patterned mirror arrays to make a crossover interconnect, and the polarizing cube beam splitters and retardation plates to interconnect arrays of optical signals with very low optical loss.

However, it is noted that in this free-space implementation a complicated mechanical alignment is required to arrange the components to within several micrometer accuracy, and this is a common problem in most of the free-space implementation approaches of regular interconnection networks as well. To overcome this alignment complexity, interest in the planar optics approach has grown recently [4-7]. The technology of planar integrated optics enables such interconnection networks to be implemented in a compact and vibrationally robust manner. Planar optical systems contain bulk optical components integrated on a single substrate. Lithographic fabrication techniques can be used to form the various optical elements (diffractive-reflective holograms[8], microlenses[9] microprisms[2], etc), and optoelectronic elements (modulators, detectors, etc) on a single side of the substrate. This has the advantages that they can be accurately aligned using one mask set to give a mechanically robust interconnect and the fabrication technique is compatible with microelectronic circuits. When such a planar optic overlay is located on a 2-D array of smart exchange-bypass pixels, the pixels can be interconnected to realise an optical switching network.

In this letter, we propose a planar optical implementation of crossover networks to integrate the free-space optical crossover interconnection system developed by Bell Labs[2], onto a compact solid optical substrate. Our implementation makes use of an unusual optical component, namely an acute-angle microprism array(MA). An experimental result demonstrating a crossover and some practical limits of the planar interconnection are also presented.

The basic configuration of the planar optical crossover interconnects is shown in Fig.1. For simplicity, we assume that the input channels are arranged in 1-D and the case of a 2-D arrangement is discussed later in relation to the full planar configuration of Fig.4. Figure 1(a) shows the standard routing of a crossover network with N input channels (N=4 in the figure). Each interconnection stage is labeled $m=0, 1, \dots, (\log_2 N - 1)$. Figure 1(b) shows our planar configuration for the $m=0$ and $m=1$ interconnection stages which makes use of an acute-angle microprism array (MA), a polarizing beam splitter (PBS), and a mirror(M).

At the m -th stage the number of acute-angle prisms is 2^m , and the width of each prism base is $W/2^m$, where W is the width of the prism at the first stage ($m=0$). The angled sides of the MA are coated to reflect light beams. Each of the array of incident beams, which are initially unpolarized, are split into two beams with s- and p-polarization states by the PBS. The s-polarization beams are reflected from the PBS (represented by dashed lines in Fig.1(b)) and propagate between the mirror and the PBS. These beams make the bypass (straight-through) connections for the crossover network of Fig.1(a). The p-polarization beams (represented by solid lines), passing through the PBS, are reflected from the MA and make the cross-connections of the network. All of the beams are recombined again at the PBS, and go on to the next stage. Detailed descriptions of the bypass- and cross-connections are illustrated in Fig.2. The propagation angle in the substrate, q , is less than 90 degrees and is equal to the apex angle of the micropisms. In the bypass-connections of Fig.2(a) the order of input channels is not changed. However, in the cross-connections of Fig.2(b) for the $m=0$ stage and Fig.2(c) for the $m=1$ stage, the orders of the input channels are exchanged, respectively. The substrate is unequally divided into two by the PBS plane as shown in Fig.1(b). The thickness of the upper part from the PBS to the top side of the substrate, is larger, than that of the lower part, from the mirror to the PBS. The path lengths of cross-connections are not constant and they could be different from those of the bypass-connections. The effect of this path length difference, to the system performance is discussed later. The use of the PBS and the MA offers the potential to implement the crossover networks with very low loss of optical energy. The function of the MA is very similar to that of the prism gratings of the free space optical crossover interconnects proposed in Ref.2, where the apex-angle of the prism gratings is 90 degrees and the beams are normally incident to the base plane of the prism array. In the planar crossover configuration, the use of the acute-angle MA makes it possible for the beams to be guided into the substrate with a given propagation angle.

For demonstration of the planar optical crossover interconnections, we have used the MA fabricated using standard silicon V-grooves technology[10]. Figure 3(a) shows the SEM photograph of the MA fabricated on a silicon wafer. The apex-angle θ , of the prism is 70.52 degrees and the base width of each prism is 128 μ m. Such V-grooves are more often used for the alignment of optical fibers on silicon wafers. They are fabricated by anisotropic wet etching techniques based on the different etching rates between the (100) and (111) surfaces of the silicon crystal. The chemical etchants, KOH or ethylene diamine pyrocatechol(EDP) can be used, to produce the V-grooves. The apex angle is determined by the crystal orientation of silicon, so it is possible to achieve a MA with very uniform apex-angles and with very high quality optical surfaces. It is also easy to fabricate the MA with sizes from a few microns to several hundreds of microns. In the experiment, we implemented only the cross-connections by using discrete optical components, with an input mask, two lenses, and the MA described above. The input was imaged to the MA via a lens and the cross-connected output was then imaged to a screen via the other lens. The angles of incidence and reflection at the MA were about 20 degrees. The input mask shown in Fig.3(b) consists of transparent and opaque pixels arranged in a 8 \times 8 array format with each pixel having a diameter of 30 μ m. We designed the dark field input pattern as an x shape by making the corresponding pixels transparent, and in this case 4 transparent pixels fall within any single 128 μ m column width as shown in Fig.3(b). Figure3(c) shows the cross-connected output of the experiment. At the corresponding microprism, each set of the four pixels in the input mask are flipped horizontally. In the output image there is some blurring of the spots in the horizontal direction (perpendicular to prism length). This is due to the fact that the experimental system does not seem to give exact one-to-one imaging, resulting in some magnification. Part of the magnified spots are clipped by the apex area of the prism, producing the diffracted horizontal blurring.

The experimental result shows the possibility for the implementation of a planar optical crossover interconnection with 3-D spatially parallel connectivity, which is defined as a 3-D network[11]. A full planar integrated design for the 3-D crossover interconnects is proposed in Fig.4, where only one of the interconnection stages is illustrated. The configuration consists of a switching node array (input stage) of a 2-D optical logic device array, connected via a 4-f imaging system to the acute-angle microprism array, and then via a further 4-f imaging system to the second switching node array (output stage). Two silicon substrates are glued together and the PBS is located in between them. The wavelength of the signal beams is in the region beyond 1.1 μ m, which is the absorption edge of silicon substrates. Two lenses, an MA, and optoelectronic devices of 2-D pixel arrays are designed on the top surface, and a mirror on the bottom surface. They can be lithographically fabricated with a very accurate alignment. For the lenses, single lenses, silicon microlens arrays[12], or Fresnel type diffractive reflection CGH s with multiple phase levels[13], would be used. The use of a silicon substrate offers the potential for integrating both the optoelectronic devices and their driving electronics with the optical components, all on the same substrate, and it would also be attractive for integrating liquid crystal devices to control the polarization of signal beams.

As discussed in accordance with Fig.1(b), the PBS splits each input beam into a pair of bypass-and cross-connections and recombines them into one. However, the path lengths of the two connections are not equal and the cross-connection routes have longer path lengths by the extra amount of the path passing in the MA. This path length difference could be one of the practical limitations to implement a planar optical crossover interconnection system. To calculate this we assume that the width of one acute-angle prism at the mth interconnection stage is $W/2^m$ and the separation between channels is Dw . Then the path length difference, PD_n , between the bypass-and cross-connection routes of the nth input beam is given by

$$PD_n = \frac{W}{2^m} + 2\left(\frac{W}{2^m} - n\Delta W\right)\cos\theta,$$

where, $n=1,2,\dots$, and $N/2m$, and $N(=W/\Delta w)$ is the total number of channels. The PD n is maximum When $n=1$ and $m=0$. As an example, for $N=32$, $\Delta w=10\mu\text{m}$, and $\Theta=70.52$ degrees, the PD1 is $527\mu\text{m}$ that is, the cross-connection length is $527\mu\text{m}$ longer than the bypass-connection. Therefore, at the output plane the imaged spot diameters are not uniform and it results in increasing both optical losses and cross-talk noise. However, we can minimize this problem by optimizing the focal lengths of the lenses to the $(N/2m+1)$ th input beam which passes through the middle of the prism, and by increasing the optical path lengths of bypass-connections to be matched to the focal length. The use of a different material for the lower substrate, which has a refractive index slightly larger than that of silicon, can make it possible to increase the lengths of bypass-connections and recombine each pair of the bypass-and cross-connections into one beam. Another practical limitation is that since the apex angle ($\Theta=70.52$ degrees) is greater than 60 degrees, the beams incident on the MA could be reflected from the left-hand surfaces of the prisms, so they do not make the cross-connections. Therefore, proper gaps between input pixels are required to avoid this effect, and the space-bandwidth product would be decreased consequently.

In conclusion, we have proposed a planar optical method for implementation of crossover interconnections. We have also demonstrated the crossover interconnections by using the acute-angle microprism array fabricated on a silicon substrate. The planar optical crossover interconnection system can overcome the alignment and stability problems of free-space optics using discrete bulk optical components. Even though there are some practical limitations in the planar integrated optical crossover system as discussed above, the use of silicon substrates makes it easy to fabricate the acute-angle microprism arrays with high quality optical surfaces. Also it offers the potential for integration of optical interconnection components and optoelectronic I/O devices all on the same substrate.

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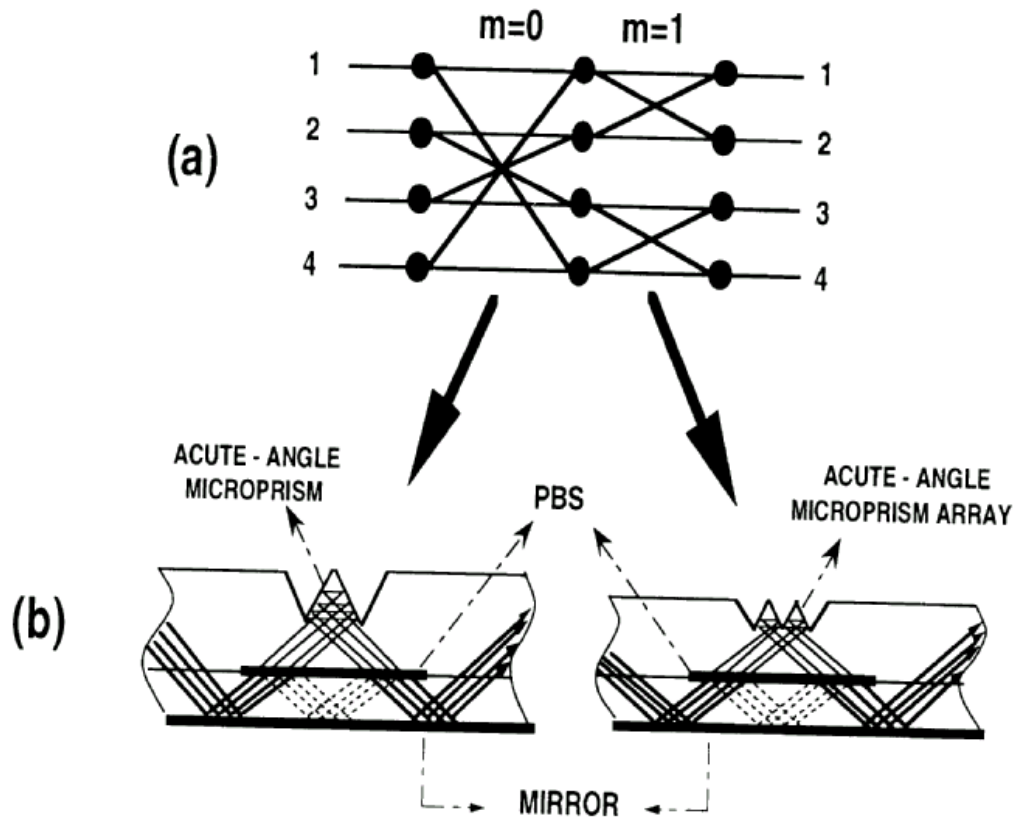


Figure 1. Planar optical crossover interconnection. (a) Crossover network for four input channels($N=4$), where m is the number of specific interconnection stage.

(b) Planar optical configurations for the implementation of the interconnection stages of $m=0$ and $m=1$. PBS is the polarizing beam splitter.

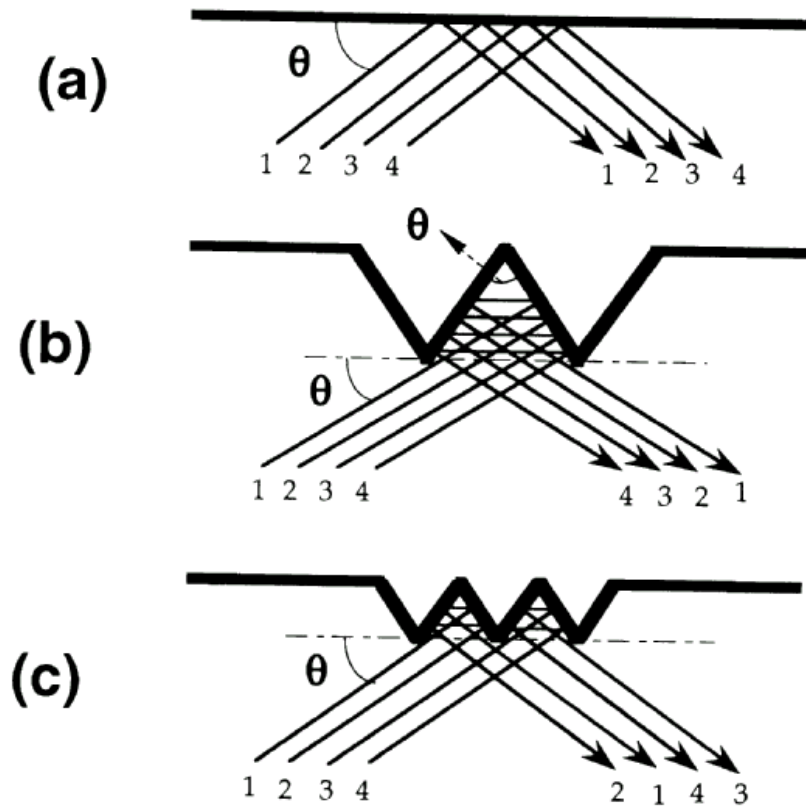


Figure 2. Crossover interconnection using acute-angle microprism array.
 (a) Bypass-connections. Cross-connections of (b) $m=0$ stage and
 (c) $m=1$ stage.

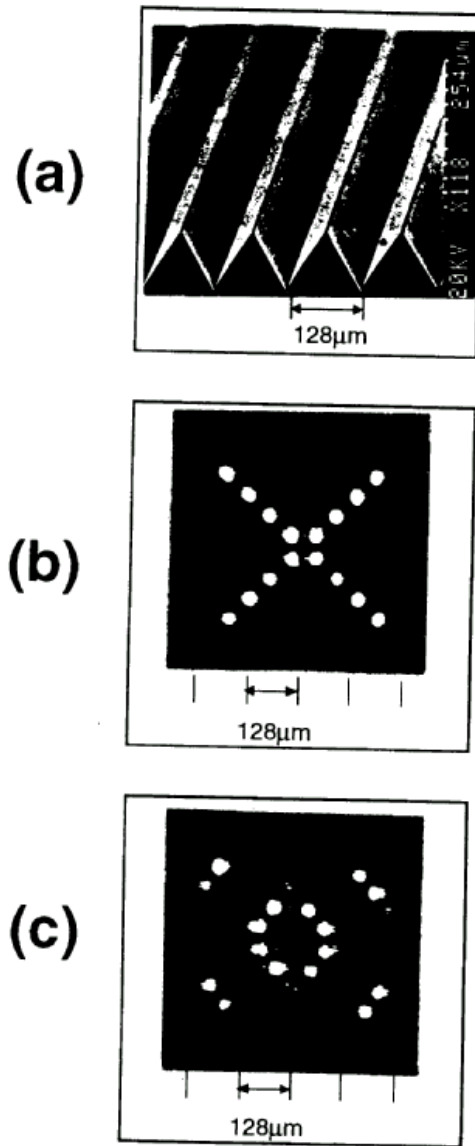


Figure 3. The experimental result of the crossover interconnections. (a) Acute-angle microprism array with 128μ pitches and 70.52 degrees apex angles. (b) 2-D Input with 30μ diameter pixels. (c) Cross-connected output.

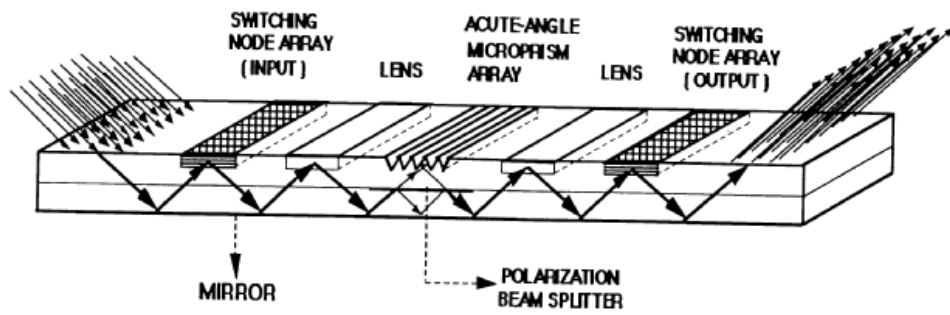


Figure 4. A planar integrated design of 3-D crossover interconnects.

부록 3-2

Planar optical configurations for crossover iterconnects

[Moc/Grin '93, Kanagawa, Japan]

[부록 3-2]

PLANAR OPTICAL CONFIGURATIONS FOR CROSSOVER INTERCONNECTS

I. Introduction

Planar optical systems, which consist free-space optical components integrated on a single substrate, have been developed by using planar fabrication techniques of microelectronic or optoelectronic circuits. It is known that the planar optics does not suffer from problems of the alignment of many components and the mechanical instability, as well as it maintains the high connectivity of the free-space optics[1]. Many of the planar optics have been developed so far, to implement clock signal distributions in an optoelectronic circuit board, one-to-one connections(imaging), and N-to-N connections (multistage interconnecting) [2,3]. In Ref.2, we have been proposed a planar integrated optics for implementing one of the photonic switching multistage interconnection networks, crossover.

In this paper, the planar integrated optics for crossover is analyzed by considering two micro-optical configurations with the base of Gaussian beams being relayed by microlens arrays. They correspond to two possible optical configurations for collimating Gaussian beams with $Z_1=f$ (represented as type-A) and $Z_1=f+Z_R$ (type-B), respectively, where Z_1 is given by the path length from an input to the microlens array with the focal length of f , and Z_R by the Rayleigh range[4]. In order to reduce the optical path differences between the bypass and exchange connections in the proposed crossover configurations, a method to use two substrate with different refractive index is also proposed.

II. Planar optical configurations for crossover

A planar optical configuration for the implementation of one link stage between two switching node stages in the crossover switching networks is depicted in Figure 1. The array of optical signals coming from the input switching node array are relayed to the output by the two arrays of microlenses, via the acute-angle micro-prism array (AMPA). Detailed description of the bypass and exchange connections is shown at Fig.2, where for simplicity the 4 input switching nodes-to-4 output switching nodes with two link stages are described. It is noted that the apex-angle of the AMPA should be equal to the angle between the mirror plane and the direction of the signal beams propagation, and the number of micro-prisms are given by $2m$ at the m th link stage.

One of the advantages of the planar crossover optics mentioned above is the flexibility to integrate the optical interconnection block to an OEIC board with a same scale. Figure3 shows two possible types of planar optical crossover interconnects, type-A of Fig.3(a) and type-B of Fig.3(b). The input and output optoelectronic devices are connected by the planar optical interconnection blocks placed on the top of the OEIC board. The microlens arrays make microbeam interconnections and they offer some advantages of high resolution and low field dependent aberration, and low angular effects of optical components, rather than the interconnection using a single lens[4]. If we assume that the incident beams have the Gaussian beam profiles, the collimation of Gaussian beams can make the use of two configurations with $Z1=f$ and $Z1=f+Z_R$, where $Z1$ and Z_R were defined at the first section. Since the type-A configuration of Fig.3(a) has both the optical and optoelectronic components on a same surface of the optical substrate, $Z1=f$ and hence $Z2=f$, as well. The $Z2$ is defined by the path length from the lenses to the position where the minimum beam waist takes place after a beam passes through the lenses. On the other hand, the type-B of Fig.3(b) satisfies the different relations of $Z1=f+Z_R$ and $Z2=f+f^2/2Z_R$, and the $Z1$ should be the half of the $Z2$. Therefore, the interconnection capacities, defined by the maximum number of channels, of the two planar optical configurations would be different and they will be discussed in the next section.

III. Interconnection Capacity

When we assume that both the total width of the AMPA and the separation distance between the microlens array and the AMPA are equal to the width of the microlens array, the interconnection capacity of the type-A, NA, can be derived by

$$\begin{aligned}
 N_A &= \frac{f}{2d_L} \cos \theta \\
 &= \frac{\pi n \omega_e^2 \cos \theta}{2\lambda d_L} \sqrt{\left(\frac{d_L}{2k\omega_e}\right)^2 - 1}.
 \end{aligned} \tag{1}$$

Figure4(a) shows the plot of Eq.1 as a function of the input beam waist of w_0 , for various sizes of the microlens diameters of $d_L=120\text{mm}$, 240mm , 480mm , and 960mm . In this plot, the clipping ratio of $k=1.52$, $\lambda=850\text{nm}$, $n=1.5$, and $q=45$ degrees. And the interconnection capacity of the type-B, NB is given as

$$\begin{aligned}
 N_B &= \frac{(f + Z_R)}{2d_L} \cos \theta \\
 &= \frac{\pi n \omega_e^2 \cos \theta}{4\lambda d_L} \left\{ \left(\frac{d_L}{2k\omega_e}\right)^2 - 2 \right\},
 \end{aligned} \tag{2}$$

and it is also plotted in Fig.4(b) by the solid line against w_0 for the four sizes of d_L . The dashed line in this figure represents the constraint of the $Z_2=2Z_1$ as shown at Fig.3(b). The four corresponding intersections of the solid and dashed lines show the maximum (possible) number of channels of the type-B configuration. From the results of Fig.4(a) and (b), it is found that the type-A configuration is more flexible to choose the diameter of microlenses for a given w_0 , and it can have the interconnection capacity greater than the type-B.

IV. Reduction of the optical path differences

As can be seen at fig.2(b), the path lengths of the exchange connection beams passing through the micropisms are longer than those of the bypass connection beams. Therefore, it could induce some practical limits of optical loss, cross-talk noise among the switching nodes, and so on. A maximum of the path length differences occurs at the first link stage which consists of one prism as shown in Fig.2. By the use of two substrates with different refractive index, n_1 and n_2 , attached to together, we propose a method to reduce the optical path differences. Figure 5 shows a schematic diagram to describe the method. The optical path length inside the prism is given by $n_1\{W+2(W-x)\cos\theta\}$. Therefore, if a substrate with a higher refractive index of n_2 greater than n_1 is attached to the bottom of the upper substrate, we can make two path lengths identical. For a beam passing through the center position($x=W/2$) of the prism, the relation between n_1 and n_2 is derived by

$$\left(\frac{n_2}{n_1}\right)^2 = \frac{W}{f}(1 + \cos\theta) - 1. \quad (3)$$

When $W=f/2$, $\theta=60$ degrees, and $n_1=1.5202$ (BK7 glass), the SF11 glass with $n_2=1.762$ or sapphire with $n_2=1.759$ can be used as the lower substrate in order to reduce the path length differences.

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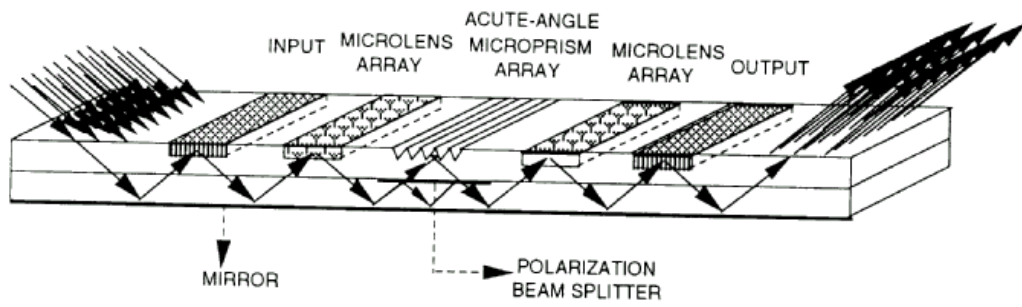


Figure 1. Planar optics for crossover interconnects.

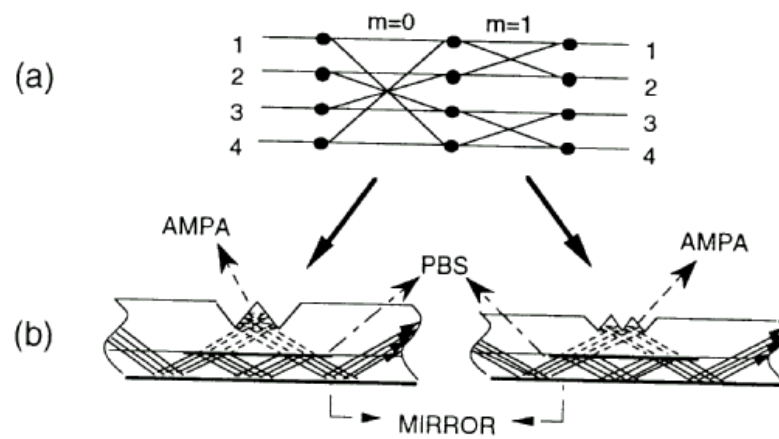


Figure 2.(a) Crossover network for 4 by 4 switching. (b) Planar optical implementation.

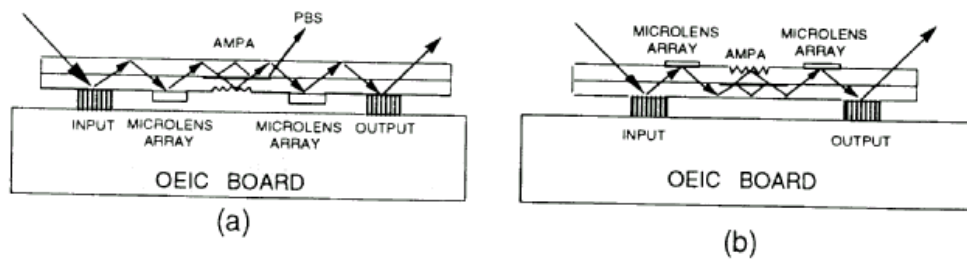


Figure 3. Two configurations for crossover interconnects, (a)type-A and (b)Type-B.

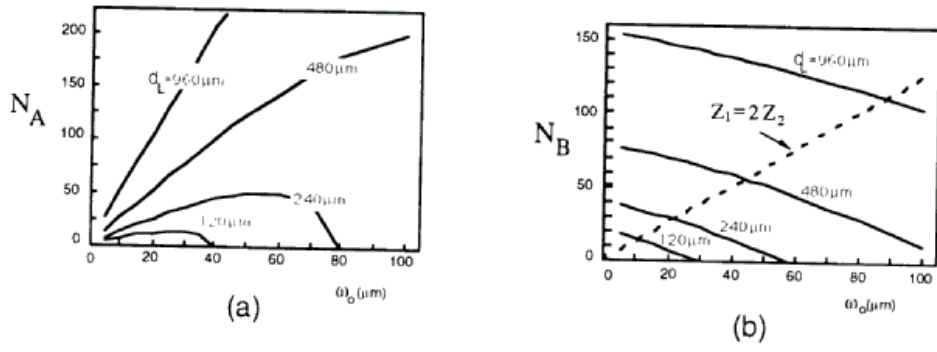


Figure 4. Interconnection capacities of type-A in(a) and Type-B in(b).

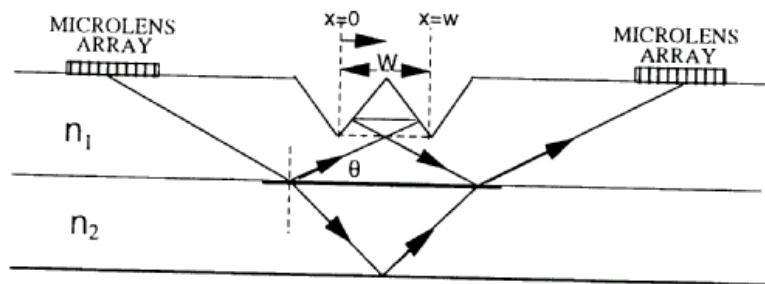


Figure 5. A configuration to reduce the path deferences between by pass and exchange routes.

제 4 장 마이크로 광학부품 설계 및 제작

제 4 장 마이크로 광학부품 설계 및 제작

광교환 및 광정보처리를 위한 3차원 광학계를 기존의 OEIC와 비슷한 규모로 꾸미기 위해서는 개개의 광배선용 광학부품들을 소규모로 제작하는 마이크로 광학기술이 요구되고 있다. 현재 보고되고 있는 마이크로 렌즈어레이 제작기술로는 PR melting 기법, Ion exchange 기법, e-beam writing system 이나 laser writing system을 이용하여 직접 원하는 패턴을 그리는 기법등 다양하게 개발되고 있으며, 각각이 응용분야에 따라 장단점을 갖고 있다.[1,2] 본 연구에서는 laser writing system(LAWS)을 이용하여 마이크로 광학부품을 제작하는 방식을 연구하였다.

그림 4-1은 laser writing system의 개략도이다. 광원으로는 공냉식 Ar ion laser (Uniphase-Model 2011, 파장:458nm, 최대출력:10mW)를 사용하였으며, raster scanning 방식으로 움직이는 XY stage (Klinger Optics-Model UT100, 0.1 μ m resolution, mm2000 Controller), 노출광원의 세기를 조절하기 위한 AOM (Acousto-optic modulator)과 DA 변환기(digital-to-analog converter, DT2801A), 그리고 초점면 정렬용으로 CCD Camera가 사용되었다. 레이저 광을 집속하는 렌즈로는 40배율(N.A.=0.65)의 대물렌즈를 사용하여, 초평면에 집속된 Airy disc의 크기를 약 2.3 μ m 정도로 얻었다. 광학부품들의 정렬은 Spindler & Hoyer사의 4-rod 마이크로 벤치 시스템을 사용하여, 정렬 상태의 높은 안정도를 얻었다. XY-stage 위에 놓인 sample holder는 진공선을 연결하여 샘플을 잡도록 하였다. AOM과 XY stage를 구동하기 위해 80486급 PC (486DX2-66, HDD-500MB, RAM 8MB)를 사용하였는데, 전체 구동 흐름도는 그림 4-2와 같다.

기판위에 약 6 μ m의 두께로 spin coating된 positive PR(AZ4562)과 AZ500MIF developer를 사용하여, 노출된 광에너지에 따른 PR의 식각 깊이를 그림 4-3과 같이 얻은 후, "LV.tbl" data conversion table file을 만든다.

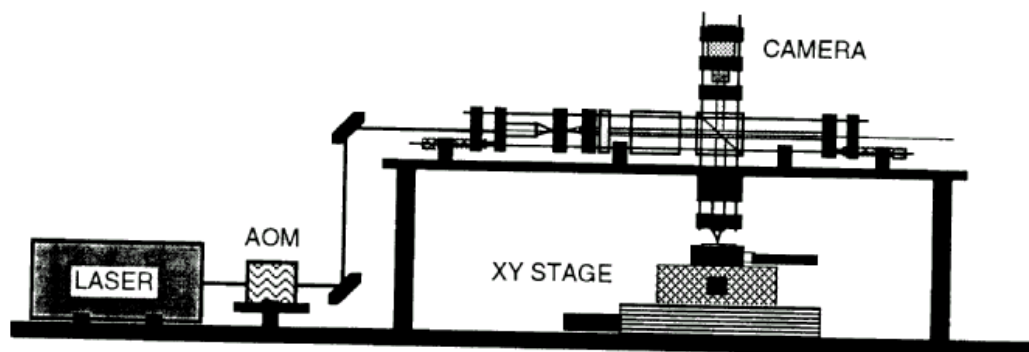


그림 4-1. 레이저를 이용한 마이크로 광학부품 제작장치인 laser writing system. AOM : 음향광 변조기(acousto-optic modulator).

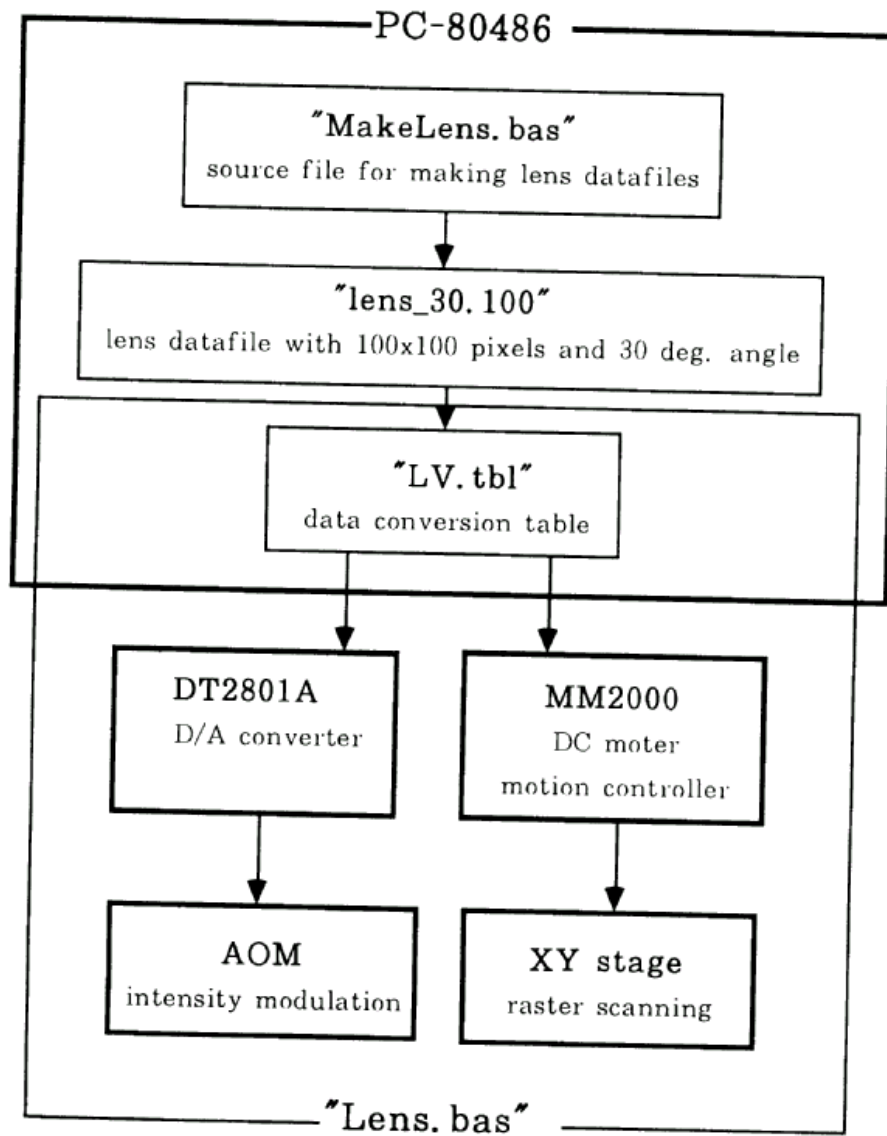


그림 4-2. 레이저를 이용한 마이크로 광학부품 제작장치의 구동 흐름도

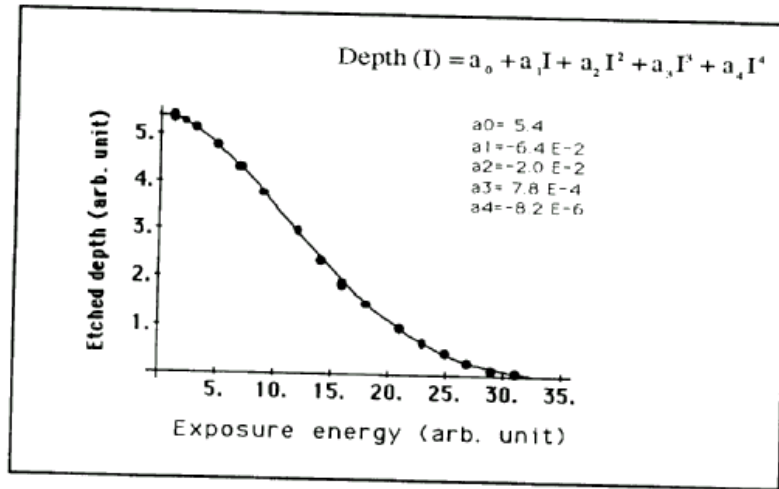


그림 4-3. AZ4562 positive PR의 노출광량에 따른 식각 깊이 특성.

이를 토대로, 설계된 렌즈의 profile을 계산하여("MakeLens.bas" source file) 렌즈에 대한 datafile("lens-30.100", angle=30 deg. dimension=100×100 μm^2)을 계산하고, AOM control용 DT2801A DA 변환기에 "lens_30.100"의 binary pixel 값을 voltage로 변환하여 가해주면, AOM에 의해 렌즈형태에 맞는 투과된 광의 세기가 PR위에 노출된다. 이때, XY stage는 raster scanning 방식으로 순차적인 이동이 AOM과 동기화 되어 움직인다. 이와 같이 렌즈의 형태에 맞게 노출된 PR기판을 현상함으로써, 단일렌즈 또는 동일한 여러개의 렌즈어레이를 얻을 수 있다.

그림 4-4는 laser writing system의 resolution을 측정하기 위해 선을 그린 실험결과이다. PR의 두께가 약 6 μm 이고 초점 맺힌 빛의 크기가 약 2.3 μm 인 경우에 약 3 μm 간격으로 그려진 선들이 나타나 있는데, 이를 토대로 본 시스템의 한계분해능이 약 3mm 정도가 됨을 알 수 있으며, 이보다 작은 간격으로 패턴을 형성하게 되면 정확한 선간의 구분이 안되게 된다. 이러한 resolution을 높이기 위해서는 대물렌즈의 N.A.를 보다 큰 것을 사용하고 임사광의 직경을 최대로 늘리면 된다. 그러나, 본 시스템의 제작목적이 수십 내지 수백 μm 크기의 surface-relief형의 refractive microoptic 부품을 제작하는데 있으므로, resolution 보다는 표면 상태 및 정확한 식각깊이 등이 더 중요한 요소로서, 40배의 대물렌즈를 사용하였다.

그림 4-5는 디지털 광신호 병렬정보처리에 필요한(8×8) 광원 어레이 발생용 Dammann Grating을 laser writing system으로 제작한 실험결과이다. 최소 선폭은 약 4 μm 이며, 한 주기를 50 μm 이 되도록 제작되어 있다. 식각면의 상태가 약간 거칠어서, 약간의 광손실을 야기시켰는데, 그림 4-6과 같은 설계된 (8×8) 배열에 근접한 점광원 어레이를 얻을 수 있었다.

그림 4-7은 laser writing system의 식각 선형성을 검증하기 위해 제작된 마이크로 프리즘으로, 크기는(100 μm)²이다. 좌측은 현상한 직후이고, 우측은 표면을 좋게 하기 위해 120도의 오븐에서 1분간 열처리한 결과이다. 전체모양을 그대로 유지한 채, 매우 좋은 표면상태를 얻을 수 있었다.

그림 4-8은 마이크로렌즈 어레이를 제작한 결과이다. 각각의 크기는 $(100\mu\text{m})^2$ 이고, 그림 4-7
에서와 같이 열처리한 후, 좋은 표면상태를 얻었다. 그리고, 이러한 렌즈의 집광결과가 그림
4-9에 나타나 있다.

그림 4-10은 마이크로 프레넬 렌즈이고, 집광실험 결과가 그림 4-11에 있다. 최소 격자간격
은 약 $3.5\mu\text{m}$ 로서, 제작장치의 분해능에 의해 제한된 수치이다. 그림 4-11에서 보면 중앙의
주집광 선모양 이외에 양쪽에 선형 집광띠가 나타났는데, 이는 그림 4-10에서 본 바와 같이
제작장치의 분해능 이하의 가장자리 격자들에 의한 효과이다.

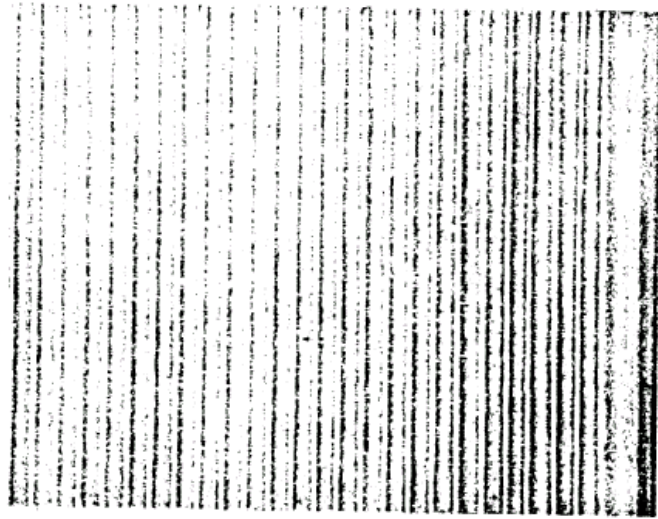


그림 4-4. Laser writing system에 의해 그려진 선모양. 선간격은 $3\mu\text{m}$ 임.

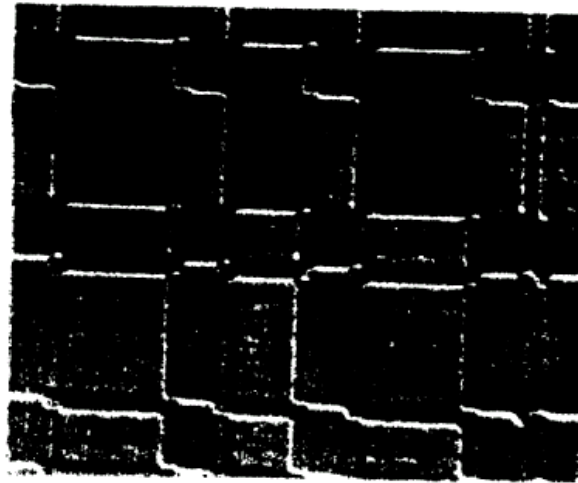
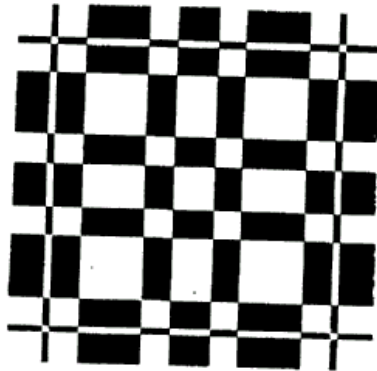


그림 4-5. 8×8 spot array generation용 Dammann grating의 설계 패턴(위)과 제작결과.

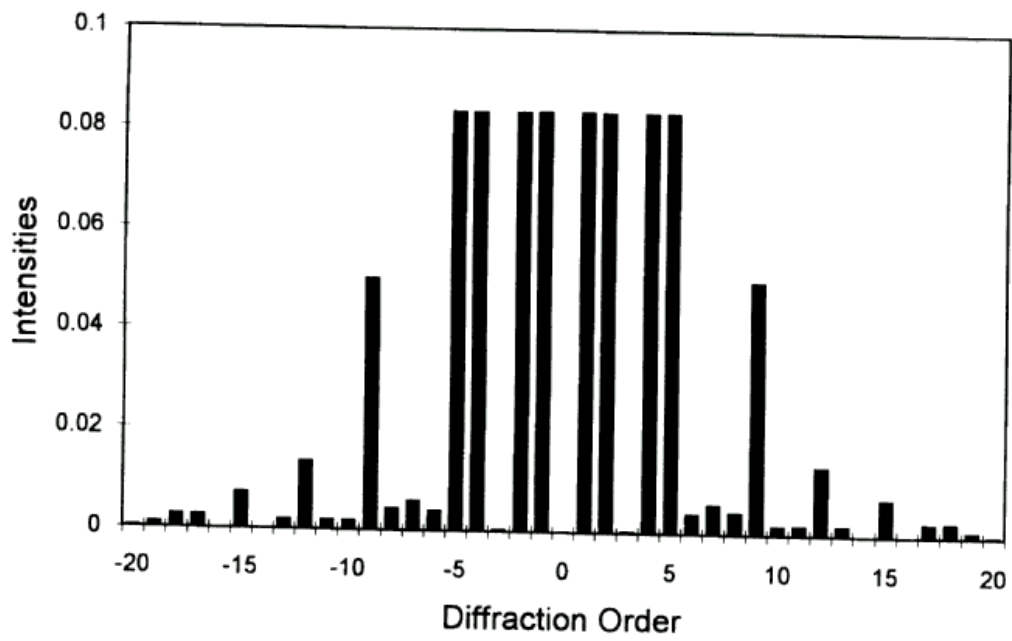


그림 4-6. 제작된 8×8 spot array generation용 Dammann grating의 설계값.

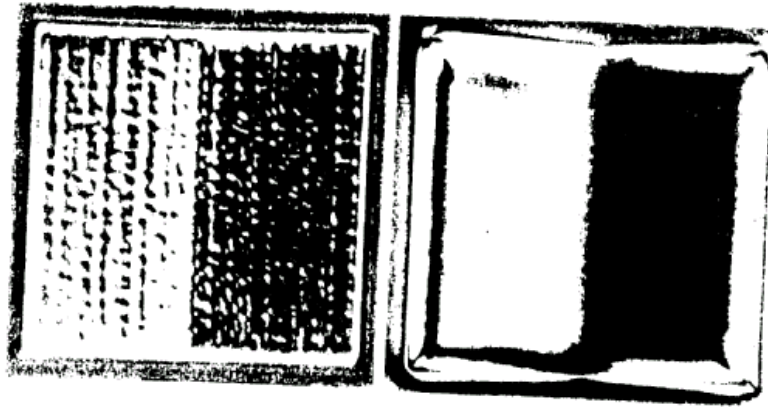


그림 4-7. 제작된 마이크로 프리즘 사진. 열처리하기 전(좌측) 및 열처리후의 모양.

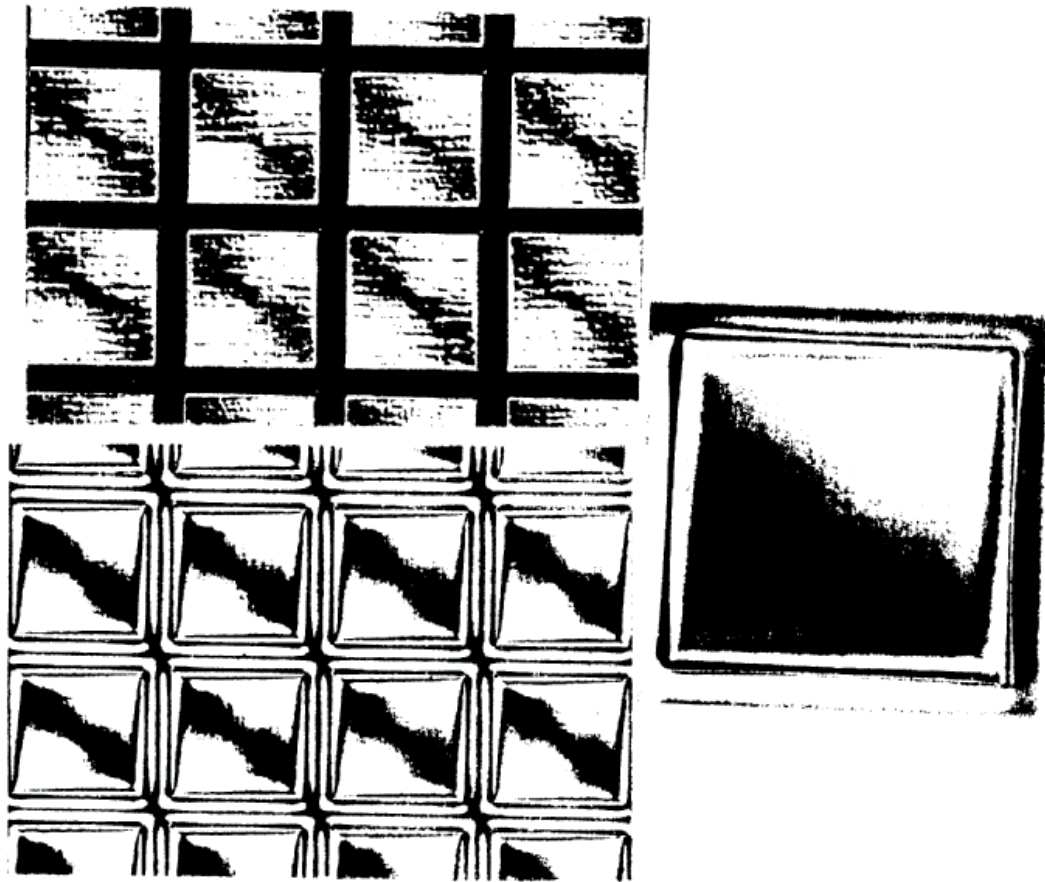


그림 4-8. 제작된 4×4 마이크로렌즈 어레이. 열처리하기 전 및 열처리후의 렌즈모양(좌측
위부터)과 확대사진.

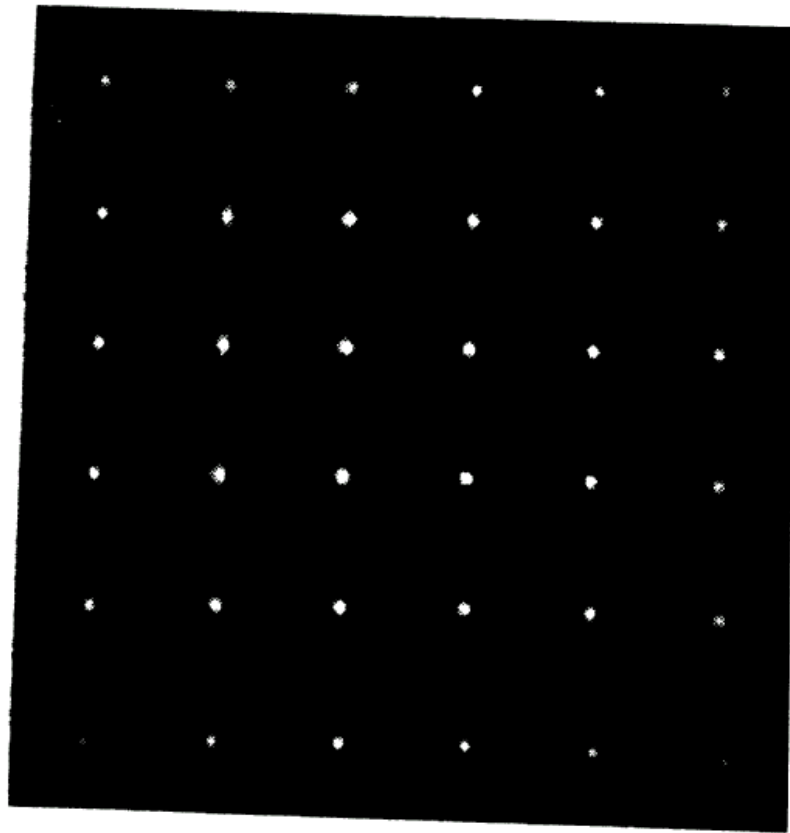


그림 4-9. 그림 4-8의 마이크로렌즈 어레이로부터 얻어진 초점패턴.

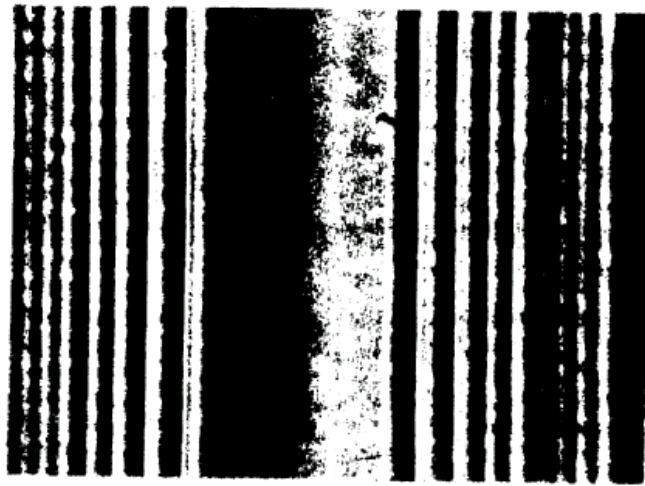
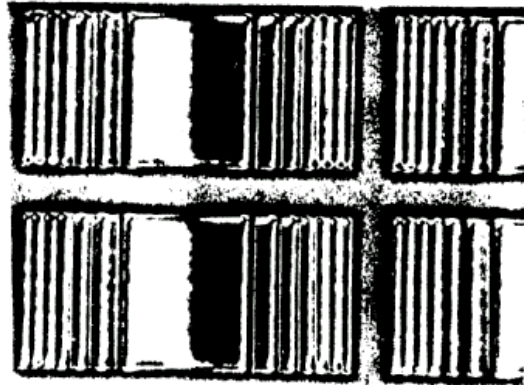


그림 4-10. 제작된 100mm×50mm 크기의 cylindrical Fresnel 마이크로 렌즈.

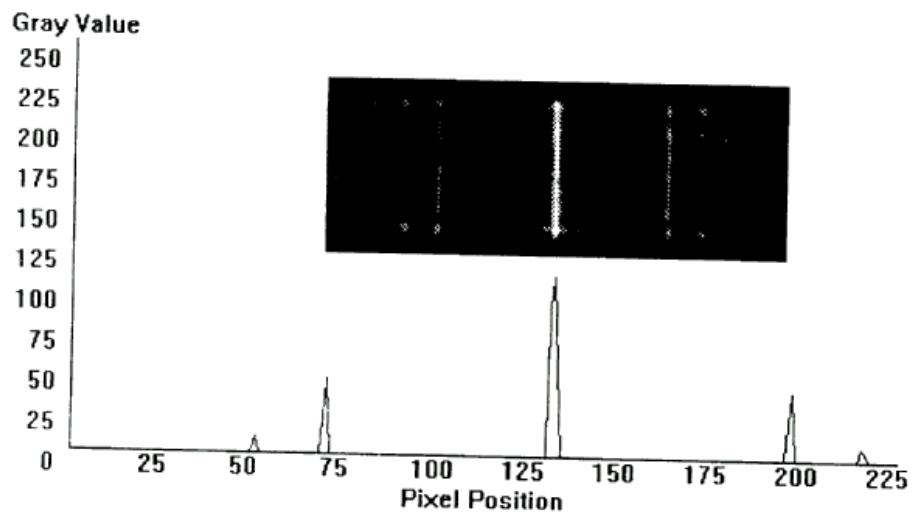


그림 4-11. Cylindrical Fresnel 마이크로 렌즈의 집광패턴.

이와 같이 제작된 마이크로 광학부품의 성능분석을 하기 위해서는 간접계 구성을 통하여 광학부품을 투과한 광파면 분석이 필요하다. 본 연구에서는 Mach-Zehnder 간접계를 이용한 phase shift 방식을 도입하였는데, 그림 4-12에 간접계의 개략도가 도시되어 있다. CCD 카메라의 상면에 그림과 같이 두갈래로부터 온 광파면을 서로 간섭시켜 간섭무늬를 측정한다. 먼저, 측정시료(microlens arrays)가 없는 경우에 아무런 간섭무늬가 측정되지 않도록 광학계의 경로차를 일치시킨다. PZT 거울은 한쪽 경로를 $\pi/2$ 만큼씩 변화시키기 위한 위상 지연용 부품으로 쓰였다. 따라서, PZT가 있는 광경로에 시료를 그림과 같이 위치시키고, 0, $\pi/2$, π 만큼씩 PZT 거울로 순차적으로 변화시키면서, 각각의 간섭무늬를 얻으면, 이들로부터 광파면의 외곡정도를 얻을 수 있다. 이러한 phase shift method를 수식으로 표현하면 다음과 같다.

세가지의 서로 다른 위상차에 의한 간섭무늬, I_A , I_B , I_C ,는

$$I_A(x, y) = I_b(x, y) + I_m(x, y) \cos[\varphi(x, y) + \pi/4 + ()]$$

$$I_B(x, y) = I_b(x, y) + I_m(x, y) \cos[\varphi(x, y) + \pi/4 + \pi/2]$$

$$I_C(x, y) = I_b(x, y) + I_m(x, y) \cos[\varphi(x, y) + \pi/4 + \pi]$$

여기서, 미지의 변수는 세개로서

$I_b(x, y)$; bias intensity

$I_m(x, y)$; modulation intensity

$\varphi(x, y)$; wavefront phase

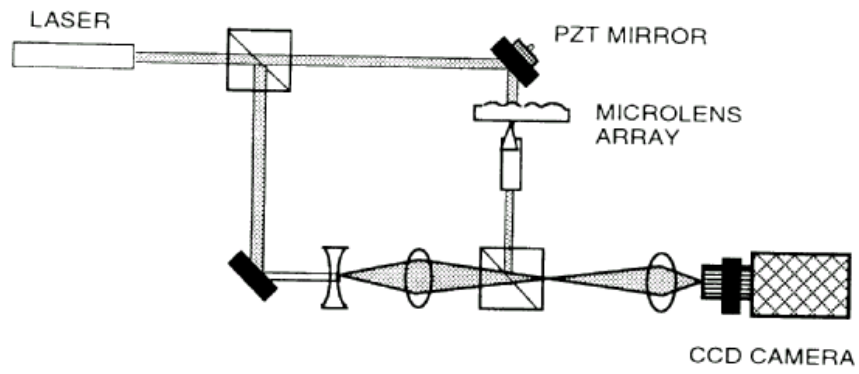


그림 4-12. 마이크로 렌즈 테스트용 Mach Zehnder Interferometer

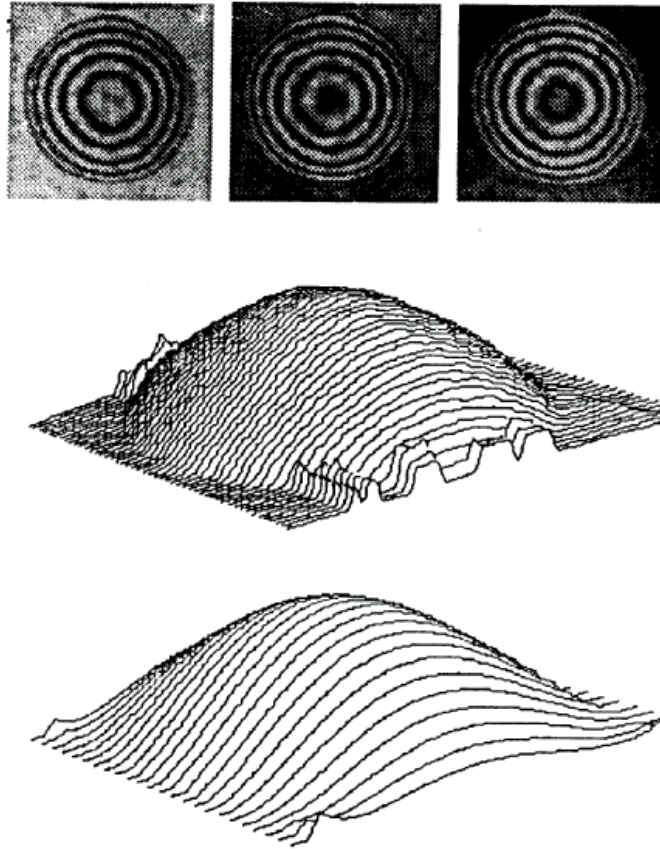


그림 4-13. 구면렌즈의 Interferogram들(위), 광파면(중앙), 그리고 polynomial fitting된 파면그림(아래).

등이다. 따라서, 위의 식으로부터 원하는 광파면에 관한 식은 다음과 같다.

$$\phi(x,y) = \tan^{-1}[(I_C - I_B)/(I_A - I_B)]$$

그림 4-13은 $\phi(x,y)$ 에 관한 위 식의 결과를 이용하여 구면렌즈 어레이의 광파면을 얻은 결과이다. 그림 4-12의 간섭계로부터 얻어진 세 개의 간섭무늬, (a),와 계산된 광파면의 3차원 그림, (b), 그리고, 분석을 위한 Zernick polynimial fitting 결과, (c), 등이 도시되어 있다. 렌즈의 크기는 직경이 약 $80\mu\text{m}$ 이었으며, 계산된 광파면의 3차원 그림에 나타난 가장자리 굴곡은 프로그램 작성시 렌즈표면과 주위기관과의 경계면 처리가 완전치 못한데서 온 오류로 보인다. 앞으로 이러한 프로그램상의 오류는 수정될 예정이다.

그림 4-14는 비축광의 결상을 위한 토릭(toric)렌즈의 제작결과이다. 입력광의 입사각도(θ)가 30도인 경우로서, 수직방향의 지름이 수평방향의 것보다 $(1/\cos\theta)$ 만큼 길다. 그림 4-15(a)에 간섭무늬, (b)는 계산된 광파면의 3차원그림, 그리고, (c)에 Zernick Polynimial fitting 결과등이 도시되어 있으며, 이와 같은 비축렌즈에 의해 맺혀지는 초점의 모양이 그림 4-15에 나타나 있다. 그림 4-15의 맨 좌측 사진에서 보는바와 같이 설계된 값인 30도의 각도로 빛이 입사할 때만이 diffeaction limited 초점 크기를 얻을 수 있으며, 수직 입사광에 대해서는 COMA 및 비점수차에 의해 X-축(중앙사진) 또는 Y-축(우측사진) 방향으로 상이 퍼지게 된다.

Laser writing system은 위와 같은 동일한 모양을 갖는 마이크로 렌즈어레이를 만드는 경우뿐만 아니라, 서로 다른 종류의 광학부품을 동일기관에 제작하는 것도 가능하다. 한 예로서, 제작된 4개의 비축렌즈 어레이로 된 마이크로 렌즈어레이의 간섭무늬 및 측정결과를 그림 4-16에 도시하였다. 4개 렌즈들의 중심축이 가운데로 몰려있는 모습이다. 이러한 렌즈어레이는 제 2장의 그림 2-3에서 살펴 본, perfect shuffle interconnection용 렌즈어레이와 동일한 역할을 수행할 수 있다.

그런데, laser witing system을 이용한 제작방식은 그림 2-3의 구도와 관련하여 논의되었던 system packaging 또는 alignment 문제를 해결하여 줄 수 있는 장점을 갖게 된다. 즉, 4개의 렌즈가 동일한 제작과정에서 동일기판위에, 마치 하나의 렌즈를 만드는 경우와 같이 이루어지므로 각 렌즈간의 alignment 및 동질성이 자동적으로 보장되게 된다. 그림 4-16의 각 렌즈 크기는 $(100\mu\text{m})^2$ 이었으며, 렌즈축들은 중심방향으로 $25\mu\text{m}$ 씩 이동되어 있는데, 두번째 그림에서 보는 바와 같이 초점들의 간격과 동일하다. 그리고, 각 렌즈들을 통과한 직후의 광파면을 보면, 3번째 그림과 같은 모양으로 동일하게 측정되어 진다.

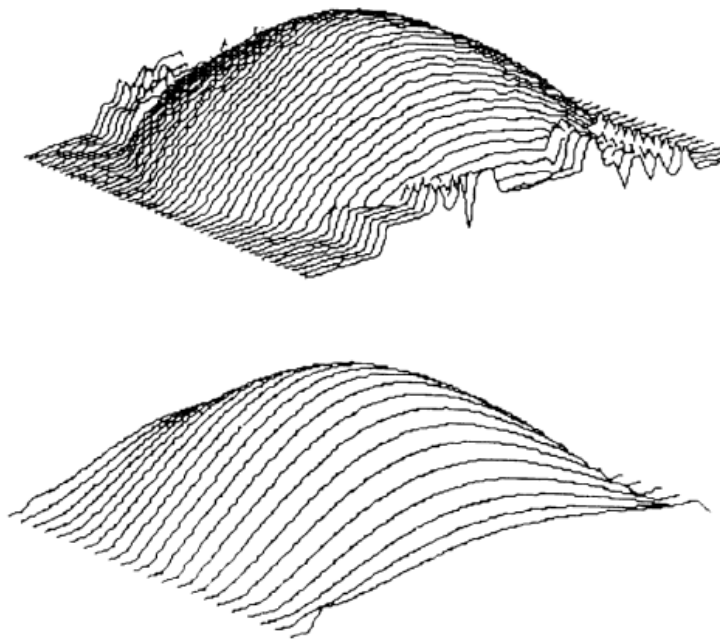
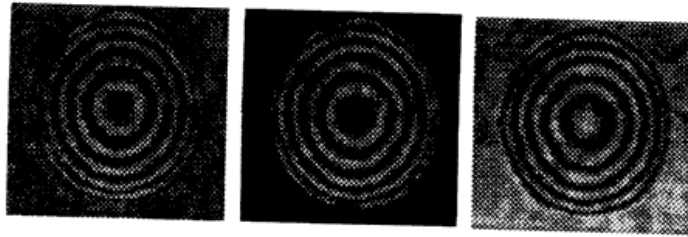


그림 4-14. 비구면(toric)렌즈의 Interferogram들(위), 광파면(중앙), 그리고 polynomial fitting된 파면그림(아래).

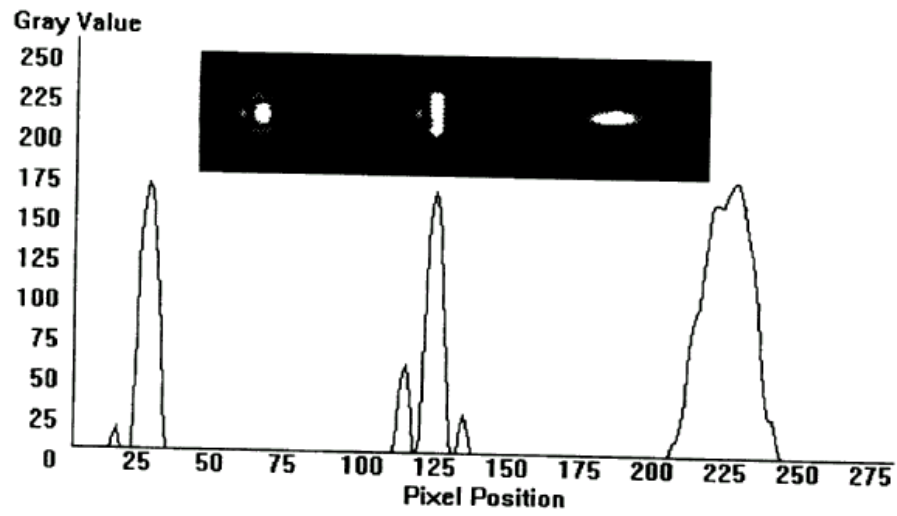


그림 4-15. 그림 4-15에 있는 비구면렌즈의 초점모양. 30도로 입사할 때(좌측), 수직으로 입사할 때 초점면에 Y-축으로 맺힌 모양(중앙) 및 X-축 경우(우측).

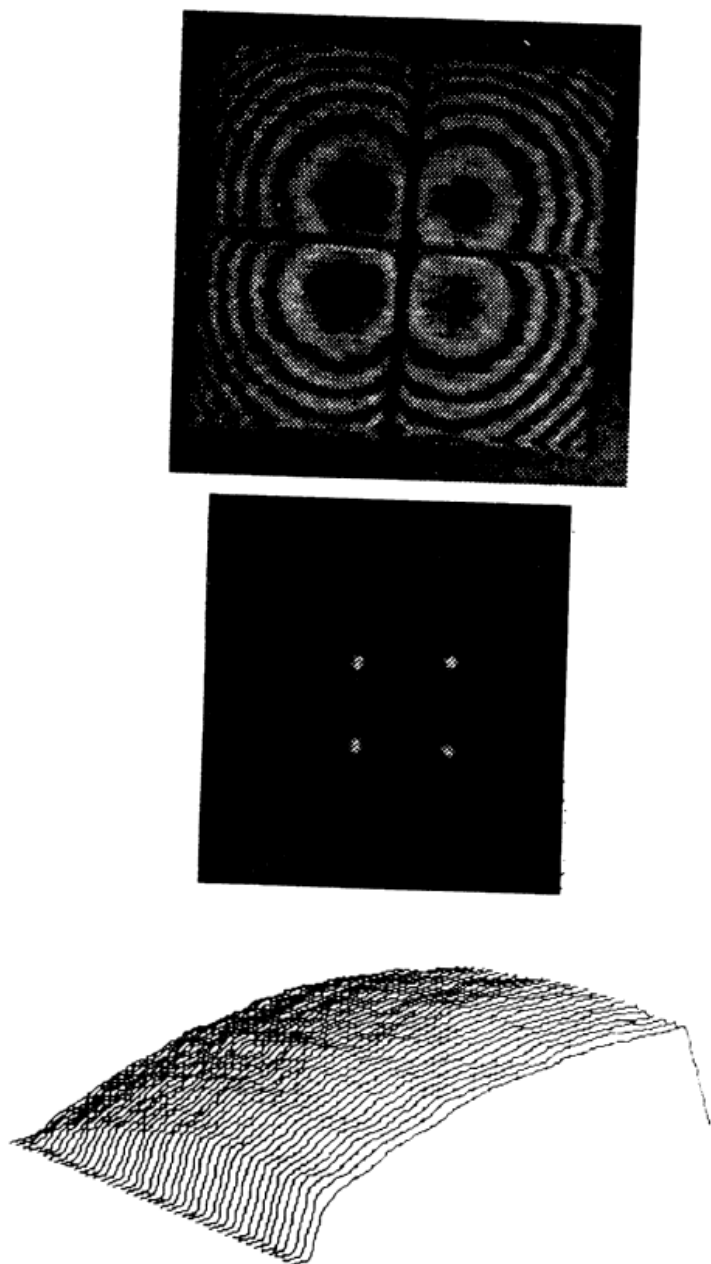


그림 4-16. Perfect shuffle interconnection용 2×2 비축 마이크로 렌즈 어레이.
Interferogram(위), 초점(중앙), 광파면(아래).

제 5 장 결 론

제 5 장 결 론

본 과제에서는 지금까지 제안되어 왔던 광스위칭 네트워크 용 자유공간 광학계(free-space photonic switching network system)를 한장의 광학기판에 집적하기 위한 마이크로 광신호 연결기술 개발과, 이를 기반으로 한 평면광학적 연결구도(planar optical interconnection schemes)창출을 목적으로 수행되고 있다.

당해년도 연구결과를 크게 두가지로 분리할 수 있는데, 첫째는 마이크로 렌즈 어레이, 마이크로 프리즘 어레이, CGH(computer-generated hologram)등을 제작하기 위한 laser direct writing(LDW) 장치의 구성이며, 둘째는 3차원 crossover 및 perfect shuffle등의 다단계연결망(multiple-stage interconnection networks) 구조를 갖는 평면광학계(planar optics)의 고안 및 성능분석이다.

마이크로 광학부품을 제작하기 위한 Laser writing system 장치는 $0.1\mu\text{m}$ 정도의 positionning resolution과, 1mm 정도까지의 diameter를 갖는 렌즈어레이, 프리즘, grating 등을 제작할 수 있었다. 성능평가용 간섭계와 프로그램을 구성하여 제작된 마이크로 광학부품들을 분석한 결과, 아직은 실용적인 수준($\text{Strehl ratio} > 0.8$)까지는 못 미치지만, 약간의 보완을 계속하게 되면 가능하리라 본다. 그리고, 이러한 장치는 기존의 광학부품제작 방식으로는 불가능하였던, 임의의 surface profile을 갖도록 제작하는 것이 가능하게 만들어 주었다. 한 예로, aspherical 또는 4개의 off-axis 마이크로 렌즈어레이를 제작할 수 있었다.

이러한 마이크로 광학기술을 기반으로 하여, 광스위칭 네트워크를 구현하기 위한 평면 광학적 광연결 방식을 제안하였다. Perfect shuffle interconnection과 crossover interconnection 등의 planar optical scheme이 제안 및 검증되었으며, 기존의 자유공간 광학계의 장점을 최대한으로 살린채, 문제점을 극복할 수 있다는 결론을 얻을 수 있었다.

따라서, 마이크로 광학과 평면 광학적 광신호연결방식등을 이용한 광스위칭 네트워크 구현에 관한 본 연구는 시스템의 정렬(alignment) 안정성과 OEIC와 직접 접속될 수 있는 규모로 광연결시스템(optical interconnection system)을 구현할 수 있게 되어, 광 신호접속 뿐만 아니라 광교환용 다단계연결망 구조를 갖는 광 스위칭 네트워크의 창출 가능성을 한층 구체화 시켰다고 할 수 있다.

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