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Diffractive microlenses for fiber optic array interconnects

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The University of Arizona, 1992
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Date: 7/20/92
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ABSTRACT

The design, fabrication, and testing of diffractive microlens arrays for use in fiber optic interconnects is presented. Advantages of using diffractive microlenses for fiber interconnects instead of refractive microlenses are discussed. A theoretical discussion of diffractive lens operation including the effects of chromatic aberration on fiber coupling is given, along with equations for mask generation. From these equations, a set of masks to fabricate an array of four phase level diffractive microlenses was produced. Experimental procedures for the fabrication of diffractive microlenses from this mask set are presented. Arrays of binary lenses in photoresist with depth errors of less than 4% were fabricated and test results are given. A novel fiber optic tap utilizing both surface relief microlenses and a volume holographic element is demonstrated. In addition, a fiber array coupler using silicon V-grooves and an array of diffractive lenses is also demonstrated.
CHAPTER 1
INTRODUCTION

The increasing need for high speed processing systems has led to the development of new technologies to help answer this requirement. As a result, electronic gate feature sizes have shrunk while the resulting gate switching speeds and on chip packing densities have increased. The interconnection of these gates, however, has become a limiting factor as electronic interconnects approach their fundamental limits. This is due to the increased power consumption, impedance mismatching, crosstalk, and dispersion problems caused by increasing the packing densities and speed of electronic gates.

The use of optical interconnects may alleviate the interconnection bottleneck experienced with electronic interconnects. Optical interconnects offer several attractive advantages. For example, since photons do not interfere with each other, optical interconnects may cross without signal interference. Optical interconnects do not exhibit the capacitive loading and mutual interference effects present in electronic interconnects. Also, optical interconnects can made out of plane, eliminating mechanical point to point interconnects, and allow for a high degree of fan-out between processing elements.

Interconnects, in general, are constructed in a hierarchal fashion. The type of interconnect used depends upon the interconnect level and the specific architecture being implemented. Optical interconnects have been proposed for use at the chip, board, and rack levels in many different types of
In all of these schemes, the optical interconnect generally consists of a source, detector, and a channel which provides the actual interconnection between the source and detector. Sources and modulators such as laser diodes, LEDs, and spatial light modulators exist in array form. Likewise, high speed detectors exist in array formats. It is therefore necessary to develop interconnect channels that can exploit the connectivity of multiple sources and detectors if the massive parallelism of optics is to be fully utilized.

An interconnection component that has the ability to exploit the parallel nature of two dimensional sources and detectors is the microlens array. Many types of refractive microlens arrays have been demonstrated for this purpose. For example, Iga et al\textsuperscript{7} proposed a method of making arrays of distributed index lenses by diffusing dopants into a substrate through a mask. These lenses were then employed in a concept called stacked planar optics\textsuperscript{8} which utilized two dimensional arrays of microlenses stacked in series with other two dimensional components to build compact, optically interconnected systems. Another type of microlens array, introduced by Borrelli et al\textsuperscript{9}, used a photothermal technique to produce microlenses in photosensitive glass. The glass was first exposed with UV radiation through a photomask and then heated. The exposed regions swelled during heating to form spherical surfaces in the glass. Refractive microlens arrays have also been produced using a plasma-activated chemical vapor deposition (PCVD) process.\textsuperscript{10} In this method, holes, which are etched into a glass substrate, are covered and filled with a film that is deposited onto the glass substrate by the PCVD process. The film layer is then ground down to the surface of the glass plate to form lenses within the
High efficiency surface relief diffractive microlens arrays have also been demonstrated. Diffractive microlenses offer greater design flexibility than possible with refractive microlenses because they are computer generated. Diffractive microlenses can thus be designed to form arbitrary wave fronts and can correct for aberrations. Arrays of diffractive microlenses can also be made on any shape grid, with varied pitch and size, and with fill factors up to 100% which increase source to detector coupling efficiencies. Another advantage of the inherent design flexibility offered by diffractive lenses is the ability to construct nonhomogeneous arrays of elements. Each element on a lens array can be designed differently and perform a different function than its neighbor allowing for greater system flexibility.

Advantages offered by diffractive microlenses also stem from their method of fabrication. Diffractive microlenses are fabricated with the same integrated circuit processing techniques used to produce electronic devices. Alignment of microlenses to electronic components may thus be done during fabrication to produce hybrid electro-optical components that are pre-aligned. Diffractive lenses etched directly onto vertical surface emitting lasers, for example, have already been reported. The precision and resolution available from integrated circuit processing techniques may also be employed to realize integrated diffractive elements using double sided wafer technology.

An application of microlenses of particular interest in optical interconnects is the coupling of light into, out of, and between arrays of optical fibers. Many demonstrations of fiber interconnects utilizing refractive
Microlenses have been presented in the literature. In these demonstrations, the microlenses usually have been utilized to couple sources into fibers. Occasionally, microlenses have been instead used to couple light between fibers. Such an example is a 2x2 optical fiber tap array constructed using two microlenses to collimate the output from two fibers. The collimated beams were reflected by a partially transparent mirror to a second set of microlenses which coupled the signal back into another set of fibers. Recently, a single mode fiber array coupler was constructed using a 1x4 array of refractive microlenses. Holographic microlenses have also been suggested for fiber coupling.

Surface relief diffractive microlenses have also been used for optical fiber interconnects. The most common application again is fiber to source coupling. A recent example of this is a novel laser coupling module which employed a diffractive lens to couple light from a laser diode into a single-mode fiber. The use of the diffractive lens allowed the coupler to be made into a compact, light-weight package. Single diffractive lenses have also been used to couple light between fibers in a pulse delay system.

Instead of using only single microlenses for fiber coupling, the design flexibility of diffractive lenses could be used to efficiently couple light between arrays of sources and fibers or between fiber arrays. It has been suggested that the use of fiber arrays is better suited for long distance high density interboard connections than free space interconnects which are more appropriate for localized interconnections. An application of diffractive microlens arrays for such an interconnect scheme is the fiber array tap illustrated in Figure 1-1. This
Figure 1-1 Fiber array tap.
element acts as an interface between free space and guided-wave channel interconnects. Light from an array of fibers is first collimated with a diffractive microlens array. A portion of the fiber signals is then tapped by a volume substrate holographic element which couples light into a substrate at an angle greater than the critical angle. The tapped signals travel laterally to different processors on a computer board via total internal reflection. The untapped signals are then coupled back into another fiber array with a second diffractive microlens array.

A novel aspect of this fiber tap is the combination of surface relief/volume diffractive elements for this use. Each element in the tap performs the function that it is suited for best. For example, the surface relief diffractive lens performs the functions of in line collimation and focusing. Volume elements can not be made to do these functions because the efficiency of volume elements decreases dramatically on axis. On the other hand, the volume element is better suited to tap the signal as shown because it can realize the high spatial frequencies required to diffract light beyond the critical angle of the substrate. These spatial frequencies would be difficult to achieve with multi-phase level surface relief gratings.

It is the goal of this thesis to design, fabricate, and test arrays of surface relief diffractive microlenses for use in optical interconnects such as the described fiber tap. This thesis is arranged in five chapters. Chapter 1 provided an introduction to optical interconnects and a brief review of microlens arrays. Chapter 2 explores fiber parameters that need to be considered when designing a lens for use in fiber interconnects. Chapter 3 is a discussion of the
theory of diffractive lenses. Chapter 4 presents the experimental fabrication procedures used to fabricate binary diffractive microlens arrays. The experimental performance of the microlenses is given in chapter 5 along with a demonstration of a fiber tap and a fiber array coupler.
CHAPTER 2
LENS PARAMETERS FOR FIBER INTERCONNECTS

The fiber optic tap presented in chapter one utilizes diffractive lenses to
couple light into and out of fibers. This chapter first reviews important fiber
parameters that need to be considered when designing lenses for this purpose.
The effects of lens size and chromatic aberration on fiber coupling efficiency are
then explored.

2.1 Optical Fibers

The characteristics of optical fibers must be taken into account when
designing a lens to be used for fiber interconnects. Important fiber parameters
to consider are numerical aperture (NA), normalized frequency parameter, and
output irradiance profile.\textsuperscript{25}

Optical fiber is designed with the index of the core being greater than the
index of the cladding so light will propagate down the fiber through total internal
reflection. The largest acceptance angle of the fiber, $\theta$, can be defined in terms
of the fiber's NA,

$$NA = \sin\theta = \sqrt{n_1^2 - n_2^2}$$

where $n_1$ is the index of refraction of the fiber core, and $n_2$ is the index of
refraction of the fiber cladding. Just as for any optical component, the NA of the
fiber is a measure of its light gathering power.

Another important fiber characteristic to consider is the normalized
frequency parameter or V number. The V number determines the number of
modes supported by the fiber and is given as

\[ V = \frac{2 \pi a}{\lambda} \sqrt{n_1^2 - n_2^2} \tag{2.2} \]

where \( a \) is the fiber core radius. When \( V \) is less than 2.405, only a single-mode, the HE_{11} mode, will propagate down the fiber. It is the single-mode region of operation that is of interest for long distance fiber communications applications because of the absence of modal noise and also the smaller dispersion effects than present in multi-mode fiber.

The HE_{11} mode has an irradiance distribution which is very close to Gaussian. Thus the mode profile of a single-mode fiber can be approximated by a Gaussian with \( 1/e^2 \) spatial width given by

\[ w_0 = d \left( 0.65 + 1.619 V^{-1.5} + 2.879 V^{-6} \right) \tag{2.3} \]

where \( d \) is the fiber core diameter.

The fiber used in this thesis experiment was Newport F-SV single-mode fiber which has a core diameter of 4 \( \mu \)m, NA=0.1, and operating wavelength of 633 nm. The \( V \) number of this fiber as calculated from Equation 2.2 is 1.9852. The resulting \( w_0 \) calculated from Equation 2.3, is 5.103 \( \mu \)m. It is interesting to note that the ratio of \( w_0 \) to \( d \) is approximately 1.28. This indicates that the size of the Gaussian spot size must be considered when coupling light into a single-mode fiber, as will be shown.

### 2.2 Single-mode Fiber Coupling

The coupling efficiency between two arrays of fibers using a lens may be examined using the analysis of Wagner and Tomlinson. In this analysis, the
power coupling efficiency, $T$, between a source and receiving fiber is calculated in the exit pupil plane by solving,

$$T = \left| \int \psi_s \psi_r L \, da \right|^2$$ \hspace{1cm} 2.4

where $\psi_s$ is the far field distribution of the source fiber mode pattern, $\psi_r$ is the far field distribution of the receiving mode pattern, and $L$ is the coherent optical transfer function (OTF). The coherent OTF describes the system aberrations and is given by

$$L = \exp[-jkW(\hat{x})]$$ \hspace{1cm} 2.5

where $W(\hat{x})$ is the wave front aberration in the exit pupil plane in normalized coordinates.

If a Gaussian source and receiving far field distribution is substituted into Equation 2.4 along with Equation 2.5, the result is

$$T = \left| \frac{2\sigma}{\pi} \int \exp[-(1+\sigma^2) \hat{x} \cdot \hat{x}] \exp \left[ -\frac{j2\pi}{\lambda} W(\hat{x}) \right] d\hat{x} \right|^2$$ \hspace{1cm} 2.6

where $\sigma$ is defined as the mode mismatch parameter between the radii of the source and receiving fiber modes. Explicitly, $\sigma$ is given by the ratio

$$\sigma = \frac{\omega_s}{\omega_r}.$$ \hspace{1cm} 2.7
Setting \( W(\vec{x}) \) equal to zero and solving first for the case of a lens with no aberrations, the integral in Equation 2.6 may be converted into polar coordinates,

\[
T = \left| \frac{2 \sigma}{\pi} \int_0^{r_{\text{max}}} \exp[-(1+\sigma^2) r^2] 2\pi r \, dr \right|^2.
\]

2.8

\( R_{\text{max}} \) is the maximum radius of the exit pupil as determined by \( h \), the aperture stop radius,

\[
r_{\text{max}} = \frac{h}{\omega_s}.
\]

2.9

To maximize coupling between the source and receiving fibers, the mode profile of the source must match the mode profile of the receiver. Setting \( \sigma \) equal to one to satisfy this condition, and solving Equation 2.8 gives the coupling efficiency between the two fibers,

\[
T = \left[ 1 - \exp(-2 r_{\text{max}}^2) \right]^2.
\]

2.10

Equation 2.10 may be rewritten in terms of the NA of the source fiber and lens NA. With the aperture stop at the lens, the lens NA is defined by

\[
\text{NA}_{\text{lens}} = \frac{h}{R'},
\]

2.11

where \( R' \) is the distance from the exit pupil plane to the image plane. For a Gaussian mode, the NA of the source fiber defined on the receiver side of the
Assuming a one to one imaging condition, the magnification (m) is equal to one. Substituting Equations 2.11 and 2.12 into Equation 2.9 and solving for \( r_{\text{max}} \) yields

\[
\frac{r_{\text{max}}}{R} = \frac{\frac{\omega_s}{R}}{\frac{m \omega_s}{R}} = \frac{NA_{\text{lens}}}{NA_{\text{fiber}}}.  
\]

The coupling efficiency may now be written in terms of the lens NA,

\[
T = \left[ 1 - \exp\left( -2 \left( \frac{NA_{\text{lens}}}{NA_{\text{fiber}}} \right)^2 \right) \right]^2.  
\]

The NA of the lens will effect how efficiently light from the source fiber is coupled into the receiving fiber. If the lens does not collect all the light from the source, the coupling efficiency between the source and receiving fibers will decrease. From section 2.1, it was shown that the mode diameter at the fiber end was 1.28 times larger than the fiber core. Hence the NA of the lens needs to be larger than the NA of the source fiber to capture all of the signal for efficient coupling. Figure 2-1 is a plot of Equation 2.14 showing this effect. At a lens NA to fiber NA ratio of 1.6, transmission loss is less than 0.06 dB and coupling efficiency is approximately 99%.
Figure 2-1 Effect of lens NA on fiber coupling.
2.3 Chromatic Aberration

Despite the advantages of diffractive lenses discussed in the previous chapter, they are dispersive and suffer from large chromatic aberration. The effect of this chromatic aberration on fiber coupling must be examined if diffractive lenses are to be used in fiber applications.

The focal length of a diffractive lens is a function of wavelength and varies according to: \[ f(\lambda) = \left( \frac{f_o}{\lambda_0} \right) f_o \] where \(\lambda_0\) and \(f_o\) are the design wavelength and focal length of the lens, respectively, and \(f(\lambda)\) is the focal length at a wavelength \(\lambda\). The transmittance function of this diffractive lens is given by: \[ t(r) = e^{-\frac{\pi}{\lambda_0 f_o} r^2} \]

When illuminated by a monochromatic plane wave of wavelength \(\lambda\) the amplitude transmitted by the lens is approximately, \[ U_o(r) = e^{-j \frac{\pi}{\lambda f(\lambda)} r^2} \]

This may be rewritten using Equation 2.15 as \[ U_o(r) = e^{-j \frac{\pi}{\lambda_0} r^2} e^{-j \frac{\pi}{f_o} \left( \frac{1}{\lambda_0} - \frac{1}{\lambda} \right) r^2} \]

The phase change in waves due to chromatic aberration is thus, \[ \text{phase change} = \frac{\pi}{\lambda_0} r^2 - \frac{\pi}{f_o} \left( \frac{1}{\lambda_0} - \frac{1}{\lambda} \right) r^2 \]
This is a maximum at the aperture edge, \( r = A/2 \),

\[
\Delta \varphi (r) = \frac{A}{8 (F\#)} \left( \frac{1}{\lambda_0} - \frac{1}{\lambda} \right) r^2.
\]

Returning back to the analysis of section 2.2, the coupling efficiency between two fibers in terms of lens aberration was given as,

\[
T = \left| \frac{2\sigma}{\pi} \int \exp[-(1+\sigma^2) \bar{x} \cdot \bar{x}] \exp[-j2\pi \int \frac{W(x)}{\lambda} dx]^2 \right|.
\]

If the chromatic aberration is treated as a defocus term, the error caused by it can be considered as a longitudinal fiber misalignment and,

\[
W(\bar{x}) = W_{020} (r^2).
\]

Solving the above integral yields the effect of defocus on coupling,

\[
T = \frac{1}{1 + \left( \frac{\pi}{\lambda} \frac{W_{020}}{\lambda} \right)^2}.
\]

Figure 2-2 is a plot of this function for a plus/minus 10 nm shift from a center wavelength \( \lambda_0 \), a reasonable range of laser diode wavelength variation. Three different center wavelengths (780nm, 1330nm and 1550nm) are plotted. As the wavelength increases, the aberration becomes less severe and so do the associated coupling losses.
Figure 2-2 The effect of chromatic aberration of diffractive lenses on fiber coupling for three different wavelengths. Lens F#=3.125, aperture=500 μm.
2.4 Output Beam Propagation

The lens discussed as a coupler above must also be used to "collimate" the output of a fiber in the fiber tap. Since the output of the fiber is Gaussian, it will expand as it propagates away from the lens. If arrays of lenses and fibers are to be used for interconnects, beam expansion must be minimized to reduce optical crosstalk between neighboring fibers. Beam expansion is determined by the microlens focal length and diameter, which in turn depend upon the spacing between fiber centers.

The minimum possible fiber spacing in an array will be equal to the diameter of the fiber cladding, a typical value being 125 μm. Assuming that the output of the fiber fills the lens, the ratio of lens diameter to beam waist as a function of distance may be calculated as in Figure 2-3 for several different lens diameters. It is clear from the figure that the beam divergence, and thus crosstalk between channels, increases with reduced lens diameter. Hence, a microlens diameter of 500 μm was chosen to minimize this problem. Table 2-1 summarizes the resulting lens parameters that were calculated based on these factors.

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<th>diameter</th>
<th>500 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>.16</td>
</tr>
<tr>
<td>focal length</td>
<td>1.5625 mm</td>
</tr>
<tr>
<td>F#</td>
<td>3.125</td>
</tr>
</tbody>
</table>

Table 2-1 Microlens design parameters.
Figure 2-3 Beam expansion versus propagation distance for three different lens diameters.
The advantages of using diffractive lenses and the intended application for them have been discussed in the preceding chapters. In this chapter, the discussion will focus on the basic operating principles and fabrication methods of diffractive lenses. It is necessary to point out there is a hierarchy of components that can be thought of as diffractive lenses. The operating effect of these components can be based on diffraction by a Fresnel zone plate (FZP). The operating principal of the FZP is thus considered first. This theory is then extended to discuss binary diffractive lenses, kinoforms, and multilevel approximations to the kinoform. The diffraction efficiency and method of fabrication of diffractive lenses are also discussed.

3.1 Basic Principles

For a general case, a diffractive lens illuminated by a plane monochromatic wave (Figure 3-1) splits the incoming wave into many spherical waves or diffraction orders. The foci of the lens occur where these diffracted orders cross the optical axis. The diffraction angle of each order is controlled by the period of the lens and may be calculated using the grating equation. The amount of light directed into each of these orders is in turn determined by the shape of the lens which modulates the phase of the incoming wave.

The principle of operation of a diffractive lens may be better understood by first examining the zone construction of Fresnel. A monochromatic
spherical wave emitted from a point source at S and traveling to a point P
maybe divided into circular zones. If the the radius of each zone is given as \( r_1, r_2, r_3, \ldots, r_m \), then the distance from the edge of each zone to point P is given
as \( f + \lambda/2, f + 2\lambda/2, f + 3\lambda/2, \ldots f + m\lambda/2 \) as shown in Figure 3-2. These zones
are defined as Fresnel half period zones and there is a \( \lambda/2 \) optical path
difference between successive zones. From Huygen’s principle, each point on
a spherical wave front maybe considered a source for a secondary wavelet of
the same phase traveling to a point P on axis. The phase of the wavelets
arriving at point P from points within successive zones will differ in phase by \( \pi \)
due to the \( \lambda/2 \) optical path difference introduced between successive zones.
This means the amplitude of light reaching point P from successive zones will
alternate in sign. The total light amplitude at point P is the sum of the
amplitudes of light coming from each zone,

\[
A = A_1 - A_2 + A_3 - \ldots + (-1)^{m-1} A_m
\]

where \( A \) is the total light amplitude at P and \( A_m \) is the amplitude of light from the
\( m^{th} \) zone.

If a circular aperture of radius \( r_1 + r_2 \), for example, is placed in front of
the wave front at a point Q, only the first two Fresnel half zones will be
transmitted by the aperture. The resultant amplitude at point P will now be

\[
A = A_1 - A_2
\]

which is approximately equal to zero. If instead an aperture consisting of
alternating transparent and opaque zones matching the radii of the Fresnel half
Figure 3-1 Plane monochromatic wave incident on a diffractive lens.

Figure 3-2 Zone construction of Fresnel.
zones is used, the light from every other zone will be blocked. This removes the negative amplitude terms from Equation 3.1 giving an amplitude at point P which is the sum of only the positive amplitude terms. Such an aperture is known as a Fresnel Zone Plate (FZP). It is a binary amplitude grating as shown in Figure 3-3.

3.2 Binary Diffractive Lenses

A binary diffractive lens maybe thought of as a Fresnel Zone Plate implemented as a phase structure. Instead of modulating the transmission characteristics of an incident beam by blocking every other zone like in the FZP, the phase Fresnel lens consists of transparent zones where the thickness of alternating zones is modulated instead. This phase modulation between successive zones causes the amplitude of light from each zone arriving at point P to be positive and allows the coherent summation of all the amplitudes from each zone at point P. Hence a phase Fresnel lens will have double the amplitude and four times the irradiance at point P than an absorptive FZP.

The radii for each zone in a FZP can be calculated by considering a FZP illuminated by a monochromatic plane wave (Figure 3-4). The focal length of the plate at wavelength $\lambda$ is $f$ and its radius is $r_m$, which is the radius of the mth or last zone of the plate. The optical path difference (OPD) between a ray going through the center of the plate and one from the edge is given by,
Figure 3-3  Fresnel Zone Plate (FZP).

Figure 3-4  FZP focusing an incident plane monochromatic wave.
The incident plane wave is thus converted into a converging wave with a resulting phase retardation of

\[ \phi = \frac{2\pi}{\lambda} \left[ \sqrt{r_m^2 + f^2} - f \right]. \]

From the discussion in section 3.1, the zone theory of Fresnel states that the phase difference from the center of the lens to the \( m \)th zone must be equal to a multiple of \( \pi \). Setting Equation 3.4 equal to \( \pi m \), and solving for \( r_m \), the radius of the \( m \)th zone, gives,

\[ r_m = \sqrt{\left( \frac{m\lambda}{2} \right)^2 + m\lambda f}. \]

The maximum number of zones for a given focal length and radius is calculated by solving Equation 3.4 for \( m \), the number of zones,

\[ m = \frac{2}{\lambda} (\sqrt{r_m^2 + f^2} - f). \]

These equations describe the parameters needed to construct a phase Fresnel zone plate or binary diffractive lens. The term binary lens arises from the two level phase structure (zero and \( \pi \)) of the lens as illustrated in Figure 3-5. It consists of transparent circular zones with a square wave profile. The thickness change between alternating zones induces the necessary \( \pi \) phase shift between successive zones. Because of its symmetry, the binary lens directs equal amounts of incident light into the +1 and -1 orders. The resulting diffraction efficiency of a binary lens is 40.5%.
Figure 3-5  Cross section of binary diffractive lens.

Figure 3-6  (a) Phase profile of refractive lens.  (b) mod $2\pi$ phase profile of kinoform.
3.3 Multi-level Diffractive Lenses

A blazed diffraction grating is designed to direct all incident light into a desired diffraction order. A kinoform is a computer generated holographic version of a blazed grating which can be made to act as a lens.\(^{36, 39}\) A kinoform can be thought of as a phase FZP made as a blazed structure which results in a high efficiency diffractive lens.\(^{37}\) Since the function of the kinoform is to perform as a lens, it is expected that the transmittance function and phase profile of the kinoform will be similar to that of a conventional refractive lens.\(^{38}\) The phase profile of a refractive lens is quadratic and is given by,\(^{39}\)

\[
\varphi = \exp\left[-j\frac{k}{2f}(x^2+y^2)\right].
\]

The theoretical diffraction efficiency of a kinoform is 100% since it has an ideal blazed profile that directs all incident light into the first diffraction order. However, the continuous structure makes the kinoform difficult to produce.

To facilitate in the production of diffractive lenses, we may approximate the continuous kinoform profile with that of a quantized step profile.\(^{40}\) Figure 3-7a is an example of a 2 level approximation to a continuous phase profile which is equivalent to the binary lens of section 3.1. Likewise, Figure 3-7b illustrates a
Figure 3-7  (a) Binary approximation to kinoform (b) 4 level approximation.
four level approximation. As the number of quantized steps, N, increases, the lens more closely approximates the continuous kinoform phase profile and the diffraction efficiency of the element will approach 100%.

As will be discussed in more detail later, a multilevel diffractive lens is fabricated using a set of binary masks. Each mask produces two phase levels. Thus, M masks are needed to produce $2^M = N$ phase levels. A two step (N=2) binary lens therefore only requires a single mask, a four level element (N=4) requires two masks and similarly for N=M.

The transition points for the boundaries of each zone in a multilevel element are calculated by examining the phase function given by Equation 3.4. For the case of the binary lens already discussed, the zone boundaries were determined by setting Equation 3.4 equal to multiples of $\pi$ to satisfy the zone theory of Fresnel. It can be seen from Figure 3.7 that the size of these zone boundaries decreases as the number of levels increases. With each successive mask, the zone widths decrease by a factor of two, and two more phase levels are added. Since every mask produces 2 phase levels, the boundary of each zone occurs when the phase function in Equation 3.4 equals $\pi/M$. Equivalently this may be expressed as

$$\varphi = \left( \frac{2\pi}{\lambda} \sqrt{r_m^2 + f^2} - f \right) = \frac{m\pi}{2^{M-1}}.$$  \hspace{1cm} 3.8

Solving Equation 3.8 for $r_m$ and m as before gives the boundary for each zone and the maximum number of zones created by M masks,
For \( M=1 \), a binary lens, Equations 3.9 and 3.10 reduce to Equations 3.5 and 3.6. Thus, Equations 3.9 and 3.10 may be used as a general description for a \( N \) level diffractive lens.

### 3.4 Diffraction Efficiency

The diffraction efficiency of a \( N \) level diffractive lens may be calculated using scalar diffraction theory, i.e. Fraunhofer diffraction. Figure 3-8 illustrates a \( N \) level element that is periodic in \( T \). For such a periodic structure, the diffraction orders can be calculated by taking the Fourier Transform of the grating transmittance function of one period of the grating.

Each period \( T \) in Figure 3-8 is composed of \( N \) sub-periods of width \( T/N \) centered at

\[
x = \frac{T}{N}(L + \frac{1}{2}),
\]

where \( L \) is an integer from 0 to \((N-1)\). These sub-periods may be defined as rect functions,
Figure 3-8  (a) N level diffractive element   (b) one sub-period.
where \( \phi \) is the phase delay imparted by a sub-period. \( \phi \) is equal to

\[
\phi = L\phi_o/N,
\]

where \( \Phi_o \) is the largest phase delay of all sub-periods. The far-field amplitude distribution of this sub-period is obtained by taking the Fourier transform of Equation 3.12,

\[
T_{sub}(\xi) = \text{sinc}
\left( \frac{T}{N} \xi \right) e^{-j2\pi \xi \phi} e^{j2\pi \phi}
\]

By the theory of superposition the Fourier transform of the total period can now be expressed as the sum of the Fourier transforms of each sub-period,

\[
T(\xi) = \frac{1}{N} \sum_{L=0}^{N-1} T_{sub}(\xi)
\]

Substituting Equation 3.14 into Equation 3.15 yields,

\[
T(\xi) = \frac{1}{N} \sum_{L=0}^{N-1} \text{sinc}
\left( \frac{T}{N} \xi \right) e^{-j2\pi \xi \phi} e^{j2\pi \xi \Phi_o}
\]

The only nonzero solutions of Equation 3.16 occur when \( \xi = m/T \), where \( m \) represents the \( m \)th diffraction order. The amplitude of the \( m \)th diffraction order is,
and the diffraction efficiency of the \( m \)th order is defined as

\[
\eta = |A_m|^2
\]

Solving Equation 3.18, the diffraction efficiency of the \( m \)th order of an \( N \) phase level element becomes,

\[
\eta_m = \left( \frac{\sin(\pi(m-\phi_0))}{\sin(\frac{\pi m}{N})} \right)^2
\]

The primary focus of the diffractive lens occurs in the first order and is the case of interest. For \( m=1, \phi_0=1 \), Equation 3.19 reduces to the familiar expression

\[
\eta = \text{sinc}^2(1/N)
\]

Figure 3-9 is a histogram of \( \eta \) as a function of \( N \) which shows that as \( N \) increases, the diffraction efficiency of multilevel element approaches 100%.

### 3.5 Fabrication

The zone boundaries for the desired \( N \) level diffractive lens are calculated for \( M \) masks using Equation 3.9. This data is then converted into a format that can be read by an electron beam writing machine. The electron beam writer approximates the circular zones of the diffractive lens by using chains of multi-sided polygons and creates a set of binary amplitude masks.
Figure 3-9  Diffraction efficiency of diffractive lens as a function of number of phase levels.
defining the structure of the lens. The resolution limit of the electron beam writer determines the smallest feature size possible for a diffractive lens. Fabrication technology limits the smallest multimask step size to approximately 0.5 μm.

The minimum mask feature size for a diffractive lens with numerical aperture NA occurs at the lens edge on the $M^{th}$ mask and is

$$f_{\text{min}} = \frac{\lambda}{NA \cdot (2^M)}.$$  \hspace{1cm} 3.21

Thus the lens must be designed so $f_{\text{min}} > 0.5 \, \mu\text{m}$.

Contact printing is the next step in the fabrication of the diffractive lenses. A mask is illuminated with a deep ultraviolet light source which exposes the mask pattern into a layer of photoresist on a glass substrate as shown in Figure 3-10. Assuming positive type resist, the regions of exposed photoresist under the clear portions of the mask dissolve upon chemical development leaving the unexposed portions of photoresist. The remaining photoresist pattern serves as mask stop for the etching process which follows.

The etching process dissolves away the glass substrate wherever there is no photoresist and thus transfers the pattern directly into the glass substrate. To induce the proper phase shift on an incident field, the depth of the surface relief pattern must be carefully controlled. If the glass substrate is treated as a plane parallel plate, the phase delay experienced by a field traveling through the glass is

$$\phi = \frac{2\pi}{\lambda} (n-1)d.$$  \hspace{1cm} 3.22
Figure 3-10 Fabrication process for binary lens. (a) mask exposure (b) development (c) etch (d) photoresist removal.
where \( n \) is the index of the substrate and \( d \) is its thickness. Setting this equal to 
\((2\pi/2^M)\), the phase height of a step for the \( M^{\text{th}} \) mask, and solving for the 
thickness \( d_M \) gives 

\[
d_M = \frac{\lambda}{2^M(n-1)}.
\]

This is the etch depth required after exposing mask number \( M \). After etching the 
substrate to this required depth, the remaining photoresist is removed. This 
process is then repeated \( M \) times for an \( N \) level element (since each mask 
produces 2 phase levels).
CHAPTER 4

EXPERIMENTAL FABRICATION PROCEDURE

In this chapter, the experimental procedure developed for fabricating diffractive lenses via photolithography is presented. While photolithography is not the only method employed to fabricate diffractive lenses, it is a commonly used method and the one employed in this thesis. Each part of the fabrication process is individually discussed. The final results of the combined processes are then discussed at the end of the chapter.

4.1 Mask Generation

The first step in fabricating a diffractive lens by photolithography is to generate a mask set that physically describes the lens. Two, four level diffractive lens designs were produced. One set of lenses was designed to operate at a wavelength of 670 nm and the other to operate at a wavelength of 780 nm. Since the lenses were designed to contain four phase levels, each mask set consisted of two masks with alignment marks which were necessary to achieve proper registration between successive masks. Several different alignment marks were examined for use (Figure 4-1). A common element to each configuration is the use of symmetry (Since the human eye is very sensitive to detecting asymmetry in a high contrast pattern). Detection of asymmetry in the overlying alignment marks indicates misalignment between successive substrate exposures.
Figure 4-1 Three different alignment marks. The left column contains the alignment mark pairs. The center column shows the marks when they are aligned with each other. The right column illustrates when the marks are misaligned with respect to each other.
Lens arrays of 1x6 and 4x4 were designed for both wavelengths. The zone radii for each was calculated using a program written in MATLAB. The program allows the user to input the desired lens wavelength, diameter, and NA and then outputs the appropriate zone radii. These zone radii, along with drawings of the mask layout, were sent to a commercial mask maker for fabrication. The lens arrays and corresponding alignment marks in these drawings were then produced on a chrome on quartz mask using electron beam lithography. Appendix A contains the program used to generate the lens radii. Drawings of the mask are given in Appendix B for reference.

4.2 Substrate Preparation

Substrate preparation and all fabrication processes thereafter were performed in a class 100 clean room to prevent particle contamination. Using a process similar to that outlined by Roncone, the glass substrates are first soaked in deionized (DI) water and 15 drops of Micro cleaner for five minutes to help loosen surface contaminants. Each sample is then scrubbed lightly by hand, while wearing gloves, and rinsed thoroughly in DI water. Next the samples are placed in fresh DI water and Micro and sonic cleaned for four minutes for a more concentrated cleaning. After the sonic clean, the substrates are again rinsed in DI water. Another sonic cleaning in 100% ethanol (absolute) follows for four minutes. The ethanol is then drained and the substrates are baked in a vented oven at 180°C for one hour. The purpose of the ethanol rinse and following bake is to help remove water from the substrate. Any residual water will affect the adhesion of photoresist to the substrate.
4.3 Photoresist Deposition

Shipley Type P primer is first spun onto the substrate prior to photoresist deposition using a Solitec spinner. The primer is hexamethyldisilazane (HMDS) based and its purpose is to increase photoresist adhesion to the substrate by both removing any residual traces of water and by forming an interfacial bonding layer for the photoresist. A syringe with a 0.2 μm filter is then used to apply two drops of primer to the center of the substrate. The primer is allowed to remain static on the substrate for 10 seconds and then is spun at 4000 rpm for 30 seconds. Four drops of Shipley 1811 positive type photoresist are then applied to the center of the substrate, again using a filtered syringe. The substrate is then immediately spun for 30 seconds at a selected speed. The speed selected determines the thickness of the photoresist film produced. Photoresist has a characteristic thickness versus speed curve based on its viscosity. The more viscous it is, the thicker it will spin at a given speed. Table 4-1 gives both experimentally obtained values and manufacturer supplied values of thickness versus speed data for the photoresist used. Experimental thickness measurements were made using a Tencor Alphastep 200 stylus profiler. Thickness vs. speed experiments were also conducted with thinner added to the photoresist. By adding thinner, the viscosity of the photoresist can be tailored to yield a desired photoresist thickness.

After the photoresist is deposited on the substrates, the substrates are
<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Experimental Values</th>
<th>Manufacturer's Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td>1.2</td>
<td>1.23</td>
</tr>
<tr>
<td>4000</td>
<td>1.09</td>
<td>1.06</td>
</tr>
<tr>
<td>5000</td>
<td>0.94</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Table 4-1 Speed vs. thickness values for Shipley 1811 photoresist.

baked again. This stage of the process is known as the soft-bake and it occurs for thirty minutes at 90° C.

4.4 Exposure and Development

A Karl Suss MJB3 mask aligner with a 325 nm UV light source was used to expose the mask onto the substrates. The mask aligner was used in a constant intensity mode at 15 mW/cm². The exposure time setting varied as a function of photoresist thickness. The thicker the photoresist layer, the longer the exposure time necessary to expose the mask pattern all the way through the photoresist to the glass substrate. To determine the necessary exposure time, a mask with linear gratings was exposed to a number of substrates, each for a different exposure time. The substrates were then examined using the stylus profiler to determine the proper exposure time. The proper exposure time was determined by examining the square well pattern formed in the photoresist by the mask exposure. If the height of the square well features in the photoresist was not equal to the known height of the photoresist, the exposure time used was insufficient. Figure 4-2 is an example of the output from the stylus profiler used to determine the appropriate exposure times. Using this experimental
Figure 4-2 Exposure test results from stylus profiler. (a) under exposure (b) near proper exposure time (c) proper exposure time.
procedure, it was determined that the necessary exposure time for a photoresist thickness on the order of 1 μm was 15 seconds and 8 seconds for a thickness on the order of 0.6 μm.

After exposure, the samples were immersed in Shipley 352 developer for one minute. They were then immersed in DI water for another minute and then blow dried with nitrogen gas. A hard bake followed at 110° C for thirty minutes.

Figure 4-3 presents a summary of the fabrication steps thus far.

4.5 Reactive Ion Etching

Reactive ion etching (RIE), also known as ion assisted chemical etching or plasma enhanced etching, is the last step in the fabrication cycle. In RIE, a plasma is created by exciting a gas via a high frequency RF discharge. The plasma generates an active species that diffuses to the substrate and reacts with it to form volatile products. The plasma also supplies energetic radiation to bombard the substrate surface. Thus etching occurs due to both chemical processes and physical bombardment.

The gas chosen for use in RIE is dependent on the substrate material. The gas chosen must react more strongly with and etch the substrate faster than it does the photoresist acting as the etch mask. The substrates used in this experiment were ordinary microscope slides made of soda lime glass. Etching was attempted using the parameters given in Table 4-2. Etching of the substrate was not achieved using either set of parameters. In fact, polymerization or deposition was observed instead.
A. Substrate Preparation:

1. Soak slides in DI water and 15 drops Micro for 5 minutes.
2. Scrub lightly while wearing gloves.
3. Sonic clean in fresh DI water and Micro for 4 minutes.
4. Rinse thoroughly with DI water.
5. Sonic clean in 100% ethanol for 4 minutes.
6. Drain and bake in a vented oven at 180° C for one hour.
7. Cool to ambient.

B. Photoresist Deposition:

1. Place 2 drops of primer on substrate. Let stand for 10 seconds. Spin dry at 4000 rpm for 30 seconds.
2. Place 4 of drops photoresist on substrate. Immediately spin for 30 seconds at appropriate speed for desired thickness.
3. Bake at 90° C for 30 minutes.
4. Cool to ambient. Place substrates in dark box.

C. Exposure and Development:

1. Deep UV exposure of substrate.
2. Immerse in developer at 21° C for 60 seconds.
3. Immerse in DI water for 60 seconds.
4. Blow Dry with N₂.
5. Hard bake at 110° C for 30 minutes.

Figure 4-3 Procedures for substrate preparation and development.
The difficulty in etching soda lime glass stems from impurities in its varied chemical composition. Because of this, soda lime glass is not usually used as a substrate in reactive ion etching. Instead, fused silica or quartz substrates are used. Etching of these substrates is more common because of the wealth of information on etching silicon available from the semiconductor industry. Samples were hence prepared on silicon substrates to repeat the etching experiments. Due to difficulties which arose with the etcher, however, etching experiments using the silicon substrates were not able to be performed.

4.6 Binary Photoresist Gratings

Without the ability to etch, the realization of four level lenses was not possible. However, using the surface relief profile of the photoresist, the formation of binary lenses in photoresist was possible. The thickness of the photoresist necessary to produce a binary element with the proper phase

<table>
<thead>
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<th>Set 1</th>
<th>Set 2</th>
</tr>
</thead>
<tbody>
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<td>CHF3</td>
<td>30 sccm</td>
<td>30 sccm</td>
</tr>
<tr>
<td>Ar</td>
<td>4.5 sccm</td>
<td>4.5 sccm</td>
</tr>
<tr>
<td>pressure</td>
<td>60 mToor</td>
<td>60 mToor</td>
</tr>
<tr>
<td>power</td>
<td>350 W</td>
<td>600 W</td>
</tr>
<tr>
<td>time</td>
<td>40 min</td>
<td>41 min</td>
</tr>
</tbody>
</table>

Table 4-2 Etching parameters.
modulation is calculated using Equation 3.22,

\[ d_M = \frac{\lambda}{2^M(n-1)} \]

In this case, M equals one since only one mask is necessary to produce a binary lens. The index of refraction of Shipley 1811 photoresist at 670 nm is approximately equal to 1.64. Thus the necessary photoresist thickness is 0.52 \( \mu m \) for a wavelength of 670 nm and a thickness of 0.61 \( \mu m \) for a wavelength of 780 nm. The photoresist thickness was tailored to be close to these thickness values using the spinning parameters discussed in section 4.4.

A portion of one of the resulting lens arrays produced is shown in Figure 4-4. The ring structure of the binary photoresist lenses from this 4\( \times \)4 array is clearly evident. Each lens in the array has 500 \( \mu m \) diameter, 59 zones, and a f-number of 3.5. More detailed information on the lens structure obtained from a scanning electron microscope is provided in Figure 4-5. The optical performance of these binary lenses will be discussed in chapter five.
Figure 4-4 Photograph of portion of 4x4 array of binary lenses in photoresist.
Figure 4-5 Photographs from a scanning electron microscope of binary lenses in photoresist. (a) portion of single lens. (b) cross section of lens showing binary surface relief profile.
CHAPTER 5
EXPERIMENTAL RESULTS AND CONCLUSIONS

The experimental fabrication of two level binary photoresist lenses was presented in chapter four. In this chapter, the experimental performance of the binary lenses is presented. Focal length, diffraction efficiency, spot size, beam divergence, and coupling efficiency measurements are given. Two applications for these microlenses are demonstrated and conclusions given.

5.1 Focal Length

The focal length of the microlenses was measured using the Foucault or knife edge test. In the Foucault test, a knife edge placed behind an illuminated lens produces a characteristic shadow pattern or Foucault graph in image space. The shadow pattern allows the viewer to determine where the knife edge is with respect to focus (Figure 5-1). When the knife edge is inside focus, it will block the lower rays leaving the lens causing the shadow pattern to consist of a dark region on top and bright pattern on the bottom. The opposite shadow pattern is obtained when the knife edge is placed outside of focus. When the knife edge is exactly at focus, the shadow pattern will be all dark.

Light from a 670 nm laser diode incident on a 500 μm pinhole was used to illuminate a single microlens at a time. A razor blade serving as the knife edge was placed on a x-y-z translation stage and positioned directly against the substrate. The knife edge was then translated away from the substrate until the focus point was located by observing the shadow patterns. The focal length
was taken as the distance the knife edge was translated from the lens and was measured to be approximately 1.5 mm. This is in close agreement to the design focal length of 1.562 mm. The accuracy of this measurement was limited to the precision of the micrometer on the translation stage, which was 10 μm and the small thickness of the razor blade. Another limiting factor was determining the exact location of focus from the Foucault graph because of noise present from light scatter. This poor signal to noise ratio is a result of the relatively low diffraction efficiency of a binary element (i.e. 40.5%).

5.2 Diffraction Efficiency

To measure diffraction efficiency, light from a 670 nm laser diode was first coupled into 4 μm diameter single-mode fiber. A microlens array was placed one focal length from the output of the fiber, and a single lens in the array was illuminated at a time. Light intensity was measured at two locations behind the lens array with a silicon photodiode. The first measurement was taken with the detector immediately behind the lens to measure the total power present in all diffraction orders. The second measurement was made two feet behind the lens to determine the power present in only the first diffraction order. The diffraction efficiency of each microlens was taken as the ratio of the power in the first diffraction order to the total power in all the orders. Table 5-1 gives the diffraction efficiencies from three experimental runs for several lenses on two different substrates. The average diffraction efficiency for the lenses on
Figure 5-1 Knife edge test for perfect lens (after 53).
Each substrate is very close to the calculated theoretical maximum diffraction efficiency which takes into account errors in depth. The depth error for samples one and two was less than 4%, and thus had very little effect on the maximum possible diffraction efficiency. A third sample having a 13.9% photoresist depth error was also tested. The resulting maximum theoretical diffraction efficiency was lowered to 38.04%. Diffraction efficiency measurements of this sample are given in Table 5-2. Again, experimental results were very close to theoretical. The major source of error between experimental and theoretical values is attributed to errors in measuring the actual photoresist depth and calculating depth error. This is due to variations in photoresist thickness across

---

Table 5-1 Diffraction efficiencies of diffractive lenses from two different samples. \( \eta_{\text{MAX}} \) is the maximum theoretical diffraction efficiency.

<table>
<thead>
<tr>
<th>LENS</th>
<th>SAMPLE 1 ( \eta_{\text{MAX}}=40.37% )</th>
<th>SAMPLE 2 ( \eta_{\text{MAX}}=40.39% )</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>#1</td>
<td>#2</td>
</tr>
<tr>
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<td>38.48</td>
<td>37.31</td>
</tr>
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<td>38.18</td>
<td>38.21</td>
</tr>
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<td>38.14</td>
</tr>
<tr>
<td>11</td>
<td>37.52</td>
<td>38.59</td>
</tr>
</tbody>
</table>

|      | Total Average= 38.05\% | Standard Dev.= .54 |
| 1    | Total Average= 39.36\% | Standard Dev.= .25 |

---

Each substrate is very close to the calculated theoretical maximum diffraction efficiency which takes into account errors in depth. The depth error for samples one and two was less than 4%, and thus had very little effect on the maximum possible diffraction efficiency. A third sample having a 13.9% photoresist depth error was also tested. The resulting maximum theoretical diffraction efficiency was lowered to 38.04%. Diffraction efficiency measurements of this sample are given in Table 5-2. Again, experimental results were very close to theoretical. The major source of error between experimental and theoretical values is attributed to errors in measuring the actual photoresist depth and calculating depth error. This is due to variations in photoresist thickness across
Table 5-2 Diffraction Efficiencies for lenses with depth errors.

<table>
<thead>
<tr>
<th>LENS</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36.49</td>
<td>35.66</td>
<td>37.5</td>
<td>36.55</td>
</tr>
<tr>
<td>2</td>
<td>36.73</td>
<td>36.96</td>
<td>36.36</td>
<td>36.82</td>
</tr>
<tr>
<td>3</td>
<td>35.57</td>
<td>35.97</td>
<td>36.36</td>
<td>35.97</td>
</tr>
<tr>
<td>4</td>
<td>35.14</td>
<td>35.51</td>
<td>35.23</td>
<td>35.29</td>
</tr>
<tr>
<td>5</td>
<td>36.9</td>
<td>35.66</td>
<td>34.78</td>
<td>35.78</td>
</tr>
<tr>
<td>6</td>
<td>36.2</td>
<td>35.66</td>
<td>34.78</td>
<td>35.55</td>
</tr>
<tr>
<td>7</td>
<td>35.8</td>
<td>35.21</td>
<td>35.16</td>
<td>35.39</td>
</tr>
</tbody>
</table>

Total Average= 35.89%
Standard Dev.= .55

the substrate. Other sources of error arise from misalignment of the lenses and losses due to Fresnel reflections.

5.3 Demonstrations

A single fiber tap was demonstrated using the fabricated binary lenses. Figure 5-2 is a schematic of the setup. Light from a 670 nm laser diode was coupled into a 4μm single-mode fiber, and a single microlens collimated the light exiting the end of this fiber. This collimated beam was then incident on a volume holographic quadrant beam splitter which tapped the signal. The remaining portion of the signal was incident on a second microlens which coupled the light back into the single-mode fiber. Both microlens arrays were mounted on x-y-z translation stages for alignment purposes. Figure 5-3 is a
Figure 5-2 Schematic of optical fiber tap

Figure 5-3 Photograph of fiber tap demonstration.
photograph of the experimental setup.

The beam divergence of the collimated beam and the coupling efficiency of the microlenses in the fiber tap were measured. To measure beam divergence, the beam spot size was measured at different locations after the lens to see how much it expanded. A photodiode with a 25 μm pinhole over it was mounted on a translation stage, and spot size was measured by taking data points across the beam. From the data, the spot size was obtained at the 1/e^2 points. Figure 5-4 is an example of the measured beam profile. Also plotted in the figure is an ideal Gaussian profile given by

\[ I(d) = I_0 e^{-\frac{2d^2}{d_1^2}} \]

where \( d_1 \) is the diameter of the beam at the 1/e^2 points. The experimental data closely fits this Gaussian profile. The beam spot size was found to be 255 μm at a distance of 1.8 cm away from the lens and 480 μm at a distance 14 cm away from the lens. The corresponding half angle beam divergence is thus .92 mradians.

Coupling efficiency was calculated by measuring both the power directly in front of the second lens array at a point A in Figure 5-3 and the power at the fiber output indicated by point B in the figure. The ratio of power at point B to point A was taken as the coupling efficiency of the lens. The maximum coupling efficiency obtained was 17%. One of the main reasons for this low value of
Figure 5-4  Beam profile measured 14 cm away from lens compared to ideal Gaussian profile.
coupling efficiency is that the maximum diffraction efficiency of a binary lens is less than 41%. Hence more than half the light measured at point A was not focused onto the fiber core. Another factor influencing coupling efficiency was the difficulty of mounting and properly aligning the microlenses.

As a final demonstration, a 1x6 array of lenses was used to couple light into and out of a fiber array. The fiber array was built using silicon V-grooves (Figure 5-5) with 125 µm pitch. Six single-mode fibers were stripped, cleaved, and placed using tweezers into every fourth V-groove. Every fourth V-groove was used to create a fiber array with the same 500 µm pitch as the diffractive lenses. This fiber spacing was verified under magnification. A glass cover slip was then placed against the V-grooves and the fibers were butted up against it so they would all be flush to the end face. The fibers were then glued into place and the process was repeated on the other side of the fiber.

Figure 5-6 is a photograph of the experimental setup used to realize the fiber array coupler. A cylindrical lens focused the output from a HeNe laser into a thin line which was incident on a 1x6 array of microlenses. The lens array coupled the light into the 1x6 fiber array. On the output side of the fiber array another array of microlenses was used to couple light out of the fibers. The six output beams were incident onto Fairchild linear CCD array (model CCD-123) connected to a digitizing oscilloscope. An example of the six output beams from the array is given in Figure 5-7. The beams are Gaussian in shape as expected. Variations in spot size are attributed to the difficulty in aligning the lens and fiber arrays.
Figure 5-5 Example of silicon V-groove.

Figure 5-6 Photograph of fiber array coupling demonstration.
Figure 5-7 Output of six beams from 1x6 lens arrays placed after a fiber array.
5.4 Conclusions

The design, fabrication, and testing of diffractive microlens arrays for use in fiber optic interconnects have been presented. The potential advantages of using diffractive microlenses for fiber array couplers have been discussed. The wavelength sensitivity of diffractive lenses and the effect of chromatic aberration on fiber coupling efficiency was calculated. This was found to have a minimal effect at the longer wavelengths which are commonly used in fiber communications systems. Effects of lens size on crosstalk between array elements was also discussed.

A theoretical discussion of diffractive lens operation and fabrication was presented. From this discussion, equations for mask generation were derived. A program using these equations was written to fabricate a mask set for a four phase level diffractive microlens. These microlenses were placed in one and two dimensional arrays on the mask. Different alignment marks were also enlisted for registration accuracy between mask levels.

Experimental procedures for the fabrication of diffractive microlenses were presented. Experiments were conducted to control photoresist thicknesses and to find optimal exposure times. Etching of soda lime substrates was explored and found to be impractical. More commonly used substrates such as fused silica or quartz are recommended instead.

Arrays of binary lenses in photoresist with depth errors of less than 4% were fabricated and tested. An average diffraction efficiency of 39.36% was shown for a set of these lenses. This is very close to the 40.5% maximum diffraction efficiency possible with an ideal binary lens.
A novel fiber optic tap utilizing both surface relief microlenses and a volume element was demonstrated. A fiber array bundle in a silicon V-groove was also made to test diffractive lens coupling. The best measured single lens coupling efficiency was 17%.

Future work in this area should be directed at making higher order phase level lenses which exhibit much larger diffraction efficiencies. This should lead to improvements in coupling efficiency. Alignment and packaging techniques for maximizing coupling with the microlens arrays is another area for future research.
Appendix A: MATLAB PROGRAM
% f3mask.m
% m.file to calculate Fresnel zone plate parameters
% for multi-level/multi-element arrays
% all #'s are in microns

% lens parameter input
clear
crc
lam=input(' what wavelength ');
mask=input(' # of masks ');
na=fn*1.6;
f=d/(2*na);
fmin=lam/na/2^(mask-1);
num=f/d;
max=d/2;
=2^mask;

% performance section
diary
crc
diffeff=(sin(pi/l)/(pi/l))^2;
if mask > 1
    zm=(((1/lam)^2+sqrt(rmax^2+f^2)-f))
a=round(zm)
    rm=sqrt(((a*lam)^2)+(2*f*lam*a));
else
    zm=(2/lam)^2*(sqrt(rmax^2+f^2)-f)
a=round(zm)
    rm=sqrt(((a*lam/2)^2)+(2*lam*a));
end
% Gaussian beam propagation (units are mm)
mm=f/1000;
dmm=d/1000;
lammmm=lam/1000;
theta = 4*lammm/pi/dmm;
z = 0:100;
dg = dmm*sqrt(1 + ((theta.*z)/dmm).^2);
div = (dg)./dmm;
mxdiv = max(div);

% output performance

diary
disp('Lens Parameters')
disp('

disp(sprintf('wavelength %5.4f um',lam))
disp(sprintf('diameter %7.3f um',rm*2))
disp(sprintf('NA %5.4f ',na))
disp(sprintf('focal length %6.4f um ',f))
disp(sprintf('F# %4.1f ',fnum))
disp(sprintf('#masks %2.0f ',mask))
disp(sprintf('diffrac eff. %4.3f ',diffeff))

zmax = (1/lam)*(sqrt(rmax^2+f^2)-f);
for n = 1 : mask
    int = a*n;
fmin = lam/na/2^(n);
disp(sprintf('mask %2.0f has %3.0f zones w/ min feat. %6.4f um',n,int,fmin))
end;
disp('')
disp(sprintf('beam divergence ratio at 100mm is %6.3f',mxdiv))
disp('')

% mask generation section
if mask > 1
    for n = 1 : mask
        disp(sprintf('the radii for mask %2.0f are ',n));
a = round(zmax)*n:-1:1;
r = sqrt(((lam*a/(2^(n-1))).^2)+(2*f*lam*a/(2.^(n-1))))
    end;
else
    disp(sprintf('the radii for mask %2.0f are ',n));
zmax = (2/lam)*(sqrt(rmax^2+f^2)-f);
a = round(zmax)*n:-1:1;
r = sqrt(((a*lam/2).^2)+(a*lam*f))
end;
diary
Appendix B: MASK LAYOUT
Figure B-1  Mask layout. A one inch center is used because of the limiting aperture of the mask aligner.
Figure B-2 One inch center of mask shown in detail.
Figure B-3 Details of a two dimensional lens array layout.


29 ibid.


45 Private communication with Ron Roncone, Optical Sciences Center.

46 *Micro* is a cleaner made by International Products Corp., Trenton, NJ.

47 Shipley product guide.


52 private communication with Rubin Castille, Shipley Corporation.
