CHAPTER - I

MICROOPTICS

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1.1 Introduction

The word “Microoptics” was presented by Dr. Teiji Uchida and Dr. Ichiro Kitano in the late 1960’s for forming practical optical components based on gradient index fibers and lenses. By adding some other miniature optical elements, microoptics have been really playing an important role to provide various optical subsystems in the optoelectronics field. In the communication and electronics fields, there are optical components that consist of very small lenses for focusing, imaging, branching and transmitting lightwaves. This classification of optical components or optics is known as microoptics. Prof. Dr. Kenichi Iga, Tokyo Institute of Technology, Japan in 1969 proposed and tried to use the new wording “microlens”, but this was not accepted by optical societies[1]. But now, it is registered in the standard keywords.

In the 1970’s planar lithographic fabrication techniques were adopted from semiconductor processing to the fabrication of optical components: for example, to fabricate special beam splitters[2] and lenslet arrays[3]. The use of these techniques allows one to generate optical components with dimensions in the micrometer range. Various lithographic techniques have been developed for micro-optic fabrication is listed in the Table 1.1.
<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Technology</th>
<th>Processing technique</th>
<th>Mounting technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>classical optics</td>
<td>grinding, polishing, diamond turning</td>
<td>fine mechanics</td>
</tr>
<tr>
<td></td>
<td>(&quot;macrooptics&quot;)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>&quot;miniature</td>
<td>grinding, polishing, gradient index optics, LIGA</td>
<td>miniaturised mechanics, micromechanics</td>
</tr>
<tr>
<td></td>
<td>optics&quot;</td>
<td>process (components), fiber pulling</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>&quot;microoptics&quot;</td>
<td>lithographic: optical, electron beam, X-ray, LIGA</td>
<td>micromechanics, integration on single</td>
</tr>
<tr>
<td></td>
<td></td>
<td>non-lithographic: diamond turning, microjet printing</td>
<td>substrate bonding techniques</td>
</tr>
</tbody>
</table>

The use of lithographic fabrication techniques allows for a large amount of flexibility in the design of the microoptics. The possibility to process materials like, for example, silicon and gallium arsenide is of interest since it allows one to put microoptics directly onto optoelectronic devices. This indicates a special feature of microtechnology, i.e., the trend towards the integration of components and systems. This trend is exemplified by names like MST (micro systems technology) and MOEMS (Micro-Opto-Electro-Mechanical Systems) which means the combination of different functions by the use of lithographic fabrication.
1.2 Classification of optical hardware

Optical hardware classified in terms of optics is waveguide optics, free-space optics and combination of waveguide and free-space optics (or integrated optics). In waveguide optics, a light wave is confined by a lateral variation of the refractive index (either using a step profile or a gradient profile) as shown in Figure 1.1(a). In the longitudinal direction, the propagation medium is usually homogeneous. Lateral dimensions vary from a few micrometres for single mode waveguides to the order of 1 mm for multimode plastic fibers, for example. In free-space optics, a light wave is not confined laterally. Rather, it is “guided” by lenses (as the key elements in free-space optics), beam splitters and mirrors which are positioned at discrete positions in a longitudinal direction (i.e., along the optics axis). Between these components, the propagation medium (air, glass, etc.) is homogeneous in the lateral direction as shown in Figure 1.1(b). In integrated optics one can find “hybrid” structures that combine waveguide and free-space optics as shown in Figure 1.1(c).

Figure 1.1. Schematic representation of (a) Waveguide optics (b) Free-space optics and (c) A combination of waveguide and free-space optics.
Another distinction can be made between discrete and integrated optics. Discrete means that a system consists of individual components, which have to be mounted together mechanically. Classical optics and fiber optics/miniatuized optics belong to the class of "discrete optics". Mounting is mostly achieved by using fine mechanics. For fiber-optical applications, micro-mechanical components like V-grooves etched into silicon have recently been used since they provide better precision than fine mechanical parts. The difficulty of alignment and mechanical stability has been the motivation for trying to integrate optics. This attempt was certainly also motivated by the success of microelectronic integration (VSLI) which is the cause for the high functionality, low cost and reliability of electronic systems. In 1969, it was proposed to build integrated waveguide-optical circuits that combine several functions on a single optoelectronic chip[4].

In the 1980's, when free-space optics was heavily investigated for interconnection and computing purposes, the integration of free-space optics was suggested. Two approaches were put forward: "the stacked planar microoptics[5]" and the "planar integrated free-space optics[6]". Common to the different approaches for integrated optics is the absence of mechanics, the stability and small size. By using hybrid integration techniques (such as flip-chip bonding and thermo-anode bonding) the passive optics can be combined with other types of components or sub-modules. Yet another distinction has to be made between "passive" and "active" optics. By passive optics, we mean
optical elements for light propagation, such as waveguides, lenses, lens arrays, beam splitters etc. By active optics, we mean optoelectronic devices for light generation, modulation, amplification and detection.

1.3 Optical functions and their implementation

The implementation of a free-space optical system requires two basic operations: imaging (or focusing and collimation, respectively) and beam deflection (or/×N beam splitting). For the first task, one uses lenses, for the latter one use prisms, grating and mirrors. Both functions can be implemented by using refraction, diffraction and reflection, as well as combinations there of Figure 1.2.

![Diagram of optical functions and their implementation](image)

**Figure 1.2. Optical functions and their implementation**
Most classical macrooptical elements are based on refraction at an optical interface, for example, between air and glass, as described by Snell’s law. More recently, in the seventies and eighties, elements with a gradients-index (GRIN) structure were developed, so that now we can distinguish between refractive surface relief elements and GRIN-type elements as shown in Figure 1.3.

Figure 1.3. Classifications of refractive optical elements.

For Refractive Optical Elements (ROE’s), diffraction only occurs at finite apertures. This means that diffraction is not usually utilized for the functionality but rather limits the performance. This is of importance especially for optical arrays, when, for example, “crosstalk” becomes an issue. In a few cases, refractive array components may be used as diffractive elements. An example is the implementation of an optical array illuminator based on Fraunhofer diffraction at a lenslet array.
A diffractive optical element (DOE) is a periodic structure. The classical
diffraction grating is an example. Its action is described by the grating equation
that one may consider as the analogue to Snell’s equation for refraction.
A whole variety of DOEs has been developed including diffractive lenses,
lenslet arrays and special types of beam splitters. There exist a large variety of
techniques for fabricating diffractive optics. Here we are going to distinguish
between amplitude and phase gratings on the one hand and blazed and
quantized phase profile on the other as shown in Figure 1.4.

![Diagram of diffractive optical elements]

Figure 1.4. Classification of diffractive optical element.

In the early 19th century, Joseph von Fraunhofer measured the
wavelength of light by using grating diffraction. Initially, he performed his
experiments with gratings consisting of a set of thin stretched wires. Soon after
that, ruling was developed as a technique for grating fabrication. Fraunhofer
already achieved periods of a few micrometers by ruling with a metallic
“comb” over a glass plate coated with soot. This type of grating would now be called (binary) amplitude grating since it only influences the amplitude of a light wave, not its phase.

In accordance with this definition, a phase grating acts only upon the phase of a light wave. An early example of a phase grating is the blazed grating (or echelette grating) introduced[7]. This type of grating has a continuous sawtooth profile. In a sense, a blazed grating represents diffractive-refractive elements, since to fully understand its operation, one has to take diffraction and reflection into account. The diffracted energy will be high in the direction corresponding to a reflection. With blazed gratings, very high diffraction efficiencies are obtained that is close to the theoretical value of 1. A practical problem is the high cost associated with the fabrication of blazed metallic gratings if mechanical ruling is used. Therefore, many blazed gratings are made by replicating from a master.

In the 60s and 70s, the advent of the laser caused much interest in areas such as optical image processing using spatial filtering. Furthermore, holography was developed as a major tool for optics[8]. Analog and computer-generated holograms were added to the hardware catalogue of optics. In analog holography, an optical setup (two interfering waves) is used to generate an interferogram in a (thin or thick) photographic emulsion holography. Holography has also been used as a technique to fabricate microoptical elements (beam splitters and lenslets) in materials such as dichromated gelatin and photopolymers.
Computer-Generated Holograms (CGHs) were invented in order to be able to implement “arbitrary” wavefronts without the need for optical recording[9]. Rather, the elements were designed by computer and fabricated using digital plotters. Almost simultaneously with CGHs, kinoform elements were introduced[10]. However, whereas CGHs are usually based on the detour-phase principle, kinoforms are phase-only elements where the phase modulation was originally realized by a dielectric layer of variable thickness. Despite certain limitations of both the CGH and the kinoform, which are mostly due to limited capabilities of the technology existing at the time, they can be considered as a new paradigm introduced into the world of optical fabrication. This implies the use of computer design techniques in combination with digital or analog processing tools.

This was perpetuated by the adaptation of lithographic fabrication for the manufacture of optics in the seventies and eighties[11]. Lithographic fabrication includes the structuring of a photosensitive layer (photoresist) and the transfer of the structure into some substrate material (usually some glass or semiconductor). Binary and multi-level phase technology was developed which allowed one to implement elements with high diffraction efficiencies. “Binary optics[12]” (where binary is reminiscent of the digital approach to fabrication rather than the number of phase levels) can be considered as a continuation of what started with CGH’s, only based on improved fabrication technology. More recently, during the nineties analog lithographic techniques using direct-writing with laser and electron beams allowed one to realize continuous or
stepped phase profiles with very high precision, thus finally realizing the kinoform concept with precision that could not be achieved in the sixties. Therefore, reflection can play an important role for optical elements. In practice, any optical element can be made reflective by some metallic or dielectric coating. Purely reflective elements are of importance for a number of purposes.

1.4 Scaling – from macro-to-micro components:

(a) Scaling of diffractive and refractive lenses: The scaling of lenses can be performed in various ways[13,14] as shown in Figure 1.5. In order to illustrate the effect of the different scaling techniques, we consider how they would influence the lithographic masks if the lenses were fabricated as diffractive lenses. These masks consist of a series of concentric rings. The period and thickness of the rings decrease with increasing radii. The numerical aperture of the lens is determined by the largest diffraction angle, i.e., by the period of the outermost ring system.

(i) Photographic scaling: It results in a scaling of the diameter $D$ as well as the minimum feature size $\omega_{\text{min}}$ as shown in Figure 1.5(A). Consequently, the maximum deflection angle, i.e., the numerical aperture is scaling with magnification $M$:

\[
\text{diameter: } \quad D \rightarrow M \cdot D \\
\text{minimum feature size: } \quad \omega_{\text{min}} \rightarrow M \cdot \omega_{\text{min}} \quad \text{ ...(1.1)}
\]
(ii) **Microscopic scaling:** The microscopic structure of the lens is scaled, while the diameter D is kept constant as shown in Figure 1.5(B). The focal length is scaled with $M$, due to the change in the minimum feature size.

- diameter: \[ D \rightarrow \text{const.} \]
- minimum feature size: \[ \omega_{\text{min}} \rightarrow M \cdot \omega_{\text{min}} \] \[\text{...(1.2)}\]
- focal length: \[ f \rightarrow M \cdot f \]

(iii) **Constant f/# scaling:** It is yet another type of scaling to be applied to lenses as shown in Figure 1.5(c). To this end, all angles are kept constant, while the diameter and the focal length of the element are scaled. For diffractive lenses this means that the microscopic features of the lithographic mask need to be kept constant, while the lens diameter is scaled.

- diameter: \[ D \rightarrow M \cdot D \]
- minimum feature size: \[ \omega_{\text{min}} \propto \frac{f}{D} \rightarrow \text{const.} \] \[\text{...(1.3)}\]
- focal length: \[ f \rightarrow M \cdot f \]

For diffractive lenses, constant F/# scaling means that the technological requirements on the lithographic fabrication (i.e., the minimum feature size, $\omega_{\text{min}}$) remain constant. We want to consider the effect of this scaling concept on some of the quality criteria.
Numerical aperture: \( \text{NA} = \frac{D}{2f} \rightarrow \text{const.} \)

Wave aberrations: \( \Psi \rightarrow M. \Psi \) \hfill ...(1.4)

Ray aberrations: \( \zeta \rightarrow M. \zeta \)

For the behaviour of the other quality criteria due to scaling we obtain:

\[
G_{\text{ray}} : G_{\text{ray}}(x) = \left[ \int \int |\Psi|^2(x) \right] dxdy \rightarrow M^2 . G_{\text{ray}}(x) \quad \hfill \ldots(1.5)
\]

\[
G_{\text{psf}} : G_{\text{psf}}(x) = G_{\text{wave}}(x) + G_{\text{ray}}(x) \rightarrow \text{const.} + M^2 . G_{\text{ray}}(x)
\]

Strehl ratio:

\[
S = 1 - \left( \frac{2\pi}{\lambda} \Psi_{\text{rms}} \right)^2 \rightarrow S = 1 - M^2 \left( \frac{2\pi}{\lambda} \right)^2 \Psi_{\text{rms}}^2
\]

\[
\text{SBP} : \text{SBP} = \frac{\Delta x \Delta y}{\delta x \delta y} = \frac{\Delta x \Delta y}{G_{\text{psf}}(x,y)} \rightarrow M^2 \frac{\Delta x \Delta y}{\delta x \delta y + M^2 \zeta^2}
\]
Figure 1.5. Illustration of the different ways scale lenses.
As can be seen from the relations is Equation in (1.5) the ray optical aberrations of a lens are significantly reduced under constant f/# scaling. At the same time the wave optical PSF, which is proportional to the numerical aperture, remains constant. The Strehl ratio is improved with reduced lens diameter since it is proportional to the root-mean-square wavefront aberration. The amount of information transmitted through the lens is calculated from the space-bandwidth product. With a reduction of the lens diameter the image field of the lens is reduced, as is the ray-optical PSF. Since the wave-optical PSF remains constant the overall SBP is reduced. Thus, as expected, a reduction of the lens diameter results in a reduced SBP. The SBP curve saturates for large lenses if the effect of aberrations is taken into account. This is the case as long as aberration effects dominate the PSF of the lens. For interconnection applications it is interesting to consider the information density $\rho_{inf}$ transmitted through the optical system. $\rho_{inf}$ can be calculated from the SBP and the image field size as:

$$\rho_{inf} = \frac{SBP}{\Delta x \Delta y} = \frac{1}{G_{psf}}$$

...(1.6)

In spite of the reduced SBP of single microlenses the information density of an optical system can be maximized by using a large number of microlenses in parallel rather than one single lens with larger dimensions.
1.5 Microoptics applications

The available optical and optoelectronic components allow a micro-integration of simple but very effective set-ups, as well as construction of complex optical systems, example, for data processing. For short-term applications less complex systems can also be envisaged. Specific areas of application are:

(a) *Stacked planar optics for display technology*: In certain applications, stacking of complex systems will not be required, but the array property of the planar integrated optical components is employed. The later example can be employed for security reasons as well as for enhancing the brightness of displays. A further simple concept of stacked planar optics for imaging, utilizing only microlenses discussed. The set-up will possibly trigger tremendous developments in flat panel display fabrication[15].

(b) *Micro-optical sensor*: A wide range of optical measuring and sensing techniques has been applied on an industrial scale. These systems are typically based on bulk optics and by three-dimensional integration that can be reduced in size and improved in terms of stability. Micro interferometers for measuring distances or physical parameters such as temperature, pressure, distance etc, are examples of this type. Micro-optical integration also allows *in situ* measurement in medical applications.
(c) Parallel pick up systems: For optical disk applications the high interconnection density of imaging can improve the rate of data transfer. With integrated planar pick-up systems based on microlenses and microprisms several hundreds of pixels can be read simultaneously.

(d) Optical interconnections: Three-dimensional micro-integration can provide suitable technology for different levels of communication. At the system-to-system level integrated connectors for parallel fiber interconnect can be built[16]. For flexible connectors the alignment again profits from the planar surfaces. However, a connection to a stacked planar optical system, which benefits from the space bandwidth product of every lens is not straightforward. In this case, an intermediate set-up cascaded image division has to reduce high density of data points to be coupled into the fibers with larger physical dimensions.

At the board-to-board level optical bus connects are more feasible[17]. Stacked planar optics can form the backplane of electronic or optical boards. The chips can be fixed directly to the optical components, forming the optical motherboard. In this application, direct communication between electronic processing units will be possible with approximately $10^5$ data channels, actually restricted only by the detector and source dimensions. The electrical support of the electronic integrated circuits can be performed conventionally.
(e) Optical data processing units: Different concepts of systems for optical data processing have been developed[18,19]. Demonstrators have already been built with macro-optics[20,21]. By integration of modulators, prisms and microlenses, complex micro-optical systems such as data processing units can be implemented. Figure 1.7 shows an example of a general modulator design, employing aperture stops or electrooptical modulators as filters in the space and frequency domains. A first demonstration of a micro-optical integrated interface device shown in Figure 1.8[22].

![Static fiber connection](image1)

![Fiber -Fiber connection](image2)

Figure 1.7. Static and flexible fiber connectors with planar microlens arrays.

![Electronic support](image3)

![Frequency filter](image4)

Figure 1.8. Space and frequency filtering with active modulators of stop.
1.6 Digital optical information processing

Optical correlators represent special purpose processors which are capable of performing specific operations very efficiently. Analog optical computing, however, is usually restricted to linear operations such as a Fourier transformation and correlation. General purpose computing requires the realization of nonlinear operations. The use of highly parallel free-space optical interconnections and optoelectronic switching devices has been investigated[23]. The fine-grain (often gate-level) architectures, however, did not turn out to be promising. Nevertheless, out of these efforts the concept of “smart pixel devices” has emerged. In general, the smart pixel concept involves some amount of information processing. Often, however, a smart pixel may simply be an optical input/output device on an electronic chip consisting of an emitter/detector pair. As such, smart pixel arrays and three dimensional free-space optical interconnections are of growing interest for VLSI[24-26].

1.7 Optical interconnects

The use of optics as an interconnection technology for electric systems is motivated by the observation of a variety of advantages over electronic interconnections. Above all the 3D nature of free-space optics has been listed frequently as the major advantage, leading to the potential for interconnecting planar arrays of logic components in parallel by means of the third dimension. This is in contrast to the planar nature of electronic interconnections, which results in a limited number of interconnects (pins) with the origins at the chip
boundaries. In particular, the unfavourable scaling behaviour is a major problem in this case. With rapidly proceeding integration technology, the number of electronic logic circuits is constantly increasing proportional to the chip area $A$, while the number of electronic interconnects only scales as $\sqrt{A}$. The performance of electronics today is limited by the interconnect technology rather than by the switching speed of electronic devices. The topological advantage is complemented by physical as well as architectural reason in favour of optical interconnections in VLSI systems in Figure 1.9[27-31].

Optical interconnections behave very much like perfectly matched transmission lines. The propagation speed in a transmission line is the same as in an optical fiber, for example. However, for electrical interconnections to achieve transmission line speeds they must be driven by low impedance drivers always behave as if they were driven by a low impedance source and optical reflections at detectors are usually not a problem[32].

Optical interconnections also offer the advantage of a bandwidth-independent low and they can support larger fanouts [33,34]. Another major advantage is that they lack mutual coupling effects, which is why optical signals can cross through each other without the generation of noise or loss of information. A comprehensive overview of the state of the art of optical interconnect technology for computers from the perspective of a computer scientist has recently been published[35].
(a) Space-invariant and space-variant interconnects: Interconnections for discrete input and output arrays can be represented as so-called bipartite graphs. Both the input and output are represented by a regular array of positions that are denoted by characters (e.g., a, b, c, ..) or numbers (0, 1, 2, 3 ..., ...)

very often the number of positions is a power of 2.

Linear optical systems can be characterized as either space-invariant or space-variant. A system is called space-invariant if every input position generates the same output pattern. In a bipartite graph this means that the number and direction of the lines emerging from all input positions are the same. For arrays of finite size, space-invariance is not strictly possible since some lines would not connect to a position in the output array. Occasionally, the lines are wrapped around in a cyclical fashion. A system is called space-variant if the array of lines emerging from one input position to the next varies. Even though the space-variant interconnect scheme varies from one input to the next this does not necessarily mean that the interconnections are irregular. Therefore we also distinguish between regular and irregular interconnects.
(b) Regular and irregular networks: These terms are not precisely defined since they are used according to the general understanding of what regular and irregular mean. As pointed out above, space-variance does not always mean irregularity. Certain space-variant interconnections exhibit a high degree of regularity. On the other hand, space-invariant interconnection networks are always regular. Actually, the interconnection patterns for space-variant multistage networks can be explicitly expressed in terms of a mathematical mapping of input to output positions. As we see later on in this chapter, free-space optics can be used for implementing space-invariant regular interconnects as well as space-variant irregular networks.

(c) Fixed and dynamic interconnections: In electronics, interconnections are usually fixed (with a couple of exceptions, such as switchboards). For metallic wires, a change of a connection requires a mechanical displacement. As we have seen earlier, (micro) mechanical switches are also used in optics. However, since they are slow (milli-to microseconds) their use is limited. Optical interconnections can also be switched by changing the refractive index of a material. Examples are the directional waveguide coupler and dynamic holograms realized in photorefractive materials. Some of these effects can be very fast (nanoseconds or less) and they offer the possibility for dynamic routing of light signals. The usefulness of dynamic interconnections, however, this could also be because current electronic computers are based on fixed interconnections.
1.8 References


