PRODUCTION OF HOLOGRAPHIC OPTICAL INTERCONNECTION ELEMENTS

by

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ABSTRACT

Current trends in computing and telecommunications point to a growing need for devices that are able to switch optical beams carrying information without having to convert them to electric signals. This would create a whole new generation of hybrid optoelectronic processors combining the computational strength of electronics with the very large information throughput density of optics.

Holographic optical interconnection elements for a proposed optoelectronic integrated coprocessor are characterized and a feasibility study of the interconnection scheme is conducted. The performed interconnection simulation presents a rigorous analysis of the scheme within a framework of diffraction and holography theory.

A novel method for production of holographic optical interconnection elements has been devised, and a corresponding production system designed and built. The system is made to be highly versatile in order to accommodate the production of interconnection elements that are two-dimensional arrays with either small or large (e.g. 3x3 or 128x128) of pixels where the element has a different diffraction angle. Thus an investigation of a variety of interconnection schemes is possible.

Ideal parameters for production of interconnection elements on traditional holographic silver-halide plates were determined. The plates were then tested for diffraction efficiency and acceptability of the diffracted beam profile. Although these thin holographic optical interconnection elements had an expectable low diffraction efficiency of typically 10%, they successfully demonstrated the functionality of the proposed interconnection scheme and the production system.

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<tr>
<td>FFT</td>
<td>Fast Fourier transform</td>
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<tr>
<td>HOIE</td>
<td>Holographic optical interconnection element</td>
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<tr>
<td>LCD</td>
<td>Liquid crystal display</td>
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<tr>
<td>MTF</td>
<td>Modulation transfer function</td>
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<tr>
<td>OEIC</td>
<td>Optoelectronic integrated circuit</td>
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<tr>
<td>ONN</td>
<td>Optical neural network</td>
</tr>
<tr>
<td>RCLED</td>
<td>Resonant cavity light emitting diode</td>
</tr>
<tr>
<td>SBWP</td>
<td>Space-bandwidth product</td>
</tr>
<tr>
<td>SLM</td>
<td>Spatial light modulator</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
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<tr>
<td>VCSEL</td>
<td>Vertical cavity surface emitting laser</td>
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<td>Very large system integration</td>
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1 Introduction

All-optical interconnection and the ability to harness the switching of light is at present a "Holy Grail" sought by many researches around the world. It is widely accepted that solving this problem would make new roads for further explosion of technological advancements, much like invention of an electronic switch, the transistor, did in this century.

I assume it was hard to believe Moore when he predicted the growth and achievements of the electronic IC industry many years ago, but his predictions have certainly come true so far and today many of us take his law for granted. [1] It is now hard to imagine that this exponentially rising trend would ever stop. However, the ever-decreasing size and increasing complexity of ICs is making a crisis in the area of information processing more and more apparent. Current VLSI systems and the hierarchical elements they consist of, although very fast and capable of carrying out complex nonlinear operations, are serial machines that must rely on heavy communication between many elements in order to cope with majority of the problems, which are in essence parallel and multidimensional. The main problem is then that a performance of a processor is governed by the speed and complexity of its interconnections rather than electronic gates and alternative system architectures are needed. [2]

Realizing electronic interconnections is becoming increasingly difficult and cumbersome, and it is not uncommon that wires instead of gates take up most of the chip area and a lot of energy has been put into layout optimization algorithms. This is only an ad hoc solution, but the problem still remains, which is fundamental in nature: electronic paths are unable to cross each other without interaction, which ironically is the property enabling the operation of a nonlinear electronic gate. The inverse is true for optical signals, and is therefore natural to explore the
possibilities of hybrid optoelectronic architectures (OEICs) that take advantage of the potency of optical connections between computationally powerful electrical elements. [3] Light has been used for a long time already as a carrier of information through telecommunications fibers, but only to connect computer networks and large systems where the processing of this information takes place. Optics has in many cases taken place of RF communications, providing much higher bit rates. Take for example free-space infrared communication widely used by many devices today. The trend is to employ optical communication down the hierarchy wherever possible: board-to-board or chip-to-chip optical interconnections are already made possible by optic fibers or MEMS mirrors. The end goal is to incorporate in-chip optical interconnections, which would solve the problem of evermore cluttering electronic ones.

Speed and convenience are not the only advantages optics has to offer. One should only consider analog optical processors, such as classic Vander Lugt filters to realize where the real potential of optics lies. [4] Machines like this have the ability to “instantly” perform certain operations on images or two-dimensional data sets in general, as they are readily carried and processed by light propagation. [5] No artificial constructs, such as endless series of bits, are necessary to process this information. The problem is, on the other hand, that these highly parallel traditional optical processors can often perform one operation only, and lack the general purpose of a serial electronic processor.

From these quick observations, it seems logical to create a marriage of the two and get the best of both worlds. Because of inherent parallelism connected with light propagation, optoelectronic processors are very well suited for general multidimensional signal processing and can be applied to many problems not having a simple serial structure. Possible applications are pattern recognition and morphological processing in medical environment, machine vision, adaptive optics, or sensor fusion and contrast enhancement. [6]

1.1 Proposed OEIC Architecture

The research interest of our Photonic Systems Group lies exactly in this area of integration of optical devices into next generation of information processors. There is currently an effort made by several research groups specializing in different areas to design and produce a hybrid
optoelectronic integrated coprocessor that would aid a traditional serial processor in tasks that are highly parallel in nature. The proposed architecture of the OEIC is shown in Figure 1.1.

Each OEIC layer consists of a photodetector array (input stage), threshold electronics, and a light source all on the same, double sided GaAs wafer, and a holographic diffraction grating serving as the interconnection element. Depending on the input signals, some simple processing is performed by the threshold electronics that determines how the connection is to be established with the following layer and so on.

This architecture is inspired by the structure of neural networks and is particularly well suited for neural network implementations or fuzzy logic processing. Each layer is divided into independently operating smart-pixels (neurons), which are optically connected to the neurons of the following layer. The processing power and performance of such a network is very dependent
on the interconnection scheme implemented in it. [7] A neural network where one pixel can connect to all the pixels in the following layer and vice versa (global interconnection scheme) is thought to have the most computational power, but all evidence from nature (part of human brain) imply that global interconnections are cumbersome and not really necessary. [8]

The proposed OEIC architecture assumes a model of a weakly connected neural network that has limited fan-in and fan-out. One possible scheme of interconnection is nearest neighbor, where a pixel is connected only to the limited number of pixels in the next layer that are closest to it. A prototype with a small number of pixels and only one layer of interconnection with electronic feedback already exists [9], but it utilises expensive blazed gratings as interconnection elements that are available off-the-shelf. Holographic gratings have many advantages over blazed gratings and is therefore essential to investigate the possibility of fabrication and use of HOIEs in optoelectronic processors. First, blazed gratings have a factory determined pitch that often does not match the wavelength of the light source being used, which means the diffraction efficiency of the blazed grating is decreased. Another consequence of fixed pitch is that diagonal gratings require different distance from the photodetector plane. These problems completely dissaper when using holographic gratings because we can produce them so they are matched for our application. Holograms are also much cheaper to produce than blazed gratings and we also have a possibilty of having reconfigurable interconnections (not constrained only to nearest neigbor) which are essential in a self-learning neural network.

The main motivation of this thesis is to devise a method for production HOIEs that would be suitable both for the replacement of existing blazed gratings and easily expandable to the application in the integrated processor. I plan to do this in the following manner. The proposed OEIC nearest neighbor interconnection scheme is studied in more detail in Chapter 2. The structure of the HOIE is outlined together with some important considerations and requirements imposed on the interconnection scheme that the reader must keep in mind throughout this document. Initial design of a system for production of HOIEs is introduced at this point. The theoretical framework in which the optical interconnection takes place is set in Chapter 3. Tools for analysis of diffraction problems as linear systems are presented and so are basic holographic principles. The section dealing with Bragg diffraction is very important for this particular application, since thick phase-only holograms have the potential of being excellent interconnection
elements because of their high selectivity and excellent diffraction efficiency. The theory is put to work in Chapter 4 where we calculate all the parameters required by the interconnection scheme and the production system is specified with more detail. All of the system considerations are then included in a simulation of interconnection from a single HOIE pixel, supporting the feasibility and proving the functionality of the proposed OEIC interconnection scheme. Chapter 5 presents some preliminary results of the production. The HOIE produced behave as predicted, though having low diffraction efficiency of typically 10%, which was to be expected for thin holograms made on silver-halide plates. Concluding remarks summing up the project are given in Chapter 6, together with recommendations for future research and further improvement of HOIEs.
2 OEIC Interconnection Scheme Overview

The basic interconnection module of the proposed optoelectronic processor is shown in Figure 2.1. It consists of a configurable light source and the holographic element that then diffracts this light. In order for the processor to be useful and efficient, communication should be established with as many pixels possible in the following layer on a need-to-basis. In other words, interconnections need to be reconfigurable in a sense that at any point in time we can choose an arbitrary number and combination (out of a fixed set) of ways to connect a pixel to the following layer. The ability to change connections with time provides us temporal multiplexing.

![Figure 2.1: Structure of basic OEIC building block](image)

It is therefore required of the HOIE to diffract light in more than one fixed direction. It is a well known property that many hologram gratings can be present in a same volume of material, simultaneously diffracting light in different directions. The problem is that we would like to control when each grating is active, rather than have to choose all or none. The solution to this problem is to divide the HOIE pixel area into sub-pixels, each containing a different grating. The
repercussion of such a decision is a need for a configurable light source that will be able to illuminate each of these sub-pixels independently when required, thus preserving the important property of spatial multiplexing of each pixel. This is clearly advantageous than having the possibility of only one kind of multiplexing in a processor. [10]

There are several possible solutions to the configurability of the light source. In the large-scale prototype we have a collimated laser beam expanded to the size of the whole HOIE array. The configurability is achieved by placing an LCD in front of the HOIE, which acts then as an SLM, transmitting or blocking light to desired sub-pixels. This approach, on the other hand, is not very economical for the integrated processor since most of the power would be blocked and wasted (all gratings are rarely illuminated at the same time). We rather revert to partitioning of the wafer to the same sub-pixel areas as the HOIE array. Each area then accommodates a separate small light source dedicated to the corresponding HOIE sub-pixel. These individual miniature light sources should also have desirable beam properties as the laser beam, so we might want to choose RCLEDs or surface emitting lasers such as VCSELs.

Figure 2.2: HOIE structure
Chapter 2

If we want to establish a connection between two pixels, the appropriate light source area should be illuminating the grating that diffracts light on the detector of the desired pixel in the following layer. For nearest neighbor connection, the gratings should diffract light to the pixels immediately above and below, to the left or right and in the four diagonal directions. The last possibility for light is to go through undiffracted. There are therefore nine grating orientations in a HOIE pixel, as shown in Figure 2.2 above. The illustration also shows the full layout of a $3 \times 3$ HOIE array. It is interesting to note the absence of the outmost string of sub-pixels since they would lead to connections to the off-chip area. The omission of these sub-pixels is essential to keeping the size of all layers the same, thus enabling the modular and cascadable structure.

![Detector array](image)

Figure 2.3: Interconnection formation

This interconnection scheme is visualised in Figure 2.3. In order to prove practical, we must impose a set of requirements on HOIEs:

- the diffracted light should hit the center of the desired photodetector (careful fabrication of HOIEs and alignment of layers)
• the main lobe of the diffracted light should not overfill the area of the pixel it is targeting (also taken care of by production parameters and restriction of interlayer separation)

• any undiffracted light should not arrive at the detector of the projected pixel in the next layer (this is already ensured by limiting the detector active area to the size and location of the HOIE pixel that is passing light undisturbed, as shown in Figure 2.3)

• the holographic gratings should have high efficiency and transfer most of the power in the diffracted direction (we plan to do satisfy this by using thick phase-only holograms).

We shall consider these again in later chapters with a more detailed and systematic approach.

2.1 HOIE Production System Design

There are many ways of producing HOIEs with the beforehand mentioned properties. A simple solution might be to make large area gratings, cut them in desired sub-pixel size and arrange in a desired pattern on a substrate. This approach was taken in the construction of the large-scale Hopfield ONN prototype where blazed gratings were employed. As we saw, two different interconnection planes had to be implemented for horizontal/vertical and diagonal connections. Problems may also arise from the assembling errors that may cause misalignment. Optical properties of such a diffraction element are also in question, as it unavoidably must include some kind of substrate and the glue that was used to fix the gratings to it. Introduction of these additional ingredients only increases the noise of the diffracted signal. These issues make blazed gratings impossible to implement in an integrated processor.

I propose a system that could produce a one-plane uninterrupted HOIE, an approach that would eliminate the mentioned problems. The architecture of such a system is shown in Figure 2.4. Gratings are produces holographically, with the reference beam being normal to the recording material, and the object beam in the direction of desired diffraction. This ensures that when such a grating is illuminated by a light source at normal incidence, this object beam would be reconstructed, having the intended direction of propagation.
The holographic recording material is fixed on a platform that can translate in two perpendicular directions (we will refer to the as x and y) and in addition it can rotate about the axis of the system. By translating the recording material below an aperture mask that has the square opening of the size of the desired sub-pixel, we can write a grating on a particular location. The aperture should be as close to the recording material surface, barely touching it (this could be done by mounting it on springs, so the tension on the surface is not too great). In order to accomplish horizontal/vertical and diagonal grating orientations, all we need to do is rotate the recording material in 45° steps in between translations, when the shutter is closed and the recording material not exposed. With this procedure it is easy to construct a pixel as shown in Figure 2.2, and repeat a procedure for an arbitrary N×N array of them.

The mirrors producing reference (M₁) and object (M₂) beams should be mounted in such a manner that the optical path difference from the two is minimized at the film surface. A third
mirror \( M_3 \) is needed to provide for a slightly incidence diffraction angle when writing diagonal interconnection sub-pixels (the reason for this explained in Chapter 3). Rather than constantly changing the position of a single mirror, this is achieved by employing two mirrors at slightly different positions. Furthermore, mirror \( M_2 \) should be easily removable from the optical path so the light can reach mirror \( M_3 \), but still be sturdy and vibration-free when put back into position.

The laser we plan to use for production emits a collimated beam, which might not be case for the OEIC light source. RCLEDs for example emit a divergent and diffused beam. In order to achieve the greatest diffraction efficiency possible, the HOIE should be produced with a reference beam having the same properties as the reproduction light. The lens \( L_1 \) therefore has the role of imitating the light source in the processor (a diffuser is also to be considered in case of LEDs). Taking this reasoning further, we can require the HOIE to focus the diffracted power in a small area on the detector array by making the object beam converging with the lens \( L_2 \).

The whole system should be set up on an optical table having hydraulic vibration-isolating legs since holographic recording is an interferometric process extremely sensitive to vibrations. The optical components are mounted on an optical breadboard, which will then be vertically suspended over the moving platform with two thick damped rods. Since the shutter is the only part of the system that is active during exposure, it will be best not to attach it to the optical table.

A list of parts together with their manufacturers and main features that I intend to use to build this system follows:

Rotary table: Dayton\textsuperscript{®} 10" horizontal rotary table 4K730
- 0°0'45" maximum spacing error
- \(~40kg\) weight increases the stability of the system

Translation stages: Aerotech\textsuperscript{®} ATS0300 linear stage
- 0.16\(\mu\)m maximum resolution
- controlled by the Unidex 1 motion controller attached to a computer via serial port

Aperture mask: To be designed and manufactured
Chapter 2

Movable mirror $M_2$: New Focus\textsuperscript{®} Flipper\textsuperscript{TM}
- 200\textmu rad repeatability

Shutter: Uniblitz\textsuperscript{®}
- SD-10 shutter driver connected to a computer thru a D/A board

Laser: Coherent\textsuperscript{®} Innova 70 argon (Ar) ion laser
- 1200mW output power at green line $\lambda$=514.5nm

The system would be completely automated if we had chosen a computer controlled rotational stage and a motorized version of the Flipper\textsuperscript{TM} mirror, but this would drastically increase the construction cost of the system. The operation of computer controllable parts is graphically programmed in LabVIEW.

But before the production system is built and put into operation, it is crucial to conduct a detailed theoretical diffraction analysis and a feasibility study of the interconnection scheme we are trying to implement.
3 Diffraction and Holography: Theoretical Review

In order to prove useful, optical interconnections have to satisfy a number of important conditions. Our first and obvious task is to steer the light in a given direction and understanding mechanisms of propagation and diffraction of light is of utmost importance. Secondly, we require all of our optical channels to be well contained. In other words, we have to make sure that all the beams are confined at desired locations and by doing that minimize crosstalk. This is a big concern having in mind the dispersive nature of light that is even more pronounced as we introduce additional diffractive elements. Lastly, but not of least concern, low power consumption must be attained and that is very dependent on the efficiency of our diffraction elements.

It is therefore very important to rigorously investigate, having these requirements in mind, whether using the previously described interconnection scheme is at all feasible. In the following sections I will present the underlying principles of propagation and diffraction of light, basic principles of holography, including thin and thick Bragg holograms, which are essential to power and efficiency requirements. All of these considerations are put together in a simulation that is trying to explain how light behaves in our proposed architecture in the next chapter.

3.1 Basic Propagation and Diffraction Theory

Since electromagnetic propagation is described by the polarization, amplitude and phase of the electric field at a certain point in space, those being the physical quantities we can measure, early diffraction theories manipulated these quantities directly in the spatial domain in order to predict the electromagnetic disturbance at different points. Even with numerous approximations these calculations remain confusing and cumbersome, even involving tabulated integrals. [11]
Chapter 3

Fortunately this model is not too hard to implement, but is very resource and time dependent as we need to generate output points one by one.

A different, linear systems approach can provide us with much more insight as to how diffractive elements act on propagating light, and as it turns out with a more compact formalism as well. If we represent the electric field distribution as a weighted superposition of plane waves traveling in all possible directions, by means of Fourier transform we would instantly have access to the spatial frequency spectrum which tells us how much energy is propagated in which direction. Spatial frequencies correspond to direction cosines, measured from the \(x\)-, \(y\)- and \(z\)-axes, of the propagating wave vector \(\vec{k}\) (the reader may consult [12] for more details). Equations embodying this concept are given below:

\[
\begin{align*}
\tilde{U}(f_x, f_y; 0) &= \int_0^\infty U(x, y, 0) e^{-j2\pi(f_x x + f_y y)} dx dy \\
U(x, y, 0) &= \int_0^\infty \tilde{U}(f_x, f_y; 0) e^{j2\pi(f_x x + f_y y)} df_x df_y,
\end{align*}
\]

where \(U(x, y, 0)\) is the complex electrical field distribution in the plane \(z=0\) and \(f_x\) and \(f_y\) the mentioned spatial frequencies. The additional index in the spectrum \(\tilde{U}(f_x, f_y; 0)\) reminds us that we still have not moved from plane \(z=0\). The electric field as part of a wave must satisfy the Helmholtz equation \(\nabla^2 U + k^2 U = 0\) where \(k = \frac{\omega}{\sqrt{\varepsilon_0 \mu_0}}\). Applying this constraint to Eqn. (3.1) results in a differential equation for \(\tilde{U}\), and it is easy to show that the solution in spatial frequency domain at an arbitrary \(z\) plane is

\[
\tilde{U}(f_x, f_y; z) = \tilde{U}(f_x, f_y; 0) e^{j2\pi\frac{z}{\lambda} \sqrt{1 - (f_x^2 (\lambda^2 - f_y^2)}}.
\]

Taking a closer look at this expression, we can immediately write down a system function describing propagation of light through free space as a linear space-invariant system:

\[
H(f_x, f_y) = \begin{cases} 
0 & \text{otherwise} \\
\left( e^{j2\pi\frac{z}{\lambda} \sqrt{1 - (\lambda^2 - f_y^2) \sqrt{f_x^2 + f_y^2}}} \right)^{-1} & \sqrt{f_x^2 + f_y^2} < \frac{1}{\lambda}.
\end{cases}
\]
Diffraction and Holography: Theoretical Review

The limitations on \( f_x \) and \( f_y \) are necessary because all true directional cosines of a wave are not independent and must satisfy the condition

\[
\frac{1}{\lambda^2} = f_x^2 + f_y^2 + f_z^2.
\]

We now have a powerful tool that enables us to treat diffraction problems as linear systems with a known transfer function. Calculating the output field pattern is then a simple procedure involving:

- alteration of the input field by the diffractive element transmission function
- transformation of the transmitted field distribution to acquire the input spatial frequency spectrum
- modification of the input spectrum with the propagation system function
- inverse transforming of the modified spectrum to retrieve the output field distribution

There are also other widely used approaches to calculating diffracted field patterns. It is possible, for certain classes of problems, to make suitable approximations that further simplify diffraction calculations. The paraxial approximation is valid for small angles of diffraction only. In other words, it restricts us to very low spatial frequencies \( |f_x|, |f_y| < \frac{1}{\lambda} \), when it becomes possible to simplify the exponent of Eqn. (3.2)

\[
\frac{1-(\lambda f_x)^2-(\lambda f_y)^2}{2} \approx 1 - \frac{(\lambda f_x)^2}{2} - \frac{(\lambda f_y)^2}{2}.
\]

We now can easily inverse transform the simpler version of Eqn. (3.2) resulting in the Fresnel diffraction formula

\[
U(x, y, z) = \frac{e^{j kz}}{j \lambda z} e^{j \frac{k}{2z}(x^2 + y^2)} \left\{ U(\xi, \eta, 0) e^{j \frac{k}{2z}(\xi^2 + \eta^2)} \right\} e^{-j \frac{2\pi}{\lambda z} (\xi x + \eta y)} d\xi d\eta,
\]

which is very effective for calculating patterns close to the axis and in the vicinity of the diffractive element. This regime of diffraction is referred to as near field.
Chapter 3

If, on the other hand, we are interested only in the field disturbances very far from the input plane, or far field, further simplification of Eqn. (3.5) when \( z \gg \frac{k(\xi^2 + \eta^2)_{\text{max}}}{2} \) eliminates the quadratic phase exponential in the integral. It is exciting to note that the integral remaining is simply the Fourier transform of the input field distribution evaluated at spatial frequencies \( f_x = \frac{x}{\lambda z} \) and \( f_y = \frac{y}{\lambda z} \), giving us the Fraunhofer diffraction formula

\[
U(x, y, z) = \frac{e^{jkz}}{j\lambda z} e^{\frac{j}{2z}(x^2 + y^2)} \tilde{U}\left(\frac{x}{\lambda z}, \frac{y}{\lambda z}; 0\right).
\] (3.6)

All of here mentioned methods have found great application in optical system analysis and holography in particular, as we shall see in the following sections.

3.2 Holographic Principles

Holography is the science of wavefront reconstruction: its goal is to form an image by means of light diffraction such that the produced wavefront has the exact same profile as if the diffracted light were coming from a real object that was previously recorded on the holographic recording material. As opposed to photography, which preserves only the intensity distribution of light diffracted from a real scene and hitting the film, holography enables us to capture both amplitude and phase information of incident waves. This is possible when we compare the object beam with a known reference beam and record their interference pattern on a medium such as traditional silver-halide film or some other photosensitive material. [13]

Let us consider the following situation where the object beam is interfering with a predefined reference beam on the recording medium surface (plane \( z = 0 \)), producing a writing field:

\[
U_w(x, y, 0) = U_o(x, y, 0) + U_r(x, y, 0)
\] (3.7)

A typical reference beam is a plane wave propagating in a certain direction and has the form \( U_r(x, y, 0) = Ae^{-j2\pi(f_\alpha x + f_\beta y)} \) where \( f_\alpha \) and \( f_\beta \) are known spatial frequencies. Since recording
materials are only sensitive to the intensity of light, what is actually retained is the total energy absorbed by the material. The measure of this energy is called exposure and is defined as

\[ \varepsilon(x,y,0) = \frac{1}{T} \int_0^T I_w(x,y,0,t) \, dt \]  

(3.8)

where \( I_w(x,y,0) \) is the intensity of the writing field distribution which is usually not time dependent during recording so we simply have \( \varepsilon(x,y,0) = TI_w(x,y,0) \). The transmittance function of the hologram \( t(x,y,0) \) is directly proportional to the exposure and in the case of interfering object and reference beams

\[ t(x,y,0) \propto |U_o|^2 + |U_r|^2 + U_o U_r^* + U_o^* U_r, \]  

(3.9)

where the arguments are omitted for compactness.

When the hologram is illuminated by a beam with the same properties, excluding intensity, as the reference beam used in the recording step, say \( Be^{-j2\pi(f_o x + f_y y)} \), the transmitted field directly after the hologram is

\[ U_t(x,y,0) \propto (|U_o|^2 + |A|^2) Be^{-j2\pi(f_o x + f_y y)} + ABU_o + ABU_o^* e^{-j4\pi(f_o x + f_y y)}. \]  

(3.10)

We can immediately recognize the scaled reconstructed object wavefront \( ABU_o \), or the virtual image of the recorded object. The other two terms in Eqn. (3.10) represent the undiffracted light in the direction of the reference beam and a conjugated object wavefront carried at the doubled spatial frequency of the reference beam. This last term is called the real object image. Conversely, if the hologram were illuminated with a replica of the object beam, the reference beam would be reconstructed. To predict the field distribution in a plane away from the hologram, we can use the technique described in Section 3.1.

Depending on the material properties and its processing, the transmittance of a hologram acts by absorption or phase modulation or combination of the two mechanisms. Absorption holograms modify either the amplitude or the intensity of the incident electric field thus incurring
energy loss to the transmitted field, while phase holograms are potentially lossless optical elements.[14][15] We will therefore focus our attention on phase holograms in this thesis since they will better satisfy the requirements of our application.

3.3 Bragg diffraction

The holographic principles of diffraction presented in the previous section assume that the recording emulsion has no thickness and ignore the effects of light propagation through a volume of material. The formulas presented work very well if the thickness of the hologram is comparable to or smaller than the wavelength of the waves we are writing and reading it with. [14][15] In that case we are dealing with plane, or thin holograms. When the thickness of the emulsion is much greater than the features of the interference pattern being recorded, we have a case of thick, volume holograms. Thick phase hologram gratings consist of successive planes of higher and lower indices of refraction that are analogous to planes of point scatterers in a crystal. Diffraction is then governed by Bragg’s law very well known from crystallography:

\[ m\lambda = n\lambda (\sin \varphi_1 + \sin \varphi_2), \]

which very rigorously correlates the grating period \( \Lambda \) to the wavelength \( \lambda \) used at an angle of incidence \( \varphi_1 \) from the grating planes in order to achieve constructive interference of order \( m \)

![Figure 3.1: Illustration of Bragg diffraction with \( \varphi_1=\varphi_2=\theta/2 \) and \( m=1 \)](image-url)
diffracted at angle \( \varphi_2 \). Bragg diffraction from a simple periodic refractive index grating, such as ones we intend produce, is illustrated in Figure 3.1 above. This situation is typical in holography, where it can be mathematically shown that the grating planes are oriented at recording in such a manner as to bisect the angle between the object and reference beams so \( \varphi_1 = \varphi_2 = \theta/2 \). [15]

It is also very common to replay the hologram with a reference beam of different wavelength. As a consequence, the reconstructed object is scaled because the angle of diffraction changes. To understand this phenomenon, we will use wave vectors to describe creation of and diffraction from a Bragg grating. When two beams of same wavelength \( \lambda \) interfere at angle \( \theta = 2\varphi_1 \) as in Figure 3.2a, a standing interference pattern (and subsequently the grating) is created. We can describe this interference pattern with a wave vector \( \vec{K} = \vec{k}_o - \vec{k}_r \), where \( k_o = k_r = 2\pi/\lambda \) and \( K = 2\pi/\Lambda \). If we now try to illuminate this grating with a beam of different wavelength \( \lambda' \) incident at the same angle \( \varphi_1 \), the diffraction occurs in the direction \( \varphi_2 \) (shown in Figure 3.2b) from the grating in accordance with Eqn. (3.11).

![Figure 3.2: Vector representation of Bragg diffraction when a) grating is created and b) grating diffracts light of different wavelength](image)

Grating period \( \Lambda \) remains constant, which allows us to relate angles \( \varphi_1 \) and \( \varphi_2 \)

\[
\sin \varphi_2 = \left( \frac{2\lambda'}{\lambda} - 1 \right) \sin \varphi_1, \tag{3.12}
\]
and after applying a couple of trigonometric identities we arrive at the equation connecting reference and object beam incidence angles $\theta$ and $\theta' = \phi_1 + \phi_2$, which are the measurable quantities in our system:

$$\cos \theta = 1 - \frac{2 \sin^2 \theta'}{1 + \left( \frac{2 \lambda'}{\lambda} - 1 \right)^2 + 2 \left( \frac{2 \lambda'}{\lambda} - 1 \right) \cos \theta'} \quad (3.13)$$

The ability to create and replay thick holograms at different wavelengths is important, as we might not be in the position to use the same light source for production of HOIEs and operation of OEIC.

The conditions for maximum diffraction intensity from thick gratings are much more strict when compared to diffraction from a perfectly thin grating which allows us to chose the wavelength and angle of incidence independently. [14] The greatest difference between the two types however, is efficiency. With thin holograms it is impossible to avoid higher orders of diffraction and the presence of strong undiffracted zero order light. A lot of the power is hence wasted and in addition we have to worry about this noise interfering with the communication channels we are trying to establish. Thick holograms on the other hand have the potential of transferring all of the power in the desired direction as predicted by Kogelnik's coupled wave theory. [16] Thick phase holograms are therefore of particular interest to our intended application since they offer high diffraction efficiency and very good SNR.
4 Production System Design Considerations

Before a system for production of HOIEs is constructed, it is essential to model the behavior of the intended interconnection scheme. This step supplies essential parameters of the system which can save a considerable amount of experimentation time during the construction of the system and production of HOIEs. In accordance with the theory presented in the previous chapter, we will first determine the set of minimal specifications required for the system (both for the production of large-scale and integrated gratings), which are then used in a simulation demonstrating the functionality of interconnection.

4.1 System Specifications Calculation

A detailed illustration of a part of the nearest neighbor interconnection scheme is shown in Figure 4.1. We observe that it is necessary to have two different grating periods, since the distance from the HOIE pixel to the neighboring horizontal/vertical or diagonal detectors is not the same. Therefore, diagonal sub-pixels need to diffract light at a slightly different angle than the horizontal ones. These angles are calculated using the following equations:

\[
\sin \theta_{h,v} = \frac{p - d}{\sqrt{L^2 + (p - d)^2}}
\]

\[
\sin \theta_{d} = \frac{\sqrt{2}(p - d)}{\sqrt{L^2 + 2(p - d)^2}}
\]

(4.1)
where $p$ is the pixel pitch, $d$ is the sub-pixel dimension and $L$ is the separation of HOIE and detector planes. The Bragg condition for maximum first order diffraction in both cases is derived from Eqn. (3.11) and requires

$$\lambda = 2\Lambda \sin \frac{\theta}{2},$$  

(4.2)

keeping in mind this formula is only valid when grating are produced.

![Figure 4.1: Interconnection light paths](image)

Using basic trigonometric identities, it is not hard to calculate what the corresponding grating periods would be:
So far we have ensured that the light diffracted by the HOIE will hit the center of the appropriate photodetector, but we also have to take care that this field distribution does not overfill into neighboring detector pixels, causing crosstalk. Limiting the distance between the HOIE and detector planes, according to the Fraunhofer field distribution, secures this. [12] The width of the main lobe of the beam should be smaller than the shortest distance between two detectors. We thus concern ourselves with the situation of diagonal interconnection (longest path traveled by light) and horizontal/vertical adjacent detectors. For the case of square aperture of size \( d \), the condition for avoiding overfill can than be put as: [11]

\[
\frac{2\lambda\sqrt{L^2 + 2(p-d)^2}}{d} < p-d,
\]

which, after suitable approximations, can be simplified to

\[
L < \frac{pd}{2\lambda}.
\]
4.2 Large-scale Prototype HOIE Production Specifications

Since our goal is to replace the blazed gratings already implemented in the Hopfield ONN prototype [9], the sub-pixel dimension is predetermined to be $d=6.2\,\text{mm}$ and the accompanying $p=18.6\,\text{mm}$. The distances of separate horizontal/vertical and diagonal gratings from detectors were $39\,\text{mm}$ and $55.25\,\text{mm}$ respectively, and we would like our separation $L$ to be in the similar range. The reader should note that these lengths are many orders of magnitude smaller than the limit imposed by Eqn. (4.5), so we should not need concern ourselves with overfilling. Choosing $L$ will unambiguously set $\theta_{hv}$ and $\theta_{diag}$, and we can aid ourselves with Figure 4.2 in making a proper decision.

![Figure 4.2: Dependence of diffracting angles $\theta_{hv}$ and $\theta_{diag}$ on separation $L$ ($p=18.6\,\text{mm}, d=6.2\,\text{mm}$). Derived from Eqn. (4.1)](image)

We are somewhat restricted by the size of optics we intend to use in the production system, as it might not be possible to physically mount the components (especially mirrors $M_2$ and $M_3$ in Figure 4.3) to achieve two angles that are very similar. In order to have adequate angular
separation, we may want to choose $L=40\text{mm}$. The angles and corresponding grating periods are then easily calculated using Eqns. (4.1) and Eqn. (4.3), having in mind that both the production of HOIEs and the operation of the prototype Hopfield ONN is being conducted with the green spectral line of the $\text{Ar}$ ion laser, $\lambda=514.5\text{nm}$:

$$
\theta_{hA}=19.030^\circ \quad \Lambda_{hA}=1.718\mu\text{m}
$$

$$
\theta_{diag}=29.195^\circ \quad \Lambda_{diag}=1.254\mu\text{m}
$$

![Figure 4.3: Realization of different horizontal/vertical and diagonal diffraction angles](image)

We now have all the information needed to mount the mirrors at appropriate locations. The average heights ($h_2$ and $h_3$ in Figure 4.3) of the mirrors are set to about 20cm to provide for sufficient horizontal separation $l_3-l_2$.

It is also sensible to turn our attention to the requirements on the holographic recording material at this time. From the grating periods calculated above, the maximum resolution that the
recording emulsion needs to cope with is \( \frac{1}{1.254 \times 10^{-3} \text{mm}} = 797.45 \text{ lines/mm} \), which is well below the MTF cutoff frequency of most currently used holographic materials. [17][18] We intend to use silver-halide plates that can handle up to 5000 lines/mm. Photopolymers promise to be excellent materials for thick phase holograms and can typically resolve 2000 lines/mm.

One last note before we can proceed to the actual production of holograms. The shape of the aperture used to separate each sub-pixel is critical in this application, since it determines how light is propagated after it. This means that the diffraction properties of the aperture are also stored in the HOIE at the time of production, and are subsequently replicated when the hologram is used. We would therefore like to have a well-defined square aperture with sharp edges, so that we can easily predict the diffraction effects from it. An acceptable aperture design is shown in Figure 4.4.

The 45° slanted profile serves a double purpose: it provides us with the required sharp “knife edge”, mimicking a perfectly thin aperture, and it also reflects the excess light away from the aperture. For this reason is the side facing the incident light made reflective, while the side facing the film is absorptive in order to restrain any light scattered by the emulsion. The actual part drawing is given in APPENDIX A: Aperture Design.

Manufacturing an aperture with these properties imposed a big difficulty, since it is impossible to achieve sharp corners on a milling machine and commercially available punches do not come in the size required, so a new production method specific to our problem had to be
invented. First, we would make a conic incision with the suitable inclination in a piece of aluminum on a lathe. If we were to make a cut across this incision, a circular aperture would emerge, but a square one is wanted. Next we need to create a punch tool that has a shape of a pyramid, and with this tool deform the conic incision. Making a cross cut at appropriate depth results in the desired square aperture with very sharp edges.

Having all the vital components and parameters of the production system, it is now possible to finalize the assembly and commence with the production of HOIEs for the large-scale Hopfield ONN. Resulting holograms are presented in the following chapter.

4.3 Integrated HOIE Production Specifications

Although the production of HOIEs for the integrated system will occur at a later stage of the bigger OEIC effort, it is important for us to make the necessary preparations presently.

The HOIE specifications of the integrated system have to be matched to the ones of the RCLED and detector arrays, which were predetermined in the VLSI design stage. Normally, we would like the pixels to be as small as possible in order to have a compact system. This size is not only limited by VLSI design rules, but also with optical properties of HOIEs. Namely, many grating periods need to be present in a diffractive element in order to have satisfactory efficiency.

It has been decided that a suitable pixel size would be \( p=250\mu m \), with a sub-pixel dimension of \( d=50\mu m \) (the rest of the pixel area is occupied by controlling circuits on the electronic wafers, or is simply unused in the HOIE). The interlayer distance is planned to be \( L=1mm \), well below the limit of Eqn. ( 4.5 ) which ensures we will not be overfilling into neighboring detectors. Knowing that RCLEDs emit light at \( \lambda'=890nm \), we can calculate the following desired parameters:

\[
\theta_\lambda'=11.310^\circ \\
\theta'_{\text{diag}}=15.793^\circ
\]
We have to keep in mind that the holographic production of gratings with these specifications will be operated with an Ar ion laser, specifically the green line $\lambda = 514.5 \text{nm}$. This means that in order to generate the required grating period at this wavelength, we need to use different incidence angles according to Eqn. (3.13). So, in the hologram writing process we would like to have

\[ \theta_{h\lambda} = 6.525^\circ \quad \Lambda_{h\lambda} = 4.520 \mu\text{m} \]

\[ \theta_{\text{diag}} = 9.095^\circ \quad \Lambda_{\text{diag}} = 3.245 \mu\text{m}. \]

Comparing to the size of a sub-pixel we find there are at least $\frac{50 \mu\text{m}}{4.520 \mu\text{m}} = 11$ grating lines present that should provide for satisfactory diffraction efficiency.

The required grating period of this configuration is larger than in the case of the prototype gratings, and therefore requires weaker recording material resolution of $\frac{1}{3.245 \times 10^{-3} \text{mm}} = 30817$ lines/mm. Again, there is no danger of reaching the MTF cutoff of the recording material, which promises very good signal reproduction.

The only difficulties that may arise during the setup of the production system for this configuration are mounting of optics and construction of the small aperture. Since the angles involved are relatively small and very similar, it will be hard to mount mirrors $M_2$ and $M_3$ in appropriate positions. It is possible to supply more separation space between the mirrors by increasing their height from the recording material, but we are then in danger of decreasing the stability which is crucial for any interferometric system. Another option would be to employ smaller optics.

Producing an aperture of required sub-pixel size of $50 \mu\text{m}$, with sharp corners and edges, is unachievable by any mechanical means. Instead, the aperture will be etched in a photolithographic process, and a proper holder for the glass substrate should be constructed.

Since HOIEs for the integrated system are not produced at this stage, a computer simulation demonstrating their functionality follows.
4.4 Interconnection Simulation

A set of MATLAB functions was composed in order to simulate the behavior of interconnections in the integrated system and the code can be found in APPENDIX B: MATLAB Functions.

The main function `diffcalc(lambdaw, lambdar, z, wavefront)` plots a calculated diffraction pattern from one HOIE pixel. The input arguments are `lambdaw`, the wavelength at which we write the hologram, `lambdar`, the readout wavelength, and `z`, the distance between HOIE and detector planes. The string argument `wavefront` designates what kind of reference beam (with plane or focused wavefront) the hologram was produced with. All units are assigned in millimeters.

The calculation of system parameters is then done internally, starting from pixel pitch `p` and sub-pixel dimension `d`, which were determined in the previous section (OEIC specifications are assumed throughout the simulation). The required angles of diffraction $\theta_{hv}$ and $\theta_{diag}$ are found using Eqns. (3.13) and (4.1), and have to be modified since they are measured from the $z$-axis. We need to know the angles of the object beam wave vector $\vec{k}$ from x- and y-axes in order to calculate spatial frequencies $f_\alpha$ and $f_\beta$ involved in Eqn. (3.10). The diffraction angles from different axes are related in the following expression:

$$\cos^2 \theta_x + \cos^2 \theta_y + \cos^2 \theta_z = 1,$$

(4.6)

from which we can easily calculate that $\theta_x=90^\circ-\theta_{hv}$ and $\theta_y=0$ (or vice versa) in the case of horizontal/vertical diffraction, and $\theta_x = \theta_y = \cos^{-1}\left(\frac{\sin \theta_{diag}}{\sqrt{2}}\right)$ for diagonal diffraction. These angles are then used to construct the transmittance function of the pixel using `tf9(x, y, d, lambdaw, theta1, theta2, [f])`. Significant input arguments are sub-pixel dimension `d`, writing wavelength `lambdaw` with two different incident angles `theta1` and `theta2`. If the optional argument `f` is included, it indicates that the reference beam used is not plane, but the other solution to the Helmholtz equation: [11]
where \( f \) is the focal distance from the plane \( z=0 \). When illuminated with a plane beam at normal incidence rather than a replica of the reference beam, this nonlinear phase factor is transferred to the reproduced wavefront, which then inherits this focusing property. A careful reader will notice that for simplicity we include only the term of Eqn. (3.9) yielding the desired diffracted beam.

This transmittance function \( t \) is then multiplied with an incident plane wavefront with wavelength \( \lambda_{\text{d}} \) in \( \text{diffract}(t, f_x, f_y, \lambda_{\text{d}}, z) \), and then propagated a distance \( z \) according to the theory presented in Section 3.1.

The result of the whole exercise is a plot consisting of the field intensity distribution directly behind the pixel and its spatial frequency spectrum, the field intensity distribution on the detector plane and a detailed field intensity distribution at one of the diagonal detectors since diffraction effect should be the most pronounced there because this detector is the most distant from the pixel plane. Several examples are given in the following pages.

Figure 4.5 is the result of \( \text{diffcalc}(0.5145 \times 10^{-3}, 0.5145 \times 10^{-3}, 1, \text{"plane"}) \). Plane wavefront beams of an Ar green \( \lambda=514.5\text{\,nm} \) laser are used to construct the gratings and establish interconnection in this case. The HOIE-detector separation is 1mm, same as in the OEIC architecture. Since we are able to plot only the intensity of the field distribution, we cannot distinguish the 9 sub-pixels in the illuminated pixel area shown in Figure 4.5a. To learn about the phase, we take a Fourier transform of the field distribution. Each of the 9 sub-pixel linear phases translates to a shift in the spatial frequency domain, which is clearly seen in Figure 4.5b. It is important to notice that the spatial frequency peaks of individual beams are not infinitely narrow, as one would expect when dealing with plane waves. Instead, this profile inherits the properties of the aperture used when producing each sub-pixel. The existence and spread of the side lobes is due to the finite sub-pixel size and highly depends on it. It is at this stage that we can already predict whether there will be any cross-talk affecting the interconnection. This spread in spatial frequency is also responsible for diffraction artifacts visible in Figure 4.5c: the intensity pattern in
the detector plane is no longer a perfect square (a shadow of a sub-pixel). From the power efficiency standpoint, we also need to examine the detailed field intensity distribution at a single detector location, as shown in Figure 4.5d. The square box represents the detector active area, and as we can see, most of the diffracted power is concentrated within it, with very little excess light being wasted.

Figure 4.5: Result of `diffcalc(0.5145e-3, 0.5145e-3, 1, 'plane')`:

a) field distribution in pixel plane and its b) spatial frequency spectrum

b) field distribution at the detectors and d) detailed field pattern compared
to the detector size
In Figure 4.6 we show the result of diffcalc(0.5145e-3, 0.89e-3, 1, 'plane'), where the HOIE is created with plane Ar green $\lambda=514.5\mu$m laser beam, and read out with RCLEDs of $\lambda=514.5\mu$m. The assumption that RCLEDs emit collimated plane wavefront beams in reality is not entirely correct, and a better description of the wavefront profile would be an expanding or diffused beam. This case is nevertheless valid since volume gratings,
due to their high selectivity, act as band-pass filters, retaining only the plane wave component of the incident beam. Naturally, this scheme is not very efficient as the grating absorbs a considerable amount of power.

![Figure 4.7: Result of diffcalc(0.5145e-3, 0.5145e-3, 1, 'focused'): a) field distribution in pixel plane and its b) spatial frequency spectrum c) field distribution at the detectors and d) detailed field pattern compared to the detector size.](image)

The main difference from the previous situation can be seen in Figure 4.6b, where the spatial frequency spectrum has "shrunk" as predicted when we have greater readout wavelength. Diffraction effects are also more pronounced for greater wavelength, with the main power peak
Chapter 4

still located at the center of detector (Figure 4.6d) and side lobes drawing off some power to the inactive area.

Figure 4.7 and Figure 4.8 show the results of the previous two situations when using a focused reference beam instead of a plane one. It is interesting to notice that the similarity of the

Figure 4.8: Result of `diffcalc(0.5145e-3, 0.89e-3, 1, 'focused')`:

a) field distribution in pixel plane and its b) spatial frequency spectrum
c) field distribution at the detectors and d) detailed field pattern compared to the detector size
Production System Design Considerations

individual spatial frequency spectrum peak profiles in Figure 4.7b and Figure 4.8b to the field
distribution in Figure 4.5c and Figure 4.6c. This effect is the result of an extra Fourier transform
introduced by the lens used to focus the reference beam. [12]

The focal length used in the case of same writing and readout wavelengths is simply \( f = L \),
and the result (Figure 4.7d) is drastically improved, as all of the diffracted power is confined to the
detector area. For the same reason that we require altered incidence angles when producing a
hologram at a wavelength different from the reproduction one, a modified focal length is
necessary. Looking at Eqn. (4.7), we conclude that \( f = \frac{\lambda'}{\lambda} \) \( f' = \frac{\lambda'}{\lambda} L \) should do the trick. This
unavoidably has the effect on the \( x^2 + y^2 \) term which leads to corresponding spot size scaling
(Figure 4.8d). Improvement in this case is also clearly visible, as virtually all diffracted power is
concentrated on the detector active area. It also important to keep in mind the comments on
RCLEDs beam profile made earlier.

The results of this simulation prove the feasibility of the OEIC interconnection scheme
and confirm the system parameters. Although many assumptions have been made (ideal gratings
with 100% efficiency, ideal plane and spherical wavefront, perfect alignment, etc.), the outcome is
very optimistic, as it shows us there is plenty of margin left to endure the problems one might run
into when building a real physical system, such as noise coming from grating and beam
imperfections or small misalignment errors. Furthermore, it provides the possibility to estimate
these margins and subsequently the errors we are ready to tolerate. This information is invaluable
for the design and improvements of the system.

The reason that an interconnection simulation for the large-scale Hopfield ONN is not
included in this thesis is twofold. The dimensions of all parameters involved, especially the size of
diffractive sub-pixel, are many orders of magnitude greater than the wavelength \( \lambda \) of light driving
the network. Diffraction effects are in such case negligible and we can simply revert to
geometrical optics. [11] If we were to decide to carry out such simulation, we would soon find out
that such an endeavor would be impractical and a waste of resources.

Namely, the SBWP of that particular problem is very high and we need many sampling
points to process it. [20] With a fixed number of sampling points, we have to make a tradeoff:
more spatial range means less bandwidth in spatial frequency and vice versa. The only way to have both is to keep increasing the number of sampling points, which are limited by the processing power and storage capacity of the computer used for simulation. In our case a Pentium II at 300MHz with 128MB of RAM was used, which was able to handle two-dimensional FFTs of up to \(1024 \times 1024\) points, which were not sufficient for this particular problem. On the other hand, \(768 \times 768\)-point FFTs sufficed for the integrated system simulation.

We will rather go straight into production and characterization of HOIEs required by the large-scale Hopfield ONN instead of pursuing their simulation.
5 Production Results

After the extensive theoretical study, it is now time to see if the produced HOIEs will live up to their expectations. The production system is assembled as described earlier in Section 2.1 with the components already mentioned. The alignment of the system is critical and must be carefully conducted. Most importantly, the reference beam should be perpendicular to the platform surface carrying the recording material and coincide with axis of the rotary table. The object and reference beams are expanded so they overfill the aperture and are aligned to interfere on the surface of the recording material.

The production process takes place in complete dark and consists of the following step. The holographic recording material is first attached to the moving platform and the aperture lowered and adjusted so it barely touches its surface. The computer then translates the recording material so that a specific area is under the aperture. After a short pause after the stages have stopped moving in order for the system to settle, the shutter is opened for a specified time and the exposure takes place. This is repeated until all sub-pixels containing gratings with the same orientation are written. We are at the point now when we must turn the rotary table to a different position, as we would like to write the next grating orientation. A weak red LED had to be attached near the rotary table scale readout that enables us set the orientation correctly. On the other hand, we have to be careful not to expose the recording material to this light, so after each step we must cover the aperture. The platform containing the hologram is cloaked with a special photographic focusing cloth that is highly reflective on the outside and absorptive on the inside.

It has been decided that the sub-pixels should not be created in a sequence in which me rotate the platform by 45° only. This is undesirable because that means we would need to flip the
mirror $M_2$ out of the beam path many times, which could cause alignment problems later on. It is therefore advisable to create all the horizontal/vertical sub-pixels together, flip the mirror, and write the diagonal sub-pixels (this implies $90^\circ$ turns of the rotary table). An acceptable writing sequence is illustrated in

![Sub-pixel exposure sequence](image)

Figure 5.1: Sub-pixel exposure sequence

The system is set up with parameters calculated in Section 4.2 to accommodate the production of large-scale prototype HOIE array with a small number of pixels. The limit is $3\times3$ because the linear stages can only move a given amount. We will first test the production system (and the interconnection scheme with that) with traditional silver-halide plates.

5.1 Thin holograms: Silver-halide Plates

The holographic recording material we will use for preliminary HOIEs is silver-halide emulsion on a glass substrate. The emulsion is called BB-PAN and has characteristics very similar to the widely used Agfa holographic plates that are not produced anymore. [21][22] This emulsion has a fine grain size of $25\text{nm}$ providing a very high resolution, which means we need not worry about MTF cutoff.

The spectral sensitivity graph provided by the retailer is shown in Figure 5.2. It gives us a useful guideline in which range of exposure we should operate. The plates are first characterized by making an array of increasing exposure times, while keeping the laser power constant. For recording with the Ar green line $\lambda=514.5\text{nm}$ it has been determined that the most suitable exposure is $1\text{sec}$ at the output power of $350\mu\text{J/cm}^2$ for the reference beam. The beam splitter
used in the system is approximately is 50/50, meaning that the object beam has almost the same intensity. This configuration results in the greatest grating amplitude changes, which positively affects the diffraction efficiency.

The exposed plates can be developed using the recipe of the manufacturer [24] or a process known to our group to yield good results. [25] The plate is first developed in Kodak D-19 developer on OD=2. If we wish to have amplitude holograms, we can now fix the plate with a Kodak Fixer. For phase-only holograms, which are of greater interest, the plate is bleached in a reversal bleach bath until the amplitude grating is transformed into a refractive index one. Different bath times and agitation periods are given below:

<table>
<thead>
<tr>
<th>Kodak D-19</th>
<th>Stop Bath</th>
<th>Wash (deionized water)</th>
<th>Reversal bleach</th>
<th>Rinse</th>
<th>Hypo-clear</th>
</tr>
</thead>
<tbody>
<tr>
<td>5min.</td>
<td>30sec</td>
<td>2min</td>
<td>5-10min</td>
<td>30min</td>
<td>5min</td>
</tr>
<tr>
<td>10sec</td>
<td>3sec</td>
<td>5sec</td>
<td>10sec</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.2: BB-PAN spectral sensitivity [23]
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The typical diffraction efficiencies attained are shown in Figure 5.3. The low efficiency and the appearance of the $-1^{st}$ order is to be expected when we are dealing with thin holograms.

![Figure 5.3: BB-PAN diffraction efficiency](image)

The diffracted beam hitting a plane at a distance where the detectors should be looks very clean and is centered at the desired location. The spread of the beam is negligible since the hologram and the projection plane were close enough to be considered as near field regime.

These experimental results prove the successful design of the OEIC interconnection scheme and the functionality of the HOIE production system.

Unfortunately, no holographic recording material was available at the time of writing of this thesis, so I could not produce any thick holograms demonstrating their high diffraction efficiency. Photopolymers seem to give satisfactory results as interconnection elements. The photopolymer from DuPont is reported to have desirable properties such as high diffraction efficiency in addition to simple handling and dry processing. [26][27]
6 Concluding Remarks

The purpose of this thesis was to carefully study a specific holographic optical interconnection scheme to be integrated in a future hybrid optoelectronic processor. The nearest neighbor interconnection was chosen because it is easy to implement and has the desirable properties of modularity and cascadability. The optical interconnections of such a processor were simulated successfully in order to verify the feasibility of the OEIC design. Furthermore, a system for production of such HOI Es was designed and built and preliminary holograms were produced and tested. Thin holograms on silver-halide plates, although having lower diffraction efficiency than can be utilized in the existing prototype ONN, fulfilled other important requirements set before them, such as centering the diffracted light where necessary and not spreading out the diffracted beam, avoiding overfill and crosstalk. The results of this project are very encouraging and suggest more research should be done in this area.

6.1 Recommendations for Future Research

I would like to take this opportunity and make some recommendations for future improvements of the HOIE production system:

- the production of HOI Es on silver-halide plates should continue in order to improve the diffraction efficiency (addition of antihillation backing or different aperture design) in order to optimize the system for
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- the production of HOIEs on photopolymer in order to achieve diffraction efficiencies acceptable for processor integration (other volume holographic recording materials should be investigated as well [28])

- adaptation of the system to the larger number of pixels that are being minimized (an update to a fully automated system is desired)

- investigation of other approaches of forming the reference and object beams to closer represent the light beam profiles present in the processor [29]

- the potential of the system to fabricate each pixel with an arbitrary grating orientation should be exploited, thus opening possibilities to interconnection schemes other than nearest neighbor

One should also keep eyes open for the wide variety of approaches to the subject of holographic optical interconnection elements. [30] All of might not be the best solutions, but each offers some new ideas that can prove to be most useful.
BIBLIOGRAPHY


APPENDIX B: MATLAB Functions

This appendix includes the set of MATLAB function that were written in order to simulate the optical interconnection scheme of the OEIC. The code is based on theory presented in Chapter 3, and the parameters calculated are the same as stated in Section 4.3.

function diffcalc(lambdaw,lambdar,L,wavefront)
    % Calculates and plots the diffraction pattern a distance L from
    % the pixel plane. Pixel gratings are written with a wavelength
    % LAMBDAW and a reference WAVEFRONT ('plane' or 'focused') and
    % read with wavelength LAMBDAR.

    range=0.768;
    npoints=768;
    step=range/npoints;
    scale=-range/2:step:range/2-step;
    ftscale=(npoints/range^2)*scale;
    [x,y]=meshgrid(scale,scale);
    [fx,fy]=meshgrid(ftscale,ftscale);

    p=0.250;
    d=0.05;

    % Calculate the required diffraction angles
    thetaprimehv=asin((p-d)/sqrt(L^2+(p-d)^2))*180/pi;
    thetax=90-thetasolve(lambdaw,lambdar,thetaprimehv);
    thetaprimediag=asin(sqrt(2)*(p-d)/sqrt(L^2+2*(p-d)^2))*180/pi;
    thetadiag=thetasolve(lambdaw,lambdar,thetaprimediag);
    thetaxy=acos(sin(thetadiag*pi/180)/sqrt(2))*180/pi;

    % Focus not same for writing and reading wavelengths
    f=L*lambdar/lambdaw;

    if strcmp(lower(wavefront), 'plane')
        t=tf9(x,y,d,lambdaw,thetax,thetaxy);
    else
        t=tf9(x,y,d,lambdaw,thetax,thetaxy,f);
    end

    [DP,FT,I]=diffract(t,fx,fy,lambdar,L);

    figure;

    colormap('gray');
    cmap=1-colormap;
    colormap(cmap);

    subplot(2,2,1);
    imagesc(scale,scale,I);
function TF=tf9(x,y,d,lambda,thetal,theta2,f)
% Assembles the transmission function TF of a pixel with 9 sub-pixels.
% If focal length F is given, the transmission function includes
% nonlinear phase to achieve focusing property.

scale=x(1,1:length(x));
k=2*pi/lambda;
fl=cos(thetal*pi/180)/lambda;
f2=cos(theta2*pi/180)/lambda;
tftemp=zeros(size(x));
for m=-1:1
    for n=-1:1
        % Here we construct the spherical or plane reference beam wavefront
        % at each sub-pixel location
        if nargin==7
            r=sqrt((x-m*d).^2+(y-n*d).^2+f.^2);
            ref=(exp(j*k*r)./r).*(rect(scale',d/2,n*d)*rect(scale,d/2,m*d));
        else
            ref=rect(scale',d/2,n*d)*rect(scale,d/2,m*d);
        end

        % The reference beam is multiplied by the appropriate linear phase
        % (i.e. plane wavefront object beam)
        if abs(m*n)==0
            TF=TF+ref;
        end
    end
end
zoom on;
tftemp = tftemp + ref.*exp(j*2*pi*(-m*f1*(x-m*d)-n*f1*(y-n*d)));
else
    tftemp = tftemp + ref.*exp(j*2*pi*(-m*f2*(x-m*d)-n*f2*(y-n*d)));
end
end
TF = tftemp;

function [DP, FT, I] = diffract(t, fx, fy, lambda, z)
    % Calculates general diffraction pattern DP at distance Z from
    % a transmission function T. Also returns the input field distribution I
    % and input spatial frequency spectrum FT.
    u0 = ones(size(t));
    ul = u0.*t;
    ult = fftshift(fft2(ul));
    u2t = ult.*h2(fx, fy, z, lambda);
    u2 = ifft2(fftshift(u2t));
    I = abs(ul).^2;
    FT = abs(ult);
    DP = abs(u2).^2;

    Auxiliary functions used in the calculations are also included:

    function t = thetasolve(lambdaw, lambdar, thetaprime)
        % Calculates the required writing incidence angle for LAMBDAW
        % in order to have diffraction in direction of THETAPRIME when
        % reading at LAMBDAR.
        a = 2*lambdar/lambdaw - 1;
        b = sin(thetaprime*pi/180);
        c = cos(thetaprime*pi/180);
        t = acos(1 - 2*b^2/(1 + a^2 + 2*a*c)) * 180/pi;

    function r = rect(x, w, c)
        % Rectangular window on vector X of width 2W around center C.
        r = (sign(x-c+w)-sign(x-c-w))/2;
function h = h2(fx,fy,z,lambda)
% Calculates the free space transfer function in spatial frequency
% space FX,FY for diffraction by a distance Z at wavelength LAMBDA.

fz2=1/lambda^2 - fx .^2 - fy .^ 2;
if fz2>0
    htemp = exp(- i * 2 * pi * z .* sqrt(fz2));
else
    htemp=0;
end

h=htemp;