Magenta: Etched Focusing Lens for Photodiode Array

Diffractive Optics

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Introduction

The rapid growth of technologies within the last few decades has brought many innovations and inventions that are now ingrained into all aspects of society. It was all possible thanks to the development of optical elements. One place that uses these optical elements is MIT Lincoln Laboratory (MIT LL) whose mission is to research and develop technologies for national security.

At MIT LL, microlenses are installed on top of photodiodes in many research tools. A microlens is an optical element with a diameter less than a millimeter (smaller than the tip of a pencil). A photodiode is a device that converts light into an electrical current, and an array of photodiodes can be used in image sensors, optical communication, and passive imaging. The microlenses installed onto the photodiodes are there to collect and focus light that would have otherwise fallen onto the non-sensitive areas in the photodiode arrays. To reduce the cost and wait time to make the arrays, the microlenses we suggested to be fabricated right onto the photodiodes. This technote is dedicated to introducing microlenses to a general audience and exploring the Multi-level Diffractive Lens (MDL) that my team has chosen for our Senior Design Project. Due to optical elements being a subject that required a large amount of knowledge and research, this technote will only provide a brief introduction to the topic. Further research and exploration are recommended if the reader has further interest in optical elements.

Background

Basics of Optical Elements

Optical elements exist in many modern systems for illumination, communication, imaging, and sensing. They can be divided into two groups: transmissive and reflective. Our focus for this paper will be on the transmissive group, specifically lenses. A lens is a piece of a transparent substance with curved sides designed to manipulate light. Conventional lenses rely on their physical characteristics to exploit refraction and bends light. Refraction is the bending of a wave as it travels through one medium to another due to the change in the wave's speed or direction. The use of refraction required a conventional lens to make a trade-off between the thickness and weight of the lens with the numerical aperture (the angles the lens can accept or emit light) (1). A piece of glass that curves outward, being thicker near the middle and thinner near the edge, is called a convex lens. A convex lens needs to be thicker for larger bending angles which place a limit on where it can be used due to space and weight constraints. In recent years, these Refractive Optical Elements (ROEs) became less useful as new applications of lights such as imaging and sensing were founded. These new applications required finer controls of where the light goes and smaller areas since they are used in more compact systems. ROEs, with their performance based on the thickness of the lens, are ill-suited for such jobs. Thus, most ROEs are replaced by Diffractive Optical Elements (DOEs), which can fulfill these requirements.

Fundamentals of Diffractive Optics

Diffractive Optical Elements

Diffractive optics are commonly used in experimental and commercial systems for their subwavelength thickness and high focusing efficiency. Focusing efficiency is the ratio of power integration of the focus and the incident power. In other words, it's the light intensity distribution at an output plane. Intuitively, "flat" diffractive lenses are designed to have the highest focusing efficiency possible while still retaining a reasonable thickness. Indeed, DOEs can also be engineered to nanometer accuracy to fit the needs of the designer. A Refractive Optical Element (ROE) bends light by using the geometry of the structure and index of refraction. On the other hand, a Diffractive Optical Element (DOE) bends light using its features and aperture edges (Figure 1).

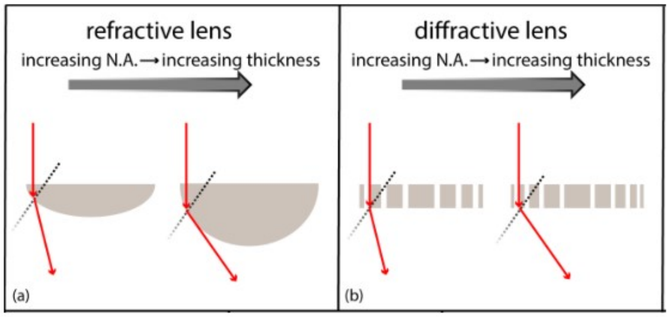

Figure 1. Optical elements bending lights via (a) refraction and (b) diffraction. (3)

Do note that there are no purely refractive or purely diffractive optical elements. All-optical elements have refractive and diffractive properties, with the dimension of the elements being the decider on which property will dominate. The dimension of a DOE refers to the overall dimension of the lens (height and width) and the feature size (step size and layer width). Our team has designed two DOEs with 100 µm diameter for wavelengths of 1550 nm and 1065 nm, i.e. infrared lights. The DOEs have feature sizes that are smaller than the wavelength (subwavelength features) which require some form of vector theory to deal with the element and its effect on light. Instead of diving into the details of the required theories and making DOE designs from scratch, our team opted to use one of the MATLAB® programs for the design of a 4-level Fresnel Zone Plate in the SPIE paper as the foundation of our designs (1).

Multi-level Diffractive Lens (MDL)

Before the MATLAB® program can be discussed, we must first understand the structure of the diffractive lens design. As stated before, MIT Lincoln Lab is looking for a microlens design that can be integrated into the fabrication of the photodiodes. To meet the thickness requirement of at most 5 µm, our team chose the Fresnel Zone Plate patterned as a blazed phase structure (Figure 2). A Fresnel Zone Plate (FZP) is composed of sections of concentric rings, known as Fresnel Zones, that are arranged on a flat plane to provide a short focal length (5). The structure alternates between being transparent and opaque, with light being diffracted around the opaque zones. The zones are usually structured so that the diffracted light will constructively interfere with the desired focus to form an image. The application of the Fresnel diffraction theory, which computes the behavior of light waves on the output plane of the substrate, is required to determine the location of the rings in the FZP (1). The MATLAB® program was written to simplify the process of computing the output architecture of the microstructure.

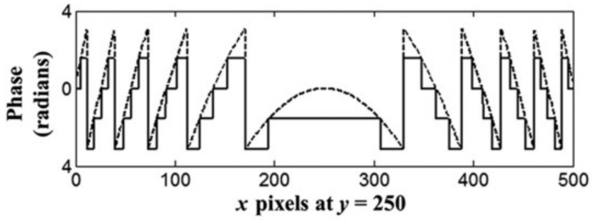

Figure 2. Phase profile of (a) a blazed FZP (dashed line) and (b) 4-level approximation (solid line) (1)

The MATLAB® program provided by the SPIE paper takes in the features of the DOE and outputs a matrix of the phase profile of a 4-level Fresnel Zone Plate(1). To do this, the program first constructs the matrices for the FZP using the input parameters and then builds the n-levels of the FZP through a series of matrix computations. To make viewing the structure better, we modified the code to also output a graph of the matrix. We also modified the original program simple uniform quantization (seen in Figure 2) to produce the phase values to a non-uniform quantization. Uniform quantization has an equal step size while non-uniform quantization does not. This allows non-uniform quantization to produce quantized values that are closer for smaller amplitudes and further apart for larger amplitudes, allowing for a constant signal-to-noise ratio for both small and large signals. Since the MDL might face different amplitudes of light, this would make our design more adaptable to real-world conditions and not just a simulation setting. The uniformly quantized phase matrix could then be modified with the refractive index of the material used to make the MDL get the correct height for each zone.

Other Considerations

Lens Material

In addition to the structure of a diffractive lens, we must also take into account the material that will be used to fabricate it. We learned earlier that a Refractive Optical Element (ROE) usually relies on its shape and refractive index of the single unit to determine its focusing efficiency and other properties (1). The Refractive index is the ratio of the velocity of light in a vacuum to the velocity of light in the material. A common example of this can be shown when you stick a straw into a glass of water. Looking at the glass from the side, your eye will see an image of a disjointed straw. Unlike ROE where the image produced relies on the material's property, DOE produces an image that relies on the superposition of lights diffracted from its various zones. Since every point in the DOE could contribute to the intensity of the output, we can get more focusing efficiency out of a diffractive lens than a refractive lens. Regarding our project, MIT Lincoln Laboratory is currently using Germanium Fresnel

Lens with a claimed 99% focusing efficiency installed on top of their photodiodes. While the lens does have great performance, it also comes with a steep price tag. To reduce cost, our team has successfully produced two Indium Phosphide Multi-level Diffractive Lens designs (for wavelengths of 1550nm and 1064nm) that met the requirement of +75% focusing efficiency (Figure 3).

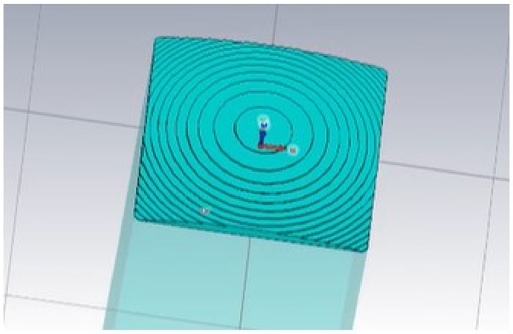

Figure 3. 3D model of the Indium Phosphide MDL

We chose Indium Phosphide because it is easy to handle and because it is already being used to fabricate the photodiodes. The availability of the material and our fabricator, Emily Carlson, having prior experience handling the material also played a role in the decision. Other materials such as Germanium, Hafnium Oxide, and Silicon Nitride were considered but weren't chosen due to the requirement of a complex fabrication process or complications with obtaining the material.

Fabrication Process

To produce the FZP structure, some possible fabrication techniques that can be used are RIE etching and photolithography. RIE etching is a dry etching method that uses chemically reactive plasma to remove materials deposited on the wafer (4). Photolithography uses UV lights to pattern a thin film or substrate (4). Etching masks are also required during the fabrication process. A mask restricts fetching of the substrate to some area by covering the areas that are not to be etched. To date, Emily Carlson from the Renewable Energy and Applied Photonics Lab was able to produce the masks for our two Indium Phosphide diffractive lens designs using photolithography (Figure 4).

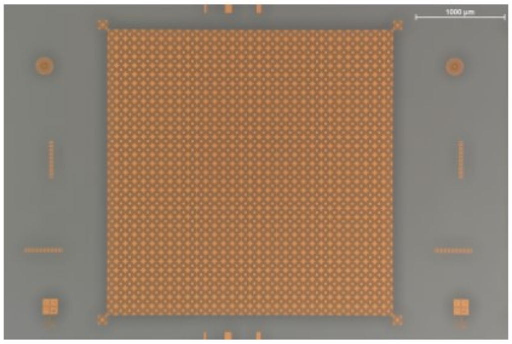

Figure 4. Mask image for Indium Phosphide MDL taken at MIT Lincoln Laboratory

The next step would be to fabricate prototypes using those masks and test their actual performance. We expect the actual performance to be similar to the simulated results, though fabrication errors could slightly affect the result. One fabrication error photolithography is susceptible to is etch depth error (2). An incorrect etch depth would alter the phase profile of the DOE, thus lowering its performance. One way to reduce such errors is to eliminate the need for deep wells where the zone boundaries are located. Doing so preemptively lowers the performance of the DOE but makes the final products have a more consistent performance.

Conclusion

The applications of diffractive optics are vast thus they are commonly used in modern imaging, optical-computing, and sensing technologies. Recent advancements in these technologies have a major contribution made by diffractive components. In this paper, the reader was introduced to microlenses and the fundamentals of diffractive optics. An example of how an MDL could be designed was shown, though due to external factors and constraints, a final physical product could not be shown.

Acknowledgement

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