Eric G. Johnson: Diffractive and Micro-Optical Systems

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Abstract

The material discussed in this paper relates to the study of physical optics in order to prepare and help students starting out in optics be prepared for the year that lies ahead for them. Most of this paper will explain diffraction and only some applications in the optics community. The basis for my paper is from an article written by Eric G. Johnson in 1996. This may benefit in helping any underclassmen in the college of optical sciences or any student with some basic knowledge of physics in their studies and understanding of the field of optics.

Dr. Eric G. Johnson is a faculty member at the University of Central Florida the Center for Research in Electro-Optics and Lasers. He has a BS in Electrical Engineering from Purdue University, MS from the University of Central Florida with his PhD from the University of Alabama at Huntsville. In 2000 he became a faculty member with CREOL, and his research includes many different fields from diffractive and micro-optical systems, data communications, as well as micro-optics fabrication. Since this class (Optics 310) is in physical optics I will focus on Professor Johnson’s work in the field of diffractive optics and micro-optical systems.

Phase encryption is one part of the field of diffractive optics that Dr. Johnson has conducted research in and is the main focus in this paper. Phase encryption is used in optical correlators; a diffractive optic that is widely used in the design of security systems [1]. The main purpose concerning these diffractive optics, or diffractive optical elements, is that they take these phase encryptions that contain data needed for security systems. Professor Johnson’s research presented in an article in 1996 provides different methods for phase encryption in diffractive optics.

Before I go into detail of Johnson’s work, I should first explain some basic physics and calculations behind diffraction and explain how it pertains to the field of physical optics. First to make distinction between the geometrical study of diffraction and the physical optic study of diffraction;
diffraction occurs whenever we have plane wave-front on course to an observation screen that is interfered with by an aperture or slit that is placed between the source and screen. According to geometrical optics, the aperture forms a shadow resembling the shape of the aperture on the observation screen. Physical optics shows that the object between the source and screen will bend the light waves around it, causing them to interfere with one another [2]. Because of this we get multiple wave fronts viewed on the screen. This can be better understood from the following diagram:

Here we see the Huygens-Fresnel principle taking place in the diagram. This principle states that at any given time an unobstructed wavefront can also be a source for many other spherical waves. From the study of diffraction it has been learned that once a wave is diffracted, two different regions of diffraction come into existence. There is the Fraunhofer (far) region, as well as the Fresnel (near) region. Depending on the distance of the diffracted pattern from the source, it will be in one of these regions.

As stated earlier there are multiple techniques for phase encryption of information in diffractive optical elements. From this point on we will refer to them as DOE’s. DOE’s and other refractive optics can be fabricated using many different techniques such as binary masking [3]. However, not many methods of phase encryption exist for these diffractive optics. During some research in 1996, Dr. Johnson presented some new ways in which these new techniques can be accomplished. He used image recovery algorithms in order to explain the design process of some of these DOE’s. The study of image recovery requires knowing math phenomenon called Fourier transforms. Fourier analysis consist of mathematical
equations that take a function in terms of a certain variable lets say frequency, $\omega$ and transforms it into its equation if it were a function of lets say, time $t$. Below is an example calculation using Fourier analysis.

Notation:

$$f(x) = \int_{-\infty}^{\infty} [A(\kappa)\cos(\kappa x) + B(\kappa)\sin(\kappa x)]d\kappa,$$

where the $A(\kappa)$ and $B(\kappa)$ coefficients are determined by

$$A(\lambda) = \frac{1}{\pi} \int_{-\infty}^{\infty} f(\kappa)\cos(\omega \lambda d\kappa)$$

and

$$B(\lambda) = \frac{1}{\pi} \int_{-\infty}^{\infty} f(\kappa)\sin(\omega \lambda d\kappa)$$

These last two equations only give the coefficients for the Fourier integral. In physical optics, nearly all the time our mathematics involves Fourier analysis. Fourier transforms for complex analysis take form in the following equations:

$$F(k) = \int_{-\infty}^{\infty} f(x)\exp(-ikx)dx$$

and the inverse $f(x) = \int_{-\infty}^{\infty} F(k)\exp(ikx)dk$

In the example of a rect(x) function we would see the following transformation

![Figure 2a](image1.png)

![Figure 2b](image2.png)

Whereas $f(x)$ is the function where:

$$f = 1 \text{ for all } |x| < 0.5 \text{ mm}$$

and 0 for all $|x| \geq 0.5$ mm
In figure a. we see the standard rect(x) function. After performing its Fourier Transform we get the sinc function, in figure b. Mathematically computing the Fourier transform, we can confirm these graphs:

\[ f(x) = \text{rect}(x/a) \]

\[ F(k) = \int_{-a}^{a} (1) \exp(-ikx) dx = \frac{2a}{ka} \sin (ka). \]

The Fourier transform takes the function in the spatial domain, and transforms it into its function in the frequency domain. Understanding the math behind all of this is very crucial to understanding physical optics, as stated by Professor Swartzlander in a class lecture, “Optics is a manifestation of Fourier Analysis”.

One image recovery algorithm that was used for encryption purposes was the Gerchberg-Saxton algorithm. According to Aharon Levi and Henry Stark it common in restoration problems; as well as being a useful tool for phase retrieval, it is a great algorithm for the encryption process [4]. For the Gerchberg-Saxton Algorithm there are two steps in per iteration needed.

![Figure 3](image)

The above figure shows the steps for this algorithm. As described in the second reference these types of algorithms incorporate taking the Fourier transform back and forth of the specific object and Fourier domains. J.R. Fienup’s article on phase retrieval algorithms describes exactly what happens in the diagram above. First Fourier transform an object, then replace the modulus of the resulting computed transform with the measured Fourier modulus in order to form an estimate of the Fourier transform;
followed by the inverse transform and replacing the modulus with the object modulus[5]. For a more in
depth explanation of the physical process, you might start off with a laser as a light source with a DOE
containing encrypted information placed in front of the source, followed by a lens which performs the
Fourier transform on the diffractive optical element and sends it to its focal place. At the focal plane is
another DOE which after more diffraction will go through another lens with the same focal length followed
by a screen where the decrypted image(s) show up. A basic knowledge of geometrical optic would show
that this would work.

Overall, Phase encryption involves many different aspects optics, some which were covered in this
paper. Research behind diffractive optics is one of Dr. Eric Johnson’s focuses. To fully understand his
research one has to be an experienced student in physical optics and be exposed to the study of diffraction
beyond the average student. Applications to many important things such as security systems include
diffactive optical elements that are vital to their success. Eric Johnson’s research at the Center for
Research and Education in Optics and Lasers has contributed to efficient security systems and knowledge
about how the discipline of optical sciences can improve them.

References

1. E. Johnson and JD Brasher, “Phase Encryption of biometrics in diffractive optical elements”, Optics
3. E.G. Johnson and JD Brasher, “Incoherent Optical correlators and phase encoding of identification
codes for access control or authentication”, Optical Engineering, 1997, Vol. 36 (9), 2409-2416.