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SPATIAL FILTERING AND OPTICAL CONVOLUTION

Physics

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ABSTRACT

we present results from an experimental effort to understand the behavior of pinhole spatial filter, Fourier transform of a lens and pattern recognition. Due to the existence of spatial imperfections, such as dust, scratches and impurities in the optical component and optical paths, the laser beam will inevitably encounter modulation of spatial frequencies. These lead to degradation of the laser beam quality. However, many applications in optics require high spatial beam quality, and therefore, spatial filtering is broadly used to improve spatial quality of light beams. An important problem associated with the use of spatial filter is energy loss due to the blockage of higher spatial frequencies originating from the imperfections and unwanted reflections from the optical components. In this experimental work we obtained the average input power of He-Ne red laser $1.800.02mW\pm$ and the output power of $1.670.01mW\pm$. Thus, we have been able to obtain 92.8% of the input power. The experimental work also includes Fourier transform of a lens, pattern recognition and optical convolution processes.

KEYWORDS

Spatial filter, Fourier transform, Lens, Convolution

Topics discussed on this paper are shortly explained as follow. The first part of the experiment is spatial filtering with pinholes. In photonic technology Gaussian optical beams are usually used, because of their high spatial quality (spatial coherence), meaning that the beam diverges minimally and in principle retains its cross-sectional profile [1]. However, due to the existence of spatial imperfections, such as dust, scratches and impurities in the optical component and optical paths, the laser beam will inevitably encounter modulation of spatial frequencies. These lead to degradation of the laser beam quality [2]. On the other hand, many applications in optics require high spatial beam quality, and therefore, spatial filtering is broadly used to improve spatial quality of light beams. Pinhole spatial filtering is used to improve output beam quality by clearing off high spatial frequencies that come from the imperfect part of the optical components and other environmental factors such as dusts. The correct optics and pinhole size combination for this application depend on the light source wavelength and beam diameter. What are the possible impact of pinhole size for the filtering process and what property the beam should have? The goal of this experiment is improve the quality of the output power of the laser light by using pinhole spatial filtering techniques. The second part of the experimental work we discussed is Fourier Transform properties of lens and 4F convolution process. Fourier transforms have been widely used in image processing applications, such as image analysis, image filtering, image reconstruction and image compression. The physical concept is based on the wave nature of light. By regarding every light-wave as a superposition of Plane waves it turns out that optical image formation can easily be treated within the mathematical framework of Fourier methods [3, 4]. This is often used in image processing, spatial filtering and Holography. In our work, we examined the applications of Fourier transforms and convolutions in Fourier optics with specific attention devoted to the Fourier lens.

An optical convolution processor, or 4f processor, is an optical setup which enables real time implementation on the mathematical cross-correlation and convolution methods. Linear image processing is basically based on two important techniques; convolution and Fourier analysis. Convolution is the more important of these two, since images have their information encoded in the spatial domain rather than the frequency domain [6]. Linear filtering can improve images in many ways: sharpening the edges of objects, reducing random noise, correcting for unequal illumination, deconvolution to correct for blur and motion, etc. [3]. These procedures are carried out by convolving the original image with an appropriate filter and produce filtered image. This paper also deals optical filtering of images and patter recognition through a custom 4F setup and spatial filters such as low pass and high pass filter.

EXPERIMENTS

I. Spatial filtering with pinhole

The experimental setup of Spatial Filtering is depicted in Fig.1

Spatial Filtering with Pinholes consists of a converging lens having a short focal length, a metallic foil which has a small (typically a few micrometers diameter) pinhole formed in it and a mechanism which allows the positioning of the light focused by the lens to pass through the pinhole in the foil [1]. By choosing the appropriate combination of a proper focal length of the objective lens and pinhole diameter, the light scattered by dust and imperfections will be obstructed, allowing a clean beam to diverge from the pinhole. We used a pinhole diameter of 10μm and the 12mm focal length of the objective lens. The light source was He-Ne red laser (632.8nm wave length and 1mm beam diameter).

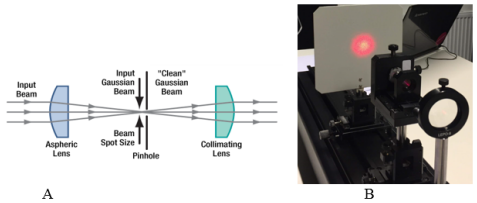

Fig.1: Spatial Filter scheme (A) and lab setup (B)

A spatial filter is comprised of three micrometers X, Y, and Z .The X and Y micrometers move the pinhole to center on the microscope objective's central light axis, and the Z micrometer moves the microscope objective forward and backward so that the narrowest point of the objective's focal point is located at the center of the pinhole. The input laser beam is incident on the back end of the microscope objective. We adjusted the spatial filtering so that the reflections from the microscope objective all coincided and surrounded the incident laser beam. A white card have been used for the alignment. Centering the back-reflections on to the hole can be done as follow. Move the pinhole mount until a small spot can be seen on a white card placed a few centimeter in front of the pinhole. Screw the microscope objective toward the pinhole, enlarging the spot on the card. Carefully adjusted the micrometers when the spot becomes weaker or off center. Alternate adjustments of the microscope objective and pinhole mount have been done until a bright beam is obtained, with few or no diffraction rings surrounding it. The correct optics and pinhole for the application depend on the input wavelength, source beam diameter, and desired exit beam diameter.

$$D_{Out} = \frac{1.27 \times \lambda \times f}{D_{Input}}, \quad D_p = 1.5 \times D_{Out}$$

Where $\lambda, D_{input}, D_{output}, D_p$ and f are the Wavelength of laser in microns, input beam diameter (mm),the output diameter of the beam ,the Pinhole Diameter (microns) and Focal length of objective lens (mm) respectively [6]. If the pinhole is too small, the beam will be clipped, but if it is too large, more than the TEM00 mode will get through the pinhole. Parameters that can be changed to alter the beam waist

diameter, and thus the pinhole size required, include changing the input beam diameter and focal length of focusing lens. Decreasing the input beam diameter will increase the beam waist diameter. Using a longer focal length will also increase the beam waist diameter. When the diameter of the pinhole is chosen appropriately, the higher spatial frequencies originating from the imperfection are blocked. Consequently, little energy is lost while a smooth Gaussian profile is restored through the spatial filtering. The fraction of power passed by a pinhole of diameter D, with the input beam is theoretical estimated as:

$$\frac{p_{D}}{P_{T}} = 1 - e^{-\frac{1}{2}\left(\frac{\pi\, aD}{\lambda F}\right)^{2}}$$

Where λ, a are the wave length and radius of the input laser beam whereas F is the focal length of the objective lens [4]. We used light source of He-Ne laser with the input beam diameter of 1mm and wavelength of 632.8nm. We obtained the average input power of the laser 1.800.02$mW\pm$ and the output power of1.670.01$mW\pm$. Thus 92.8% of the input power is finally transmitted by the pinhole. To confirm the experimental results, we calculated the theoretical expectation. Based on above equation, the theoretical expected output power is 1.68mW.The experimental value is less than the theoretical expectation and this is due to the fact that unwanted reflection inside the filter, the high frequency components of the beam have been removed by the spatial filter and the imperfection of the objective lens.

II. Fourier transform properties of a lens

In this experiment, we studied the Properties of lenses in relation to the Fourier transform. We placed an object at the focal length of the lens, and we illuminated coherent laser light beam. At the other focus of the lens we placed a white screen. As we observed from our experiment the lens automatically perform a Fourier transform on the input object.

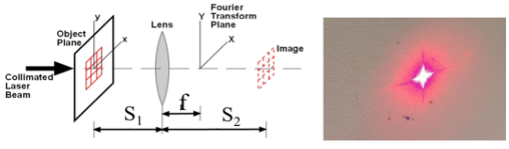

Fig.2: lens as a Fourier Transform Set-up and the corresponding Fourier image of the object.

The light travel in free space for a distance S1, is transmitted through the lens, and then propagates to the output plane. Each plane wave component is mapped to a single point in the focal plane of the lens. Every point on the input object radiates an expanding cone of rays towards the lens [4], but since the image is at the focus of the lens, thus every point of the input image is spread uniformly over the Fourier image, where constructive and destructive interference will automatically produce the proper Fourier representation. Since the low special frequency (small tilt angle) is closer to the optical axis, we observed the very bright point at the center of the object image as shown in Fig.2 (right side). Further from the optical axis, high frequency (larger tilt angle) spectrum is form less bright image.

A plane wave propagating parallel to the optic z axis has constant value in any x-y plane, and therefore is analogous to the constant DC component of an electrical signal. Bandwidth in electrical signals relates to the difference between the highest and lowest frequencies present in the spectrum of the signal. For optical systems, bandwidth also relates to spatial frequency content. It also measures how far from the optic axis the corresponding plane waves are tilted. Thus high special frequency components tilted away from the optical axis more than low special frequency. This is proved in our experiment and depicted in Fig.2 (right side). The center of the Fourier transform plot represents the amplitudes of the low frequency sine and cosine waves that make up the image, while the outer regions represent the high frequency waves. Thus a Fourier transform to any object with the help of a lens can give us amplitude information correctly.

III. Optical convolution and pattern recognition

Convolution can normally be calculated by making the Fourier transform of the two signals involved, multiply their transforms and then make the inverse Fourier transform. the convolution of two images (f(x,y) and h(x,y)) can be expressed mathematically as follow [3].

$$g(x,y) = \int\int_{-\infty}^{\infty} f(x-x', y-y')\, h(x', y')\, dx'\, dy'$$

It can be also expressed as a simple product of the Fourier transforms of both images

$$G(k_x, k_y) = F(k_x, k_y)\, H(k_x, k_y)$$

These procedures are carried out by convolving the original image with an appropriate filter, producing the filtered image.

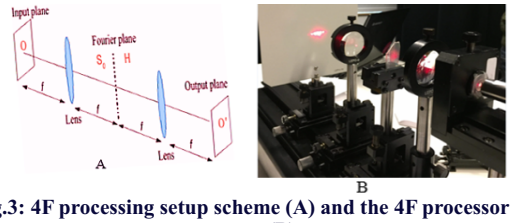

Fig.3: 4F processing setup scheme (A) and the 4F processor lab setup (B).

A simple and effective setup for optical image processing called 4f setup is depicted in Fig.3. This system provides the correlation between two images. Object O is illuminated by a mono-chromatic wave. A first lens performs the Fourier transform of the input object O (Fig.3A) in its image focal plane, S0. In this focal plane, a spacific filter H is positioned. Next, a second convergent lens performs the inverse Fourier transform in the output plane of the system to get the filtered image O`. We have been used two Fourier transform lenses having focal length (F) of 150.0 and 50.0 mm with magnification of 3 ($_{21}MFF=$).

A HeNe laser was used as a light source. When a plane wave illuminates an object in the object plane, we get the input function f(x,y). The first lens causes the Fourier transform of the input function and maps the spatial frequencies fx and fy to the points x = λFfx and y = λFfy in the focal plane. The proceeding second lens performs the inverse Fourier transform and the resulting image is obtained in the image plane. We used CCD Camera to see the detail of the profiles of the image of the object.

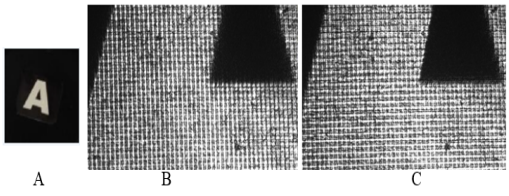

Fig. 4: Pattern recognition in Optical convolution process. Image of the original pattern (A), image obtained when we used horizontal slit (B) and image obtained when we used vertical slit on the Fourier plane (C).

By placing slits in the spatial frequency plane, we could alter the form of the image. When a vertical slit is placed in the Fourier plane, the horizontal frequency variations have been blocked (Fig.4 C) and vertical frequency variations are passed, so that re-Fourier transforming with a lens reproduces the vertical structure of the object but has eliminated all horizontal structure. Thus we smoothed out all the vertical lines by removing the high frequency content in the Fourier transform. On the other hand when horizontal slit is placed, horizontal frequency variations have been passed and vertical frequency variations have been blocked (Fig.4 B) and smoothed out all the vertical lines by removing the high frequency content is the final result. Spatial frequency filtering is another operation by which one removes (or passes preferentially) certain desired spatial frequencies by placing filters in the Fourier transform plane [3]. When we have been use a low-pass filter, this filters pass only the low frequencies (i.e., those frequency components lying near the axis). The high spatial frequencies associated with structure are filtered out (The effect is to remove the fine details, blurring the image). On the other hand, the spatial frequencies associated with the object are concentrated around zero frequency, which passes through the filter. It must be noted that through this process the high-frequency components of the object are also stopped [4] and hence the image is not exactly the same as the noise-free object. High frequencies are often associated with fine details, removing them result in a smoothing of the object, meaning if

we synthesize the image only using only waves with low frequencies (long wavelengths), then sharp features are no longer resolved (smoothed the image). The low pass filter allows the zero-order, the order +1 and the order -1 spectrum of the target to pass through the system. The imaging result is blurry as shown in figure 5(B).

On the other hand, when we apply high-pass filter, this filters allow the high frequencies to pass through while the low frequencies are stopped (it eliminates all the frequencies below a cutoff frequency). If we synthesize the image only using only waves with high frequencies (short wavelengths), then smooth features of the image are largely eliminated and the sharp edges dominate. Thus high-pass filter enhances high spatial frequencies, in particular image discontinuities and edges. With a high pass filter that can filter off the zero-order spectrum, shown in figure 5 (A). Image 5 (C) is the image without filter for the comparison.

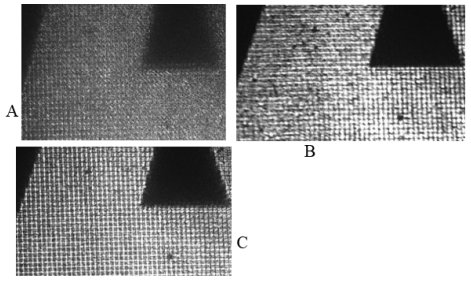

Fig. 5: Optical convolution process with filtering and without filtering. Image at CCD with a high-pass filter at Fourier plane (A), Image at CCD with a low-pass filter at Fourier plane (B) and Image at CCD without filter at Fourier plane (C).

CONCLUSION

In this paper we have shown the concept of spatial filtering, that is, the manipulation of spatial frequencies in order to alter the properties of the image of the object. On the other hand both the theoretical and experimental processes of Fourier transforms of lenses have been discussed. Firstly, we explained how a lens can be used as a Fourier transform tool. We see that when we apply a Fourier transform to any object with the help of a lens, we can get only amplitude information correctly. On the other hand, it is clear that we can also get phase information; however, it is not suitable and understandable. Therefore, as a second step, we constructed the 4F optical system with spatial filtering and collimating processes to use two lenses in order to get clear phase and amplitude information, thus we can able to recognized pattern. In this step we used different filters and investigated the effect of high and low pass filters on optical image processing. The filter, usually an amplitude mask, is tailored to transmit the desired spatial frequencies. A low-pass filter enhances the low spatial frequencies, yielding a more blurred image, while filtering out high frequency noise and the reverse is true for high pass filter. When we look at the Fourier plane with our eyes, we cannot see something in detail; however, when we used CCD Camera we can see the detail of the object structure.

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