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The Experimental Study on Optical Transfer Function under Coherent Light Based on MATLAB Simulation

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ABSTRACT

The Optical Transfer Function (OTF) can transfer spectra of different frequencies. In the process of transmission, the frequency will not change, but the amplitude will decrease, and the phase will shift. Therefore, the OTF is widely used in the evaluation of system imaging quality. In this paper, the intensity distribution, the coherent transfer function, the optical transfer function and the cut-off frequency of the image are obtained by using the back of the "5-yuan'he'coin" as the object of MATLAB simulation. Finally, the experimental results are consistent with the theoretical analysis, which proves the accuracy of the MATLAB simulation measurement method. At the same time, the relevant theoretical analysis also provides an important theoretical basis for optimizing the system parameters and improving the correlation calculation of OTF. The experimental study of OTF has great potential applications in military and aerospace fields.

Key words: Matlab Simulation; Coherent Illumination; Optical Transfer Function; Cut-Off Frequency

Introduction

The OTF is an important index to evaluate the imaging quality of optical system, which can accurately and quantitatively reflect the comprehensive effect of the aperture, spectral components and aberrations of the optical system on the image quality. The OTF can be represented by a composite function, which includes Modulation Transfer Function (MTF) and Phase Transfer Function (PTF). MTF is the real part of the OTF, which represents the ratio of the image modulation to the object modulation after the target passes through the imaging system on each frequency component; PTF is the imaginary part of the OTF, which represents the phase shift of the target background at each frequency after passing through the imaging system. In imaging system, MTF is often used to describe the quality of image. When using MTF, the imaging system needs to meet the linear and space invariance. MTF is the modulus of OTF, which is used to describe the response and resolution of the imaging system in the spatial frequency range. Therefore, the cut-off frequency of OTF is generally determined by the real resolution of the imaging system. The OTF can be calculated directly from the design parameters and can also be used to measure the actual optical system, which is convenient for the design and detection of the imaging system [1-6].

Theoretical Analysis

Under the condition of coherent illumination, the spectral distribution of the object can be decomposed into a linear combination of numerous differential functions, and each differential function

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has a corresponding impulse response on the image plane, and the relationship between the object and the image satisfies the following convolution integral:

$$I_i(x_i, y_i) = K\iint_{-\infty}^{+\infty} I_g(\widetilde{x_0}, \widetilde{y_0}) h_I(x_i - \widetilde{x_0}, y_i - \widetilde{y_0}) d\widetilde{x_0} d\widetilde{y_0} = kI_g(x_i, y_i) \otimes h_I(x_i, y_i) \quad (1)$$

Where I_i is the image intensity distribution, K is a constant, I_g is the intensity distribution of the ideal image in geometric optics and h_I is the intensity impulse response. Fourier transform is performed on both sides of equation (1), which can be obtained about the relationship of the object and image in frequency domain:

$$\widetilde{G_i}(u,v) = \widetilde{G_g}(u,v).H_I(u,v) \quad (2)$$

For the linear space invariant systems, if the output of the system needs complex convolution in the spatial domain, but the relationship becomes very simple in the frequency domain. As long as the input spectrum is multiplied by the transfer function of the system, the output frequency spectrum is obtained. $H_I(u,v)$ is called the optical transfer function [7,8]. In addition, the ratio of the contrast is called the MTF between the image and the object.

$$\text{MTF(f)} = \frac{M_{im}(\text{f})}{M_{ob}(\text{f})} \quad (3)$$

In this equation, M_{im} represents the contrast of the image and Mob represents the contrast of the object. The contrast of the object is generally fixed, and it does not change with the spatial frequency of the object, however, the decline of image contrast M_{im} and object contrast Mob depends on the diffraction and aberration of the optical system. For the same optical system, it changes with the spatial frequency [9,10]. MTF is a function of spatial frequency, it reflects the ability that optical system transmits light intensity modulation of various frequencies. After the object is imaged by the optical system, in addition to the decrease of contrast, it also produces phase shift. The so-called phase shift means that the actual image position is not in the ideal position after the reference coordinate is selected, but there is a displacement along the extension direction of the image. This phase shift is defined as PTF, which is also a function of spatial frequency f. PTF does not affect the clarity of the image in OTF. Therefore, when the aberration is small, people do not pay much attention to PTF. Generally, MTF is used more. The image is obtained after the object is attenuated by MTF (fx) and then moved by phase PTF (fx) from the above analysis. OTF is a complex function of spatial frequency, its mode is MTF, and the phase angle is PTF [11,12], i.e:

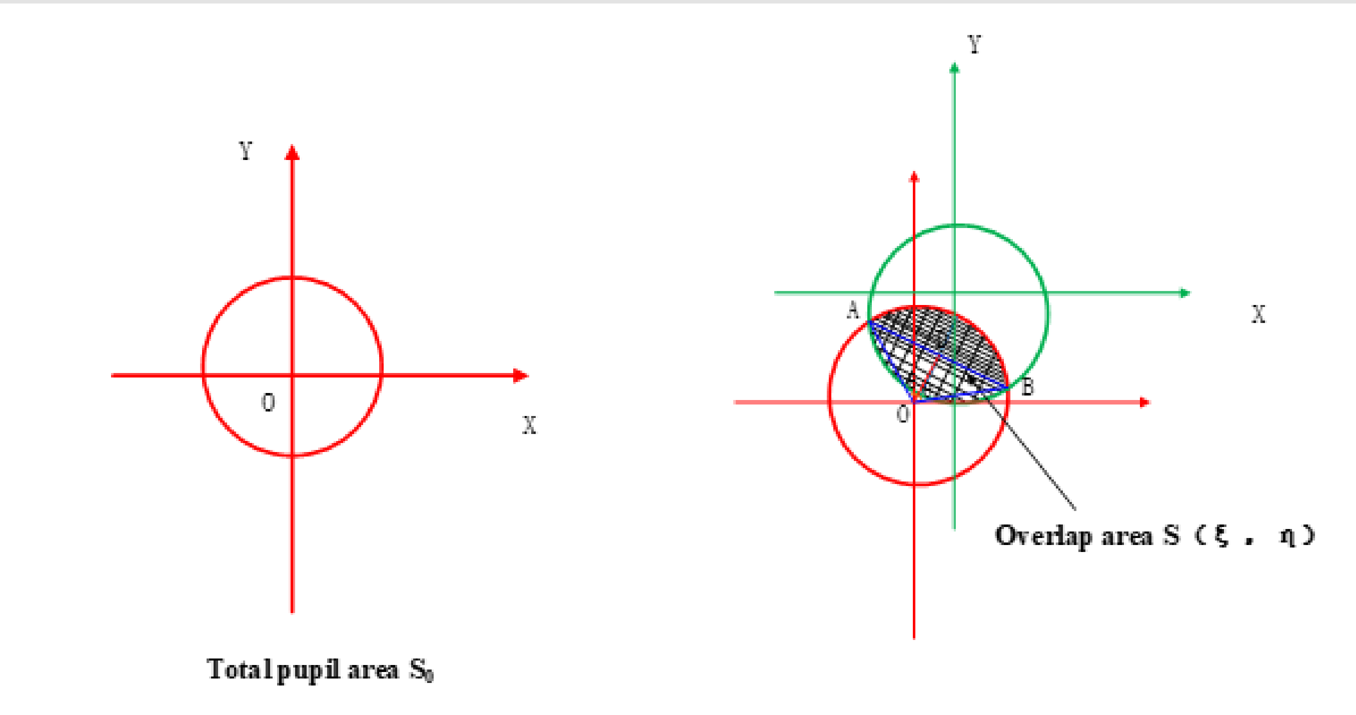

Figure 1: Geometric calculation of OTF.

$$\mathrm{OTF}(f_x) = \mathrm{MTF}(f_x)\, e^{-PTF(f_x)} \quad (4)$$

The OTF reflects the frequency characteristics of optical imaging system, which depends on the diffraction and aberration of optical system. When the coherent optical system satisfies the condition of linear invariance, OTF is the Fourier transform of point image intensity distribution function. OTF is explained in the form of geometry: Figure 1 shows the geometric calculation diagram of OTF. The circle center of the circular pupil is (0, 0) and the radius is D/2, so the total area is: $s_0 = \frac{\pi D^2}{4}$

The area of the overlapping area is twice the difference between the area of the arc OAB and the area of the triangle OAB from Figure 1, If $\angle AOD = \angle BOD = \theta$ and, $OA = OB = D/2$ the area of the overlapping part can be expressed as:

$$\begin{aligned} S_{(\xi,\eta)} &= 2(S_{arcOAB} - S_{triangleOAB}) \\ &= 2[(\frac{2\theta}{2\pi}) \times \pi \times (\frac{D}{2})^2 - \frac{1}{2} \times 2 \times \frac{D}{2}\sin\theta \times \frac{D}{2}\cos\theta] \quad (5) \\ &= 2[\frac{D^2}{4}\theta - \frac{D^2}{4}\sin\theta\cos\theta] = \frac{D^2}{2}(\theta - \sin\theta\cos\theta) \end{aligned}$$

The OTF is the ratio of the overlapping area to the original area, so it can be expressed as:

$$H(\xi,\eta) = \frac{S(\xi,\eta)}{S_0} = \frac{2}{\pi}\left(\theta - \sin\theta\cos\theta\right) \quad (6)$$

The pupil of an optical imaging system reflects the restriction of the system on the beam. The OTF is a physical quantity used to express the transmission condition from object surface spectrum to image surface spectrum, using OTF can better evaluate the imaging quality of optical system. The diffraction limited system is a circle with an exit pupil diameter of D because it is a circular symmetrical figure, the cut-off frequency of the optical transfer function is the same in all directions. Taking θ as the variable and under the condition of $0 \le \theta \le \frac{\pi}{2}$ drawing the graph of equation 6 with MATLAB, as shown in Figure 2. Figure 2 shows that OTF has the following properties: (1) If two circles intersect, under the condition of $0 \prec \theta \prec \frac{\pi}{2}$, it can be seen that $H(\xi,\eta)$ isa monotonically increasing real function greater than 0 but less than 1 from Figure 2, indicating that under coherent light illumination, not only the amplitude but also the phase of the object and image change, and some frequency components appear on the image plane; (2) If the two circles completely coincide, then $\theta = \frac{\pi}{2}$, under the condition of $\xi = \eta = 0$, it means that there is no movement, and the overlapping area is 1, that is, $\mathrm{H}(0,0) = 1$, indicating that the amplitude has not changed, the phase has not changed, and all frequency components appear on the image plane; (3) If the two circles will be completely separated, then $\theta = 0$, at this time, ξ, η are large enough, and there is no overlapping part between the two circles, then the overlapping area is 0, that is, $\mathrm{H}(\xi,\eta) = 0$, which means that the optical transfer function is 0 outside the specified range of the cut-off frequency, and these frequency components do not appear on the image plane.

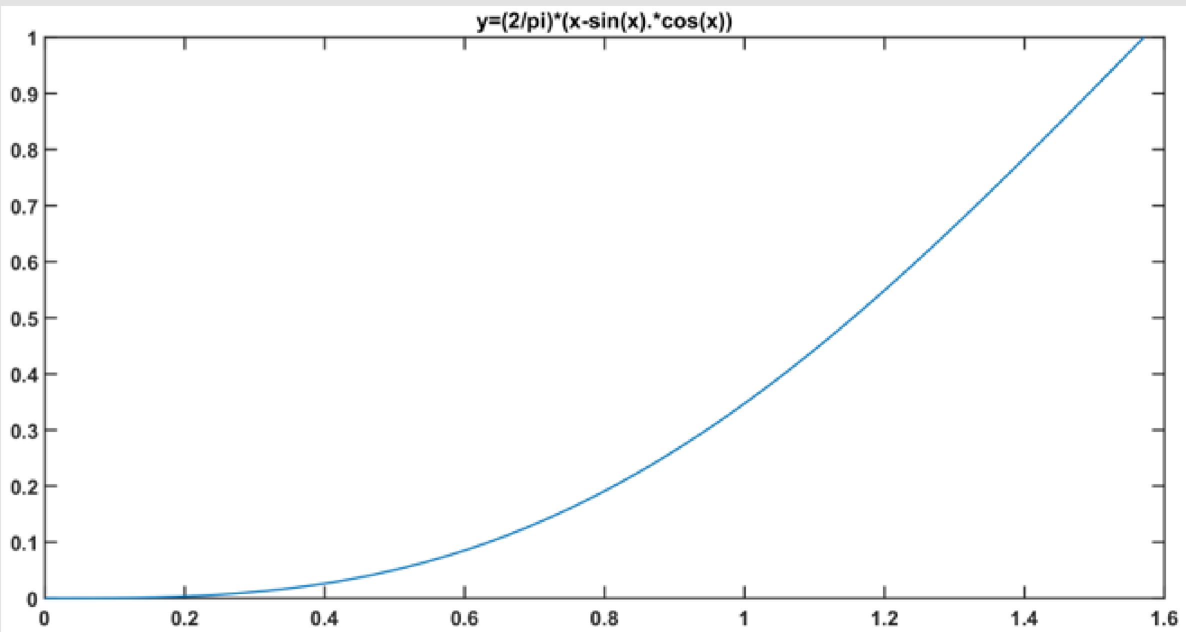

Figure 2: $H(\xi,\eta) = \frac{2}{\pi}\left(\theta - \sin\theta\cos\theta\right)$

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Simulation Verification

Figure 3 shows the back of "5-yuan-he coin " used for simulation calculation and schematic diagram of diffraction calculation experimental device. The relevant parameters are: a circle with a diameter of 10 mm, the number of sampling points is 512*512, a uniform coherent plane wave with a wavelength of 632.8 nm is used for vertical irradiation, after a distance of 1200 mm, through a thin optical aberration lens with a focal length of 400 mm, imaged on an observation screen 600 mm away from the lens, and the lens aperture size d is adjusted between 10~150 mm. Firstly, taking d=10 mm as an example, the intensity distribution of the image under coherent illumination, the coherent light transfer function, the graph of the optical transfer function and the cut-off frequency of the image are observed by MATLAB simulation. As shown in Figure 4, the original image of "5 yuan 'he' coin" and the intensity distribution of the image under coherent light can be found that the image darkens, and the transmission effect is that the contrast decreases after the object passes through the optical system, that is, the MTF is always less than or equal to 1. As shown in Figure 5, the coherent transfer function (CTF) is used to characterize the imaging quality of the diffraction limited system under coherent illumination in the frequency domain. The image spectrum is the product of the ideal image spectrum and CTF. Objects can be obtained in spatial domain by inverse Fourier transform of image spectrum. The transfer function of diffraction limited system is equal to pupil function, which provides the propagation behavior of coherent illumination system in frequency domain.

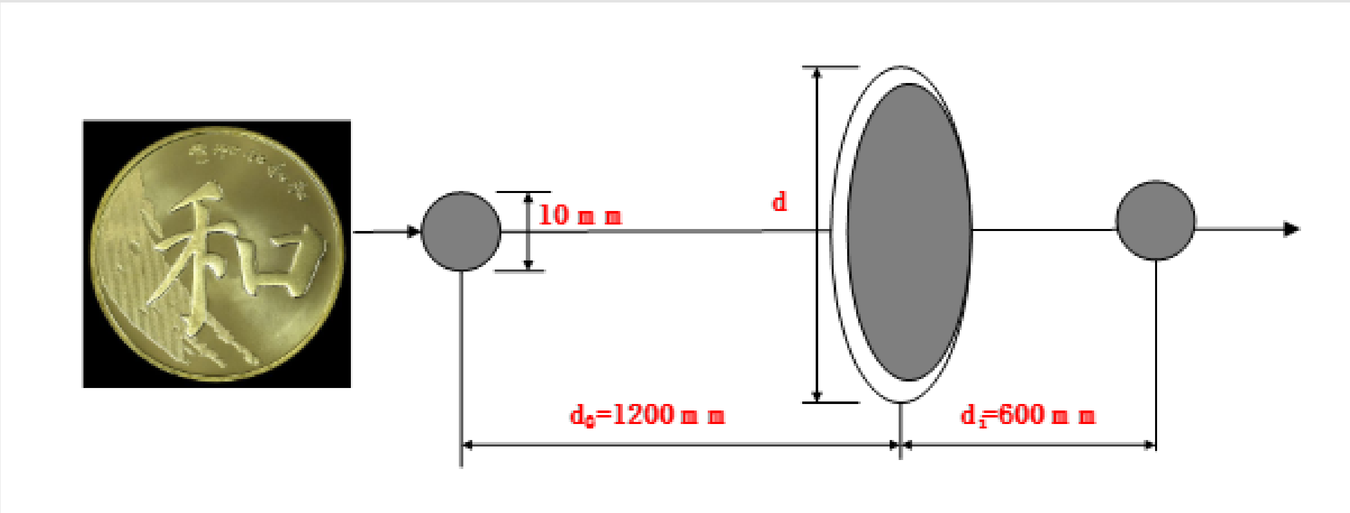

Figure 3: The back of "5-yuan-he coin" used for simulation calculation and schematic diagram of diffraction calculation experimental device.

Figure 4: The original image of "5 yuan 'he' coin" and the intensity distribution of the image under coherent light.

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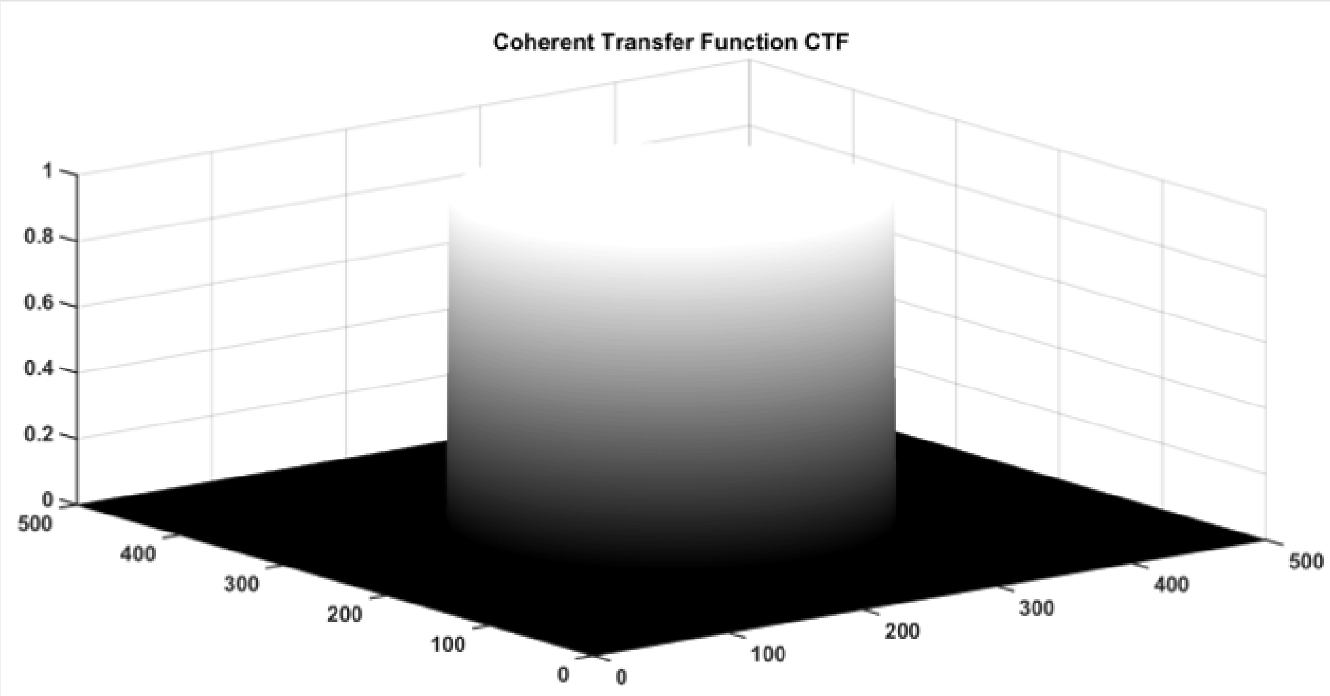

Figure 5: CTF diagram.

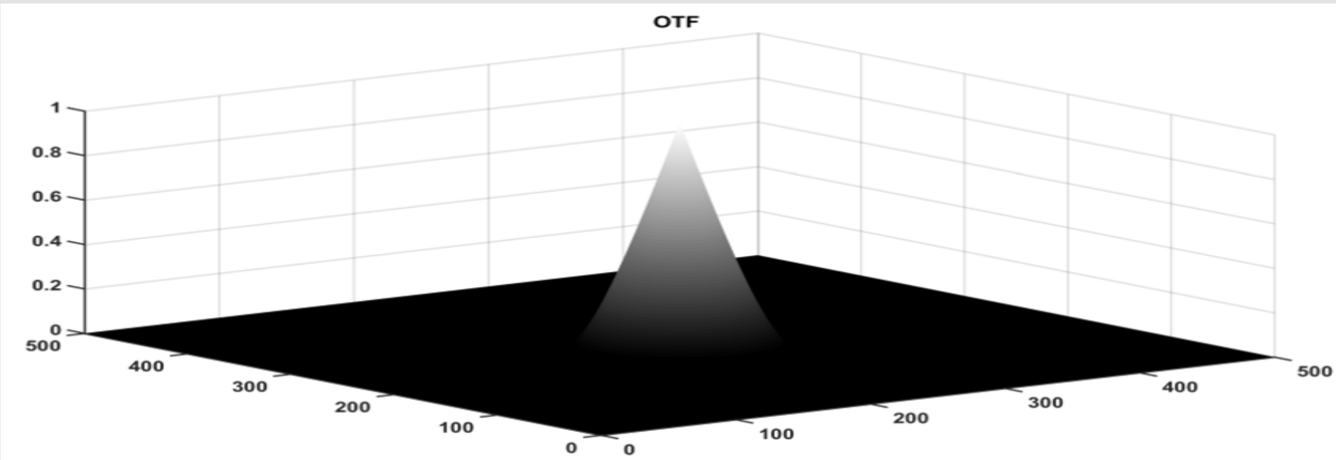

Figure 6: OTF diagram.

This also shows that the coherent optical system has a limited passband in the frequency domain, all pass through the passband, and there is a cut-off frequency outside the passband, the transfer function changes abruptly at the cut-off frequency [13,14]. Figure 6 shows the optical transfer function diagram. OTF is a conical figure. The contrast is 1 at the midpoint at most, and then decreases to 0 at the cut-off frequency, that is, the contrast transfer ability of the lens decreases with the increase of frequency. When it is higher than a certain cut-off frequency, it can't be transferred. Therefore, the optical system can be regarded as a low-pass filter. With the increase of frequency, the aberration will gradually increase until the light wave cannot be transmitted at the cut-off frequency. OTF is monotonically decreasing, that is, the higher the frequency, the smaller the contrast. Moreover, the OTFs of each optical system are multiplied, and we know that the OTF is less than 1., therefore, the more devices, the smaller the total OTF [15,16].OTF reflects the transmission ability of different frequency components of the object: The high frequency part reflects the transmission of details of the object; The intermediate frequency part reflects the hierarchical transmission of objects; The low-frequency part reflects the contour transmission of the object. We know that the maximum spatial frequency of OTF is:

$$2\rho = r/(2L_i) = \mathrm{rd}_0/(2\,\mathrm{L}_0\mathrm{d}_i) = 512*1.2/(2*0.005*0.6) = 102400\,\mathrm{m}^{-1} \quad (7)$$

Then the maximum spatial frequency of OTF is $\rho = 51200\mathrm{m}^{-1}$, and the cut-off frequency of OTF is $\rho_c = d/(2\lambda\,\mathrm{d}_i)$, where ρ_c is the cut-off frequency; d is the aperture diameter, d_i is the distance between the aperture and the point source. As shown in Figure 7: (a), (b), (c) and (d) respectively represent OTF images when d=10 mm, 30 mm, 38.83 mm and 40 mm. When d=30 mm, 38.83 mm and 40 mm, the corresponding cut-off frequencies are 39557 m^{-1}, 51200 m^{-1} and 52742.5 m^{-1} respectively. Therefore, when d is taken as 30 mm and 38.83 mm, the results will not be wrong, but if d is taken as 40 mm, the cut-off frequency has been greater than the maximum spatial frequency of OTF. We can find from Figure 7 (d), The lower edge of the OTF image has been deformed, indicating that the result is wrong. Therefore, when the aperture diameter d is greater than 38.83 mm, the results are not accurate.

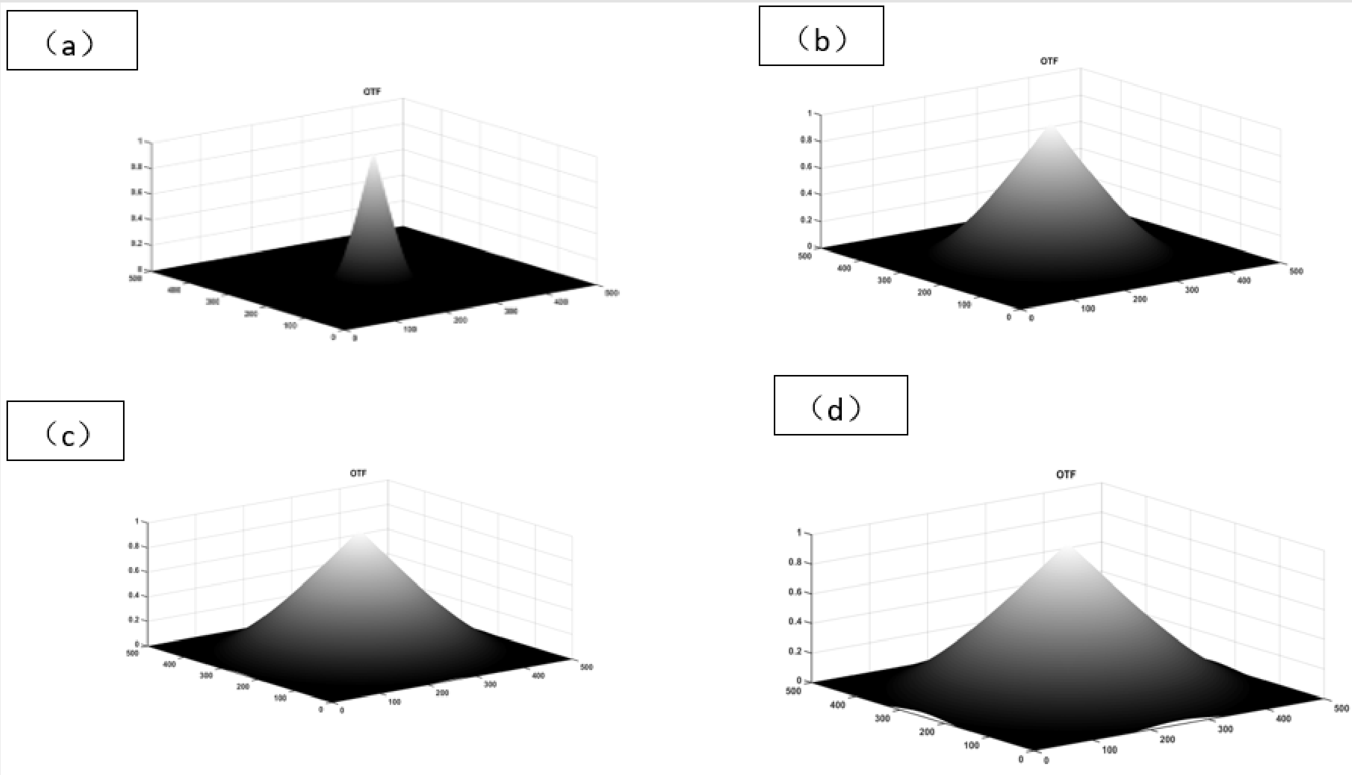

Figure 7: (a), (b), (c) and (d) respectively represent OTF images when d=10 mm, 30 mm, 38.83 mm and 40 mm.

Conclusion

Through the MATLAB simulation experiment, we can conclude that under the coherent light irradiation, after the object is transmitted through the optical system, its transmission effect is that the frequency remains unchanged, but its contrast decreases, and the phase shifts, And it ends at a certain frequency, that is, the contrast is 0, indicating that there is no brightness change in the light intensity distribution of the frequency, the contrast reduction and phase shift vary with frequency. The OTF reflects the transmission ability of different frequency components of the object, and the high-frequency part reflects the transmission of details of the object; The intermediate frequency part reflects the hierarchical transmission of objects; The low-frequency part reflects the contour transmission of the object.

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