Distinguishing fine details by Fresnel domain diffraction

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Distinguishing fine details by Fresnel domain diffraction

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ABSTRACT

The capability of distinguishing fine details in simple structures by means of Fresnel domain diffraction is shown. Through numerical simulations it is shown that the bigger Fresnel's number in the diffraction considered the bigger differentiability is reached. A circular clear aperture with two fine details is employed for illustrating.

Keywords: diffraction, Fresnel domain diffraction.

1. INTRODUCTION

Since the invention of the Fresnel's algorithm in order to understand the diffraction of optical fields through a circular aperture, it has played an important role in optics[1]. Many outstanding experiments and technological developments has been understood and carried out, respectively, thanks to the insight added by Fresnel to the optical sciences, as for instance the experiment of the Arago's spot. One issue of extensive study in this direction is the delimitation of the Fresnel and Fraunhofer diffraction domains[2]. In this way, the determination of the Fresnel-Fraunhofer limit on the diffraction process for all states of coherence, has been a topic of study since many years ago until nowadays[3], due to the implications that is has in the development of new technological devices as photolithographic systems, illuminators for optical microscopes, very novel particle-sizing apparatus, etc. All of these devices take advantage of using the diffraction in either Fresnel or Fraunhofer domain, thus becomes mandatory to establish clearly a delimitation of the Fresnel and Fraunhofer diffraction domains.

In this work we show by means of numerical simulation that the bigger is the Fresnel zones number the bigger is the capability of distinction of fine details or small defects, which will called in this work simply details. Initially the framework the Fresnel zones number is introduced and based on it, numerical calculations of the diffraction patterns of a circular aperture with fine details are obtained. Those numerical calculations are conducted in such a way that the Fresnel zones number involved in the optical setup are varied in a controlled way by modifying the observations distance. So, from the analysis of such diffraction patterns it is shown that the patterns corresponding to the Fresnel domain with great Fresnel number provide information that its counterpart of the Fraunhofer one do not. This idea validates techniques as the contact-photolithography in which the very high resolutions are reached with optical setup involving very great Fresnel number, or what is an equivalent, very short distances from the diffracting aperture to the register plane.

2. FUNDAMENTALS

The number of Fresnel zones inscribed within the associated circular aperture is another basic parameter for a quantitative description of diffraction. With its use more general considerations are developed because its value is the same for all set-ups that provide diffraction patterns with intensity distributions, only differing on scale factors or orientation. In a second order approximation, the number of Fresnel zones N will be given by[4]

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$$N = \frac{R^2}{\lambda}\left(\frac{1}{z_0} + \frac{1}{z}\right), \tag{1}$$

the wavelength being λ. The parameters are reported in the basic experimental set-up of Fig. 1. The line $\overline{SP}$ determines the optical axis of the set-up, which is normal to the aperture plane and intersects it at its aperture centre. The pupil function of the aperture is assumed to be constant. A point source is located at *S*, so that z_0 is the radius of the spherical wave front emitted by the source at the aperture centre. The point *P* located on the optical axis at a distance z from the aperture centre, will be the centre of the diffraction pattern. Eq. (1) is valid under the conditions $R << z_0$ and $R << z$, which determine the *paraxial approximation.*

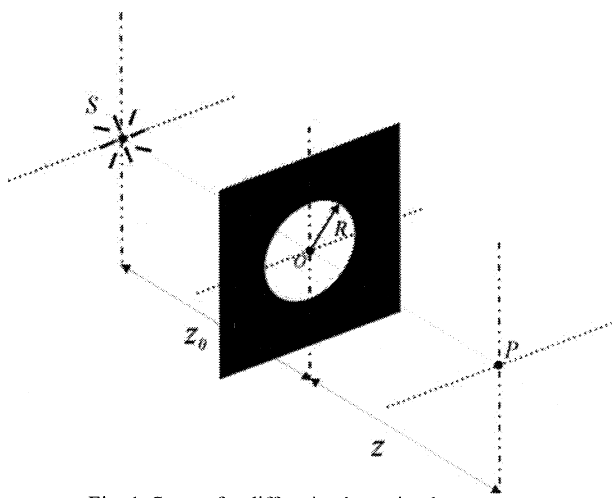


Fig. 1: Set-up for diffraction by a circular aperture

For our particular case plane wave front illumination is considered, it means $z_0 \rightarrow \infty$, the Fresnel zones number turns into:

$$N = \frac{R^2}{z\lambda}. \tag{2}$$

From eq. 2, it is clear the relationship existing between the Fresnel zones number and the observation plane, for the case we are concerned about. The smaller is the separation among the diffracting aperture and the observation plane the bigger is the Fresnel zones number, in such a way that it will approach to infinity when such separation vanish.

3. NUMERICAL SIMULATIONS

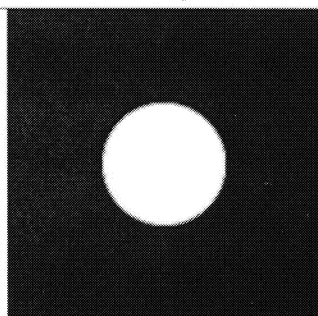
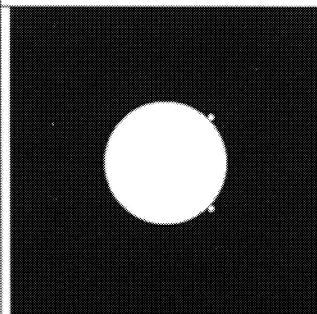
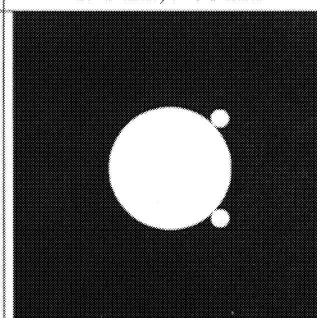
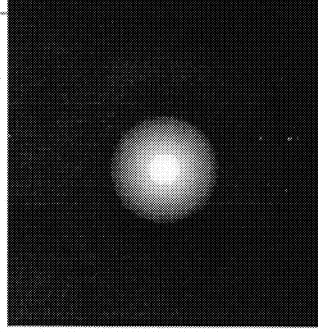
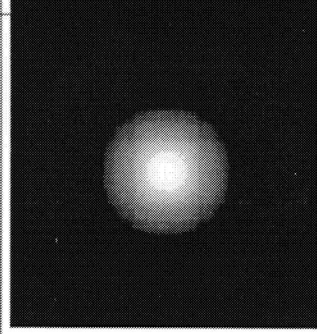
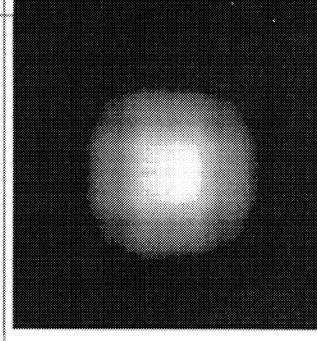
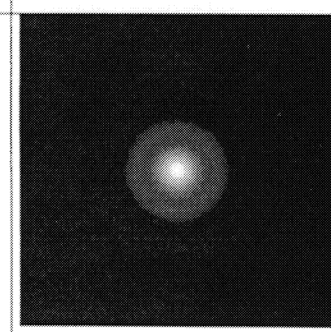
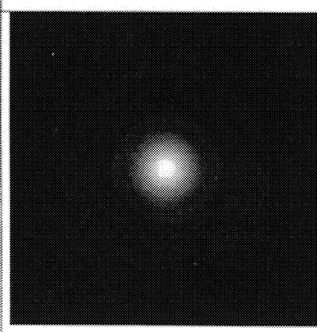
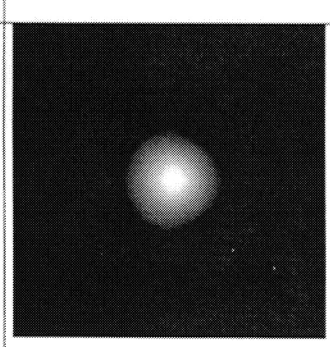
In order to illustrate the idea of using the diffraction phenomenon in the Fresnel domain as a tool to distinguish fine details in an aperture, numerical simulations have been carried out by using a diffraction modeling package working according to the modified convolution approach[5] on a matrix of 1024x1024 points with the sampling interval equal to $10\ \mu m$. We have chosen clear circular apertures in an opaque screen of fixed radius ***R***= *2mm*, accomplished of two small circular holes of variable radii ***r*** (*0.0mm, 0.1mm* and 0.3*mm*), which will call details. In the first row of Table 1 are illustrated the apertures used. These apertures are illuminated by a plane wave front of wavelength $\lambda = 632.8\ nm$, in such a way that a Fresnel zones number variable is obtained by modifying the distance from the aperture to the observation plane.

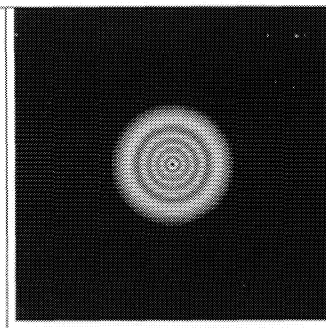
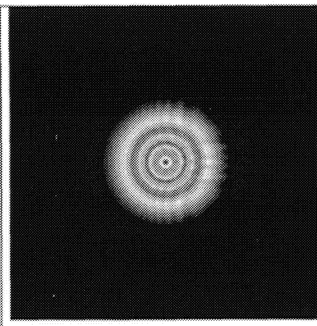
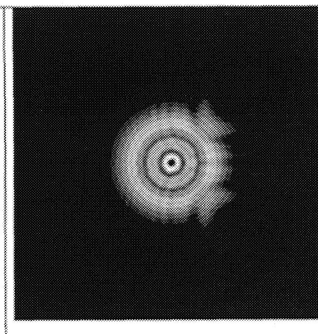
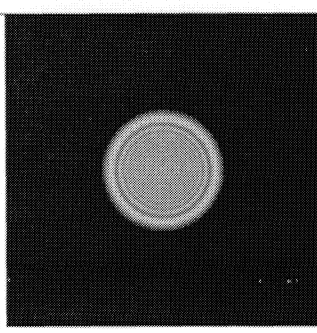
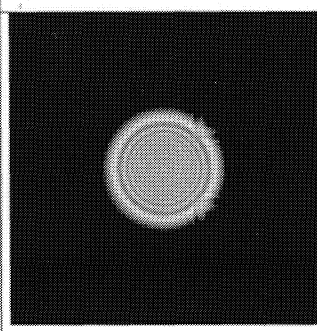
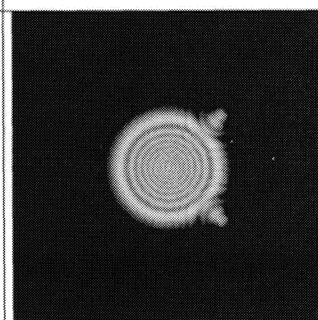
In this case the Fresnel zones number is given by:

$$N = \frac{R_e^{\ 2}}{z\lambda}, \tag{3}$$

where $R_e = R + 2r$, it is the radius that circumscribes the diffracting structure.

Table 1: Diffracting apertures and the corresponding intensity registered at the observation plane for different radii *r* and Fresnel zones number *N*.

	R=2 mm; *r*=0	*R*=2 mm; *r*=0.1 mm	*R*=2 mm; *r*=0.3 mm
Diffracting apertures			
N=0.5			
N=1			

N=10			
N=30			

From the analysis of the figures show in the above table it is plain to observe that for the case of Fraunhofer diffraction ($N< 0.5$)[6] it is impossible to determine from the diffraction pattern some difference between the diffracting apertures. Even, once the $N < 0.5$ threshold is surpassed, for instance N=1, it is not possible to distinguish from the diffraction patterns the different diffracting apertures that produce them. For the particular case in which the Fresnel zones number equals the unity, the diffraction patterns are morphologically identical, they only differ in their scales. This situation allow us to conclude that in the Fraunhofer diffraction domain, and even in the Fresnel domain with small Fresnel zones number, it is impossible to distinguish fine details on diffraction apertures from the analysis of theirs recorded intensities produced by diffraction through the aperture considered. In the case of considering $N = 1$. The separation between the diffracting aperture and the observation plane will be easily tunable by changing the experimental setup for each one diffracting structure.

As the Fresnel zones number is increased a bigger quantity of information is possible of obtaining from the diffraction pattern. For instance, when the Fresnel zones number considered is N=10 evident differences show up between the diffraction patterns. Therefore, visible differences arise from the diffraction patterns, what allows us suspect that these diffraction patterns are not generated by the same diffracting aperture.

For smaller distances (bigger Fresnel zones number) between the diffracting aperture and the observation plane than the considered so far, all the diffraction patterns present sound differences that confirm the suggested situation regard the non regularity between the diffracting apertures. For those great Fresnel zones number $N = 30$ the diffraction pattern corresponding to $\boldsymbol{r} = 0.1$mm shows the same behavior that the $\boldsymbol{r} = 0.3$mm for N=10.

Particularly, for the case $N = 1000$ the definition of these details is very acceptable, by considering that we are using coherent illumination. In this situation the most important effect that takes place is the geometrical projection of the diffracting aperture over the observation plane, so that seemed from and physical optics standpoint means a very great number of Fresnel zones involved in the setup, $N = 1000$. This is situation considered in all the contact-photolithography systems, for which the separation between the diffracting aperture (mask) and the observation plane (target) is null, and in this way a very great capacity of distinguishing fine details is achieved. For those systems additionally quality of the projected (diffracted a very great Fresnel zones number) image over the target is added to the system by considering incoherent illumination and in this way the small perturbations present in the corresponding figures of our table disappear.

4. CONCLUSIONS

In the Fraunhofer diffraction domain, the diffraction patterns do not allow to infer the existence of fine details, meanwhile it is totally possible of doing in the Fresnel diffraction region. By increasing the Fresnel zone number the capacity of distinguishing fine details is better (size and shape).

The relationship between the Fresnel zones number and the base size/ detail size ratio in order to optimize the inferring capability of fine details is a issue of current research.

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