Global Journal of Science Frontier Research
Physics and Space Sciences
Volume 13 Issue 2 Version 1.0 Year 2013
Type : Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4626 & Print ISSN: 0975-5896

Rotating X-Ray Window for Multilayer Probing of Cells; Microfocussing Techniques

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GJSFR-A Classification : FOR Code: 240402

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Strictly as per the compliance and regulations of :

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I. Introduction

Soft X-rays optical components are outperformed by those of visible light due to a number of setbacks; they suffer from poor efficiencies, poor spatial resolution, large aberrations, strong chromatic aberration and low angular and wavelength band passes. These setbacks are ameliorated by the use of zone plates, multilayer mirrors, periodic mirrors and grazing incidence mirrors. The Gray Cancer Institute (GCI) for over ten years has been active in the development and use of microfocussing techniques for radiobiological purposes. In the next section, few techniques are discussed which are diffractive optics by the use of zone plates and reflective optics by the use of multilayer mirrors and grazing incidence mirrors.

II. Zone Plates

Application of Fresnel zone plate in achieving submicrometre spot size diameter on irradiated biological samples has been a common practice. They are vital optical elements used at the GCI and King's college in the ongoing development of a micro irradiation system that uses a focused X- ray microprobe to irradiate individual cells. At short wavelengths particularly in the soft X-ray region, the use of zone plates is employed because

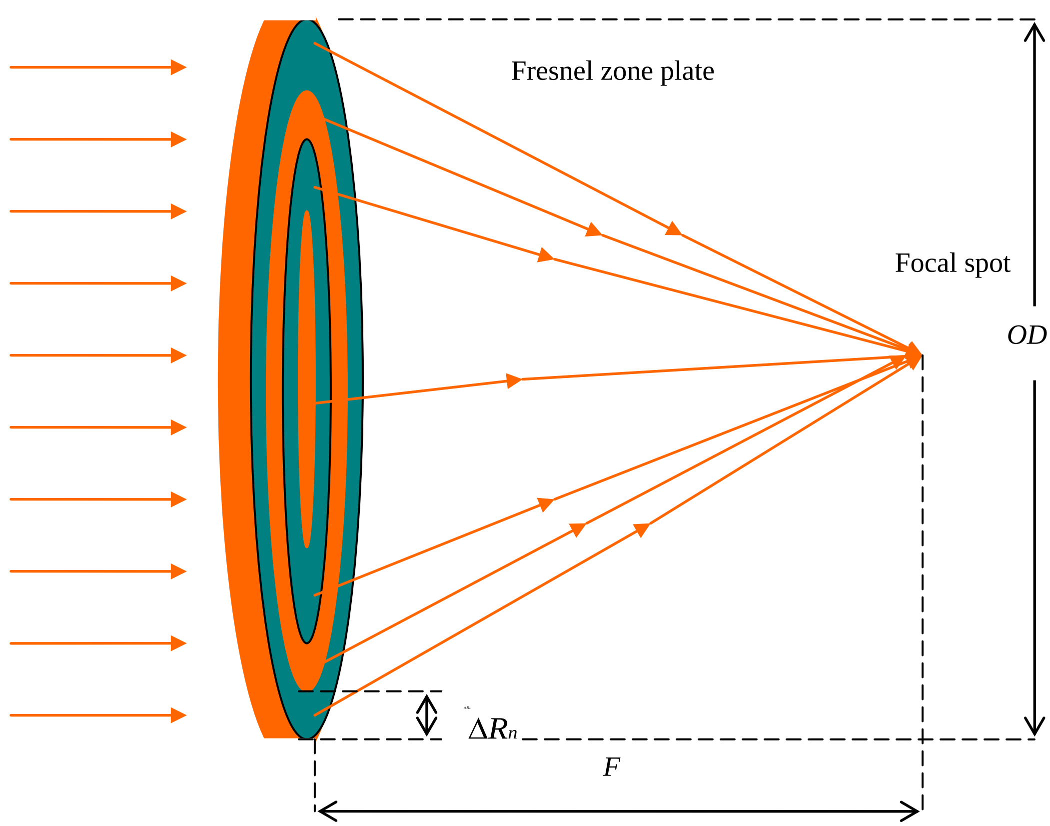

Figure 1.1 : Schematic of Fresnel zone plate of focal length, *F*, with *OD* as its diameter and ΔR_n as its outermost zone width

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sof their ability to form images at very high spatial resolution; very close to the diffraction limit and sub15nm resolution has been achieved [5]. It is able to ameliorate most of the setbacks in X-ray optics highlighted in the previous section. Diffraction patterns and the energy which each pattern represents always propagate from diffracting structures such as disks, angles of order $\theta \approx \frac{\lambda}{D}$ where D is a characteristic dimension [6].

When interference occurs between diffracted and undiffracted radiation, interference takes place at well defined positions; distances from such positions represent focal lengths. Fresnel zone plate lens is one of the focusing devices used in synchrotrons. Zone plates form a focus by using constructive interference of rays from adjacent zones The focal length ,*F,* of a zone plate is related to its diameter, OD , its outermost zone width, ΔR_n , and the X-ray wavelength, λ by

$$F = \frac{OD\Delta R_n}{\lambda} \qquad (1.1)$$

Fresnel zone plates consist of alternating transparent and opaque (amplitude of Fresnel zone plate) concentric rings (zones). The spatial resolution of the zone plate for an incoming wave is expressed according to the Raleigh criterion as

$$\varsigma = 1.22\ \Delta R_n \qquad (1.2)$$

Where ς, is spatial resolution; equations 1.1 and 1.2 indicate that for a spatial resolution of less than1 µm to be achieved all values of outermost zone width less than 0.82 µm must be used and the achievable values of focal lengths are not more than 234.78mm provided the value of zone diameter is assumed to be 80 µm hence a resolution of less than1 µm can be achieved by fabricating zone plates with zones of outermost zone width diameter less than 0.82 µm etched on a material. The value of spatial resolution, ς, is limited by X-ray photon energy of 4.5KeV (0.276nm) for titanium. The micro focusing system at the GCI which employs the use of Fresnel zone plate of 0.2-0.8mm diameter is able to focus K_α X- ray of carbon or aluminum to a beam of less than 1µm diameter, forming zone plate images. The focused X-rays are aimed at sub cellular targets and about 3000 cells per hour can be irradiated individually. The use of zone plates for producing very fine probes is now well established [7, 8].

The proposed X-ray window will be positioned under a zone plate in a table source microprobe at the GCI, which is illustrated in figure 1.1

III. Multilayer Mirrors

Multilayer coated mirrors are artificial structures designed to enhance reflectivity, through constructive interference of beams reflected from many layer interfaces [9]. Reflection coefficient and absorption coefficient of multilayer mirrors contribute significantly to the degree of precision attained.

Bragg's law states,

$$m\lambda = 2d\sin\theta_m \qquad (1.3)$$

Where *m* is an integer, *d* is the spatial periodicity, λ is the wavelength; X-rays, incident at angle θ with respect to the mirror surface will be strongly reflected at angles close to Bragg angle θ_m for *mth* order diffraction, but a maximum angle called an angle of peak reflectivity θ_{mp} may be achieved if this angle is made slightly greater than the Bragg angle [10]. i.e. $\theta_{mp} > \theta_m$. The reflectivity at an interface is determined by the Fresnel equation,

$$R = \frac{(n-1)^2}{(n+1)^2} \approx \frac{\delta^2}{4} \qquad (1.4)$$

Where *R,* is the normal incidence reflectivity, δ is the refractive index decrement, β is the absorption index and *n* is the refractive index of the multilayer material. Higher reflectivities can be obtained by making the more absorbing layers thinner or making less absorbing layers thicker [10]. This reduces absorption and enhances reflectivity. Before making a multilayer mirror choice of suitable material must be considered. Three rules are normally adopted [10]:

- Select a material with a low absorption coefficient for the "transmitting" (spacer) layer.
- Select a second material to give a large reflection coefficient at the boundary with the first (means large difference in δ values). If several materials give similar reflection coefficients, use that with the lowest. value of β to give less absorption.
- Make sure that the two materials can form physically and chemically stable boundaries, and can be deposited with low roughnesses and interdiffusion.

Multi layer mirrors (multi layer interference coatings) are made by depositing alternating layers of two materials of differing refractive index to form stable interfaces. These materials are of high and low atomic numbers so as to obtain large or maximum difference in electron density. Multilayer mirrors are elliptically bent to produce smaller spot size, hence a better defined focal spot [11].

IV. Grazing Incidence

Grazing incidence optics is a reflective optics technique based on total external reflection. Grazing incidence mirrors are used to achieve grazing incidence and grazing angles.

$$\theta_c = \sqrt{2\delta} \quad (1.5)$$

$$n = 1 - \delta + i\beta \quad (1.6)$$

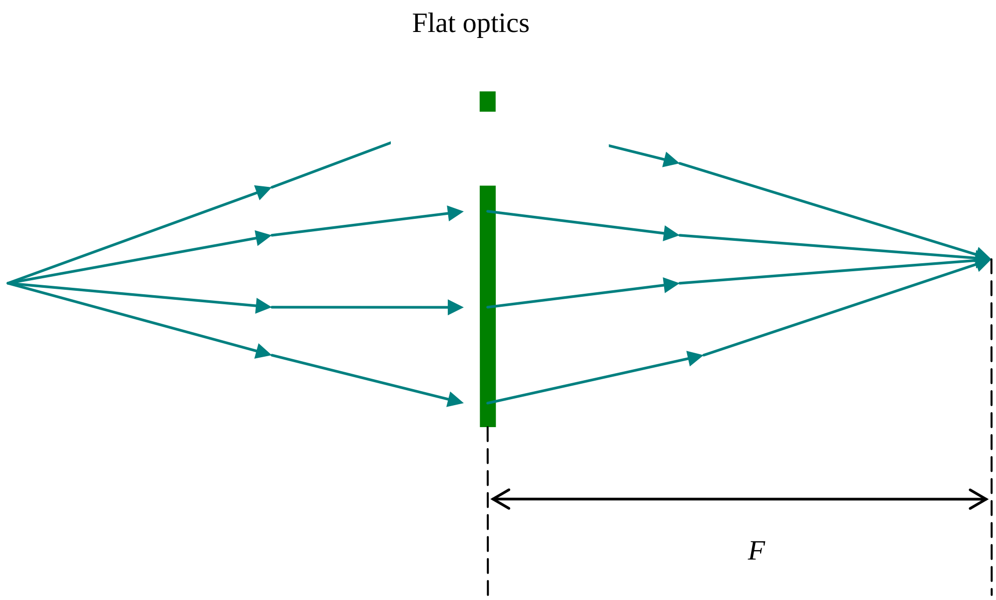
$$\theta_c \propto \lambda\sqrt{Z} \quad (1.7)$$

Where, θc, is critical angle, Z, is atomic mass, δ, is refractive index decrement, β, is absorption coefficient, and n is refractive index. Equation 1.7 shows that θ_c vary with λ; this infer that grazing incidence is limited by X-ray photon energy (wavelength). The use of a low Z material is also favourable to grazing incidence.

Grazing incidence X-ray optics facility has some advantages which are summarized as follows;

- The production of this focussing device is cost effective
- It has a large collecting
- High reflectivity, over 90% is achievable depending on the grazing angle; High reflectivity is achieved at grazing angle smaller than the critical angle
- Though this technique suffers from aberration, yet it provides high efficiency.

(a)



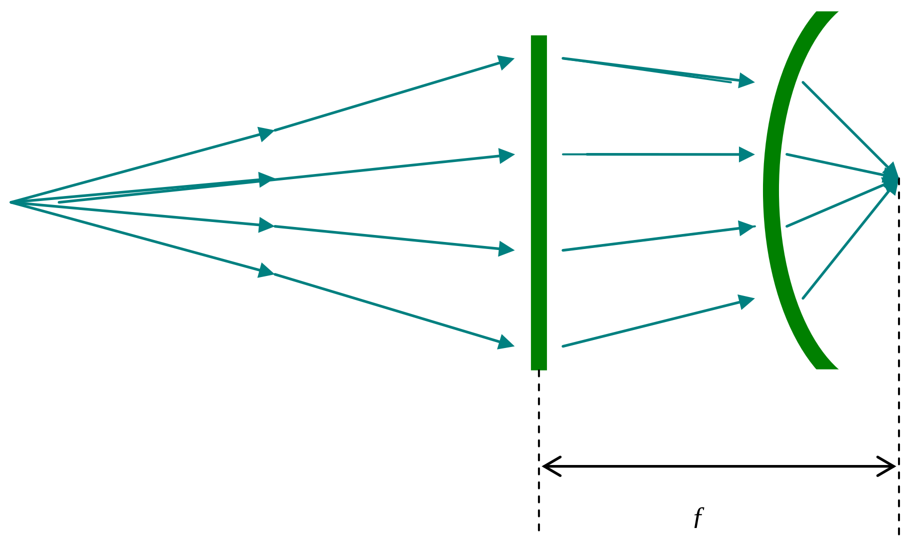


Figure 1.2 : (a) A schematic of flat optics–focal length achieved is *F*. (b) combination of flat and bent optics to improve resolution-Focal length achieved is *f* where. *F* > *f*

Since Rayleigh criterion, ς, has a limit, adopting bent optics as shown in Figure 1.3 (b) will reduce focal length *F* to *f* which results to an improvement in resolution over that delivered by the flat optics as indicated in figure 1.3(b). This agrees well with equations 1.1 and 1.2. By applying bent optics to both reflective and diffractive optics, through the use of zone plates, multi layer and grazing incidence mirrors resolution will be improved.

By using grazing incidence mirrors, bremsstrahlung radiation was reduced to 2%; Grazing incidence optics has been in use for several years. Grazing incidence mirrors have been used to produce high-resolution images of the structure and function in small animals. Adopting Grazing-incidence focusing optics provides an advanced understanding of biology, including human growth, development, and diseases.

V. Conclusion

Soft X-rays and their application in radiobiology have been considered. A brief description of the X-ray microprobe and its background has been studied. Microfocussing techniques such as diffractive, reflective and grazing incidence optics which involves the use of multilayer mirrors, Fresnel zone plate lenses and grazing incidence mirrors respectively have been considered as tools for high resolution.

Multilayer mirrors for the future must be made up of a highly reflective material i.e. high reflection coefficient and a material of low absorption index. Future work should be directed to micro fabrication of zone plates by etching zones of outer width, ΔR_n <0.82 μm on a material.

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