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Enhancing The Edge Imaging Characteristics By Variable Apodization Techniques Of Aberrated Coherent Optical Systems

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Abstract.
The images of a straight edge produced by an optical system with a circular aperture and apodized with several filters under coherent light have been explored. The edge-ringing issue is the most typical one with coherent imaging systems. Variable apodization method has been proposed to reduce edge-ringing. Edge-ringing values are assessed when image intensity distribution curves are produced. The outcomes of single, double, and triple filtering are contrasted with those of the airy situation.

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I. Introduction

In order to improve the results of an optical system, there are two methods, namely, modification of the optical system and postdetection processing. The former involves choosing an optimum optical system itself and the latter involves operations on the systems output. In many situations the first one is followed by changing the people function with suitable apodization. Apodization is the technique that modifies the imaging properties of an optical system such that the system impulse does not show ringing by manipulating its entrance pupil (1-3). Parthasaradhi et al. [4] have investigated the effect of variable apodization on the diffracted field characteristics of aperture with Straubel class of pupil functions and Triangular filters.

Imaging of coherent edge objects has assumed a significant role in the field of image science ever since the advent of lasers. Edge-ringing is measured by the height of the first intensity peak above the average irradiance of unity [5]. The term "ringing" is most often used for ripples in the time domain, though it is also sometimes used for frequency domain effects. It is the visual obstruction and has to be minimized by some means. Edge gradient is the increase in the image intensity per unit change in Z around the geometrical edge, i.e., at $Z = 0$ [6].

The studies concerning the images produced by optical systems with aberration-free and the improvement in the resulting images are almost completed in the limiting cases of coherent and incoherent illumination. Most of the past investigations [7-14]. Apodisation can be accomplished in several ways i.e., by altering the shape of the aperture or its transmission characteristics (HECHT and ZAJAC, 1987). The former is known as “Aperture Shaping” in which the shape of the aperture is altered from circular to non-circular. The later is known as “Aperture Shading” by using a spatial filter over the pupil from point to point (MONDAL and VENKAT REDDY, 1987). Thus, apodisation is the process of changing the energy distribution in the point spread function by deliberate manipulation of the pupil function so as to improve some measure of the image quality (WETHERELL, 1980). In this paper we proposed Aperture shaping along with shaded aperture in the presence of defocus and primary spherical aberration. For this rotationally symmetric, diffraction-limited and coherent optical system has been considered.

Apodization can be achieved in a number of methods, including changing the aperture's geometry or transmission qualities [15]. The former is referred to as aperture shaping and it involves changing the shape and size of the aperture. Secondly an apodized filter over the pupil known as aperture shading. Thus, apodization is the deliberate manipulation of the pupil function to change the light distribution in the PSF in order to improve the quality of image [16]. Apodization is a subset of the more general spatial filtering approach (Hecht and Zajac, 1987). Apodization can help an aberrated optical system improve certain aspects of its imaging performance [17-21]. With the goal of improving image quality, some researchers have investigated the edge-ringing and edge-shifting aspects of various pupil functions [22-24]. The edge ringing is reduced by building optical system with proper apodizer.

II. Theory and Formulation

The mathematical expression of amplitude transmitance of an opaque straight edge object [25] is given by
B(u, v) = 1 when u ≥ 0
B(u, v) = 0 when u < 0 (1)
It is evident that B (u) is a non-convergent and it does not permit Fourier transformation directly. However, this difficulty can be overcome by expressing it in terms of “signum” function as

$$B(u) = \frac{1}{2}\left[1 + Sgn(u)\right]$$

Where $Sgn(u)$ is expressed as
$Sgn(u)$ =1 when u ≥0
= -1 when u <0 (2)
A sequence of transformable functions which approach $Sgn(u)$ as a limit should be considered, as this function also has a discontinuity at u =0.
For example, the function

$$f(u) = \left[\exp(-\sigma|u|)Sgn(u)\right] \rightarrow Sgn(u) \quad as \quad \sigma \rightarrow 0 \tag{3}$$

Hence the Fourier transform of equation (3) will be

$$F.T.[f(u)] = \int_{-\infty}^{\infty} \exp(-\sigma|u|)Sgn(u)\exp(-2i\pi u x)du$$

$$= \int_{-\infty}^{0} -\exp[(\sigma - i2\pi x)u]du + \int_{0}^{\infty} \exp[(-\sigma + i2\pi x)u]du$$

$$= -\frac{1}{(\sigma - i2\pi x)} + \frac{1}{(\sigma + i2\pi x)} \tag{4}$$

As $\sigma \rightarrow 0$, the above expression equals to $\left(\frac{1}{i\pi x}\right)$ i.e.,

$$F.T[f(u)] = \exp\left[(-\sigma|u|)Sgn(u)\right] = \frac{1}{i\pi x}$$

Thus expressing the straight edge in terms of $Sgn(u)$ as given in (2) and its Fourier transform can be obtained as

$$F.T.[B(u,v)] = F.T.\left[\frac{1}{2}\{1 + Sgn(u)\}\right]$$

$$= \int_{-\infty}^{\infty} \left[1 + \left(-\sigma|u|Sgn(u)\right)\right]\exp(-i2\pi u x)dx$$

$$= \frac{1}{2}\left[\delta(x) + \frac{1}{i\pi x}\right] \tag{5}$$

Here, $\delta(x)$ is the well–known Dirac-delta function. The expression (5) represents the Fourier spectrum of the object amplitude distribution. In this spectrum, the presence of a large zero frequency impulse at $x=0$ is observed, in addition to the other non-zero frequency components. Looking at the object function in fig (1), it appears at the first sight that $B(u,v)$ is purely zero frequency input to the optical system and therefore, the presence of those non-zero frequencies in the spectrum of such an object may appear rather strange. It should be, however, observed that the object function has zero transmission over one-half in its own plane and a transmission equal to unity over the other half. In other words, $B(u,v)$ is zero for $u < 0$ and then there is an abrupt discontinuity at $u = 0$. Thus, $A(u,v)$ is not a true D.C. signal as it is not constant over the entire interval ranging from $-\infty$ to ∞ and this describes the presence of the other frequency components in the spectrum.

The imaging positions, encountered in optics are generally concerned with objects where amplitude or intensity variations are to be considered in two dimensions. The complex object amplitude distribution as defined in equation (1) implies that there is no variation in amplitude transmission of the object along the entire y-direction. This will give rise to an infinite impulse at $y=0$ in the spectrum plane and can be represented by the Dirac-delta function $\delta(y)$. Finally, therefore, the two-dimensional F.T. of the object function is obtained as

$$a(x,y) = \frac{1}{2}\left[\delta(x) + \frac{1}{i\pi x}\right]\delta(y) \quad (6)$$

The above expression gives the amplitude distribution spectrum of the object $B(u,v)$ at the entrance pupil of the optical system. The modified amplitude distribution spectrum of object at the exit pupil of the optical system can be expressed as

$$a'(x,y) = a(x,y).T(x,y) \quad (7)$$

Here $T(x,y)$ represents the pupil function of the given optical system having aberrations and can be expressed as

$$T(x,y) = f(x,y)\exp[i\phi(x,y)] \quad (8)$$

Where f(x, y) denotes the amplitude transmittance over the pupil and ϕ(x, y) indicates the wave aberration function of the optical system. In the absence of apodization, f(x, y) is taken to be equal to unity i.e., for the Airy pupils, f(x, y) = 1.

For defocus, coma and primary spherical aberrations, the aberration function can be expressed as

$$\phi(x,y) = \left[-\left(\frac{1}{2}\phi_d r^2 + \frac{1}{3}\phi_c Cos(\theta) r^3 + \frac{1}{4}\phi_s r^4\right)\right]$$

Here ϕ_d -Defocus coefficient, ϕ_s -Primary spherical aberration coefficient and ϕ_C - Coma and $r = \sqrt{x^2 + y^2}$

From the expressions (6), (7) and (8) the modified amplitude spectrum at the exit pupil is given by

$$a'(x,y) = \frac{1}{2}\left[\delta(x) + \frac{1}{i\pi x}\right]\delta(y) f(x,y)\exp[i\phi(x,y)] \quad (9)$$

The above equation (9) gives the modified spectrum of the object at the exit pupil of the optical system. The amplitude distribution spectrum in the image plane will be given by the inverse Fourier Transform of expression (9). Therefore,

$$B'(u',v') = \frac{1}{2}\int_{-\infty}^{+\infty}\int\left[\delta(x) + \frac{1}{i\pi x}\right]\delta(y) f(x,y)\exp[i\phi(x,y)]$$

$$\exp\left[2\pi i(u'x + v'y)\right]dx\,dy \quad (10)$$

The integration limits of equation (10) are only formal because the pupil function given by T(x, y) vanishes outside the pupil and can be assumed to be unity inside. Thus, after some manipulation in the integration of Eq. (10) by employing the filtering property of Dirac-delta function the expression (10) can be simplified as

$$B'(u',v') = \frac{1}{2} f(0,0)\exp(i\phi(0,0)) + \frac{1}{2\pi}\int_{-1}^{1} f(x,0)\frac{\cos(\phi(x,0) + 2\pi u'x)}{x}dx$$

$$-\frac{i}{2\pi}\int_{-1}^{1} f(x,0)\ \frac{\cos(\phi(x,0) + 2\pi u'x)}{x}\,dx \quad (11)$$

The filtering property of Dirac-delta function is represented by

$$\int_{-\infty}^{+\infty}\delta(x)\ f(x)\,dx = f(0) \quad (12)$$

For the central transmittance of the pupil function f(0)=1, then the expression (11) can be expressed as

$$B'(u',v') = \frac{1}{2} + \frac{1}{2\pi}\int_{-1}^{1} f(x,0)\exp[i\phi(x,0)]\frac{\sin(2\pi u'x)}{x}dx - \frac{i}{2\pi}\int_{-1}^{1} f(x,0)\exp[i\phi(x,0)]\ \frac{\sin(2\pi u'x)}{x}\,dx \quad (13)$$

For the rotationally symmetric pupil function

$$f(x,y) = f(-x,-y)$$

Setting $2\pi u' = Z$ in equation (13), then it reduces to the more explicit formula for the image of an edge object.

$$B'(Z) = \frac{1}{2} + \frac{1}{2\pi}\int_{-1}^{1} f(x,0)\exp[i\phi(x,0)]\frac{Sin(Z\,x)}{x}dx \quad (14)$$

On further simplification equation (14) reduces to

$$B'(Z) = \frac{1}{2} + \frac{1}{\pi}\int_{0}^{1} f(x,y)\exp[i\phi(x,0)]\frac{\{Sin(Z\,x)\}}{x}dx \quad (15)$$

The present work deals with the 1-D straight edge object and hence the general form of amplitude distribution is given by

$$B^{'}(Z)=\frac{1}{2}+\frac{1}{\pi}\int_{0}^{1} f(x,0)\exp[i\phi(x,0)]\frac{\{Sin(Z x)\}}{x}dx \quad (16)$$

For the given pupil apodized with shaded aperture in the presence of defocus and primary spherical aberration the expression (16) becomes

$$B^{'}(Z)=\frac{1}{2}+\frac{1}{\pi}\int_{0}^{1} f(r)\exp[-i(\phi_d\frac{x^2}{2}+\phi_s\frac{x^4}{4})]\frac{\sin(Zx)}{x}dx \quad (17)$$

The is given by the squared modulus of expression (17)

$$I(Z)=|B'(Z)|^2 \quad (18)$$

For va

f (r) =

f (r) = $\cos^2(\pi\beta r) * \exp(-\beta r^2)$- Double Filtering

f (r) = $\cos^2(\pi\beta r) * \exp(-\beta r2) * (1-\beta^2 r^2)^2$ - Triple Filtering

III. Results and Discussion

The investigations on the effects of defocus and primary spherical aberrations on the images of straight edge objects formed by coherent optical systems apodized by multiple amplitude filters in the case of circular aperture have been evaluated using the expression (5) by employing Matlab simulations. The intensity distribution in the images of straight edge objects has been obtained for different values of dimensionless diffraction variable Z varying from −5 to 25.

(i) f (r) $=\cos^2(\pi\beta r)$

Figures 1, 2 and 3 depict intensity distribution curves in case of circular aperture of a variable apodizer for focused and defocused optical systems. It is observed that edge ringing is maximum for clear aperture (β=0). The edge ringing is reducing as apodization parameter β increasing from 0 to 1. However, edge ringing is not fully reduced with single filter. In order to reduce further variable apodization is adopted.

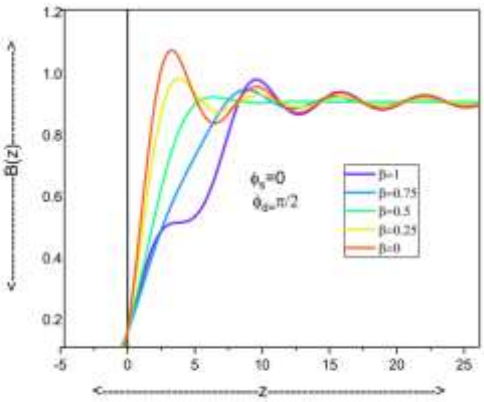

Fig.1 Intensity distribution curves for single filtering

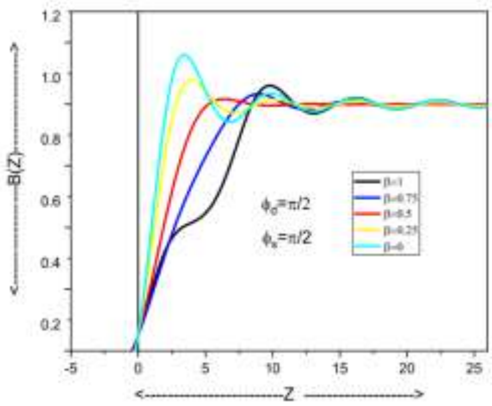

Fig.2 Intensity distribution curves for single filtering

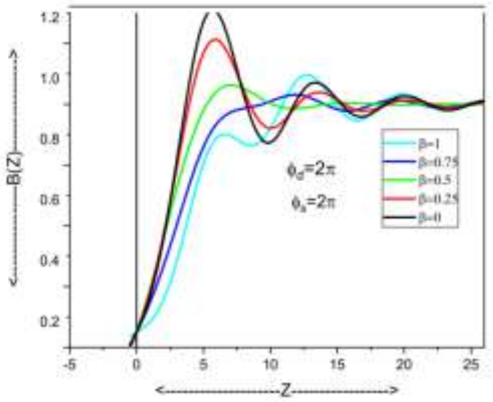

Fig.3 intensity distribution curves for single filtering

(ii) **f (r) = cos^2 (πβr) * exp (-βr^2)**

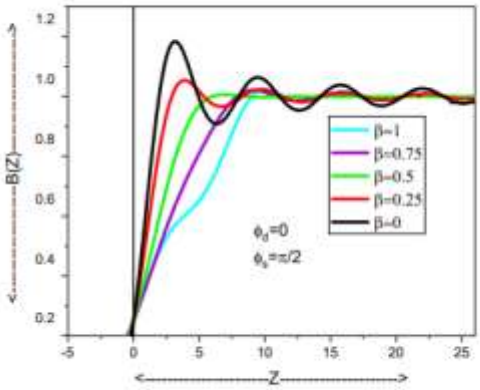

Fig.4 Intensity distribution curves for double filtering

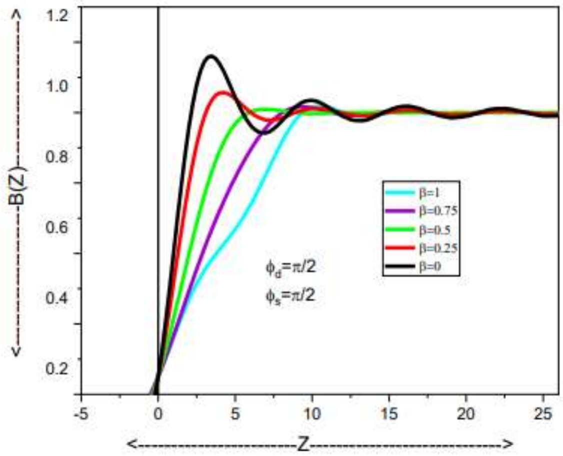

Fig.5 Intensity distribution curves for double filtering

Figures 4, 5 and 6 illustrate that the edge ringing is maximum at ϕ_d = 2π & β=0 and edge ringing is minimum at ϕ_d =0 and β = 1.

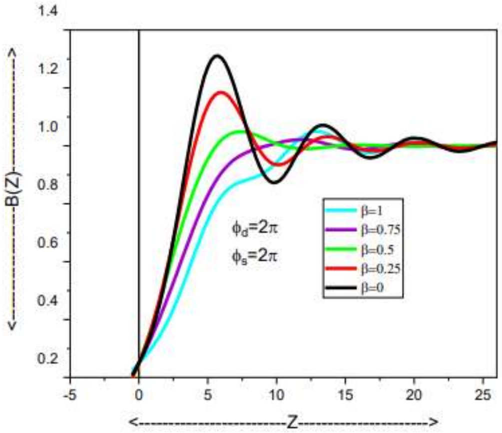

Fig.6 Intensity distribution curves for double filtering

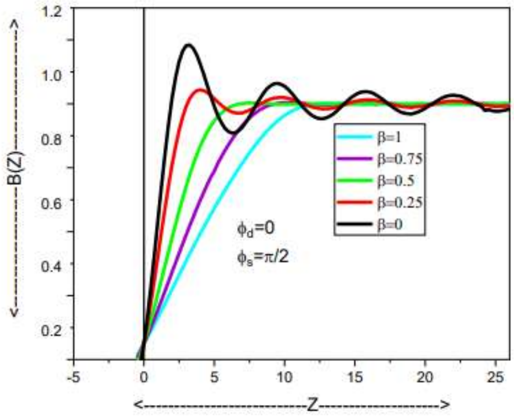

Fig.7 Intensity distribution curves for triple filtering

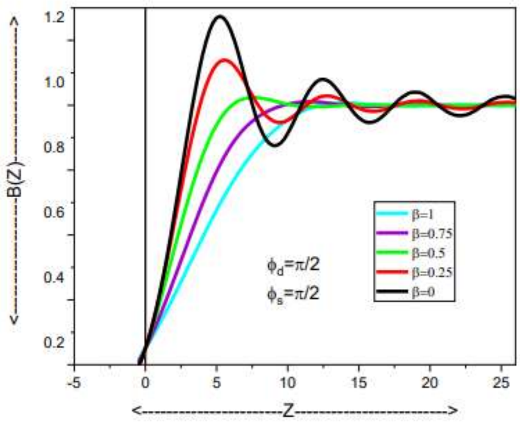

Fig.8 Intensity distribution curves for triple filtering

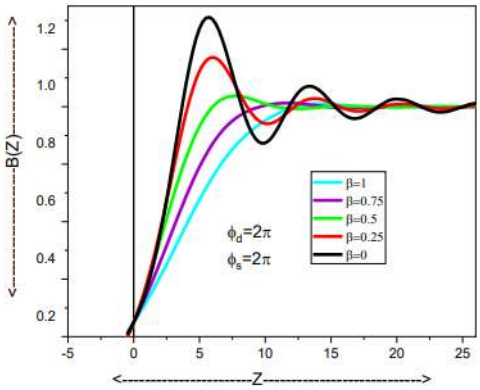

Fig.9 Intensity distribution curves for triple filtering

Figures 7, 8 and 9 illustrate that the edge ringing is reduced at larger level in triple filtering compared to single and double filtering.

IV. Conclusions

As the apodization value goes from 0 to 1, the edge-ringing decreases along with the edge gradient at the expense of an increase in the edge shift. The single filter does not, however, totally eliminate edge ringing. The variable apodization has been implemented in an effort to further reduce or eliminate undesired ringing. As opposed to using a single filter, the double filtering technique reduces edge ringing to lower levels. Similar to this, undesired edge ringing is lessened or almost completely eliminated when the aberrated coherent optical system is shaded with three filters at once. As a result, this feature of reducing or eliminating edge ringing comes at the expense of increasing the edge shift and further losing edge gradient. The amplitude transmittance gradually decreases from the center of the pupil outward due to varying apodization. Due to apodization, the higher spatial frequency components of the image are reduced since the pupil transmittance at the margins is lower than that in the center.

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