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Investigation of Point Spread Function ofTwo Zone Aperturewith Variable Apodization under the influence of Defocus and PrimarySpherical Aberration

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Abstract. *The basic merit functions of the point spread function are to increase the intensity of central maxima and elimination of side lobes or to reduce the radius of first dark ring. The point spread function of the two zone optical system of the second order in the presence of defocus and primaryspherical aberration with Hanning (outer zone) and Triangular (inner zone) amplitude filters is studied. A significant increase in the intensity of central maximum when apodization parameter for β=1 is achieved. Employment of the Hanning and Triangularfilters under the higher degree of primary spherical aberration and defocusing effect helps the aberratedoptical systems increase the resolution thus making it a super resolver. Our aim is to improve the lateral resolution of the central peak by the highest degree of the amplitude apodization parameter β and to realize least possible radius for the first minima as the presence of first minima with zero intensity is necessary for Rayleigh criterion which can be used to study two-point resolution.*

Keywords:*point spread function; amplitude apodization; primary spherical aberration; defocus; two-zone aperture;super-resolver.*

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I. INTRODUCTION

The image of a point object produced by any source is not a point but actually it is a patch of light distributed over a finite region in the image plane. This is due to diffraction and aberrations present in optical systems. This is also called as "Airy pattern". These aberrations influence the width of PSF. The point spread function PSF is a vital feature to study the imaging characteristics of any optical system. The PSF is considered as an important tool in designing optical systems as well as to analyze the images [1]. In the field of optical imaging and telecommunications, the suppression of secondary side-lobes in the diffraction pattern also known as point spread function (PSF) is highly desirable in certain cases. The process of achieving this is known as apodization. Many apodization filters have been proposed in instrumental optics for various purposes [2]. By properly choosing the transmission function of the pupil of the system, the intensity in the outer parts of the diffraction pattern can be totally suppressed or at least considerably reduced without increasing the dimensions of the pupil. In the present study, the diffracted field characteristics of rotationally symmetric optical systems with variable apodization of two zones using Hanning and Triangular filters have been considered to analyze the intensity distribution in terms of the width of the central maximum and suppression of side lobes completely or partially by shaping the circular aperture into two-zone aperture with varying zone parameters under the combined influence of defocus and primary spherical aberration.

II. EXPERIMENTAL

The diffraction characteristics due to a circular aperture in an optical imaging system can be derived from its amplitude PSF. The diffracted light amplitude associated with a rotationally symmetric pupil is given by [3],

$$S(Z) = 2\int_0^1 (f(x)J_0\,(Zx)x\,dx \quad (1)$$

The investigation is done to study the effect of the Hanning and Triangular amplitude filter on the optical system which is under the combined influence of high Seidel aberration and maximum defect of focus. The Triangular filter is placed in the inner zone and Triangular filter is placed in the outer zone of the two zone pupil of the apodized optical system. The point spread function is subjected to a higher degree of defocusing and primary spherical aberration effect by varying zone limits. The general expression for diffraction field of two amplitude filters is given by:

$$S(Z) = 2\int_0^a (f_1(x) J_0\,(Zx) x dx + 2\int_a^1 (f_2(x)\,J_0(Zx) x dx \quad (2)$$

Where ***f₁(x)*** is Triangular amplitude pupil function, ***f₂(x)*** is Hanning amplitude pupil function of the optical system; **Z** is the dimension less variable which forms the distance of the point of investigation from the centre of the diffraction field; and ***J0 (Zx)***is the zero order Bessel function of the first kind**; '*x*'** is the reduced radial coordinate on the exit-pupil of aberrations influenced optical system.

The generalized expression for the amplitude impulse response of the pupil function in the presence of higher degree of primary spherical aberration and defocusing can be written as:

$$S(\emptyset_d, \emptyset_s, Z) = 2\int_0^a f_1\,(x) \exp\left[-i\left(\emptyset_d \frac{x^2}{2} + \frac{1}{4}\emptyset_s x^4\right)\right] J_0(Zx) x dx + 2\int_a^1 f_2\,(x) \exp\left[-i\left(\emptyset_d \frac{x^2}{2} + \frac{1}{4}\emptyset_s x^4\right)\right] J_0(Zx) x dx \quad (3)$$

WhereΦ_d, Φ_s,are the defect-of-focus and the primary spherical aberration parameters respectively. In current study, the two pupil functions we have considered to study variable apodizationare Triangular and Hanning filter of second order in the inner and outer zone respectively which can be represented by:

$$f_1(x) = (1 - \beta x) \quad (4)$$

Triangular filter in the inner zone

$$f_2(x) = \cos(\pi\beta x) \quad (5)$$

Hanning filter in the outer zone

Where '**β**' is the amplitude apodization parameter controlling the non-uniform transmission of the pupil function.

The intensity PSF *B*(*Z*) which is the measurable quantity can be obtained by taking the squared modulus of *S(Z).* Thus,

$$B(Z) = |S(Z)|^2 \quad (6)$$

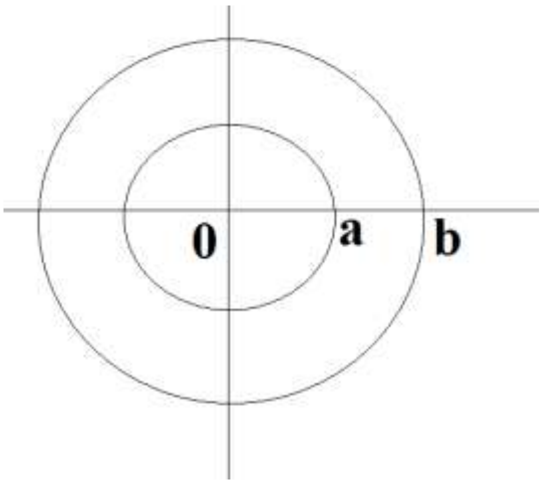

Fig. 1 Two-zone aperture

III. RESULTS AND DISCUSSION

Equations (3), (4), (5) and (6) have been used to derive the point spread functions of the apodized apertures with variable apodization using two amplitude filters.

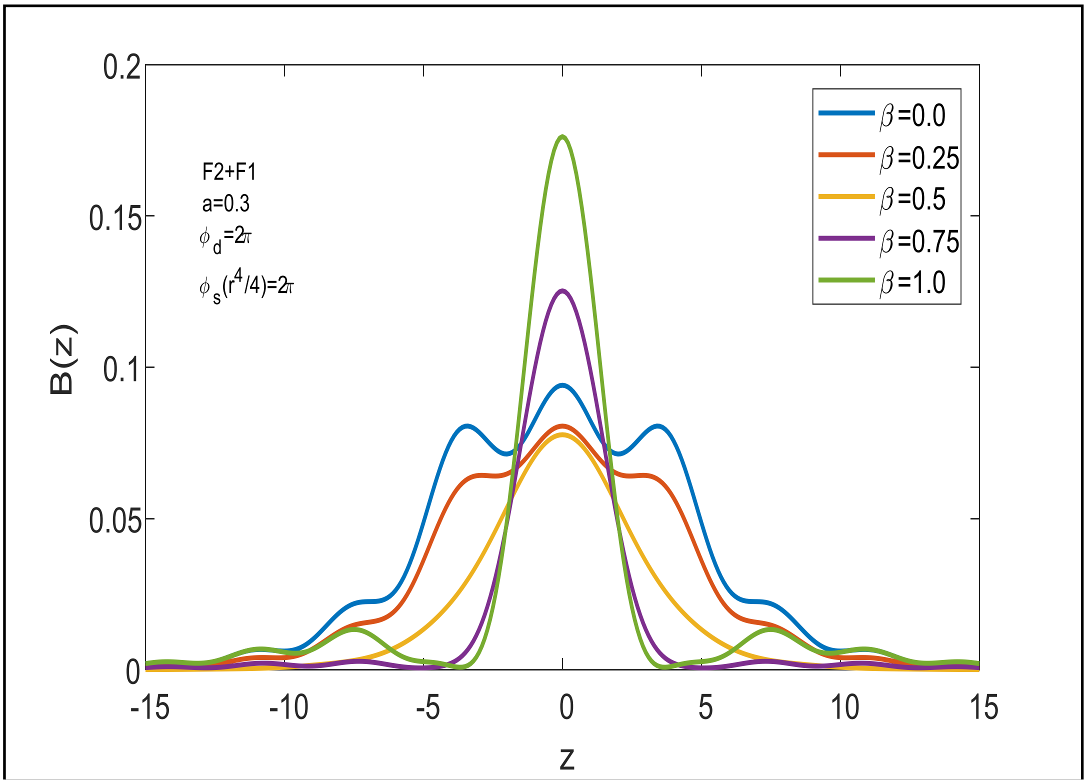

Fig. 2 Intensity distribution curves for two zone aperture with variable apodisation for a=0.3.

Table 1 Maximaminima positions& values at a=0.3

	c. max		f. min		f. max		s. min	
β	**Pos**	**Value**	**Pos**	**Value**	**Pos**	**Value**	**Pos**	**Value**
0	0	0.094	2.0175	0.0713	3.4266	0.0806	10.0084	0.0062
0.2	0	0.0845	2.1764	0.0666	3.1933	0.0691	10.1288	0.0047
0.4	0	0.0734	13.7615	0.0004	14.2484	0.0004	---	---
0.6	0	0.0913	8.7859	0.0005	9.846	0.0006	12.3934	0.0001
0.8	0	0.1379	4.8599	0.0001	7.4296	0.0044	9.2815	0.0019
1	0	0.1763	3.6753	0.0008	7.4905	0.0133	9.6153	0.0055

Figure 2 depicts the intensity distribution curves for various degrees of apodization parameter for two-zone aperture (a=0.3) with Triangular filter in the inner zone and Hanning filter in the outer zone. From the pattern of the intensity distribution curves it is evident that for β = 0.50, i.e., for partial apodization there appears to be a total elimination of the optical side-lobes thus shaping the point spread function to the desired profile. However, for extreme apodization β =1, the intensity in the central lobe tailors to the desired profile there by an increase in the intensity of the central maximum and reduction in the value of full width at half maxima (FWHM) is the outcome by employing the variable apodization. Table 1 provides the computed values of the radius of the first and second dark rings for two zone aperture for different values of β at a=0.3.

Table 2 Maximaminima positions &values at a=0.5

	c. max		f. min		f. max		s. min	
β	**Pos**	**Value**	**Pos**	**Value**	**Pos**	**Value**	**Pos**	**Value**
0	0	0.094	2.0175	0.0713	3.4264	0.0806	10.0075	0.0062
0.2	0	0.0828	2.1925	0.0639	3.2486	0.0667	10.022	0.0047
0.4	0	0.0716	13.8545	0.0004	14.2521	0.0004	---	---
0.6	0	0.0953	8.7266	0.0007	9.7113	0.0007	12.3386	0.0001

0.8	0	0.1567	4.9007	0.0002	7.3832	0.0035	8.9954	0.0019
1	0	0.2132	3.8292	0.0001	7.3967	0.0103	9.1969	0.0055

Table 2 provides the computed values of the radius of the first and second dark rings for two zone aperture for different values of β at a=0.5.

Figure 3 depicts the intensity distribution curves for various degrees of apodization parameter for two-zone aperture (a=0.5) with Triangular filter in the inner zone and Hanning filter in the outer zone. From the pattern of the intensity distribution curves it is evident that for β = 0.50, i.e., for partial apodization there appears to be a total elimination of the optical side-lobes thus shaping the point spread function to the desired profile. However, for extreme apodization β = 1, the intensity in the central lobe tailors to the desired profile there by an increase in the intensity of the central maximum.

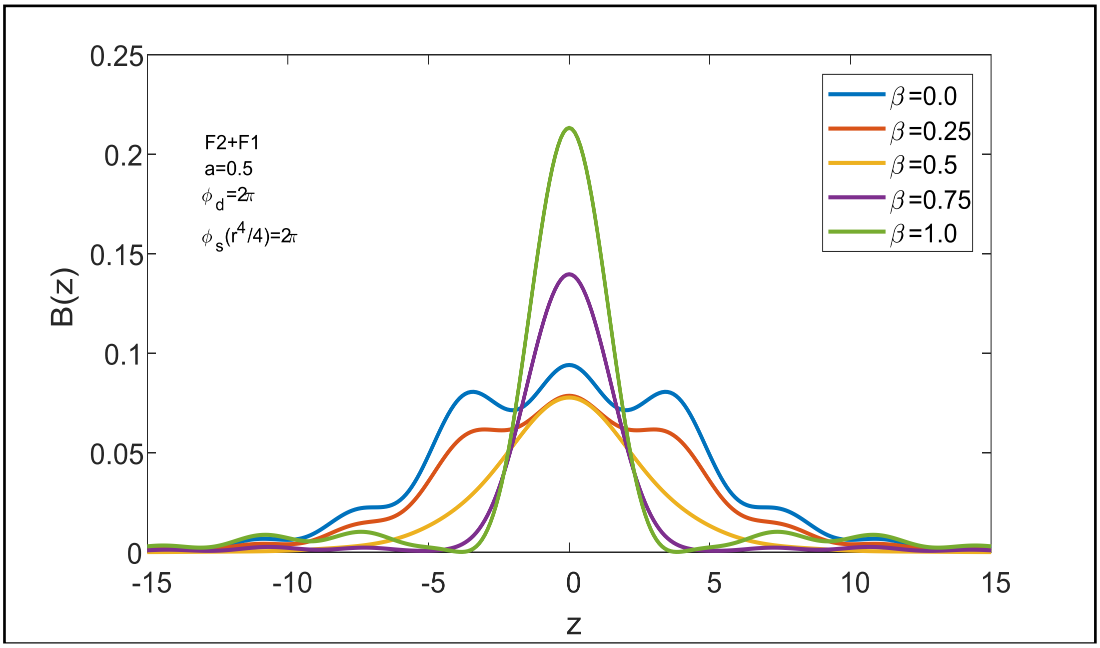

Fig. 3 Intensity distribution curves for two zone aperture with a =0.5

Figure 4 depicts the intensity distribution curves for various amounts of apodization parameter for two-zone circular aperture (a=0.7) with Triangular filter in the inner zone and Hanning filter in the outer zone in the presence of higher degrees of defocus and primary spherical aberration. From the profile of the intensity distribution curves it is evident that for β = 0.50, i.e., for partial apodization there appears to be a total elimination of the optical side-lobes and for higher values of apodization with β = 1, the intensity in the central lobe shapes to the desired profile resulting in an increase in the intensity of the central maximum and reduction in the radius of the first dark ring , in other words the energy in the central maximum is increased with reduced size of the spot rendering it to be super-resolved.

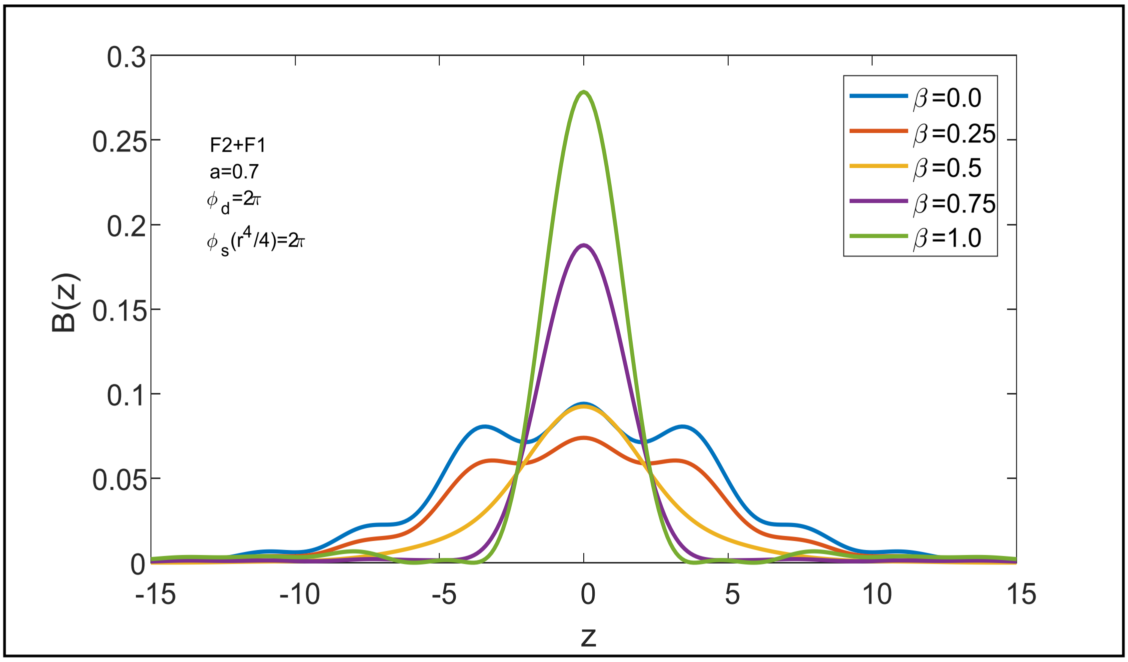

Fig. 4 Intensity distribution curves for two zone aperture with a =0.7

Table 3 Maxima minima positions& values at a=0.7

	c. max		f. min		f. max		s. min	
β	**Pos**	**Value**	**Pos**	**Value**	**Pos**	**Value**	**Pos**	**Value**
0	0	0.0941	2.0177	0.0713	3.4264	0.0806	10.0073	0.0062
0.2	0	0.077	2.0551	0.0604	3.35	0.0656	10.095	0.0045
0.4	0	0.076	13.6658	0.0004	14.4437	0.0005	---	---
0.6	0	0.123	---	---	---	---	---	---
0.8	0	0.2108	4.6135	0.0007	7.6603	0.0028	9.5054	0.0013
1	0	0.2784	3.8361	0.0001	4.7583	0.0016	5.88	0.0001

Table 3 provides the computed values of the radius of the first and second dark rings for two zone aperture for different values of β at a=0.7.

IV. CONCLUSIONS

From the present work, it is found that employing combination of triangular amplitude filter (from 0 to 0.7) and Hanning amplitude filter (from 0.7 to 1) is effective in achieving a super-resolved PSF for higher values of amplitude apodization (β = 1), even in the presence of high degree of defocus($\phi_d = 2\pi$) and primary spherical aberration ($\phi_s = 2\pi$). The process of apodizing the optical system, suppresses the optical side-lobes. For β = 0.5, the side-lobes are almost eliminated. For β = 1, the axial shape and the lateral resolution of the PSF is modified into the required module of maximum intensity and suppressed side lobes.

The process of apodization of the two zone optical system with variable apodization amplitude filter, suppresses fully or partially the optical side-lobes. On the whole it is evident that by employing Triangular amplitude filter in the central zone and Hanning amplitude filter in the outer zone under the combined influence of defocus and primary spherical aberration results in a feature effective in shaping the point spread function of the given optical systems in terms of enhanced intensity and elimination of non-zero first minima thus improving the lateral resolution of the central peak by the highest degree of the amplitude apodization parameter β.

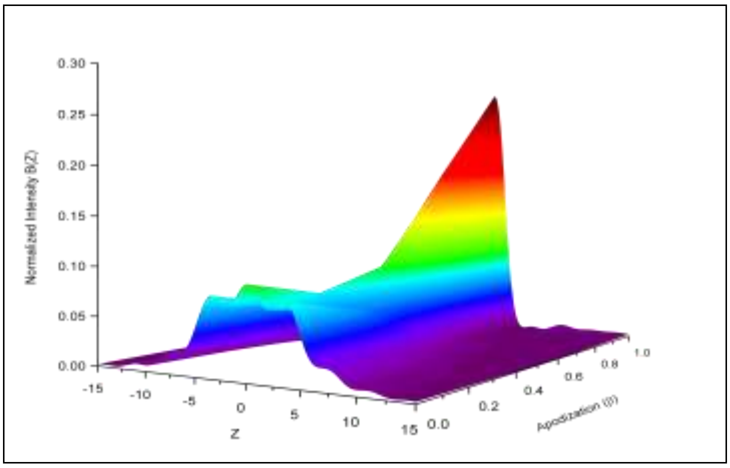

Fig. 5 3DIntensity distribution for two zone aperture at a =0.7under highest degree of defocus and primary spherical aberration

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