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Analysis of Point Spread Function Using Central Circular Obscuration Aperture

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Abstract.
The point spread function (PSF) of an optical system apodized with a Hanning amplitude filter, featuring a central circular obscuration (ε = 0.4 & 0.5), is analyzed in the presence of primary spherical aberration and defocus. The primary objective is to enhance the intensity in the central lobe, suppress the side lobes, and reduce the radius of the first dark ring. It is observed that when the apodization parameter is set to β=1, the central maximum intensity increases, and the radius of the first dark ring is minimized, even under significant spherical aberration and defocus.

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I. Introduction

In an ideal optical system, the image should perfectly replicate the object under study. However, in reality, the image of a point object appears as a spread function called the Airy diffraction pattern. The quality of this point spread function (PSF) is determined by two key factors: a narrower width of the central maxima and a higher intensity of the central lobe. When the radius of the first dark ring in the diffraction pattern is smaller than that of the standard Airy pattern, the PSF is considered "super resolved." Modifying the light intensity at the exit pupil whether through amplitude or phase adjustments can redistribute the light intensity in the image plane, enhancing the PSF's characteristics. This process of altering the pupil transmission properties (either in amplitude or phase) to improve image quality is known as apodization.

To enhance the resolution of an optical system, the pupil function must be modified using appropriate apodisation. Apodisation is a technique that alters the imaging characteristics of the system by adjusting the entrance pupil, thereby reducing ringing in the system’s impulse response [1]. The primary purpose of an optical system is to produce an image that closely resembles the original object. However, in practice, even a single point object is not imaged as a perfect point. Instead, due to light diffraction, it appears as a spread-out pattern known as the point spread function (PSF), commonly recognized as the Airy pattern [2]. "The point spread function (PSF) plays a vital role in evaluating the image quality of an optical system [3–5]. Because the side lobes of the Airy pattern degrade image quality, minimizing them is essential for improving the performance of the point spread function (PSF) [6–8]. In this study optical system apodized with a Hanning amplitude filter, featuring a central circular obscuration (ε = 0.5), is analyzed in the presence of primary spherical aberration and defocus. This setup allows for the analysis of intensity distribution, emphasizing the central lobe’s width and the suppression of side lobes, under the combined effects of defocus and primary spherical aberration [9–15].

Theory and Formulation

The amplitude point spread function (PSF) of an optical system affected by defocus and primary spherical aberration can be expressed as:

$$G_F(\phi_d, \varphi_s, \ Z) = 2\int_0^1 f(r) \exp\left[-i\left(\phi_d \frac{r^2}{2} + \frac{1}{4}\varphi_s r^4\right)\right] J_0(Zr) r dr \qquad (1)$$

Where ‘f(r)’ is the pupil function of the optical system; ‘Z’ is the dimensionless variable which forms the distance of the point of observation from the Centre of diffraction head; and ‘$J_0(Zr)$’ is the zero order Bessel function of the first kind; ‘r’ is the reduced co-ordinate on the exit-pupil of the system. In the present study, Hanning amplitude filter is employed with central circular obscuration. The equation [1] becomes

$$G_F(\phi_d, \varphi_s, \ Z) = 2\int_\in^1 f(r) \exp\left[-i\left(\phi_d \frac{r^2}{2} + \frac{1}{4}\varphi_s r^4\right)\right] J_0(Zr) r dr \qquad (2)$$

$f(r) = \cos^2(\pi\beta r)$ Hanning amplitude filter (3)

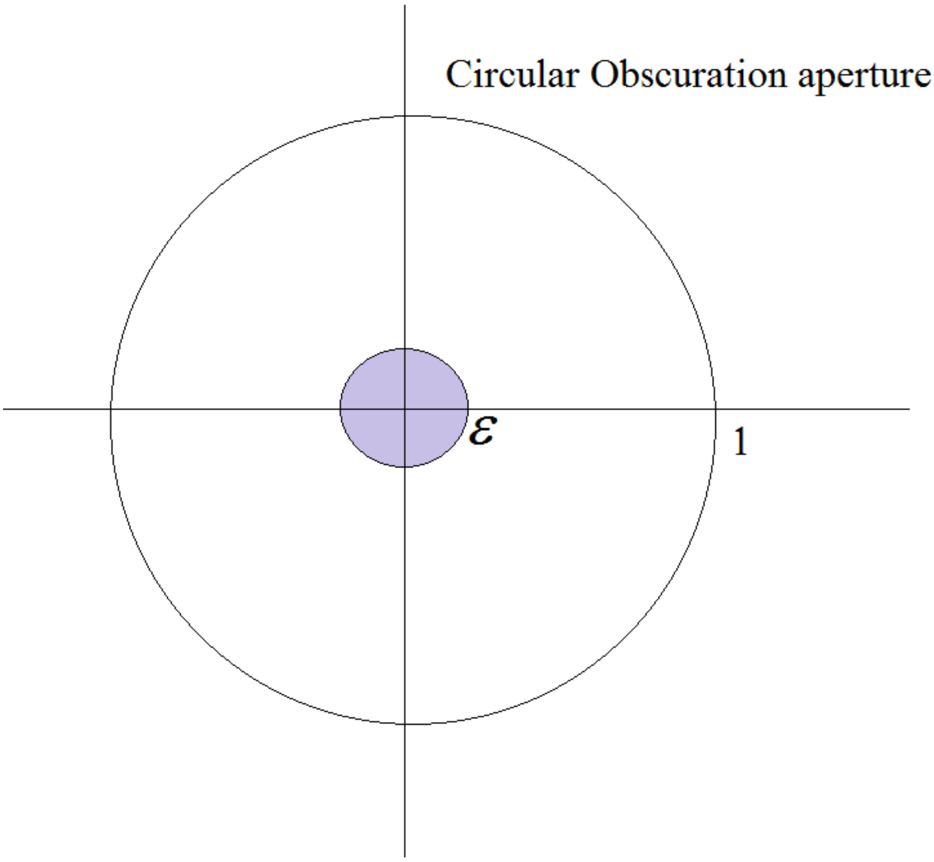

Fig: 1 Central Circular Obscuration aperture

II. Results and Discussion:

Figures 2(a), (c), and (e) display the intensity profile curves for a highly apodized optical system under the combined effects of defocus and primary spherical aberration, with a central obscuration parameter (ε) of 0.4. In contrast, Figures 2 (b), (d), and (f) present the corresponding profiles for a higher obscuration parameter (ε = 0.5).The results show that the central lobe intensity reaches its maximum in the case of highly aberrated apertures. Furthermore, the amplitude filter used proves effective in reshaping the central irradiance distribution, even for optical systems experiencing significant aberrations and defocus.

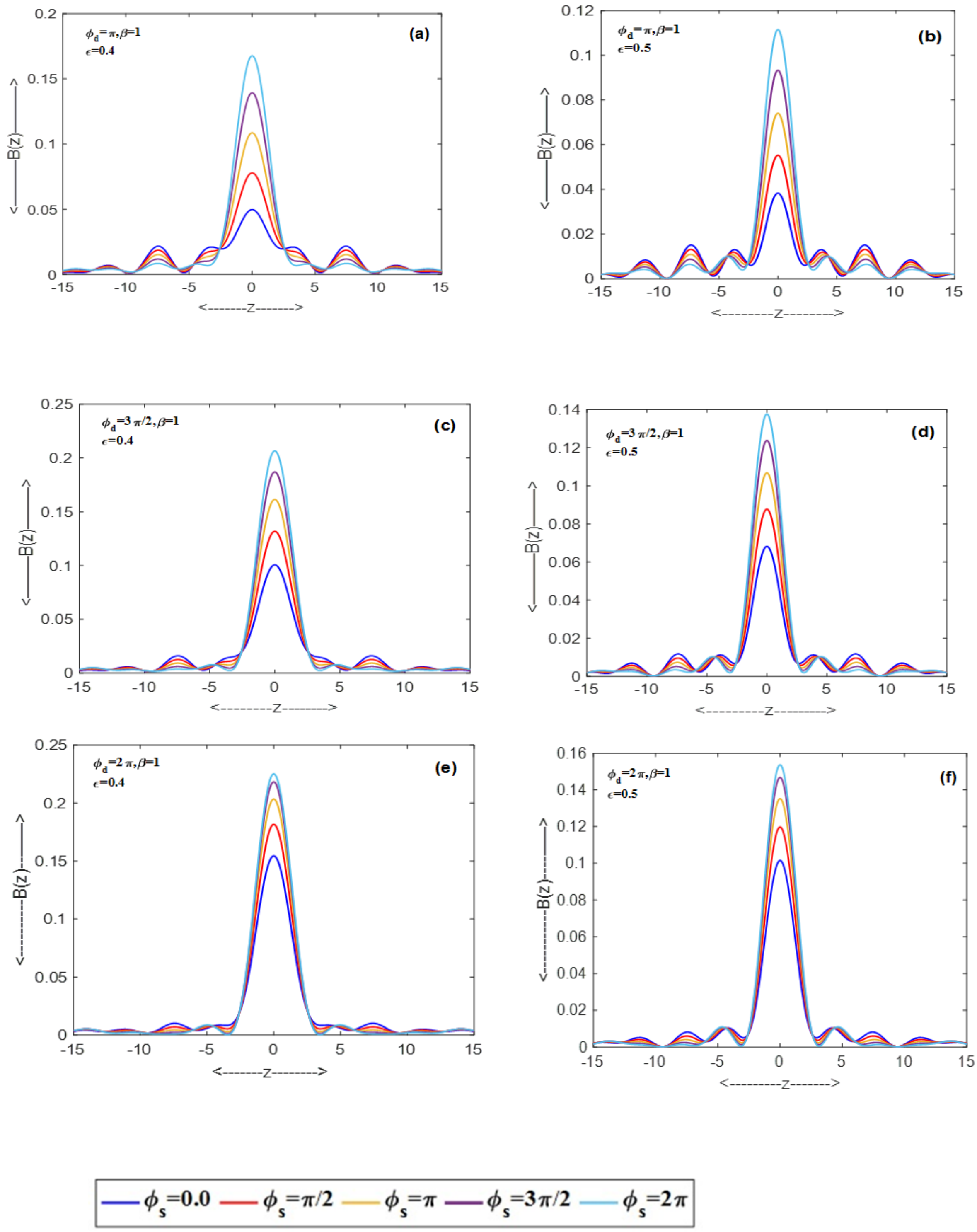

Fig.2 INTENSITY DISTRIBUTION CURVES

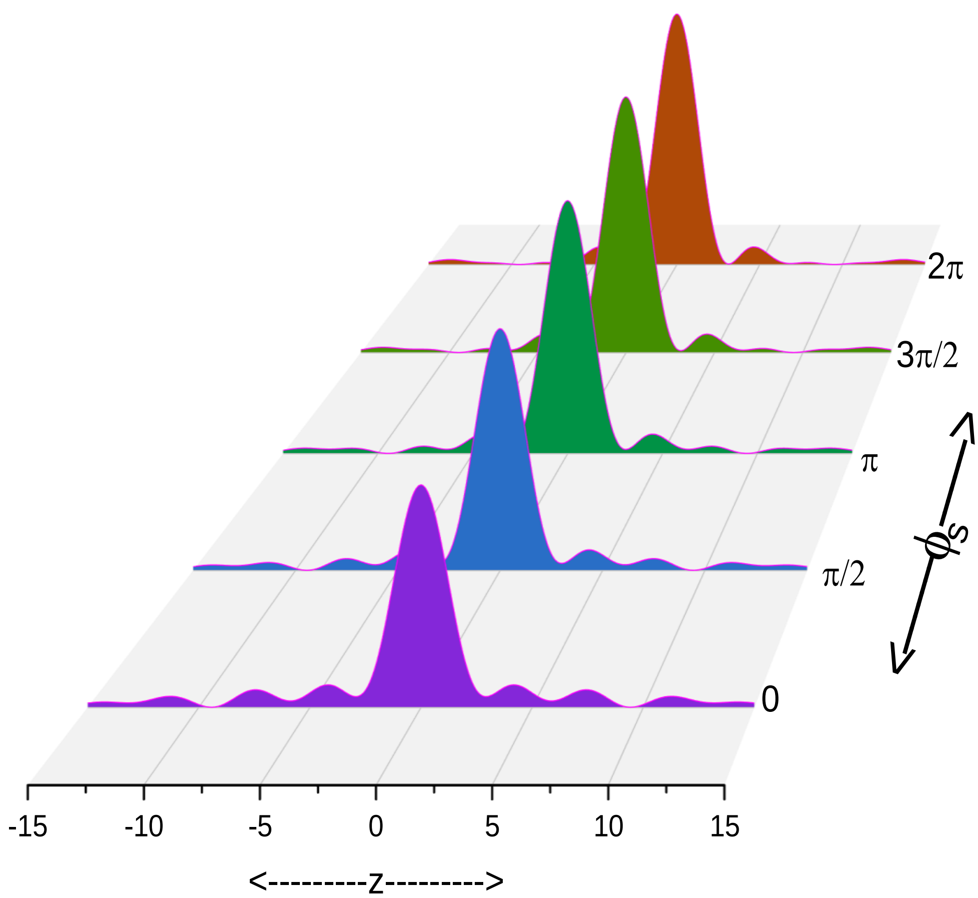

Fig: 3 3D Graph: Hanning Amplitude Filters with Central Circular Obscuration (ε=0.5) with aberrations φ_d= 2π and β=1

TABLE-2.15: MAXIMA AND MINIMA VALUES FOR HANNING APODISER CENTRAL CIRCULAR OBSCURATION APERTURE

Φ_d= 2π,ε=0.5	β	central maxima		First minima		First maxima		Second minma		second maxima	
		pos	value	pos	value	pos	value	pos	value	pos	Value
Φ_s = 0	0.0	0	0.3459	3.1233	0.0095	4.7549	0.0382	7.2694	0.0126	9.8444	0.0052
	0.2	0	0.1084	3.3596	0.0027	5.1576	0.0114	9.6018	0.0019	10.89	0.0022
	0.4	0	0.0658	2.7217	0.0000	4.3008	0.0094	6.2403	0.0002	7.8662	0.004
	0.6	0	0.2684	3.0128	0.0047	4.6577	0.0326	6.8481	0.0066	8.1427	0.0101
	0.8	0	0.1447	3.5523	0.0007	5.5329	0.0172	8.1742	0.0014	10.0452	0.0044
	1.0	0	0.1016	2.9269	0.0049	4.18	0.0103	5.8735	0.0030	7.4404	0.0081
Φ_s = π/2	0.0	0	0.2901	3.1264	0.0115	4.7393	0.0336	9.6563	0.006	11.0223	0.0085
	0.2	0	0.0931	3.3959	0.0032	5.2363	0.0102	9.4294	0.002	10.9574	0.0027
	0.4	0	0.0623	2.7352	0.0000	4.3101	0.0087	6.2507	0.0003	7.861	0.0036
	0.6	0	0.2312	3.0068	0.0057	4.6453	0.0291	6.822	0.0082	7.9834	0.0104
	0.8	0	0.1397	3.5458	0.0009	5.5211	0.0165	8.1899	0.0017	10.0469	0.0042

	1.0	0	0.1199	3.0093	0.0036	4.3486	0.0103	6.1039	0.0029	7.4968	0.0059
	0.0	0	0.235	3.1346	0.0132	4.7183	0.0288	9.5125	0.0066	10.9894	0.01
	0.2	0	0.078	3.4511	0.0036	5.3882	0.0092	9.3507	0.0021	10.9915	0.0031
$\Phi_s = \pi$	0.4	0	0.058	2.7484	0.0001	4.3185	0.0078	6.2595	0.0004	7.8487	0.0031
	0.6	0	0.1936	3.0006	0.0066	4.6303	0.0254	6.7812	0.0096	7.7679	0.0108
	0.8	0	0.1339	3.5406	0.0011	5.5116	0.0157	8.2216	0.002	10.065	0.004
	1	0	0.1353	3.0641	0.0022	4.4835	0.0105	6.3703	0.0023	7.5835	0.004
	0.0	0	0.1830	3.1535	0.0144	4.6841	0.0241	6.348	0.0198	6.8074	0.0199
	0.2	0	0.0637	3.5369	0.0038	5.7197	0.0083	9.3045	0.0022	11.0142	0.0035
$\Phi_s = 3\pi/2$	0.4	0	0.0532	2.7607	0.0001	4.3254	0.007	6.265	0.0005	7.8245	0.0027
	0.6	0	0.1571	2.9941	0.0073	4.6113	0.0218	6.703	0.0107	7.4985	0.0113
	0.8	0	0.1271	3.5377	0.0014	5.5065	0.0148	8.2813	0.0024	10.1256	0.0038
	1	0	0.1469	3.103	0.0012	4.5842	0.0107	6.6382	0.0015	7.7166	0.0025
	0.0	0	0.1362	3.1993	0.01510	4.6007	0.0196	5.5455	0.0187	6.9078	0.0211
	0.2	0	0.0507	3.6717	0.00380	6.212	0.0079	9.2731	0.0022	11.0334	0.0038
$\Phi_s = 2\pi$	0.4	0	0.0477	2.7717	0.00020	4.3295	0.0061	6.2647	0.0006	7.7806	0.0024
	0.6	0	0.123	2.988	0.00780	4.5855	0.0182	6.5211	0.0115	7.2303	0.0118
	0.8	0	0.1194	3.538	0.00170	5.5084	0.0139	8.3931	0.0027	10.3391	0.0037
	1	0	0.1537	3.1328	0.00040	4.6584	0.0109	6.8729	0.0007	7.9077	0.0013

Table 2.15 shows the intensities of the central lobe and the first two side lobes in the diffraction pattern generated by an optical system that uses a Hanning apodization filter and includes a central circular obscuration ($\varepsilon = 0.5$). This is evaluated under the influence of primary spherical aberration with the defocus plane set at $\Phi d = 2\pi$. The results indicate that higher apodization values ($\beta = 1$) lead to increased central maximum intensity, while the width of the central lobe narrows as apodization increases.

III. Conclusions

The key findings from the study can be summarized as follows:
Apodization of the optical system effectively eliminates side lobes at higher apodization levels (β). Strong apodization significantly enhances the intensity of the central maximum. In the presence of notable defocus and primary spherical aberration, the intensity of the central lobe increases substantially when using a Hanning amplitude filter with central circular obscuration ($\varepsilon = 0.4$ and 0.5). This also results in a reduced width of the central lobe at high apodization levels. When both defocus and primary spherical aberration are present, the central maximum intensity rises considerably at extreme defocus planes, particularly for $\beta = 1$ with Hanning amplitude filters.

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