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# Investigation of a new modulated aperture using speckle techniques

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## Abstract

**Background:** A design of equally spaced eight-circles placed at equal distances from the origin is suggested. Three models corresponding to the eight-circle design considering conic, linear, and quadratic distributions are investigated. This arrangement is considered for the sake of improving both microscope resolution and image contrast as compared with the pure annular aperture. This design is different compared with other recent work on aperture modulation.

**Results and discussions:** The point spread function (PSF) is computed in all the models using the fast Fourier transform (FFT) algorithm that computes the discrete Fourier transform (DFT) corresponding to the models and compared with the corresponding PSF in the case of uniform circular aperture. In addition, the autocorrelation images for the apertures are shown differently. It is shown smooth pattern for the circular arrangement as compared with the deformation and shrinking appeared in the central peak in case of conic model. Finally, the speckle images corresponding to the considered apertures are investigated. Reconstructed apertures are obtained from the speckle images using the FFT algorithm.

**Conclusions:** The PSF is computed for the described models, and the autocorrelation corresponding to the apertures showed difference. The reconstructed apertures from the speckle images can be improved using filtering techniques. It is noted that MATLAB codes are constructed in the computations of all images and plots.

**Keywords:** Modulated apertures, Point spread function, Speckle imaging

## 1 Background

The speckle effect [1–5] is a result of the interference of many waves of the same frequency, having different phases and amplitudes, which add together to give a resultant wave whose amplitude, and therefore, intensity varies randomly. The size of the speckles is a function of the wavelength of the light, the size of the laser beam which illuminates the first surface, and the distance between this surface and the plane where the speckle pattern is formed. Dainty [3] derives an expression for the mean speckle size as  $\sigma = \lambda z/D$  where  $D$  is the width of the illuminated area, and  $z$  is the distance between the object and the location of the speckle pattern.

A multiple-image encryption based on different modulated apertures in an optical set-up under a holographic arrangement was proposed in [6]. The system is a security architecture that uses different pupil aperture mask in the encoding lens to encrypt different images. The technique is based on multiplexing to perform high-density holographic storage [7].

Speckle can be modeled by analysis of the statistics of the image of a phase object such as a rough surface. The image can be calculated using the coherent transfer function of the imaging system and the angular spectrum representation. This approach gives a three-dimensional image and includes the effects of high numerical aperture and the finite depth of the structure. Different correlation coefficients can be assumed, including fractal distributions, such as exponential correlation, as well as Gaussian correlation [8]. The laser speckle contrast images (LSCI)

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are investigated in many biomedical publications [9–19] while using modulated apertures as in [20].

Linear and quadratic apertures are used in the formation of speckle images [21, 22]. While annular Hermite Gaussian aperture is investigated in [23].

Recently, a slab waveguide that comprises a linear substrate, an exponential graded index guiding layer, and a power-dependent refractive index covering medium is investigated [24]. While a three-layer slab waveguide with a graded index film and a nonlinear substrate is shown [25]. In addition, other work of a planar waveguide with an exponential grade-index guiding layer and a nonlinear cladding is given in [26]. A numerical analysis is presented in [27] for the proposal of a novel decahedron photonic crystal fiber where the central elliptic core is filled with a highly nonlinear 2D material molybdenum disulphide ( $\text{MoS}_2$ ).

In this paper, we designed a new aperture, composed of eight equally spaced conic circles placed shifted outside the center and using it in the formation of speckle image. Reconstruction of the aperture is obtained. In addition, we computed the PSF and the autocorrelation corresponding to the cited model. The aim of the work using the cited apertures is to gain better transverse resolution and improved contrast as compared with annular apertures that gives poorer contrast.

## 2 Methods

A new aperture, in the form of eight equally spaced conic circles and placed at a constant distance from the center, is fabricated. Where four circles are placed along the cartesian coordinates while the other four circles placed along the rotated coordinates by angle  $= 45^\circ$ . The design of this aperture and other similar arrangements using the linear and the quadratic distributions is realized using MATLAB code. In the next, theoretical analysis corresponding to the design of the conic arrangement of eight conic circles is given followed by the computation of the PSF using the FFT algorithm.

### 2.1 Theoretical analysis

The equally spaced eight conic apertures shown in Fig. 1 is described as follows:

$$P_T(x, y) = P_1 + P_2 + \dots + P_8 \quad (1)$$

with the apertures  $P_{1,2}$  located along the  $x$ -axis at distances  $\pm x_0$ , and the apertures  $P_{3,4}$  located along the  $y$ -axis at distances  $\pm y_0$  represented as follows:

$$P_{1,2}(x, y) = 1 - \sqrt{(x \pm x_0)^2 + y^2} \quad (2)$$

$$P_{3,4}(x, y) = 1 - \sqrt{x^2 + (y \pm y_0)^2} \quad (3)$$

For rotated coordinates by angle  $45^\circ$ , another four apertures are shown in the same Fig. 1 and represented as follows:

$$P_{5,6}(x, y) = 1 - \sqrt{\left(x \pm \frac{x_0}{\sqrt{2}}\right)^2 + \left(y \pm \frac{y_0}{\sqrt{2}}\right)^2} \quad (4)$$

$$P_7(x, y) = 1 - \sqrt{\left(x - \frac{x_0}{\sqrt{2}}\right)^2 + \left(y + \frac{y_0}{\sqrt{2}}\right)^2} \quad (5)$$

$$P_8(x, y) = 1 - \sqrt{\left(x + \frac{x_0}{\sqrt{2}}\right)^2 + \left(y - \frac{y_0}{\sqrt{2}}\right)^2} \quad (6)$$

The Fourier transform corresponding to this model of eight conic apertures is not easily solved while we make use of the FFT technique to solve it getting the PSF.

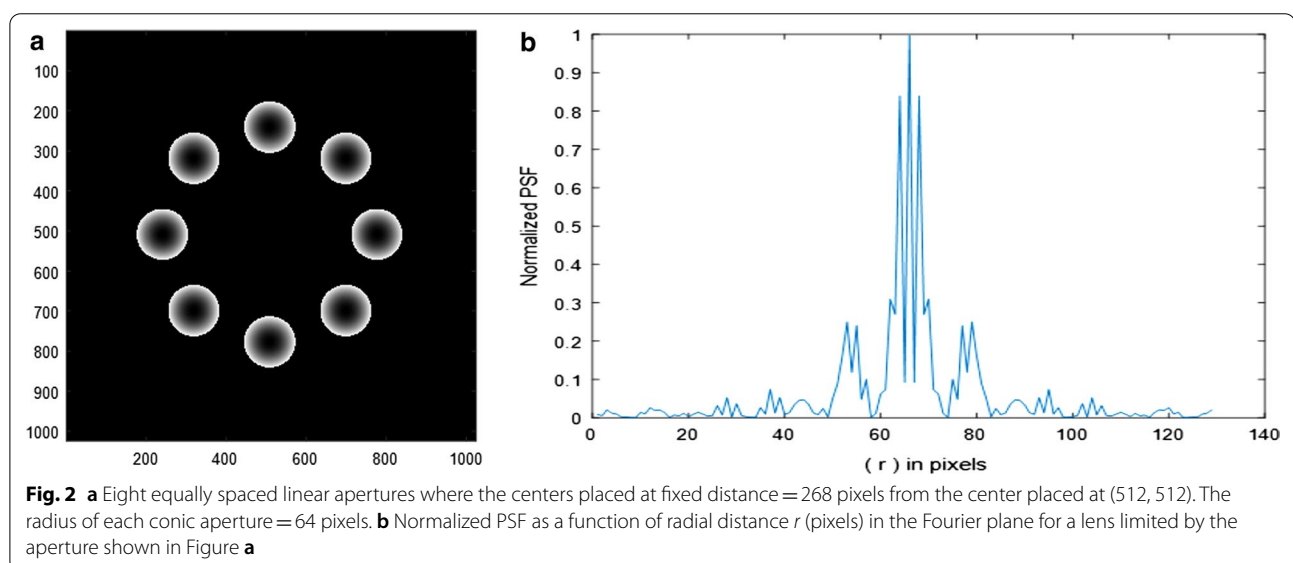
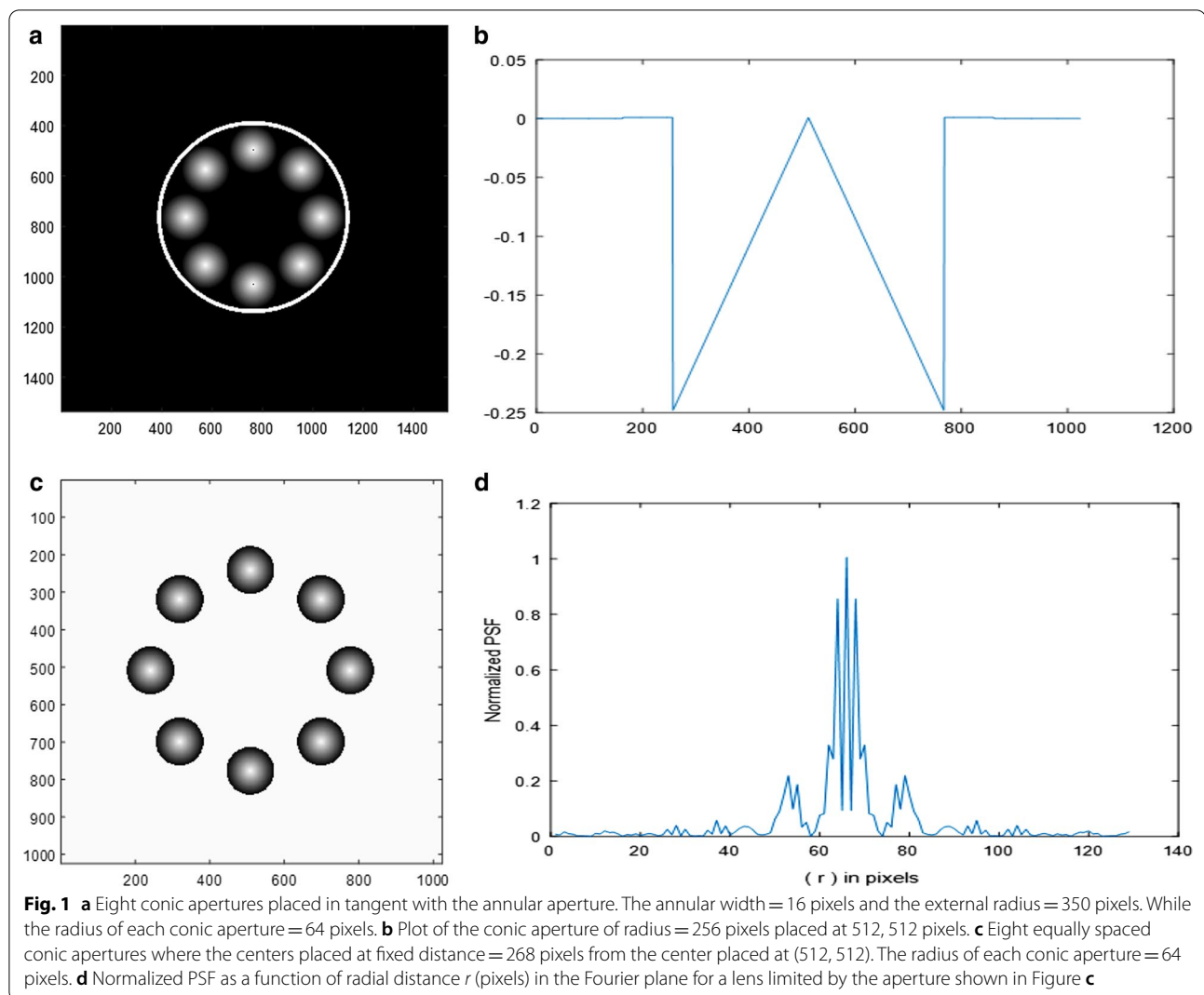
Similarly, the PSF is computed for the other eight equally spaced apertures of the linear and the quadratic distributions using the FFT technique.

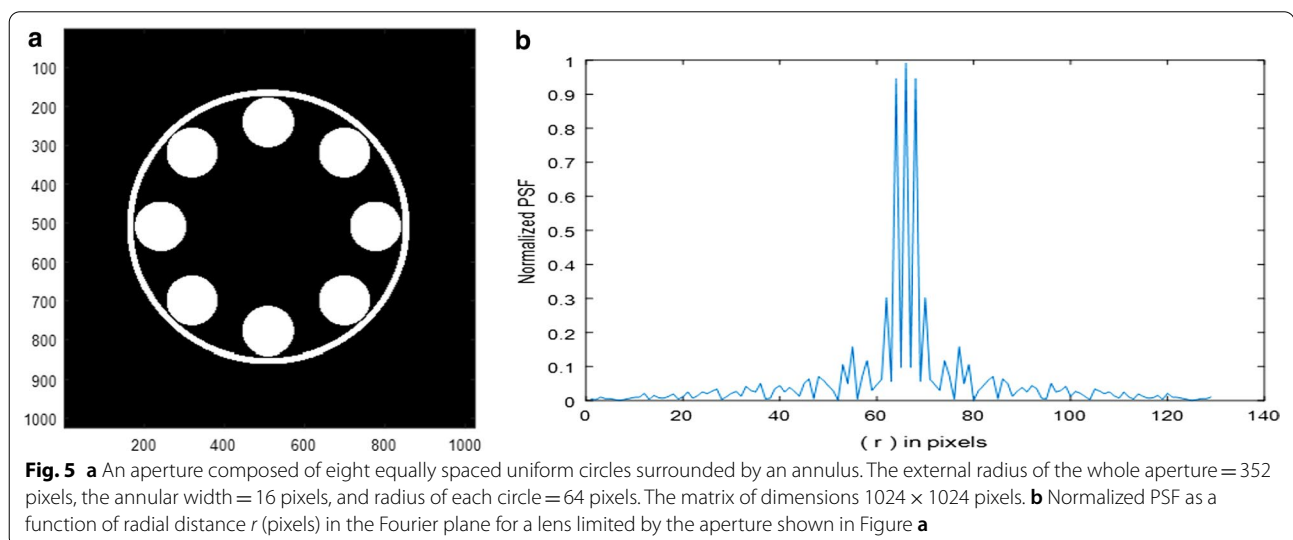
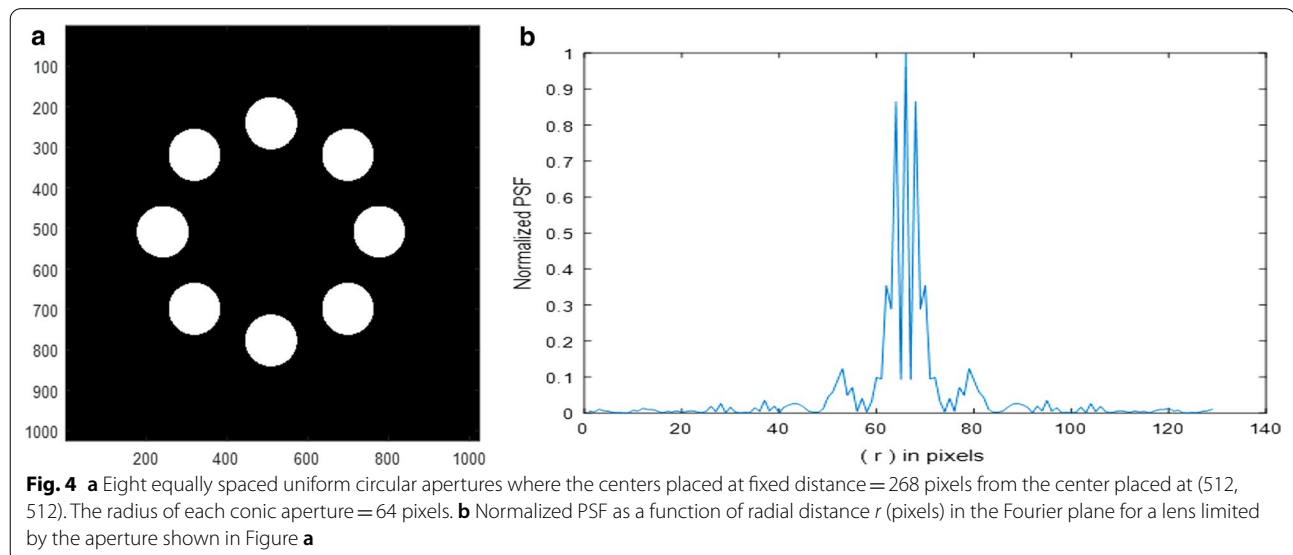
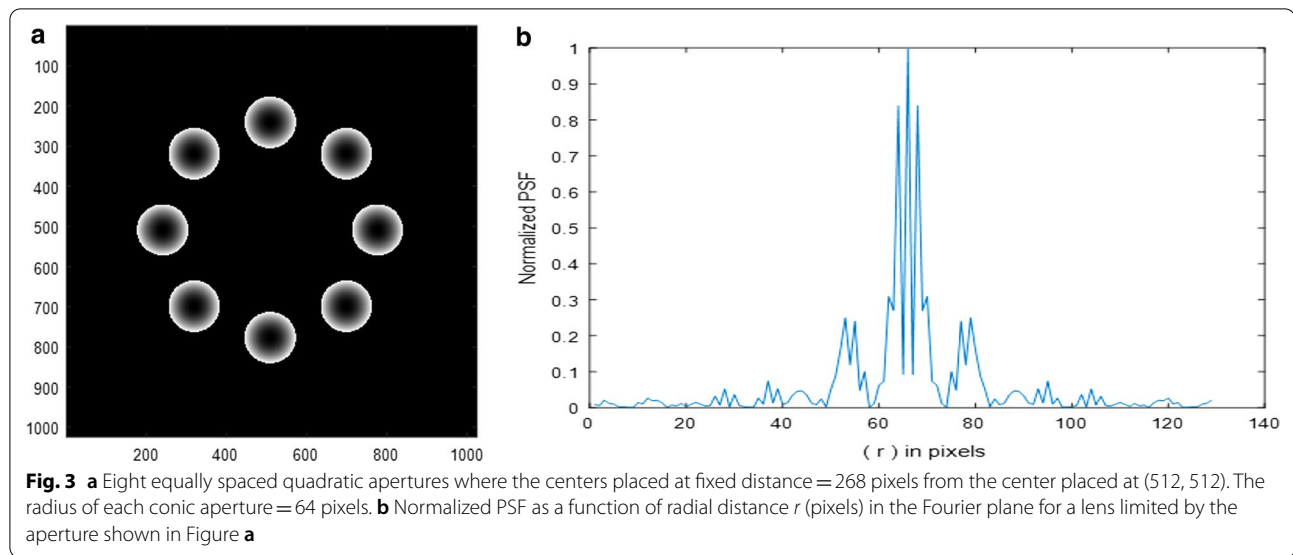
## 3 Results

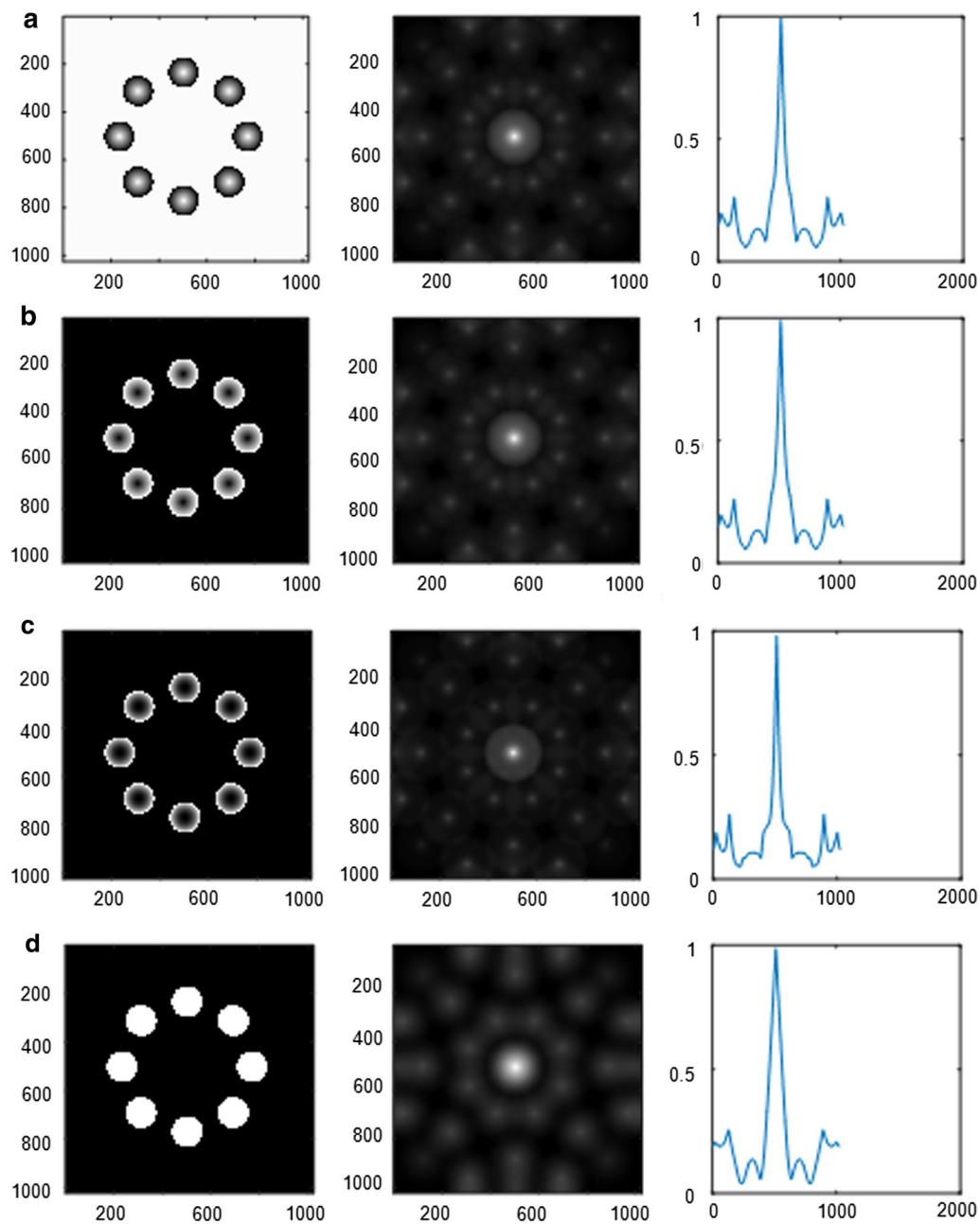
Design of eight conic apertures placed in tangent with the annular aperture is shown in Fig. 1a. The annular width = 16 pixels and the external radius = 350 pixels. While the radius of each conic aperture = 64 pixels. A plot of the conic aperture of radius = 256 pixels placed at 512, 512 pixels is shown in Fig. 1b. Eight equally spaced conic apertures where the centers placed at fixed distance = 268 pixels from the center placed at (512, 512) are shown in Fig. 1c. The radius of each conic aperture = 64 pixels.

The PSF is computed using FFT for all apertures. The Normalized PSF as a function of radial distance  $r$  (pixels) in the Fourier plane for a lens limited by the aperture in Fig. 1c is shown in Fig. 1d. While for the same arrangement for the apertures described above is shown in Figs. 2a and 3a for the linear and quadratic distributions. The corresponding plots of normalized PSF are shown in Figs. 2b and 3b. Finally, eight equally spaced uniform circular apertures shown in Fig. 4a are shown for comparison. The corresponding normalized PSF plot is shown in Fig. 4b. The same arrangement surrounded by an annulus and its corresponding normalized PSF are shown in Fig. 5a, b. The normalized PSF showed similar shapes for the eight conic, linear, and quadratic apertures.

The autocorrelation images and their line plots at the center are computed using FFT techniques, for the conic, linear, quadratic, and uniform circular as shown in Fig. 6a–d.







**Fig. 6** **a** Autocorrelation image and the plot for the conic aperture. **b** Autocorrelation image and the plot for the linear aperture. **c** Autocorrelation image and the plot for the Quadratic aperture. **d** Autocorrelation image and the plot for the uniform circular aperture

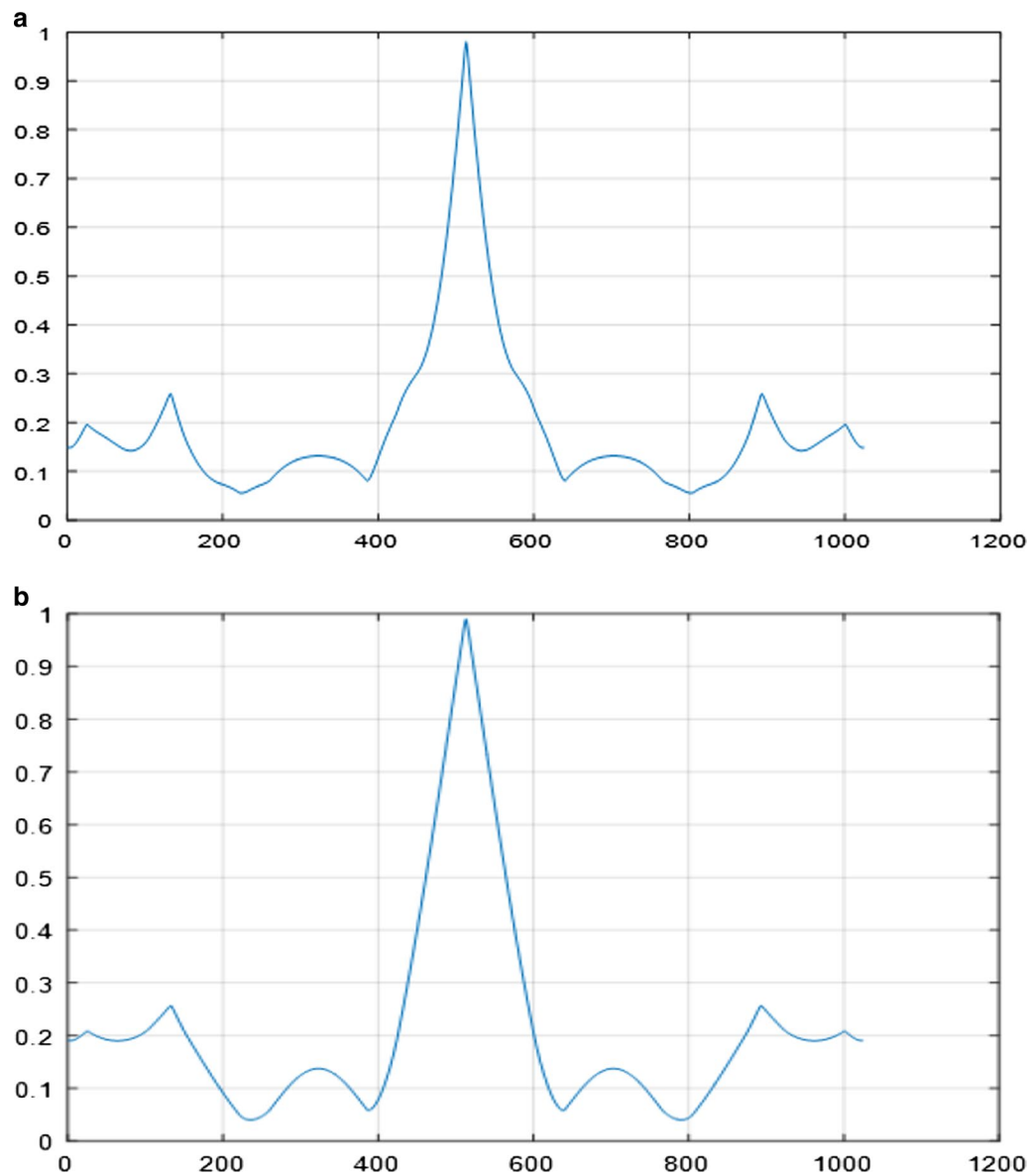
The line plot corresponding to the autocorrelation of the conic and the uniform circular models are plotted as shown in Fig. 7a, b.

Finally, speckle images formed using the above apertures combined with the same diffuser are computed and plotted as shown in the L.H.S. of Fig. 8a–c for conic, linear, and uniform circles, respectively. The reconstructed images of

apertures are obtained using the inverse FFT as shown in the R.H.S. of Fig. 8.

#### 4 Discussions

It is shown, referring to the plotted PSF corresponding to the apertures in Figs. 1, 2, 3, 4, and 5 a great similarity in the distribution, in the central peak. In addition, a noticeable difference is shown in the legs of the patterns for all



**Fig. 7** **a** Autocorrelation of conic model. **b** Autocorrelation of circular uniform model

the plots, while a remarkable difference is in Fig. 5b since the model is surrounded by annulus as expected. Consequently, the PSF distribution is mainly dependent upon the aperture distribution assuming monochromatic light for the illumination. It is shown different irregular shape for the legs of the diffraction pattern.

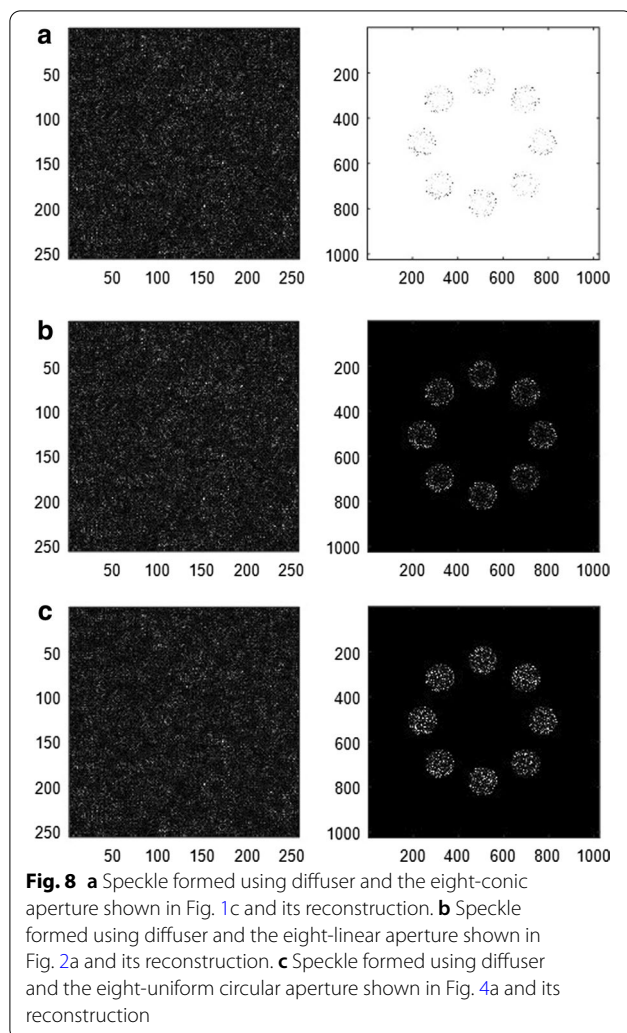
Referring to Fig. 7a, b corresponding to the autocorrelation plots, it is shown smooth pattern for the circular arrangement as compared with the deformation and shrinking appeared in the central peak in case of conic model. In addition, the total width corresponding to the autocorrelation is two times the aperture diameter as expected.

The reconstructed images of apertures shown in Fig. 8 are affected by a noise originated from the diffuser. The reconstructed images may be improved using Wiener filtering allowing to reduce the produced noise from the diffuser.

## 5 Conclusions

We have manufactured apertures in the form of equally spaced conic, linear, and quadratic circles. The normalized PSF computed for all apertures have nearly the same shape. In addition, the autocorrelation corresponding to





the apertures is computed and plotted. Finally, speckle imaging using diffuser limited by the manufactured apertures are computed and plotted. The reconstructed apertures are obtained from the speckle images which can be improved by filtering techniques.

#### Abbreviations

PSF: Point spread function; FFT: Fast Fourier transform; DFT: Discrete Fourier transform; LSCI: Laser speckle contrast images.

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#### Consent for publication

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