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Letter to the Editor

Point spread function in a confocal microscope with trigonometric pupil filters

ANNA MAGIERA

Institute of Physics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50–370 Wrocław, Poland.

In this paper the distribution of point spread function was examined versus the spatial frequencies of the filters of $\cos(N\rho)$ type modulating the aperture of the confocal CSM for different values of numerical aperture. In particular, the following relations were determined: i) PSF as dependent on the pupil modulating spatial frequency r for $N = 1, 2, 3, 4, 5, 6, 7, 9, 11$ and numerical aperture NA = 0.8; ii) PSF for filters of $\cos(4\rho)$, $\cos(10\rho)$ type and NA = 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4; iii) cut-off spatial frequences r_c for the aperture modulated by $\cos(N\rho)$ for $N = 0, \ldots, 20$, NA = 0.2, 0.5, 1.0 and $\lambda = 0.6328$ μm.

In paper [1], the point spread function (PSF) was determined as a function of spatial frequency r in a CSM microscope of apertures modulated by ρ^n for $n = 2, 4, 6, 8, 10, 12, 14, 16$ and for NA = 0.5 and NA = 0.8. Also a characteristic of the cut-off spatial frequency $r_c(n)$ was examined as dependent on parameters n for NA = 0.5.

In the present paper, the distribution of the PSF is examined as a function of spatial frequency r in a confocal CSM microscope of aperture modulated by the filters of $\cos(N\rho)$ type (for $N = 1, 2, 3, 4, 5, 6, 7, 9, 11$) and NA = 0.8. Here, ρ is the absolute value of the radius-vector in the pupil plane. Additionally, the PSF has been examined for different r and $\cos(4\rho)$, $\cos(10\rho)$ and for NA = 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4. The characteristic of the cut-off frequency r_c has been determined for the aperture modulated by filters of $\cos(N\rho)$ type (for $N = 0, 1, \ldots, 20$) and NA = 0.2, 0.5, 1.0, with $\lambda = 0.6328$ μm.

The resultant point spread function (RPSF) h_r in a confocal microscope is defined by the PSFs h_1, h_2 of the first and second objectives, respectively, *i.e.*

$$h_r = h_1 h_2.$$

For the case of two identical nonmodulated circular objectives the image of the point object is defined by

$$I(w) = \left[\frac{2J_1(w)}{w}\right]^4$$

where: J_1 — Bessel function of the first kind and first order, $w = k\rho r/f$ — reduced coordinate in the image plane, $k = 2\pi/\lambda$ — propagation constant (wave number).

The PSF is a Fourier transform of the pupil function

$$\mathrm{PSF} = \mathrm{FT}\{P(\rho)\}.$$

For apertures modulated by the trigonometric filters we obtain [1]

$$h_N(r) = 2\pi \int_0^{\rho_0} \cos(N\rho)\rho J_0(k\rho r/f)\mathrm{d}\rho$$

where: J_0 — Bessel function of the first kind and zero order, ρ_0 — rim value of ρ. In the numerical calculations $f = 1$ μm and $\lambda = 0.6328$ μm have been assumed.

In Figure 1, the pupil function modulated by $\cos(N\rho)$ for $N = 1$, 4, 10 and 20 is shown. In Figure 2, the PSF is presented as a function of spatial frequencies

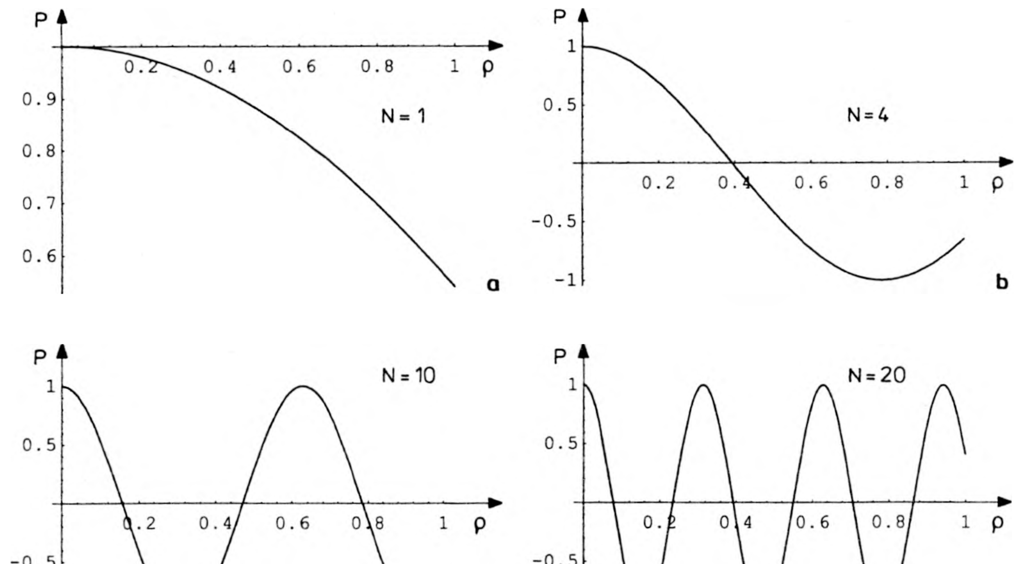

Fig. 1. Distribution of the pupil function $\cos(N\rho)$ for: $N = 1$ (a), $N = 4$ (b), $N = 10$ (c), $N = 20$ (d).

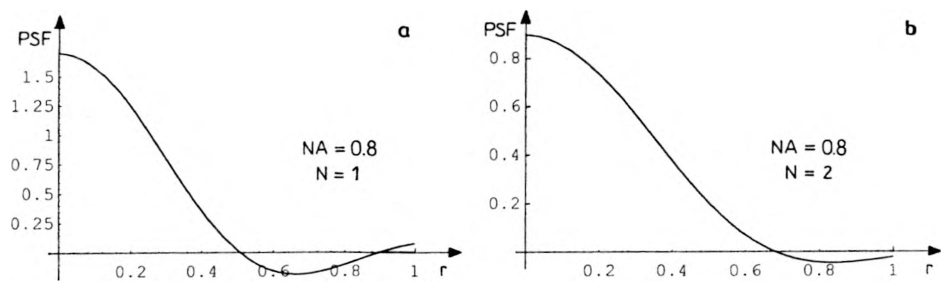

Fig. 2.a,b

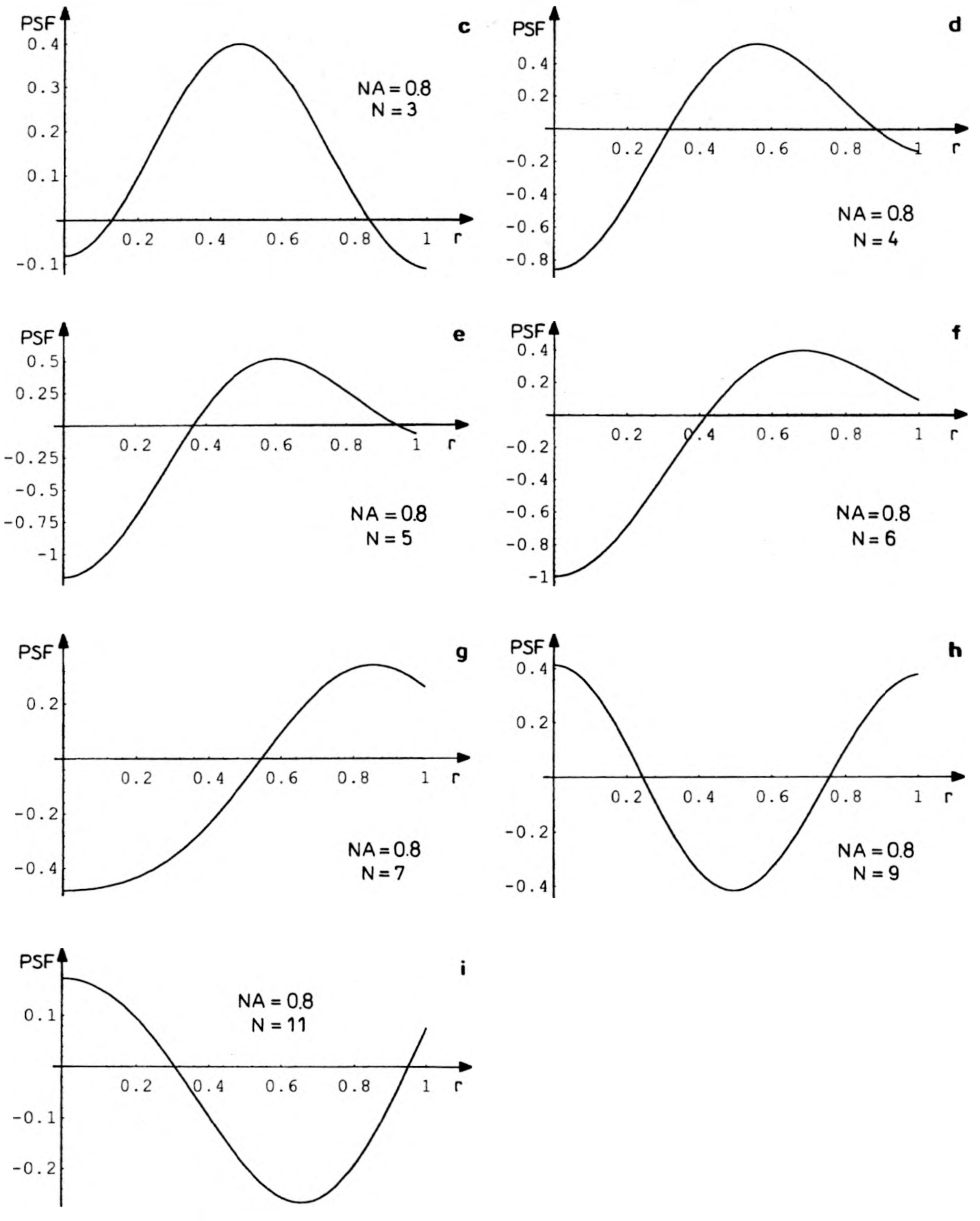

Fig. 2. Point spread function versus the spatial frequencies r [μm] for the pupil filter $\cos(N\rho)$ and the numerical apertures NA = 0.8 for: $N = 1$ (a), $N = 2$ (b), $N = 3$ (c), $N = 4$ (d), $N = 5$ (e), $N = 6$ (f), $N = 7$ (g), $N = 9$ (h), $N = 11$ (i).

r for pupil filters of $\cos(N\rho)$ type in CSM and for NA = 0.8, while N takes the values: 1, 2, 3, 4, 5, 6, 7, 9, 11.

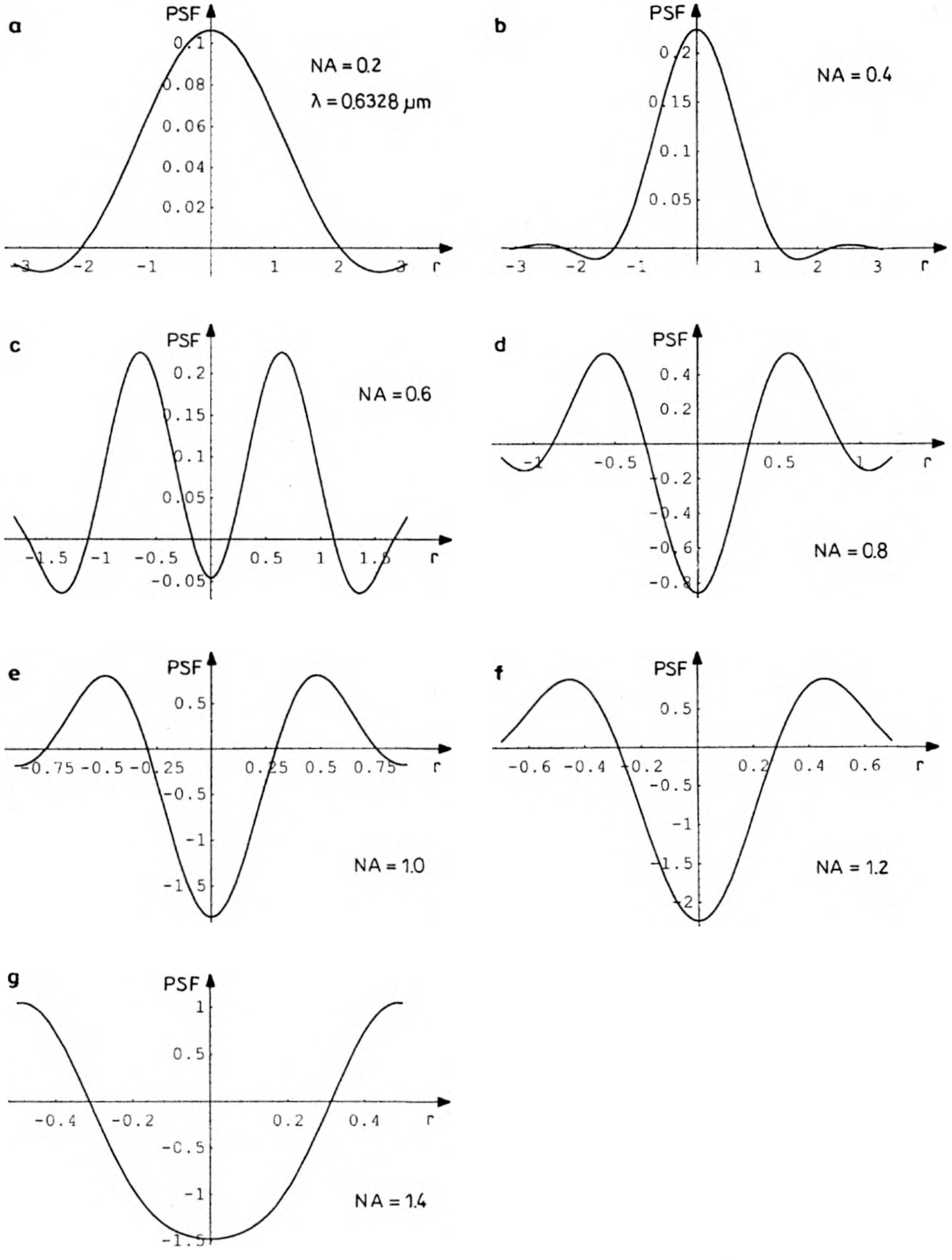

Fig. 3. Point spread function versus the spatial frequencies r [μm] for the pupil filter $\cos(4\rho)$ and the numerical apertures NA = 0.2 (a), 0.4 (b), 0.6 (c), 0.8 (d), 1.0 (e), 1.2 (f), 1.4 (g).

In Figure 3, the PSF is presented as a function of spatial frequencies r for the pupil filter $\cos(4\rho)$ and the following values of the numerical aperture: NA = 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4. In Figure 4, the PSF is presented as a function of spatial

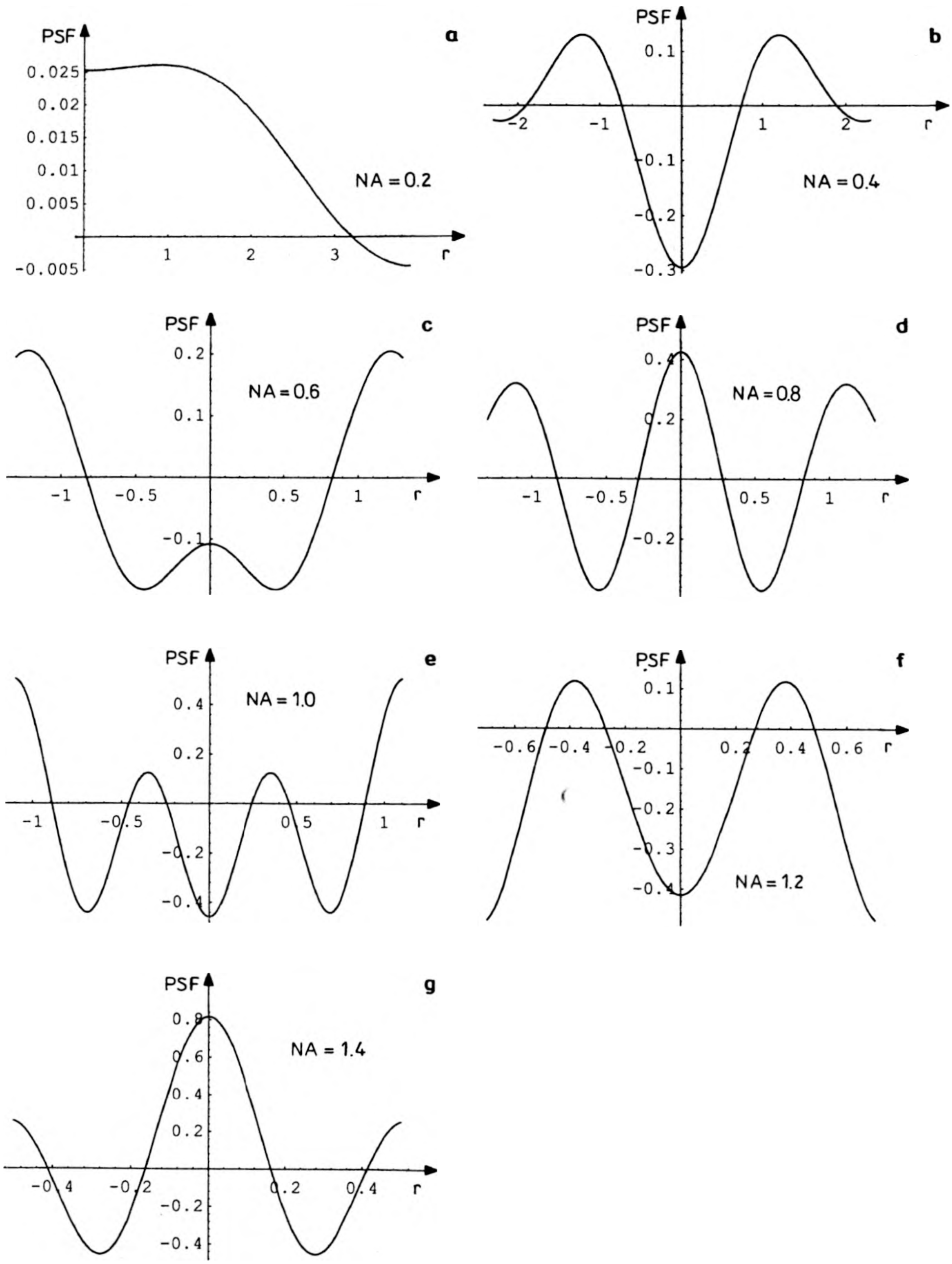

Fig. 4. Point spread function versus the spatial frequencies r [μm] for the pupil filter $\cos(10\rho)$ and the numerical apertures NA = 0.2 (a), 0.4 (b), 0.6 (c), 0.8 (d), 1.0 (e), 1.2 (f), 1.4 (g).

frequencies r for the pupil filter of $\cos(10\rho)$ for numerical apertures: NA = 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4. In Figure 5, the characteristic of the cut-off frequency r_c [μm] versus the parameter N ($N = 0, 1, \ldots, 20$) of the pupil filter $\cos(N\rho)$

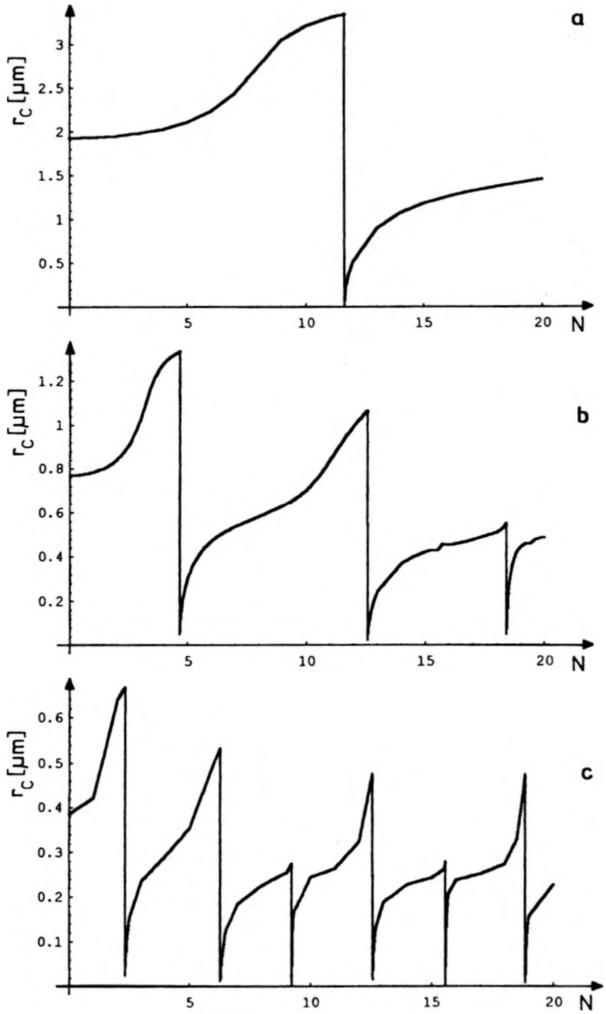

Fig. 5. Cut-off spatial frequencies r_c [μm] for different values of the parameter N of the pupil filters of $\cos(N\rho)$ type ($\lambda = 0.6328$ μm), $f = 1$ μm) for numerical apertures: NA = 0.2 (a), 0.5 (b), 1.0 (c).

has been determined for numerical apertures: NA = 0.2, 0.5, 1.0 and $\lambda = 0.6328$ μm. These frequencies have been determined by solving the equation

$$h_N = 0.$$

For a circular nonmodulated pupil ($N = 0$) and the numerical aperture of NA = 0.5, $\lambda = 0.6328$ μm, $f = 1$ μm, the cut-off frequency is equal to $r_c = 0.771807$ μm. For the aperture $P(\rho) = \rho^n$, as reported in [1], the cut-off frequency r_c ranges from $r_c = 0.772$ μm for the nonmodulated circular frequency ($n = 0$) to $r_c = 0.43$ μm for high values $n = 16$. In the case of aperture $P(\rho) = \cos(N\rho)$ and NA = 0.5 the characteristic $r_c(N)$ is shown in Fig. 5**b**. The results obtained are shown in the next page.

N	r_ε [μm]
0 (nonmodulated aperture)	0.7718
4.66	1.33425
4.66225	0.001351
12.56	1.06397
12.567	0.01034
18.41	0.5506
18.42	0.0488
20	0.487

For NA = 0.2, the characteristic $r_\varepsilon(N)$ is shown in Fig. 5a, while for NA = 1.0 in Fig. 5c.

Reference

[1] HAMED A. M., Optik **107** (1998), 161.

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