Letters to the Editor

Imaging of the clear slit in a two-photon coherent fluorescent microscope equipped with a pupil filter of $1-x^2, x^2$, and Lanczos types

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In this paper, the imaging of the clear slit in a coherent two-photon fluorescence microscope (C2P) with a circular pupil and the pupil filters of $1-x^2$ and x^2 types as well as the circular ($\varepsilon = 0$) and annular ($\varepsilon = 0.5, 0.8$) pupils and Lanczos pupil filter outside the point of inflexion is demonstrated.

In paper [1] the authors showed the light intensity distribution in the clear slit image in a scanning microscope (CSM) equipped with a circular apodized Lanczos filter and determined the values of the point of inflexion for a constant value of parameter controlling the Lanczos filter transmittance β and the annular obstruction ε. In paper [2], the intensity distribution in the image of a clear slit in a nonapodized C2P with a pupil of circular ($\varepsilon = 0$) and annular ($\varepsilon = 0.5, 0.8$) shapes has been shown and the values of the point of inflexion for nonapodized C2P with annular pupil ($\varepsilon = 0$, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8) have been determined and the clear slit image at the point of inflexion has been determined.

In this paper, the imaging of the clear slit in a two-photon C2P with a circular pupil and the pupil filters $1-x^2$, x^2, as well as circular ($\varepsilon = 0$) and annular ($\varepsilon = 0.5$, 0.8) pupils and the Lanczos filter outside the point of inflexion is shown.

The intensity distribution in a CSM is described by the relation

$$I_{\mathrm{CSM}} = |A \otimes (h_{\mathrm{obj}} h_{\mathrm{coll}})|^2$$

where: A — the amplitude transmission of the object, h_{obj} and h_{coll} — the amplitude spread function in the objective and collector, respectively, while $\otimes$ means convolution.

In the two-photon C2P the intensity distribution is described by the dependence [3]

$$I_{\mathrm{C2P}} = I^2\left(\frac{u}{2}, \frac{v}{2}\right) I(u, v)$$

where: $I(u, v)$ — point source intensity, (u, v) — axial and radial normed optical coordinates:

$$u = 4kz\sin^2(\alpha/2), \quad v = kr\sin\alpha, \quad k = \frac{2\pi}{\lambda}.$$

For an object in the form of a slit of halfwidth u_0 and the amplitude transmittance

$$A(u, v) = \begin{cases} 1 & \text{for } |u| \leqslant u_0, \\ 0 & \text{for } |u| > u_0, \end{cases}$$

the light intensity in the slit image in C2P apodized with a annular pupil ε is described by the dependence [2]

$$I(z) = \left[\left(4u_0 \int_\varepsilon^1 \frac{\sin(2\pi u_0 x)}{(2\pi u_0 x)} A^* \cos\left(z\frac{x}{2}\right) dx \right)^2 \right]^2 \left[4u_0 \int_\varepsilon^1 \frac{\sin(2\pi u_0 x)}{(2\pi u_0 x)} A^* \cos(zx) dx \right]^2$$

where: A^* takes respectively the forms:

$$A^* = 1 - x^2, \quad x^2, \quad \frac{\sin(\beta\pi x)}{(\beta\pi x)} \text{(Lanczos)}.$$

In Figure 1, the intensity distribution is shown for C2P with a circular pupil ($\varepsilon = 0$) and the pupil filter of $1 - x^2$ type for a slit width: $u_0 = 0.5$ (Fig. 1a), $u_0 = 1.0$ (Fig. 1b), $u_0 = 1.5$ (Fig. 1c and Fig. 1c′, where c′ shows an enlarged fragment of Fig. 1c)*, $u_0 = 2.0$ (Fig. 1d) and $u_0 = 2.5$ (Fig. 1e). In Figure 2 the light intensity is shown for C2P with a circular pupil ($\varepsilon = 0$) and with a filter of x^2 type for the slit width: $u_0 = 0.5$ (Fig. 2a), $u_0 = 1$ (Fig. 2b), $u_0 = 1.5$ (Fig. 2c), $u_0 = 2.0$ (Fig. 2d), $u_0 = 2.5$ (Fig. 2e). The light intensity distribution for C2P with a circular pupil ($\varepsilon = 0$) and a Lanczos filter ($\beta = 0.5$) are presented in Fig. 3 for the width: $u_0 = 0.5$ (Fig. 3a), $u_0 = 1.0$ (Fig. 3b), $u_0 = 1.5$ (Fig. 3c), $u_0 = 2.0$ (Fig. 3d), $u_0 = 2.5$ (Fig. 3e). In Figure 4 the light intensity distribution for C2P with the annular pupil ($\varepsilon = 0.5$) and Lanczos filter ($\beta = 0.5$) for slit width: $u_0 = 0.5$ (Fig. 4a), $u_0 = 1.0$ (Fig. 4b), $u_0 = 1.5$ (Fig. 4c), $u_0 = 2.0$ (Fig. 4d), $u_0 = 2.5$ (Fig. 4e) is shown, and in Fig. 5, the light intensity distribution is presented for C2P with an annular pupil ($\varepsilon = 0.8$) and the Lanczos filter ($\beta = 0.5$) for the slit width: $u_0 = 0.5$ (Fig. 5a), $u_0 = 1.0$ (Fig. 5b), $u_0 = 1.5$ (Fig. 5c), $u_0 = 2.0$ (Fig. 5d), $u_0 = 2.5$ (Fig. 5e).

In the C2P an improvement of the fringe structure in the intensity distribution in the slit image (Fig. 1) occurs as compared to that which takes place in a CSM. Moreover, it is true both for nonapodized C2P [2] and apodized one by a $1 - x^2$ filter. The latter filter, as it was shown in work [4] is an apodized filter in the transverse and axial directions. The Lanczos filter for $\varepsilon = 0$ shows a similarity to the filter $1 - x^2$ (Figs. 1, 3). The filter x^2 is superresolving in the transverse direction and apodizing in the axial direction which was shown in the paper [4]. Some change in the intensity ratio in the maxima is observed for $\mu_0 \geqslant 1.5$ (Figs. 2c,d,e) in C2P with

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* Also below the figures marked with primed letters show some enlarged fragments of respective unprimed figures.
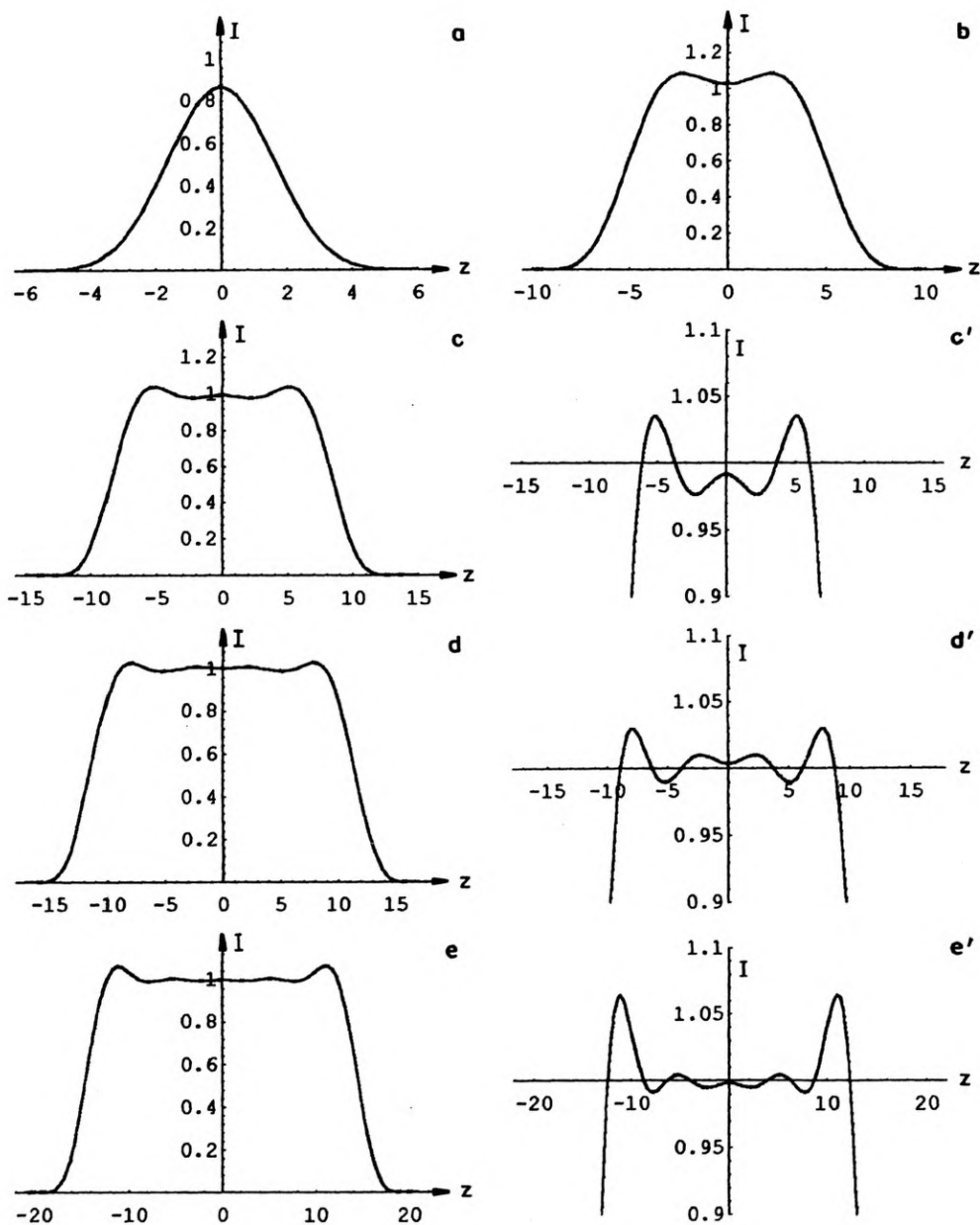
Fig. 1. Light intensity distribution in the clear slit image in C2P with a circular ($\varepsilon = 0$) pupil and a pupil filter $1 - x^2$ for slit widths specified in the text

the pupil filter x^2 as well as for $u_0 = 1.5$ $\varepsilon = 0.5$ (Fig. 4c) and $u_0 = 2.5$, $\varepsilon = 0.5$ (Fig. 4e) in C2P with the Lanczos filter. The most faithful image of the slit is obtained at the point of inflexion [2].
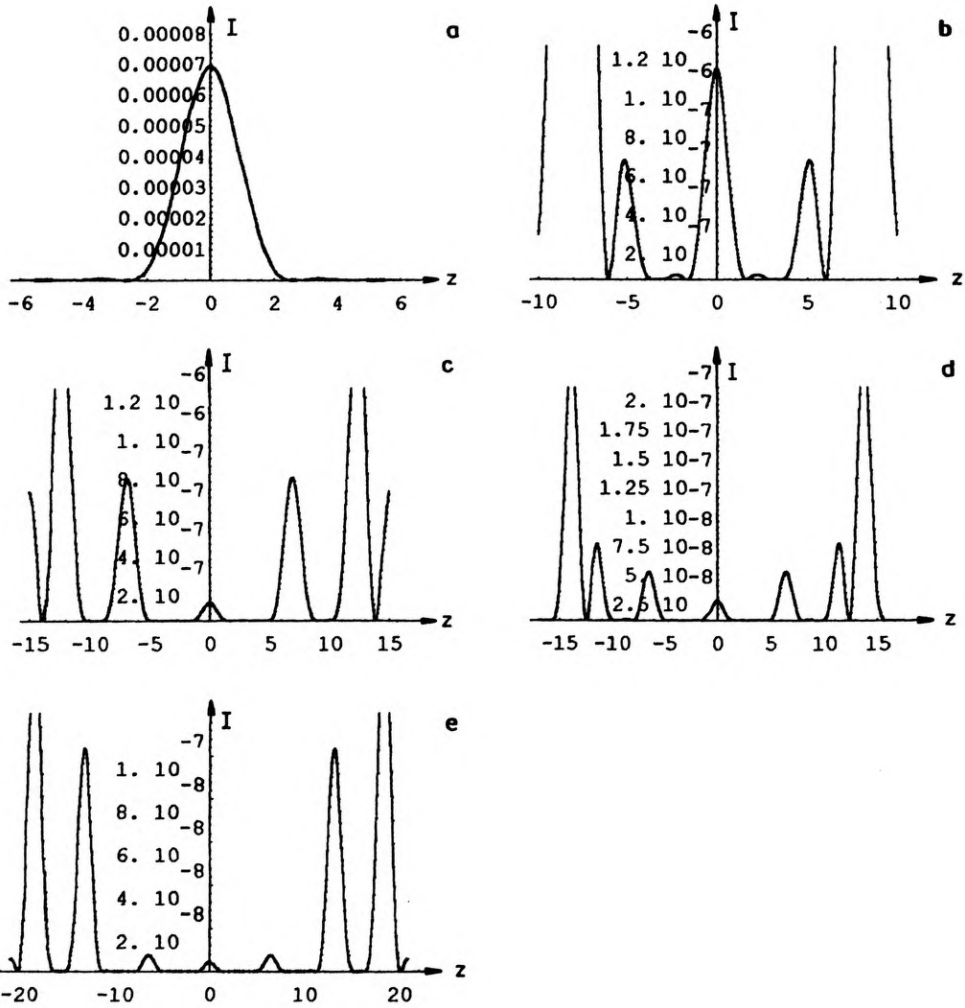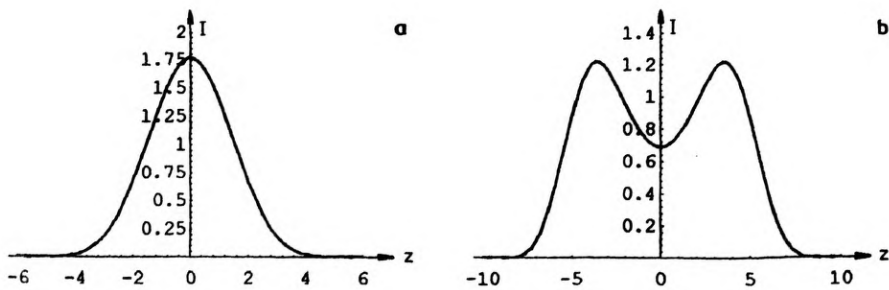
Fig. 2. Light intensity distribution in the clear slit image in C2P with a circualr aperture ($\varepsilon = 0$) and a pupil filter x^2 for the slit widths specified in the text
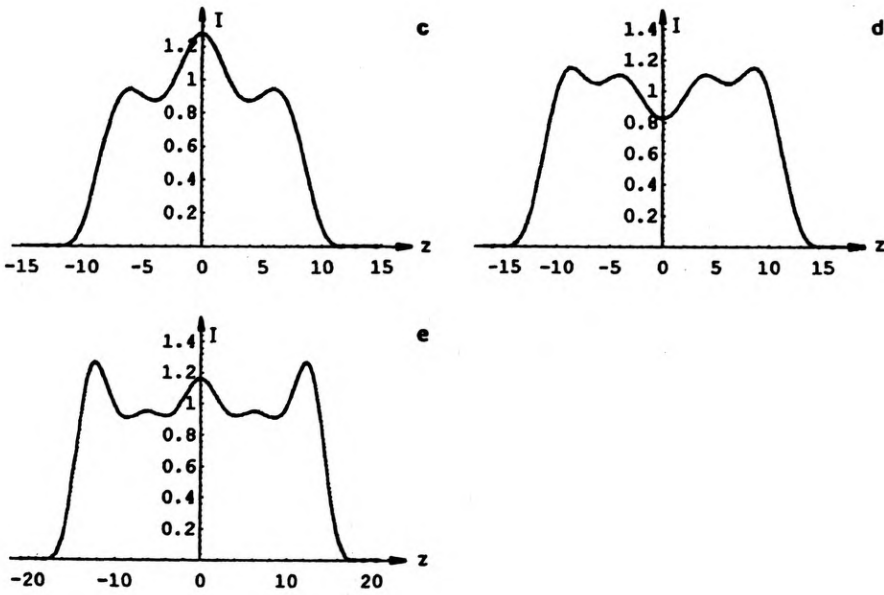

Fig. 3a,b

Fig. 3. Light intensity distribution in the clear slit image in C2P with an annular pupil ($\varepsilon = 0$) and a Lanczos filter ($\beta = 0.5$) for slit widths specified in the text
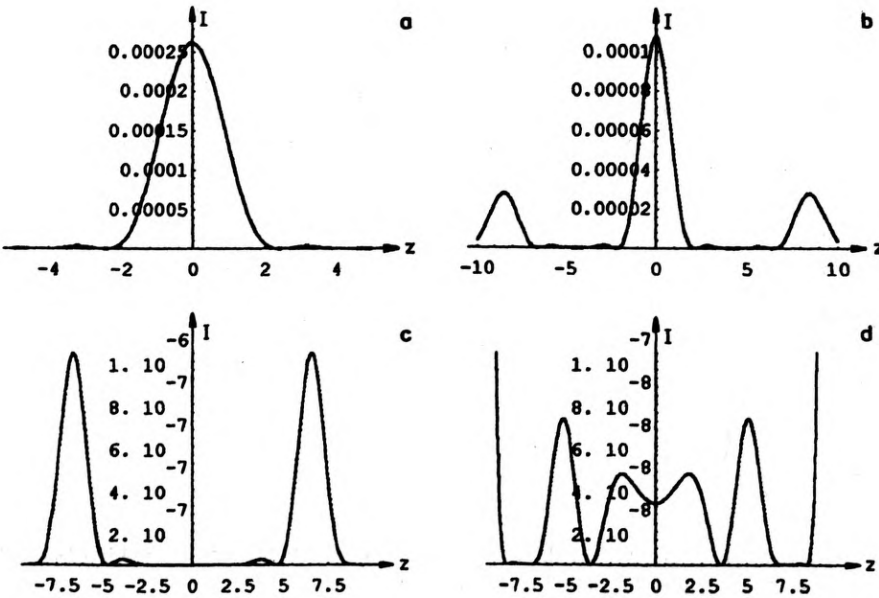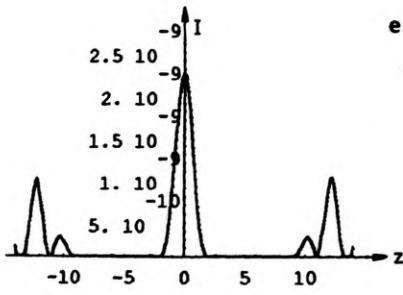

Fig. 4a, b, c, d

Fig. 4. Light intensity distribution in the clear slit image in C2P with an annular pupil ($\varepsilon = 0.5$) and a Lanczos filter ($\beta = 0.5$) for the slit widths specified in the text
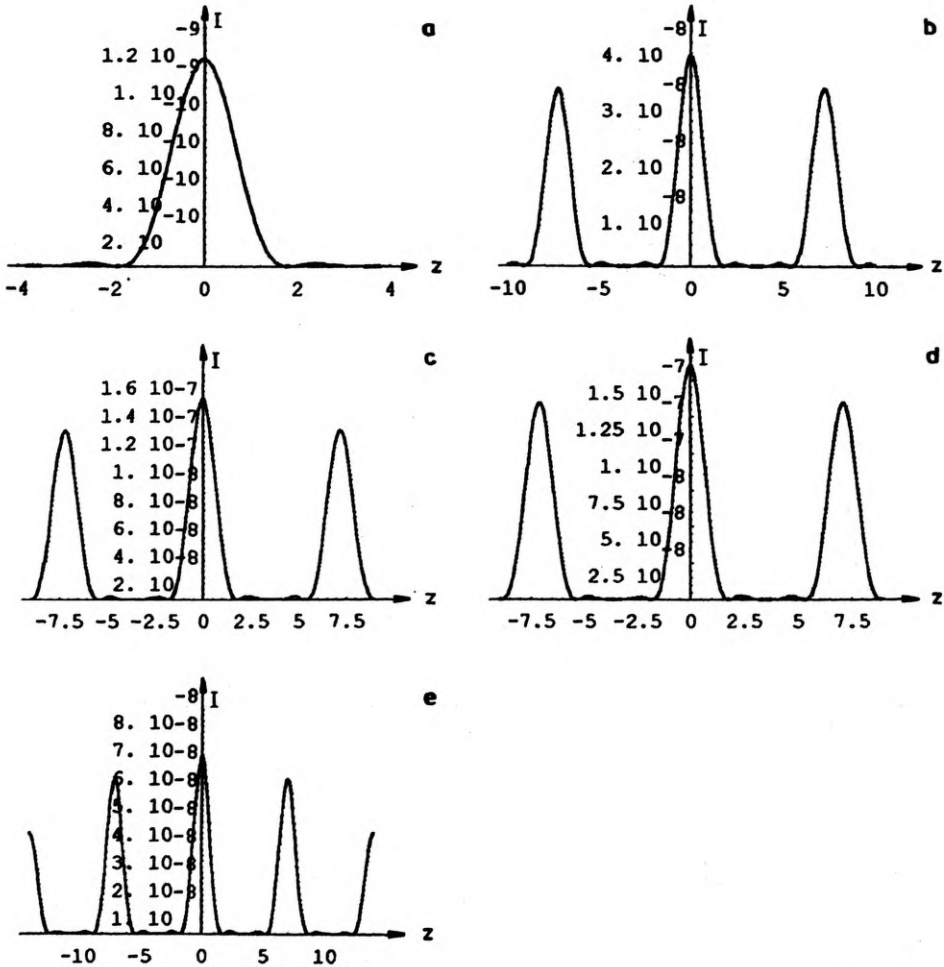

Fig. 5. Light intensity distribution in the clear slit image with an annular pupil ($\varepsilon = 0.8$) and the Lanczos filter ($\beta = 0.5$) in C2P ($\beta = 0.5$) for slit widths specified in the text

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