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Letters to the Editor

Remarks on effects of aberrating layers in confocal scanning microscopes

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In paper [1], the condition for aberration-free immersion layer in aberration-free confocal scanning microscope (CSM) is given as dependent on λ, α, n_1, n_2. A spherical aberration coefficient of the first order for the layer is equal to [1]

$$W_{40} = 2kt(n_2^2-n_1^2)\frac{n_1^2}{n_2^3}\sin^4(\alpha/2). \tag{1}$$

where: α – semi-angle of convergence, and $k = 2\pi/\lambda$, while n_1, n_2, t and θ are defined in Fig. 1.

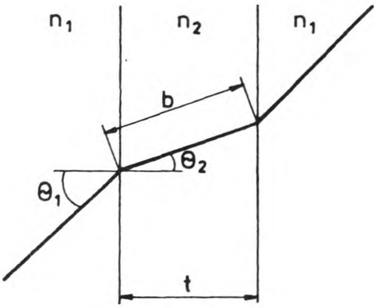

Fig. 1. Ray incident on a dielectric slab

Assuming the Rayleigh criterion, according to which the maximum of phase aberration must be less than $\pi/2$ which corresponds to the limiting resolution $\lambda/4$, the condition for aberration-free layer thickness t has been obtained [1]

$$t \leqslant \lambda n_2^3/\{2n_1^2(n_2^2-n_1^2)\sin^4(\alpha/2)\} \tag{2}$$

In this paper, a correcting term to the condition (2) has been determined as related to spherical aberration β_{040} of CSM depending on Δ_{limCSM}, k, α, n_1, n_2; where Δ_{limCMS} – limiting resolution of CSM, $n_2 = n_1 + \Delta n$. A correcting coefficient $W = \dfrac{\Delta_{\max}}{\Delta_{\min}}$ for an apodized CSM system suffering from spherical aberration has been introduced, where $\Delta_{\min}$ – minimum value of limiting resolution in CSM with apodization and spherical aberration, $\Delta_{\max}$ – limiting resolution in CSM of uniform type. In further considerations, it has been assumed that the refraction index n_2 differs only slightly from n_1. The intensity distribution in the focal plane of CSM is defined by the relation [1]

$$I(u,v) = \left|\int\limits_0^{\alpha} A(\theta)P(\theta)J_0\left(\frac{v\sin\theta}{\sin\alpha}\right)\exp\left(-\frac{1}{2}iu\,\frac{\sin^2(\theta/2)}{\sin^2(\alpha/2)}\right)\sin\theta\, d\theta\right|^2 \tag{3}$$

where u, v – optical coordinates which are defined by the axial distance z from the focus and radial distance r from the optical axis in the following way: $u = 4kz\sin^2(\alpha/2)$, $v = kr\sin\alpha$, $A(\theta_1)$ for aplanatic system is equal to $A(\theta_1) = \cos^{1/2}\theta_1$, $P(\theta_1)$ – wavefront aberration, $P(\theta_1) = e^{i\varphi}$. Basing on the formula (3), the limiting resolution of CSM denoted by Δ_{limCSM} has been numerically evaluated. The total spherical wave aberration of first order for the combination CSM plus immersion layer fullfils the condition

$$\Phi_{\max} = \frac{kt}{2}(n_2^2-n_1^2)\frac{n_1^2}{n_2^3}\sin^4(\alpha/2)+\Delta_{\mathrm{lim}} = 0,$$

$$\Delta_{\mathrm{lim}} = \Delta_{\mathrm{limCSM}}.$$

Hence

$$t \leqslant 2\Delta_{\mathrm{lim}}n_2^3/\{k(n_2^2-n_1^2)n_1^2\sin^4(\alpha/2)\}. \tag{4}$$

For $n_2 = n_1+\Delta n$ we have

$$\frac{(n_1+\Delta n)^3}{(2n_1\Delta n+\Delta n^2)n_1^2} \simeq \frac{n_1+3\Delta n}{2n_1\Delta n},$$

and, consequently,

$$t \leqslant [2\Delta_{\mathrm{lim}}/k\sin^4(\alpha/2)]\left[\frac{n_1+3\Delta n}{2n_1\Delta n}\right] \simeq \frac{2W(n_1+3\Delta n)}{2n_1\Delta nk\sin^4(\alpha/2)}, \tag{5}$$

The limiting value of resolution in a nonapodized and aberration-free CSM amounts to $\Delta_{\mathrm{lim}} = 2.89$, which was shown in paper [2]. In CSM equipped with an apodized collector and objective with the apodizer of r^2 type, the limiting value of Δ_{lim} is equal to 1.31. For CMS charged with spherical aberration $\beta_{040} = 0.5-1.5$ the limiting value Δ_{lim} does not exceed Δ_{limCSM} for the uniform case (Tab. 1). With the increase of α from 0.1 to 1.6, $\Delta_{\mathrm{lim}}/\sin^4(\alpha/2)$ diminishes (Fig. 2). The correcting coefficient $W = \dfrac{\Delta_{\max}}{\Delta_{\min}}$ has been calculated again from formula (3) (Tab. 2) for the respective two cases.

For the classic optical system, for which $\Delta = 3.83$ the correcting coefficient W is equal to ~2.9. For the sake of comparison, the same intervals for refractive index were assumed as those used in paper [1]. In CSM with $\lambda = 633$ nm, two cases were

Table 1. Dependence of the limiting resolution $\Delta_{\lim}$ on α in CSM with apodization of r^2 type, annular ε and spherical aberration β_{040} (A_o — objective, A_c collector, ε — circular central obstruction)

A_o	A_c	$\Delta_{\lim}$	α	$\Delta_{\lim}/\sin^4(\alpha/2)$
Uniform	Uniform	2.976	0.1	476954
r^2	r^2	1.31		209950
$\varepsilon = 0$	$\varepsilon = 0.25$	1.48		237195
$\varepsilon = 0.5$	$\varepsilon = 0.5$	1.425		228380
$\varepsilon = 0.9$	$\varepsilon = 0.9$	1.40		224374
$\beta_{040} = 0$	$\beta_{040} = 0$	2.98		477595
$\beta_{040} = 0.5$	$\beta_{040} = 0.5$	2.96		474390
$\beta_{040} = 1$	$\beta_{040} = 1$	2.98		477595
$\beta_{040} = 1.5$	$\beta_{040} = 1.5$	2.87		459966
Uniform	Uniform	2.976	0.5	794.34
r^2	r^2	1.31		349.659
$\varepsilon = 0$	$\varepsilon = 0.25$	1.48		395.035
$\varepsilon = 0.5$	$\varepsilon = 0.5$	1.425		380.35
$\varepsilon = 0.9$	$\varepsilon = 0.9$	1.40		373.681
$\beta_{040} = 0$	$\beta_{040} = 0$	2.98		795.408
$\beta_{040} = 0$	$\beta_{040} = 1.5$	2.88		768.716
$\beta_{040} = 0.5$	$\beta_{040} = 0.5$	2.96		790.069
$\beta_{040} = 1.5$	$\beta_{040} = 1.5$	2.87		766.047
Uniform	Uniform	2.976	1	56.331
r^2	r^2	1.31		24.7963
$\varepsilon = 0$	$\varepsilon = 0.25$	1.48		28.014
$\varepsilon = 0.5$	$\varepsilon = 0.5$	1.425		26.973
$\varepsilon = 0.9$	$\varepsilon = 0.9$	1.40		26.499
$\beta_{040} = 0$	$\beta_{040} = 0$	2.98		56.407
$\beta_{040} = 0$	$\beta_{040} = 1.5$	2.88		54.514
$\beta_{040} = 0.5$	$\beta_{040} = 0.5$	2.96		56.028
$\beta_{040} = 1.5$	$\beta_{040} = 1.5$	2.87		54.325
Uniform	Uniform	2.976	1.5	13.785
r^2	r^2	1.31		6.028
$\varepsilon = 0$	$\varepsilon = 0.25$	1.48		6.856
$\varepsilon = 0.5$	$\varepsilon = 0.5$	1.425		6.60
$\varepsilon = 0.9$	$\varepsilon = 0.9$	1.40		6.48
$\beta_{040} = 0$	$\beta_{040} = 0$	2.98		13.804
$\beta_{040} = 0$	$\beta_{040} = 1.5$	2.88		13.3406
$\beta_{040} = 0.5$	$\beta_{040} = 0.5$	2.96		13.7116
$\beta_{040} = 1.5$	$\beta_{040} = 1.5$	2.87		13.2943

Table 2. Aberration correcting coefficient in CSM with apodization optimal in uniform CSM ($\Delta_{\min}$ — limiting resolution in CSM with r^2 apodization, $\Delta_{\max}$ — limiting resolution in uniform CSM)

α	$\Delta_{\lim}$	$\Delta_{\lim}/\sin^4(\alpha/2)$	$W = \Delta_{\max}/\Delta_{\min}$
1	2	3	4
0.1	$\Delta_{\min} = 1.31$	209950	~2.27
	$\Delta_{\max} = 2.98$	477595	

1	2	3	4
0.5	$\Delta_{min} = 1.31$ $\Delta_{max} = 2.98$	349.659 795.408	~2.27
1.5	$\Delta_{min} = 1.31$ $\Delta_{max} = 2.98$	6.068 13.804	~2.27
1.6	$\Delta_{min} = 1.31$ $\Delta_{max} = 2.98$	4.947 11.2532	~2.27

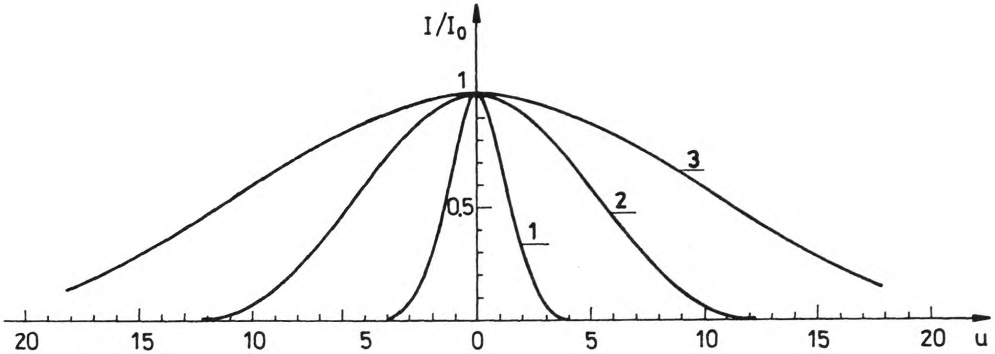

Fig. 2. Intensity in focal region in CSM as dependent on α (semi-angle of convergence), curve 1 – $\alpha = 0.5$, curve 2 – $\alpha = 1$, curve 3 – $\alpha = 1.5$

calculated. Case 1: $\Delta n = 0.01$ (while n_2 ranging within the interval 1.513–1.523), $n_1 = 1$, $t_{\mathrm{opt\,CSM}} = 19.32$ μm. Case 2: $\Delta n = 0.033$ (while n_2 ranging within the interval 1.514–1.481), $n_1 = 1$, $t_{\mathrm{opt\,CSM}} \simeq 6.25$ μm. Optimal thickness of the immersion layer should be adjusted to the resolution of CSM which in the first case corresponds to the value 19.32 μm, while in the second case to the value 6.25 μm.

References

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[2] MAGIERA A., Atti Fond. Giorgio Ronchi **45** (1990), 873.

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