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Axial intensity in a fiber-optic confocal microscope

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Abstract: A fiber-optic confocal microscope has been analyzed by Fourier optics. It is found that the detected light intensity has three parts, each of which is depennted on the coupled lens, the detective lens, and the part comprised of the fiber and the microprobe. The simulated results show that the less the value of the parameter A is, which is dependent on the fiber and microprobe, the higher the axial resolution of the system is. For the case, as $A \to \infty$, the axial resolution is zero, which is corresponding to the conventional microscope. as $A \leqslant 1$, the axial resolution changes slightly, and is close to the optimal value, which is corresponding to the perfect confocal microscope. when the reflective loss takes place at the end of fiber, the contrast of axial intensity will decrease. All that will help the design of endoscope with confocal microscope at cellular level.

Key words: confocal microscope; point spread function(PSF); single-mode fiber; object function; axial intensity

1 Introduction

In the field of endoscopy, a miniaturized high-resolution imaging systems could be especially helpful for a number of medical problems, such as the determination of tumor margins during a minimally invasive operation, the screening of large tissue sections, etc. The confocal microscope[1-4] has a good prospect in endoscopy, due to its optical sectioning property and high resolution. At present, a lot of research teams in Europe and USA. are working at a clinical endoscope with confocal microscope, which can afford a new and effective method to diagnose. For an endoscopy with fiber-optic confocal microscope, lots of correlative papers have been reported in recent years, but there is no detailed analysis in terms of optical theory. In the paper, the light distribution of a fiber-optic confocal microscope is analyzed by Fourier optics, and the axial intensity is discussed by parameter A, which is dependent on the fiber and microprobe. Meanwhile, the reflective loss at the end of fiber is discussed, which affects the contrast of intensity. Finally, all of the results are summarized to help the design of a new endoscope with optical sectioning.

2 Light distribution of a fiber-optic confocal microscope

The configuration of a microscope is shown in Fig 1. Under Born first order approximation, for point light source (x_0, y_0), the light distribu-

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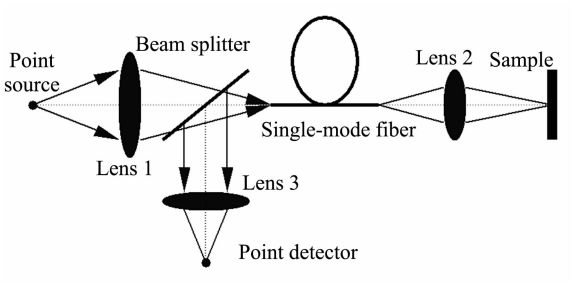


Fig. 1 Fiber-optic confocal microscope

tion on left end of fiber(x_1, y_1) through the coupling lens(lens 1) is

$$U_0(x_1, y_1)\iint_{\infty}\delta(x_0, y_0)h(x_0, y_0; x_1, y_1)\mathrm{d}x_0\mathrm{d}y_0, \tag{1}$$

because the PSF of the coupling lenses is dependent on its exit-pupil Fraunhofer diffraction, it can be expressed by

$$h(x_0, y_0; x_1, y_1) = \iint_{\infty} p(\xi, \eta) \exp\left\{\frac{-jk}{d_0}[(x_1 - Mx_0)\xi + (y_1 - My_0)\eta]\right\}\mathrm{d}\xi\mathrm{d}\eta, \tag{2}$$

where $p(\xi, \eta)$ is exit pupil function, d_0 is the space between exit pupil and the left interface of fiber, M is the magnification of lens 1, k is equal to $2\pi/\lambda$.

At the end of fiber, the operation light will stimulate fiber modes. Assumed every kind of loss in fiber is neglected, based on fiber coupling theory[5], the exit light distributing at the right end of fiber(x_2, y_2) is

$$U_1(x_2, y_2) = e(x_2, y_2)\exp(j\beta l)\frac{\iint_{\infty} e^*(x_1, y_1)U_0(x_1, y_1)\mathrm{d}x_1\mathrm{d}y_1}{\iint_{\infty} |e(x_1, y_1)|^2\mathrm{d}x_1\mathrm{d}y_1}, \tag{3}$$

where e is the single-fiber mode distribution, which is Gaussian function, $*$ denotes conjugation, β is fiber propagation constant, l is fiber length.

Gaussian-shaped light beam through microprobe illuminates the object space(x_3, y_3, z_3). Due to the thickness of sample, light near the focus in sample can be reflected back to fiber. As far as a random point near focus concerned, light distribution on the traverse plane through the point is affected by defocus distance z_3, which is the distance between the point and focal plane. Using the preceding method, the light distribution is

$$U_2(x_3, y_3, z_3) = \iint_{\infty} U_1(x_2, y_2)h_1(x_2, y_2; x_3, y_3, z_3)\mathrm{d}x_2\mathrm{d}y_2, \tag{4}$$

where axial defocused z_3 gets aberration exp $\left[\frac{jk(\xi^2+\eta^2)}{2}\left(\frac{1}{d_1}-\frac{1}{d_1+z_3}\right)\right]$, and is very small, effective exit pupil function can be expressed by $p_1(\xi, \eta)\exp\left[\frac{jk}{2d_1^2}z_3(\xi^2+\eta^2)\right]$. the PSF of microprobe(lens 2) is

$$h_1(x_2, y_2; x_3, y_3, z_3) = \iint_{\infty} p_1(\xi, \eta)\exp\left[\frac{jk}{2d_1^2}z_3(\xi^2+\eta^2)\right]\exp\left\{\frac{-jk}{d_1}[(x_3 - M_1x_2)\xi + (y_3 - M_1y_2)\eta]\right\}\mathrm{d}\xi\mathrm{d}\eta, \tag{5}$$

where d_1 is the distance between exit pupil and ideal focus, M_1 is the magnification of microprobe.

When the sample is moved randomly, the little illuminated area scans the sample in three dimensions. Because light speed and the response time of PMT are higher by far than the moving velocity, the reflective light from the scanned area can return along the same optical path back to the fiber. Assumed the object function is $o(x, y, z)$, which denotes the reflectivity of the sample. For the random point in the scanned area, its object function is expressed by $o(\boldsymbol{r}_s - \boldsymbol{r}_3)$, $\boldsymbol{r}_s$ is the coordinate of scanning point, or ideal focus. so

the distribution of reflective light modulated by the sample is

$$U_2'(x_3,y_3,z_3;\boldsymbol{r}_s)=U(x_3,y_3,z_3)o(\boldsymbol{r}_s-\boldsymbol{r}_3)\ , \tag{6}$$

Through microprobe, the reflective light distribution on the right end of fiber is

$$U_1'(x_2,y_2,\boldsymbol{r}_s)=\iint_{\infty}U'(x_3,y_3,z_3;\boldsymbol{r}_s)h_1'(x_2,y_2;x_3,y_3,z_3)\mathrm{d}x_3\mathrm{d}y_3\mathrm{d}z_3\ , \tag{7}$$

For reflective signal light, the exit pupil becomes entrance pupil. Then, the PSF of microprobe is

$$h_1'(x_2,y_2;x_3,y_3,z_3)=\iint_{\infty}p_1(\xi,\eta)\exp\left[\frac{-jk}{2d_1^2}z_3(\xi^2+\eta^2)\right]\exp\left\{\frac{jk}{d_1}[(x_3-M_1x_2)\xi+(y_3-M_1y_2)\eta]\right\}\mathrm{d}\xi\mathrm{d}\eta\ , \tag{8}$$

Because reflective light is coupled in the same fiber, the light distribution on the left end of fiber is

$$U_0'(x_1,y_1;\boldsymbol{r}_s)=e(x_1,y_1)\exp(-j\beta l)\frac{\iint_{\infty}e^*(x_2,y_2)U'(x_2,y_2,\boldsymbol{r}_s)\mathrm{d}x_2\mathrm{d}y_2}{\iint_{\infty}|e(x_2,y_2)|^2\mathrm{d}x_2\mathrm{d}y_2}\ , \tag{9}$$

When Gaussian-shaped light beam modulated by sample is detected by point detector, the light distribution on detecting plane is

$$U_3'(\boldsymbol{r}_s)=\iint_{\infty}U_0'(x_1,y_1,\boldsymbol{r}_s)h_d'(x_1,y_1;0,0)\mathrm{d}x_1\mathrm{d}y_1\ , \tag{10}$$

where h_d' is the PSF of the detecting lens (lens 3). Integrate all expression preceding, the intensity detected is

$$I_4=|\ [e(x_s/M_1,y_s/M_1)\otimes_2h_1(0,0;\boldsymbol{r}_s)]\times[e^*(x_s/M_1,y_s/M_1)\otimes_2h_1'(0,0;\boldsymbol{r}_s)]\otimes_3o(\boldsymbol{r}_s)\ |^2\left|\frac{e(x_1/M,y_1/M)\ |\otimes_2h(0,0;x_1,y_1)}{\iint_{\infty}|\ e(x_1,y_1)\ |^2\mathrm{d}x_1\mathrm{d}y_1}\right|^2\times\frac{|\ e(x_1/M_d,y_1/M_d)\otimes_2h_d'(0,0;x_1,y_1)\ |^2}{\iint_{\infty}|\ e(x_2,y_2)\ |^2\mathrm{d}x_2\mathrm{d}y_2}\ , \tag{11}$$

where the last two parts denote on the right respectively the coupling effect of the coupling lens and the detecting lens. Because only the first part has been modulated by sample, they are considered as constant for the first part. Assumed constant C,D is respectively the last two parts, optical amplitude of signal is

$$U_s=[e(x_s/M_1,y_s/M_1)\otimes_2h_1(\boldsymbol{r}_s)]\times[e^*(x_s/M_1,y_s/M_1)\otimes_2h_1'(\boldsymbol{r}_s)]\otimes_3o(\boldsymbol{r}_s)\ , \tag{12}$$

and the effective PDF of microprobe is

$$h_s=[e(x_s/M_1,y_s/M_1)\otimes_2h_1(\boldsymbol{r}_s)]\times[e^*(x_s/M_1,y_s/M_1)\otimes_2h_1'(\boldsymbol{r}_s)]\ , \tag{13}$$

Assumed fiber and lenses have circular geomery, we take cylindrical coordinates and make pupil function normalize by its radius a. According to the method[6], the coherent transfer function of microprobe is

$$c(v,u)=\left[\tilde{e}\left(\frac{avM_1}{d_1\lambda}\right)p(v)\exp\left(\frac{juv^2}{2}\right)\right]\otimes_2\left[\tilde{e}\left(\frac{avM_1}{d_1\lambda}\right)p(v)\exp\left(\frac{juv^2}{2}\right)\right]\ , \tag{14}$$

where u represents the axial optical coordinate, $u=\frac{2\pi z_sa^2}{\lambda d_1^2}$, mode function of single-mode fiber with the spot size r_0 is Gaussian function $e(x,y)=e(r)=\exp\left[-\frac{1}{2}\left(\frac{r}{r_0}\right)^2\right]$, its Fourier transform

is $\tilde{e}(v)=2\pi r_0^2\exp\left[-\frac{1}{2}(2\pi r_0 v)^2\right]$.

Assumed the reflectivity of object is 1, the axial optical intensity is

$$I(u)=K\int_{\infty}|c(0,u)|^2\mathrm{d}u=K\frac{A^2(1+e^{-2A}-2e^{-A}\cos u)}{(A^2+u^2)(1-e^{-A})^2}, \quad (15)$$

where normalized constant $K=4\pi^2 r_0^4 CD$, parameter $A=\left(\frac{2\pi r_0 M_1 a}{d_1\lambda}\right)^2$, which incorporates the effect of the fiber spot size r_0, the pupil radius a of lens 2, and the distance d_1, the magnification M_1, and the opration light wavelength λ.

When the reflection from the left end of fiber is not neglected, some reflective light will be detected. Assumed lens 1 and lens 3 are similar, the reflectivity is η, and the operation light intensity is unit, the detected reflective light intensity is

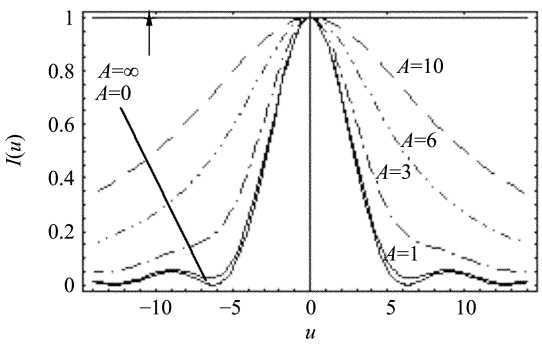
$$I_r=\eta|h(0,0,x_1,y_1)|\otimes h_d'(0,0,x_1,y_1)|^2=\eta, \quad (16)$$

Then the detected axial intensity is

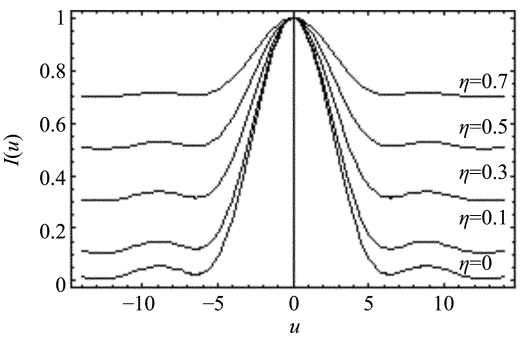
$$I_4=\eta+(1-\eta)K\frac{A^2(1+e^{-2A}-2e^{-A}\cos u)}{(A^2+u^2)(1-e^{-A})^2}, \quad (17)$$

3 Results and discussion

The simulated results are given by Eq. (15) and (17). Fig. 2(a) shows the normalized axial intensity in a fiber-optic confocal microscope without reflective loss for different values of the parameter A. As the value of A is increasing, the axial intensity profile's FWHM is decreasing. That is, the axial resolution decreases for the bigger value of A. When A is equal to infinity, the axial resolution is zero, which is corresponding to the conventional microscope. This means it has no optical sectioning property. When A is less than 1, the axial resolution has little change, which is close to the optimal value. For the case, when $A=0$, it is the perfect confocal microscope with the point source and point detector, that has the optimal axial resolution. When A is infinity, the fiber spot size is too big to block the defocal light and make the system become the conventional microscope. When A is between zero and infinity, the light will be modulated by the fiber, which can make the system have optical sectioning property. Fig. 2(b) shows the axial intensity for different reflective loss with $A=1$. It is found that, when the reflective loss on the left end of fiber is increasing, the minimal intensity is increasing. This means that the contrast of intensity decreases for higher reflectivity of the fiber, so the image quality will degrade. However, if the end of the fiber is uniform, the loss can be



(a) Different values with no reflective loss



(b) Different reflective loss with $A=1$

Fig. 2 Normalized axia intensity of a fiber-optic confocal microscope

thought as white noise, which can be delected by image process. If not, some methods are needed to decrease the reflection. In fact, the coupling lenses and the detecting lenses affect the axial intensity peak, which also decrease the contrast of intensity. So it is necessary to select the coupling lenses and detecting lenses in terms of the fiber.

4 Conclusion

Fourier optics is used to analyze a fiber-optic confocal microscope, and obtain the detected light intensity, which can be divided into three parts: the coupling efficiency of lens 1, the detecting efficiency of lens 3, and the intensity dependent on fiber and microprobe. For the case, the axial intensity peak of the system is dependent on the coupling lenses and detecting lenses, but its axial resolution is dependent on the fiber and microprobe, which is shown by parameter A. On the other side, the reflection of the fiber end decreases the contrast of intensity. All of this, it is helpful to design a endoscope with optical sectioning property at cellular level.

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LIU Yong was born in Yichun, Jiangxi. He received the B. S. degree in physics in 1999 and the M. S. degree in optics in 2002 from the Jiangxi Normal University. He is currently working toward the Ph. D. degree in optical engineering. His research includes optical imaging techniques by confocal microscope.