

Fast Lateral Line-scan Model with Doublet-cylinder-lens in Intelligent OCT

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Abstract - To solving the slow and complex scanning of spot-scan model in optical coherence tomography (OCT), a fast lateral line-scan model was investigated with doublet-cylinder-lens(DCL). For the DCL, the elimination of spherical aberration was theoretically studied, as well as the beam model and the focus. The parameters and signal characteristics of the confocus microscopy system (CFMS) with DCL were simulated and brought forward. The relation between the transverse resolution and the numerical aperture and the depth of focus (DOF) was discussed in the OCT. Results show that the spherical aberration and the sine aberration of the DCL with K9-ZF2 glass are effectively eliminated. Because the beam is uniformly focused on the arc-sagitta-plane of cylinder lens and produces the parallel interference pattern or fringe with axial symmetry, the transverse resolution interacted by the numerical aperture and the DOF is improved. The scanning velocity of the CFMS with DCL is faster three orders of magnitude than the traditional spot-scan model. The transverse resolution with system aperture 50.8 mm is 15 μ m. This advanced system will be valuable in real-time vivo imaging.

Index Terms - OCT, CFMS, Line-scan, DCL, Resolution

I. Introduction

The main reason of restriction imaging velocity in optical coherence tomography (OCT) system is the complicated scanning processes, which include two parts named axial and transverse scanning process. Thus, many solution methods to this problem have been researched. Specifically, for one mode, the scientists enhanced the axial scanning velocity through using or designing different scanning devices¹. Although the scanning speed was boosted by above way, it has very high cost of hardware and technology due to the requirement for high speed, stability and accuracy. Another way proposed by S. Bourquin in 2000 was named as the parallel OCT achieving high rate up to video frequency scanning². Because the scanning range of this full-field detecting technology is very small, the intelligent CMOS image sensor is demanded in the parallel OCT. Owing to the lack of alternating current signal model, the OCT signal is often subject to interferences from different $1/f$ noise sources. Moreover, because of the short of narrowband heterodyne demodulation technique, the signal bandwidth is further dependent on the noise jamming.

The concept of line focus was proposed by M.Suekuni, Y.Teramura and E.A.Swanson in researching the spectrum OCT scanning model in 1999. The optical path difference can

be directly got through Fourier transform and spectral density function with this scanning way³⁻⁵. This line scanning model is similar to spot-scan way, but it expands transverse scanning scope and reduces the period of visual angle in the transverse scanning process. In addition, because the slit is installed in the light path of expanding beam, the luminous flux is decreased by the slit restricting the beam shape, and then, the utilization efficiency of light source and the imaging depth and the signal to noise ratio (*SNR* or *S/N*) are all lower.

In the study, a rectangular aperture is used behind the expanded light beam, and cylinder lens is used to achieve line focus function. To reduce the scanning time, samples are linearly scanned through a confocus microscopy system (CFMS) with the cylinder lens. This line focusing way, which converts lateral point scanning model into parallel scanning model, simplifies and shortens scanning process and time. Moreover, it also holds back the advantage of point-scan way, the model can effectively restrain stray light with using confocus scanning system. After analysing and simulating the principle and the various characteristic parameters of the CFMS with doublet-cylinder-lens (DCL), we found that the proposed new scanning model can not only effectively collect light energy and converge to a thin line area for scan sample, but also ensure the same intensity at every point of the focusing line on the sample. Based on the idea, while the imaging depth and the *SNR* of system are increased, the sample scan is completed so long as a transverse scan and an axial movement, which the time of accomplishing the scan work and obtaining a 3-dimensional tomography image is shortened by three orders of magnitude.

II. Drawbacks of OCT with point-scan model

A typical OCT system with point-focus-scan model is as shown in Fig.1. It is lateral point scanning model that a light beam transmitting through the beam splitter is focused to a point via a focus lens, and that the light focus point scans on the sample plane of oxy along two perpendicular directions, i.e., the axis *x* and *y*. At first, the light focus point stays or suspends on a scan position (x_1, y_1) on the sample, in the mean time executing an axial scan to and fro along reference arm with a axial scan device, while finishing the scanning, the light point is moved to the next position (x_2, y_1) by a 2-dimensional scan device and then continuing to take the axial scanning as the

above model until accomplishing the scanning at the last position (x_M, y_1) . Secondly, the light point is moved to a position (x_M, y_2) at the next row by the 2-dimensional scan device and executing an axial scan to and fro until finishing the scanning at the last position (x_1, y_2) of the new row.

Simply, first step, one keeps the y direction invariable and conducts the light point scanning along the x direction. The light focus point is moved to the next row of the y direction in the second step. Finally, the above point scanning procedure along the x direction is repeated all around. Obviously, the repeating scanning along the x & y point by point, or named as the scanning feature of “static-accelerate-slow-static”, will exhaust much time^{1,2}.

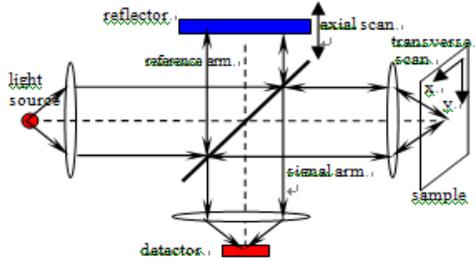


Fig.1. Time domain OCT with point-focus-scan model

III. line scanning structure and characteristic

In the original OCT system, after expanding the light beam from source we set a rectangular or square aperture in front of the expanding beam, and put a CMS with DCL before the sample. If we use the linear CCD or CMOS detector, which match with the DCL, a rapid transverse line scanning should be realized.

A. The Light Beam Model and the Focus of DCL

The 3-dimensional light beam form and imaging mode are as shown in the figure 2. We plot two mutually perpendicular planes, one plane named meridional plane parallels to the optic axis and the normal of interface, the other plane also parallels to the optic axis and is perpendicular to the meridional plane, that is to say a sagittal plane.

The characteristics of the cylindrical lens are as follows: the light beam focus on the sagittal plane with the lens, and the light paralleling the meridional plane has no refringence. Therefore, based on these characteristics not only realize the line focusing but also can theoretically ensure the same light intensity at every point of the focusing line.

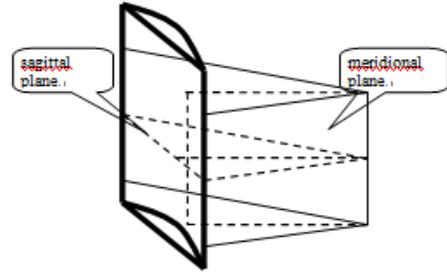


Fig.2. Imaging mode of cylinder lens.

According to the formula of the thin lens, we calculate the focus length of the cylindrical lens as follows

$$f = r_1 r_2 / (n-1)(r_2 - r_1) \quad (1)$$

where n represents refractive index of single lens, r_1 and r_2 represent two spherical radiuses respectively. As the flat convex cylinder lens, Eq. (1) can be simplified

$$f = r_1 / (n-1) \quad (2)$$

B. Spherical Aberration Analysis for Cylindrical Lens

1) Common Spherical Aberration of Cylindrical Lens

Generally, spherical aberration appears in imaging process of the optical systems. A monochromatic light beam from a point in the axis goes through an optical system, if the beam with different apertures focuses on different positions of the axis, there will be a dispersion light spot near the image point, which is named spherical aberration of the imaging system. Therefore, spherical aberration is defined as the optical aberration coming into an imaging of the object points in the axis with monochromatic wide (in aspect of diameter) beam.

The junior spherical aberration to cylindrical lens is

$$\delta L' = -\frac{h^4}{2n_1 u_1'^2} \left\{ \frac{n+2}{n} \phi \rho^2 \cdot \frac{2n+1}{n-1} \phi^2 \rho + \frac{n^2}{(n-1)^2} \phi^3 \right\} \quad (3)$$

If the lens are exposed to the air, then $n_1=1, h=l \times u$, in which l is object distance, u is light aperture angle, h is beam height content in normal section of the object space. Where u_1' represents aperture angle of the image space, ϕ is light focal power of lens, ρ is lens curvature of the first surface. According to Eq. (3), when $d\delta L'/d\rho=0$, we obtain the minimum of spherical aberration as follows

$$\delta L'_0 = \frac{n(4n-1)}{8(n-1)^2(n+2)} h^2 \phi \quad (4)$$

As per Eq. (4), the spherical aberration can't be eliminated with single thin lens.

Corresponding to thin lens group, the junior spherical aberration⁶ is

$$\begin{aligned} \delta L' &= -\frac{h^4}{2n_1 u_1'^2} [A_1(n_1, \phi_1, \rho_1, \sigma_1) + A_2(n_2, \phi_2, \rho_2, \sigma_2)] \\ &= -\frac{h^4}{2n_1 u_1'^2} \left\{ \frac{n+2}{n} \phi \rho^2 \cdot \frac{2n+1}{n-1} \phi^2 \rho + \frac{n^2}{(n-1)^2} \phi^3 \right\} \quad (5) \end{aligned}$$

2) Elimination of Spherical Aberration of the DCL

There are three methods for spherical aberration correction. (1) Using diaphragm to cover a part of light through the edge of lens may reduce the aperture angle. Although the method is simple, it narrows the optical diameter of the lens and reduces the intensity of illumination on image plane. (2) The appropriate aspheric surface is become via integrating two curved surface of the lens, which can eliminate the spherical aberration, but the treating to non-spherical surfaces is very difficult. (3) The method of adopting doublet structure or double clutch structure can eliminate the spherical aberration in optical system. So that doublet-cylinder-lens (DCL) has a lot of potential to eliminate the spherical aberration.

However, no matter what kind of optical system we use, we can only eliminate the spherical aberration caused by a certain paraxial rays, no for other spherical aberrations caused by light of all aperture angles which have anyway some residual spherical aberration. Using the DCL could solve this problem efficiently, specific explanations are as follows.

Because a plus lens always generate a positive spherical aberration while a concave lens often generate a minus spherical aberration, the DCL system can be considered as an optical system which is made up by a plus lens and a concave lens. This lens group has three refraction surfaces, in generally, one takes the lens curvature ρ_1 of glued surface as a variable, and chooses the glass group as K9+ZF2. Relevant parameters are as follows. For K9 glass, $n_D=1.51637$, $v=64.1$, $n_F=1.52196$, $n_C=1.51389$, for ZF2 glass, $n_D=1.67268$, $v=32.2$, $n_F=1.68747$, $n_C=1.66662$, where above v is the Abbe number. Substituting all the parameters into Eq. (5) and setting $\delta L'=0$, we get

$$\delta L'_0 = -(19090\rho_1^2 + 871.33\rho_1 + 9.943) = 0 \quad (6)$$

The discriminant of Eq. (6) is less than zero or very small, so that the solution from Eq. (6) can be considered as the solution of the elimination of spherical aberration. According to calculation Eq. (6), we obtain $\rho_1=-0.02282/\text{mm}$, $r_2=-43.82\text{mm}$. Moreover, we get the sine aberration $\text{OSC}=0.00049$. Because of the very small OSC, it indicates that the spherical aberration and the sine aberration could be corrected at the same time.

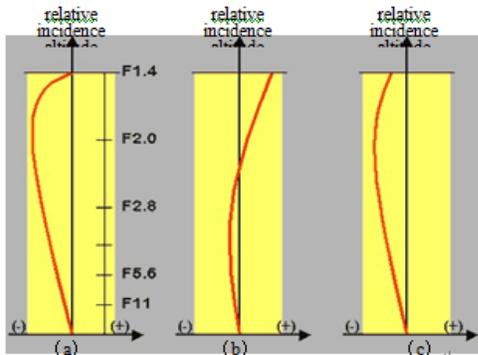


Fig.3. Spherical aberration curve of the DCL.

Using the junior spherical aberration Eq. (6) of DCL and the Matlab software, we get three sorts of curves about spherical aberration respectively (in figure 3). Figure 3(a) is the spherical aberration curve with the Full Correction method, which the curve demonstrates that other rays all have certain spherical aberration, except for the paraxial rays and the edge rays. Figure 3(b) is the spherical aberration curve with the Over Correction method. Figure 3(c) is the spherical aberration curve with the Under Correction method.

C. Focus Length of DCL

Considering the need of the correction of spherical aberration and sine aberration in the transverse scan to sample, we adopt a DCL. Its focus length can be regarded as the focal length while jointing two thin lenses together, whose focus length for a negative lens is

$$f_2 = r_1 r_2 / (n-1)(r_2 - r_1) \quad (7)$$

Whereas the focal length of the DCL is

$$f_{\text{double}} = r_1 r_2 / [r_1(n_2 - 1) - r_2(n_1 + n_2)] \quad (8)$$

where n_1 is the refractive index of the plus lens, while n_2 is the refractive index of the negative lens.

D. Confocal Microcopy System with DCL

In the scanning process of using confocal microcopy system with DCL, the stray light is greatly eliminated, the surrounding fluorescence generated background and stray light interference signals are restrained. Thus, this system plays the space gateway role^{4,7}. The light outside of the objective lens focal plane is blocked, the signal-to-noise ratio of the probe gets greatly improved, so the imaging surface has a very high contrast and clarity, and also can the system provides a high resolution.

1) Signal Characteristics

The sketch of the OCT system with DCL is as shown in Fig.4. The light vector complex amplitude from the light source can be expressed as

$$E = A_0 \exp(i\varphi) \quad (9)$$

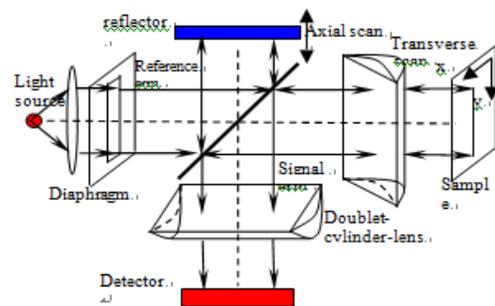


Fig.4 OCT system with DCL.

After beam splitter, the light is divided into two beams. The first is reflected by the beam splitter, and then by the

reflection of the mirror, and then through the beam splitter. The light vector of reference ray is

$$E_r = 2^{(-1/2)} A_0 \exp[i(\varphi + k l_r)] \quad (10)$$

where k is the wave vector. The second beam goes through the splitter, then it is focused by the DCL and projected to the surface and inner of the sample. The optical path differences caused by different focal points vary with different space position. So that the light vector distribution from the sample arm is

$$E_s = 2^{(-1/2)} A_0' \exp[i(\varphi + k l_s)] \quad (11)$$

where $l_s = l_s(y)$ is the optical length of the sample arm, A_0' is the amplitude of the signal light modulated by the sample. After line focused by the cylinder lens, signal light reflected by samples and reference light reflected back by reflection lens were received by the detector. The overall interference light vector is

$$E = E_r + E_s \quad (12)$$

Assume $I_0 = A^2/4$, $I' = A'^2/4$ (A and A' are the influence of the factors of loss of light intensity caused by the components), then the stacked light intensity by two waves is

$$I = \langle EE^* \rangle = I_0 + I' + 2\sqrt{I_0 I'} \cos k[l_r - l_s(y)] \quad (13)$$

Let $\Delta = l_r - l_s(y)$, if $I_0 = I'$, we obtain

$$I = 2I_0(1 + \cos k\Delta) \quad (14)$$

By Eq. (13) and Eq. (14), we can see that the change of the interference intensity is still associated with the optical path difference. Because of the low coherence of the optical source, the reflected or scattering light from a certain depth point inside the sample can only be coherent with the reference beam. All the reflected lights from different depth inside the sample have different phase delays. With the increase of phase delay, the intensity of interference signal sharply declines. The interference signals contain internal structure information of the sample. Therefore, after filtrating and amplifying the signals we can get images of the sample.

In addition, the CMS can increase the resolution of space image in the system. Because the signal intensity from the outside position of the focus is much weaker than from the position of the focus, the CMS can greatly reduce the undesired flickering noise and the noise from the scattering light.

2) Signal Simulation in the System

We adopt the ZEMAX from the INFOTEK corporate with monochromatic light (the wavelength 1310nm) to simulate the above optical system.

The beam from a point light source is expanded with a collimator which is a single lens. 3D shape of the principal light through optical center is as shown in figure 5, where component 1 is expanding lens, component 2 is the beam splitter, components 3 and 6 are the DCL, components 4 and 5

the plane mirror, component 7 the imaging surface or detector, the light path that contains plane mirror 5 is the reference arm, the light path including the component 3 (DCL) is sample arm. In order to compensate the light path difference caused by the cylinder mirror, we set up a suitable length of the reference arm, thus realize the equal light paths between the two arms.

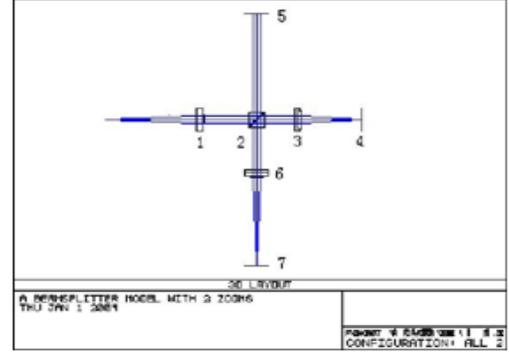


Fig.5. Simulation of the OCT system.

The simulation experiments are divided into two cases. One is thin round beam interference pattern on Michelson Interferometer, and the simulation results showed in figure 6(a). The other simulation results are as shown in figure 6(b). The case has two DCL devices with the same specification or standard, which are put in the light path of the sample arm and in front of the detector in order to compensate for the two optical path difference.

In figure 6(a) the interference pattern is concentric circles, while in figure 6(b) they are parallel interference stripes. It indicates that the functions of the cylindrical lens focusing light are the same under the limit of beam in the plane, namely, every points in the longisecion of the focus line have the same optical path difference. This kind of axial symmetry parallel interference patterns are beneficial to enhance the transverse resolution of the line scanning OCT system.

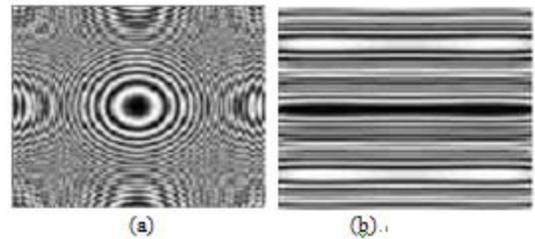


Fig.6. Two kinds of interference fringe.

E. Resolution and Focal Depth of DCL Microscopy System

1) Theoretical Formula of the Resolution and Focal Depth

The adoption of DCL line scanning confocus system has the same axial resolution with point scan of OCT system, and they are all dependent on the coherent length of the light sources^{8,9}

$$\Delta z_{FWHM} = \frac{2 \ln 2}{\pi} \cdot \frac{\lambda^2}{\Delta \lambda_{FWHM}} \quad (15)$$

where λ is the centre wavelength, $\Delta \lambda_{FWHM}$ is the spectrum width of the light source.

The horizontal resolution Δx do not simply depend on the NA of the beam, it is also relevant with the distances between image sensitive units in the detector. The horizontal resolution of the CFMS with DCL can also be shown as Eq. (16)

$$\Delta x = \frac{4\lambda}{\pi} \cdot \frac{f}{d} = \frac{4\lambda r_1 r_2}{\pi d [r_1 (n_2 - 1) - r_2 (n_1 + n_2)]} \quad (16)$$

where d is the caliber of the parallel beams of the sample arm (and a square aperture caliber consistent).

If the transverse resolution Δx is greater than the distances between photosensitive units of the detector, the transverse resolution of the line OCT scanning system is Δx ; otherwise it is the size of photosensitive units. Obviously, the transverse resolution of the line OCT scanning system can not be higher than the size of the linear array CCD image-sensing units.

For the line scanning OCT system, Its DOF was decided by two times beam parameters of the confocus Gaussian beams, using Eq.(16), we have

$$b = 2Z_R = (\pi/2)(\Delta x^2/\lambda) \quad (17)$$

2) Relationship between Transverse Resolution & NA & Focal Depth

While increasing the transverse resolution the gathering depth is decreased, the property is similar with optical microscope. The lower numerical aperture, the better gathering depth, the bigger waist radius of the beams, and the lower transverse resolution; the higher numerical aperture in the system, the smaller waist radius of beams, the higher transverse resolution, the lower confocal parameter, and the lesser converging depth.

In order to improve the scanning speed, the width of the line scan is as widely as possible. But in fact, the line width can not grow indefinitely. So we should make optimization parameters. (1) Under determining the power of the light source, line scanning is equivalent to distributing averagely the light energy of point scanning to scan line, energy reduce of single point will cause the whole detecting ability to reduce; (2) To increase the line width, it have to increase beam diameter after beam expanding, this will also increase the numerical aperture, and decrease the focal depth; (3) The lager the line width, the more stray light on every detecting point, These stray light will interact with backscatter light from other points, which will reduce the signal-to-noise ratio, and affect the quality of scanning.

The parameters designed for this work are as follows: choosing the light center wavelength 1310nm, the caliber of the parallel beams with the sample arm for $d=50.8\text{mm}$. For glass combination, taking K9+ZF2 (above parameters have be given). As shown in figure 7, when the transverse resolution is

$15\mu\text{m}$, using the software of Matlab, we obtained the relationship between r_1 and r_2 . When the axial resolution is $15\mu\text{m}$, we know the bandwidth $\Delta \lambda_{FWHM}$ is 50.5nm according to Eq. (15).

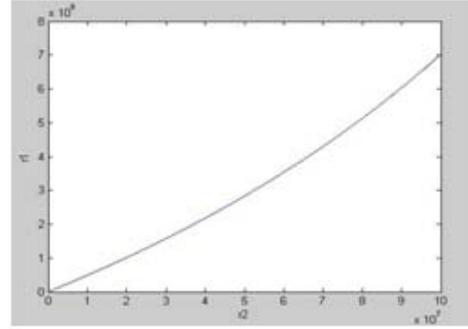


Fig.7. Relationship of r_1 & r_2 in DCL.

IV. Conclusions

Not only the CFMS with DCL inherits the advantage of the independence of the longitudinal and horizontal scanning resolution in the traditional OCT system with point scanning model, but can also make up the faults of traditional point scanning OCT technology. Therefore, the changing the point scanning into line scanning the transverse scan resolution is also increased.

The main advantage of using the confocus scanning model is filtering the out-of-focus background signals. By analysing the spherical aberration for the cylindrical lens, testing and verifying via K9+ZF2 glasses, it is clear that this method can effectively eliminate the spherical aberration and the sine aberration. After studying the relationships between r_1 and r_2 , we design the specific parameters for the CFMS with DCL. But the line scan model will lead to dispersing the energy of detecting light, the detecting depth and S/N of the system are decreased with the increasing length of the scanning line, and so many detectors with high sensitivity of detecting are essential.

While the aperture is $50.8\text{mm} \times 50.8\text{mm}$, the horizontal resolution is equal to $15\mu\text{m}$. In comparison with the point scanning model under the same conditions, the scanning speed of the new model at least achieves $50.8\text{mm}/15\mu\text{m}=3387$ times than that of the point scanning model. Theoretically, the scanning speed can be improved by three orders of magnitude. Thus the imaging velocity is significantly promoted. In terms of living body imaging, the high-speed-scan model can effectively reduce the influence from the physiological activities to the living tissue. Therefore, this research has higher value of applying to the real-time vivo imaging.

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