Confocal Measurement Approach for Enhancing Lateral Resolution Using a Phase-only Pupil

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Abstract. Confocal measurement approach is recently widely used as important tools for measurement of three-dimensional microstructures and surface contours because of its good 3D chromatographic imaging capability. But its lateral resolution is limited by the diffraction effect to about 0.4µm only while the axial resolution has reached the nanometer level. A phase-only confocal measurement approach is therefore proposed to enhance the lateral resolution. In this paper, an optimized superresolution phase-only filter is used in a confocal microscopy system to improve the lateral resolution, and the pinhole in the confocal microscopy system effectively eliminates the disturbance of ambient lighting and improves the imaging quality. Simulation results indicate that, an optimized three-zone pupil with $G_L=0.8375$ and $G_A=0.99$ can make the lateral resolution of CMS 1.18 times better while the axial resolution is almost invariable. So it therefore can improve the applicability of confocal microscopy system.

1. Introduction
Confocal microscopes are widely used as important tools for surface profiling because of their good 3D chromatographic imaging capability [1-8]. The lateral resolution of a confocal measurement system is 1.4 times better than those of other LPMS, such as astigmatic method and critical angle method under the same condition, but its lateral resolution is still two orders of magnitude below its axial resolution. It is still very difficult to satisfy the stringent requirements for high LPMS spatial resolution in measuring 3D microstructures, such as micro-step, micro-groove, integrated circuit line width, etc, this means LPMS must have both very high axial resolution and very high lateral resolution. Although the lateral resolution of a laser probe measurement system(LPMS) can be improved by increasing the numerical aperture of the measuring lens and decreasing the wavelength of incidence beam, the improvement effect is very much limited. It can be seen from this that the improvement of lateral resolution has become an important problem demanding a prompt solution for further development of LPMS. The unique light path arrangement with point lighting and point detection in a confocal microscope enables the microscope to be easily combined with a pupil filter to achieve optical superresolution thereby providing a new approach to the improvement of LPMS lateral resolution.

2. Measurement principle of confocal microscopy approach
The principle of a measurement system based on reflection confocal microscopy is shown in Figure 1 below, in which, the measuring lens is both the imaging lens and collecting lens. The point light source and the point detector are in positions conjugate to each other, so that the signal coming from the light spot illuminated zone on the object is focused by the collecting lens onto a point detector, and the
defocused displacement can be obtained by measuring the magnitude of the signal received by the point detector.

Figure 1. Imaging principle of reflection confocal microscopy system

As shown in Fig.1 above, when the measuring and collecting lens are the same lens, the pupil function is round symmetrically, and the defocused displacement of the measuring and collecting lenses are equal in values and the same in directions, the light intensity function of the signal received by the point detector is

\[
I(v,u) = \left| \int P(\rho)e^{-\frac{m^2}{2}}J_0(\rho v)2\pi\rho d\rho \right|^4
\]

where \( P(\rho) \) is the pupil function of measuring and collecting lenses, \( u \) and \( v \) are the normalized optical radius and

\[
v \approx \frac{2\pi}{\lambda} r \sin \alpha_0, \quad u \approx \frac{8\pi}{\lambda} z \sin^2 \left( \frac{\alpha_0}{2} \right)
\]

2.1. Axial resolution property

Let \( v = 0 \) in (1), the axial resolution property of a confocal microscopy system obtained through simplification is as follows:

\[
I(0,u) = \left[ \frac{\sin(u/2)}{u/2} \right]^2
\]

In a confocal microscopy system (CMS), the introduction of pinholes makes the light intensity detected while the object is right in the defocused plane weaker than the light intensity detected when the object is right in the focal plane, defocused displacement \( u \) is correlated to light intensity \( I(v,u) \), and therefore, CMS has axial depth response capability, i.e. chromatographic analysis capability. The lateral resolution property of CMS is as shown in Figure 2 below.

2.2. Lateral resolution property

In order to further study the lateral resolution properties in the focal plane, let \( u = 0 \) in (1), the following is obtained through simplification:

\[
I(v,0) = \left[ 2\pi J_1(v) / v \right]^4
\]

where, \( J_1 \) is a first-order Bessel function of the first kind.

The light intensity function of a conventional microscopy system is obtained in the same way:

\[
I(v,0) = \left[ 2\pi J_1(v) / v \right]^2
\]

The lateral resolution curve of CMS and the lateral resolution curve of a conventional microscopy system are shown in the same coordination system using (4) and (5), as shown in Figure 3 below.
3. Superresolution property of confocal microscopy approach using phase-only pupil

Assuming that the radius of the emergent pupil is $R$ and the incident wavelength is $\lambda$, pupil function $P(\rho)$ of a $N$-zone and round symmetrical phase-only pupil filter is:

$$P(\rho) = e^{i\phi_j} \quad (a_{j-1} < \rho < a_j, j = 1, \cdots, N)$$

where $\phi_j$ is the phase difference between the $j$-th zone and the first zone, $a_j$ is the normalized radius of the $j$-th zone, $a_0=0$ and $a_N=1$. The amplitude PSF of the optical system is:

$$U(v, u) = 2 \sum_{j=1}^{N} e^{i\phi_j} \cdot e^{-\frac{iu\rho^2}{2}} \cdot J_0(\rho v) \cdot \rho d\rho$$

The superresolution CMS with a phase-only pupil is shown in figure 4, the intensity response function obtained using (7) and (1) is:

$$I_{\text{comp}}(v, u) = \left| \sum_{j=1}^{N} e^{i\phi_j} \cdot e^{-\frac{iu\rho^2}{2}} \cdot J_0(\rho v) \cdot \rho d\rho \right|^2$$

It can be seen from figure 3 that the lateral resolution of CMS is 1.4 times better than that of a conventional microscopy system under the same conditions, and nevertheless, the lateral resolution of a confocal microscope is still about two orders of magnitude below its axial resolution. Fortunately, the unique light path arrangement with point lighting and point detection in CMS enables the microscope to be easily combined with a pupil filter to improve its lateral resolution.
property of superresolution CMS is obviously better than that of CMS while CMS axial resolution and axial chromatography resolution capacity are almost invariable under the same measurement conditions. In comparison with the conventional CMS, superresolution CMS makes $M$ reduced while it makes PSF sharpen in the lateral direction, and it can obviously suppress the increasing of the side lobe and improve the imaging quality while CMS lateral resolution is further improved. It is recently really why the integration of CMS with the pupil filter can be used to achieve the optical superresolution imaging in practical significance.

![Figure 6. Comparison of resolution property between superresolution CMS and CMS](image)

### 4. Conclusion

The CMS integrating with the optimized three-zone phase-only pupil can achieve the lateral superresolution of $G_L=0.85$ and $G_A=1.07$. Simulation results indicate that an approach integrating CMS with the three-zone phase-only pupil filter of $G_L=0.8375$ and $S=0.1718$ can be used to improve CMS lateral resolution, suppress the increase of side lobe caused by superresolution effect and improve the imaging quality, while CMS axial resolution is almost invariable.

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