The X ray phase contrast imaging method for the light element materials or extreme weak absorption materials

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In order to get better images from the extreme low density or weak absorption materials, a new modulation transfer function model is established for the X ray phase contrast imaging method. Then the effects of the ray source size parameter are elaborated on the basis of the partially coherent optical theory. From the simulation and calculation, the proposal and parameter optimization are revealed according to the actual materials experiment conditions.

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1. Introduction

In 1895, Roentgen discovered the X ray, then X ray imaging technology was used in a wide range of applications in engineering materials, biological materials, and industrial nondestructive testing, etc. The basic traditional X ray imaging theory keep unchanged until now, which is called the bill law, that is different image decay depends on the different object interior structure, which is determined by X ray absorption attenuation capability. The X ray absorption attenuation capability mainly depends on the X ray wavelength, the materials atomic number and density [1,2,3].

But many kinds of materials are made of light element materials or extreme weak absorption materials, such as soft tissue, biological materials, polymer foam, PVC, film materials, because of their own attenuation coefficient to X ray is extremely low, or the difference of attenuation capability is very small, so these materials are named weak absorption materials. Obviously, it is difficult to get a high image quality for the traditional X ray imaging, so in nowadays, the traditional X ray imaging can not meet the need of advanced materials scientific research [4,5,6].

In the past few years, the X ray phase contrast imaging was a research hot spot in the advanced materials field, especially for those materials with light element or extreme weak absorption characteristics, this imaging technology can give satisfactory phase contrast image results. However, in the former published research literature, there was less specifically discussion and experimental results about the light element materials or extremely low absorption material [7,8,9].

In this paper, we first establishes a new X ray phase contrast imaging theory and model, then makes a specific theoretical calculation and simulation. Finally based on the cylindrical fiber and plastic bubble imaging experiments, the boundary information was observed successfully in the light element materials and extremely low absorption material. This shows that the X-ray phase-contrast imaging method will have a brilliant future in this area.

2. X ray phase imaging theory and model establishment

The imaging system is shown in Fig. 1. X ray is assumed to spread along the z direction, a experimental ball is placed between the X ray source and the image detector, the ball radius is 250 μm, the ball material is polystyrene with the density of 1.12 mg/cm^3, this is the familiar type of extreme low density or weak absorption materials, $t(x,y)=\mu(x,y)e^{-\phi(x,y)}$ is the transmission function, where $\mu(x,y)$ is the absorption of the object, and $\phi(x,y)$ is phase information along the path. For weak absorption or weak phase objects, the transmission function can be approximated as:

$$t(x,y) \approx 1 + i\phi(x,y) - \mu(x,y) \tag{1}$$

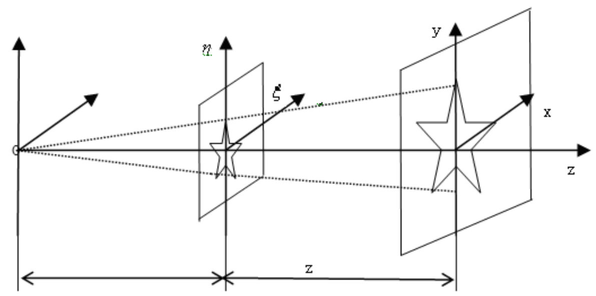


Fig. 1. X ray phase contrast imaging system diagram.

If the object size is significantly larger than the light wavelength, a paraxial approximation can be made, According to the Fresnel diffraction theory, the propagating wavefront amplitude of the X ray can be written in integral form [10,11]:

$$f(x,y,z)=\frac{1}{i\lambda z}\exp(ikz)\iint t(\xi,\eta)\exp\left\{i\frac{k}{2z}[(x-\xi)^2+(y-\eta)^2]\right\}d\xi d\eta \tag{2}$$

Where (x, y) and (ξ,η) are the image plane and object plane coordinates, z is represent of the object-image distance, then the Fourier transform of the wave function can be written as:

$$F(u,v,z)=Q(u,v)H_z(u,v)=\exp(ikz)Q(u,v)\exp[-i\pi\lambda z(u^2+u^2)] \tag{3}$$

In this equation, $Q(u,v)$ is the Fourier transform of the transmission function $t(x,y)$, u,v is the spatial frequency on the imaging plane. The Fourier transform form of Eq.2 can be written as: $Q(u,v)=\delta(u,v)+i\Phi(u,v)-M(u,v)$,where the Φ, M are Fourier transform of the ϕ, μ respectively. Combining Eq. 3 and Eq. 4 can be got,

$$F(u,v,z)=\exp(ikz)[\delta(u,v)+\sin\chi\Phi(u,v)-\cos\chi M(u,v)+i\cos\chi\Phi(u,v)+i\sin\chi M(u,v)] \tag{4}$$

Where $\chi=\pi\lambda z(u^2+v^2)$. In terms of the image intensity, the imaginary part can be ignored, get

$$F(u,v,z)\approx\delta(u,v)+\sin\chi\Phi(u,v)-\cos\chi M(u,v) \tag{5}$$

In this equation, $\sin\chi$ is the phase contrast transfer function and $\cos\chi$ is the absorption contrast transfer function respectively, From the inverse Fourier transform of above equation, the amplitude distribution and intensity distribution at the image plane can be obtained as follows,

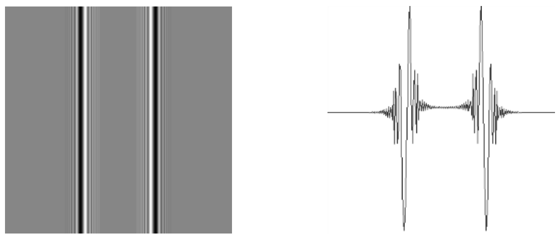
$$f(x,y)=F^{-1}[F(u,v)]\approx 1-\frac{\lambda z}{4\pi}\phi''(x,y) \tag{6}$$

$$I(x,y)=|f(x,y)|^2\approx 1-\frac{\lambda z}{2\pi}\phi''(x,y) \tag{7}$$

It can be seen from this formula and above derivation that, the image intensity is proportional to the second order Laplacian of the X ray phase, that is the $\nabla^2\phi(x,y)$, and the phase change is proportional to the electron density $\phi(x,y)=r_e\lambda\rho_e(x,y)$. So the image intensity distribution can significantly enhance the edge information of the internal structure of the objects. Therefore, this imaging modality particularly sensitive to the internal structure edges [12-14].

3. Experiment

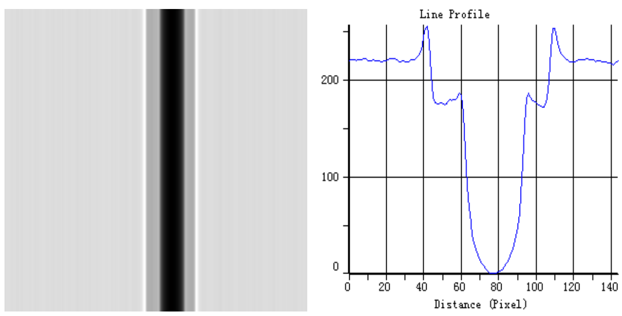
To demonstrate the theory above, we carried out a simulation using idea cylinder model. The simulation material is SiO_2 with a density of 2.4 g/cm^{-3}, the radiation energy is set to 20keV, and $\delta=1.73\times10^{-6}$, $\beta=5.01\times10^{-9}$, and the phase contrast image and its profile in this simulation are shown in Fig. 2. We can see the fiber boundary clearly.



(a) (b)

Fig. 2. (a) the simulated phase contrast image, (b). the profile of (a).

Fig. 3 is the phase contrast image of the fiber and its profile curve, the object in this experiment is a thin fiber, and the intermediate portion is empty. The fiber diameter of about 250 microns, the actual experimental results is very clear to display the internal structure. But the traditional X-ray imaging methods can not have this effect.



(a) (b)

Fig. 3. (a). the fiber phase contrast image, (b). the profile of (a).

Plastic material is another kind of light element and low absorption material, so we select a very thin plastic bubble, the wall thickness of the plastic bubble is about 2 microns. Using the X ray phase contrast imaging technology, we get the experiment result as shown in Fig. 4. It is easy to distinguish different plastic bubble boundary location in this figure.

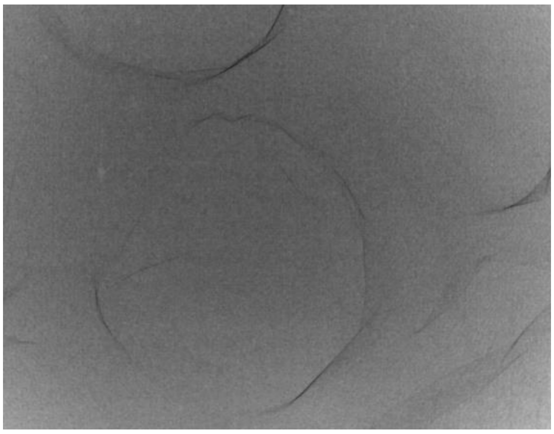


Fig. 4. The plastic bubble phase contrast image.

4. Conclusions

This paper introduces the X ray phase contrast imaging method, to explore the internal structure of those extreme low density or weak absorption materials, this technology is analyzed based on free-space propagation of partially coherent optical theory. Based on the imaging experiments on the cylindrical fiber and plastic bubble, the boundary information was observed successfully in these low light element materials and extremely low absorption material. This results show that X-ray phase-contrast imaging method will have a brilliant future in this area. But, in the actual system design and parameter optimization process, there are many other factors need to be considered, such as light intensity, sample size, current size, all of these should be discussed in the future.

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