A new method of detecting interferogram in differential phase-contrast imaging system based on special structured x-ray scintillator screen*

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An x-ray scintillator screen with a special structure, functioning as detector and analyser grating, was proposed for collecting the interferogram of differential phase contrast imaging without absorption grating and difficulty of fabrication by a state of the art technique. On the basis of phase grating diffraction, a detecting model of the scintillator screen was built for analysing the phase and absorption information of objects. According to the analysis, a new method of phase retrievals based on two-images and the optimal structure of screen were presented.

Keywords: differential phase contrast, x-ray scintillator screen, phase retrieval
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1. Introduction

Differing from the traditional x-ray radiography based on attenuation, x-ray phase contrast imaging techniques detect the phase shift of x-rays passing through an object.[1−5] The phase factor causing phase shift is three orders of magnitude greater than the absorption factor causing intensity attenuation for light elements, which are the main ones composed of soft tissues of biology in the band of hard x-ray. Compared with the attenuation-based methods, phase sensitive imaging techniques can directly obtain images of soft tissues or material made of low Z elements with high contrast and have the potential utilisation in medical, biological and industrial fields.[6] Most of phase contrast imaging techniques proposed earlier use synchrotron, whose enormous volume and exorbitant price obstruct their application, as an x-ray source.[7−11] With micro-focus source based on x-ray tube the in-line phase contrast imaging method proposed by Willkins *et al.*[12−16] overcame the obstacles of volume and price and provided the feasibility that phase sensitive imaging techniques can be performed in common laboratories. But as limited by the problem of heat dissipation for target of x-ray tube, micro-focus beam source cannot provide sufficient radiation flux and this kind of experiment can only be implemented in laboratories for demonstration. An absorption mask with transmitting slits placed close to the traditional x-ray tube was suggested by Pfeiffer *et al.*[17] in order to create one-dimensional spatial coherent source in differential phase contrast imaging system. The mask partly overcame the conflict between spatial coherence and the flux of source, and provided a new method to implement phase sensitive imaging in common laboratories. A second absorption phase grating immediately placed before x-ray detector was used to decrease the requirement for the detector spatial resolution. However, the fabrication of absorption grating with high contrast and big-sized area is a challenge for the state of the art microfabrication process. At the same time, the fields of view limited by the angle of divergence of the mask is also a serious problem, which means that it is difficult to put the technique into medical applications. Besides, at least three image-acquisitions are necessary for this method to retrieve phase distribution with current phase-stepping algorithm.[18,19] Recently Zhu group[20] have proposed a two-stepping algorithm of phase retrieval recently, which has special requirements on the precision of grating positions.

A new detecting apparatus, which consists of

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structured scintillator screen and visible light detecting system rather than absorption grating and x-ray detector, was designed to detect interferogram. Thus the detecting system can avoid the use of absorption grating that is difficult to fabricate. According to the model of detecting system given in this paper, the feasibility of detecting fringes pattern with a structured scintillator screen is analysed. We propose a new method of phase retrieval with two images of object but without special requirements of the position of phase grating based on the pre-exposures of phase grating.

2. Model of detecting system

2.1. Interference fringes

The complex transmission function $T(x)$ of the phase grating can be expressed with Fourier series as follows:

$$T(x) = \sum_{n=-\infty}^{\infty} a_n \exp\left(\mathrm{i}\,\frac{2n\pi}{p_1}x\right), \tag{1}$$

where a_n is the amplitude of the nth harmonic and p_1 is the period of the grating. For simplicity, only one-dimensional expressions are given. The complex amplitude of the propagating field at a distance l behind the phase grating illuminated by a plane wave is given by

$$U(x,z) = \sum_n a_n \exp\left(-\mathrm{i}\,\pi n^2 \frac{l\lambda}{p_1^2}\right) \exp\left(\mathrm{i}\,\frac{2n\pi}{p_1}x\right). \tag{2}$$

Corresponding to Tallbot effect, the phenomenon of self-image will appear at the Tallot distance downstream of the phase grating. When an object immediately placed before the phase grating, the phase can be considered as a beam splitter expressed as

$$\begin{aligned} U(x,z) \;=\; & a_0 A(x)\exp[\mathrm{i}\,\varphi(x)] + a_1 A(x-s)\exp[\mathrm{i}\,\varphi(x-s)]\exp\left(-\mathrm{i}\,\pi\frac{l\lambda}{p_1^2} + \mathrm{i}\,\frac{2\pi}{p_1}x\right) \\ & + a_{-1}A(x+s)\exp[\mathrm{i}\,\varphi(x+s)]\exp\left(-\mathrm{i}\,\pi\frac{l\lambda}{p_1^2} - \mathrm{i}\,\frac{2\pi}{p_1}x\right), \end{aligned} \tag{3}$$

where φ and A are phase-shift and absorption components of the object, respectively; $s = l\lambda/p_1$ is the shear amount. According to the optimum diffraction efficiency, the phase-shift of phase grating is chosen to be π.[11] Thus the ±first-order diffraction efficiencies are close to 80%, and the zero order diffraction disappears completely as in theory. So only ±first-order diffractions are considered in Eq. (3). The shear amount s is so small for x-ray phase grating that the intensity of imaging plane can be written as

$$I_{\mathrm{c}}(x) = \frac{8}{\pi^2}A^2(x)\left[1 + \cos\frac{2\pi}{p_2}\left(x - l\frac{\lambda}{2\pi}\frac{\partial\varphi}{\partial x}\right)\right], \tag{4}$$

with the approximation that $A(x-s) \approx A(x) \approx A(x+s)$, where p_2 is the periodicity of the fringes.

2.2. Structured x-ray scintillator screen

Usually, x-ray images are converted into visible light singles by scintillator screen, which are read out by a visible light detector through an optical coupling system. The periodicity of interference fringes generally does not exceed a few micrometers, which is hard to be resolved by common x-ray detector. So an analyser grating is placed close to and before the scintillator so that no requirement is needed for the resolution of detector. As mentioned above, the difficulty of fabrication of analyser grating is one of the main obstacles with respect to the application of differential phase contrast imaging. A new x-ray scintillator screen with functions of analyser grating and common scintillator was proposed to detect the x-ray interferogram. The structure of scintillator screen is shown in Fig. 1. The white part is made of x-ray fluorescence material and the grey part of non-fluorescence material such as silicon. The period of the structured scintillator screen, along the orientation of fringes, must be the same as the interference fringes and the value of duty ratio is 1/2. The grey part cannot convert the x-rays into visible light and plays the role of the analyser grating.

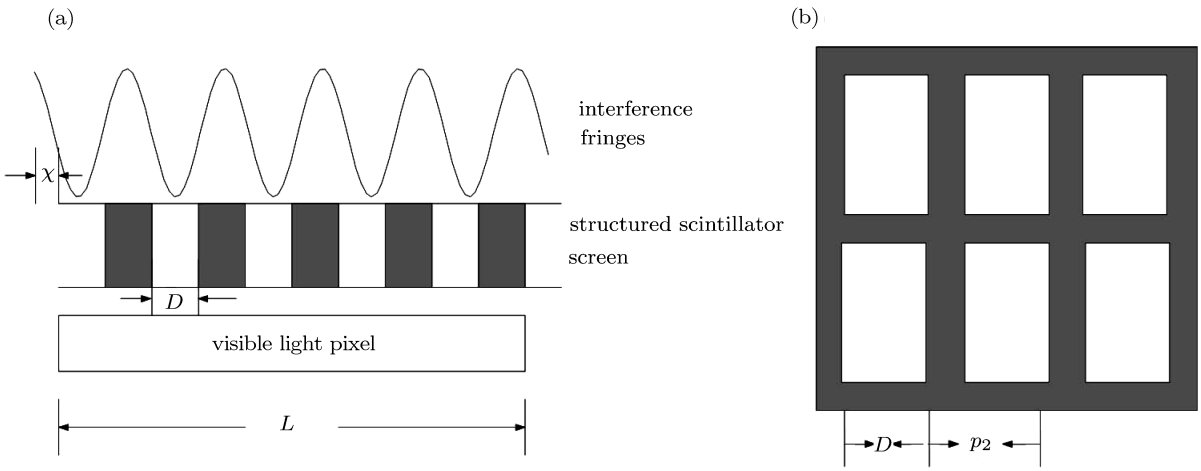


Fig. 1. (a) The model of detecting interferogram with structured x-ray scintillator screen. (b): Schematic of two-dimensional structure.

Next, the intensity of one visible light pixel will be considered. We denote the periodicity of the screen and fringes as p_2 , the width of x-ray sensitive part as D and the pixel width of the visible light detector as L as shown in Fig. 1(a). The whole intensity signal is in proportion to the integration along L for one pixel. In one period of fringes, the integration is given by

$$I' = \kappa \int_{\chi}^{\chi+D} I(x)\mathrm{d}x, \tag{5}$$

where κ is the transforming efficiency of the scintillator and χ is the displacement of interference fringes with respect to scintillator screen. When one visible light pixel collects N periods of fringes, the intensity signal of one pixel is

$$I_m = \kappa\Big[\int_{\chi}^{\chi+D} I(x)\mathrm{d}x + \int_{p_2+\chi}^{p_2+\chi+D} I(x)\mathrm{d}x + \ldots + \int_{(N-1)p_2+\chi}^{(N-1)p_2+\chi+D} I(x)\mathrm{d}x\Big] = NI' \tag{6}$$

with the assumption of 100% optical coupling efficiency. The ultimate resolution of imaging system cannot exceed the width of pixel L so the assumption that the gradient of phase is constant in the range of L is reasonable. Considering Eq. (4), Eq. (6) is rewritten as

$$I_m = \kappa N A_m^2 p_2\Big\{\gamma + \frac{1}{\pi}\cos\Big[\gamma\pi - \frac{2\pi}{p_2}\psi_m + \alpha\Big]\sin(\gamma\pi)\Big\}, \tag{7}$$

where $\alpha = 2\pi\chi/p_2$ is the initial phase of fringes, $\gamma = D/p_2$ is the aspect ratio of scintillator screen and $\psi_m = z\frac{\lambda}{2\pi}\frac{\partial\varphi}{\partial x}$. Obviously the optimal value of γ is 1/2 for the modulation of phase information $\sin(\gamma\pi)$ has the maximum value, which means that the optimum structure of scintillator screen is that half period is x-ray insensitive material.

3. Phase retrieval

3.1. Method of phase retrieval with two images

Whatever is the object that exists in the imaging system, the intensity signal will oscillate with χ. The difference is that the amplitude and phase of oscillation will change, which are caused by attenuation and phase coefficients of the object as shown in Fig. 2.

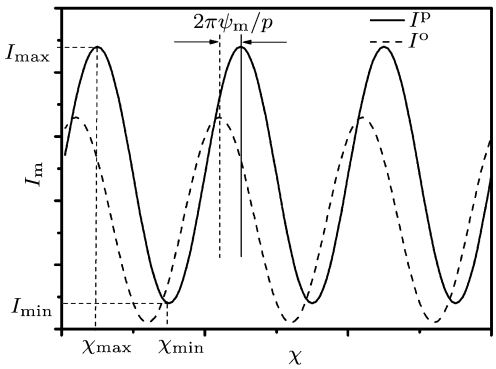


Fig. 2. The oscillation of intensity for one pixel versus χ. Solid line is the curve of oscillation I^{P} only with phase grating, and the broken line I^{o} is that without object.

As long as the two curves of oscillation are obtained, the information of attenuation and phase is

easy to be retrieved. However, the curve of oscillation for the object is usually measured by stepwise increase in χ, which means that the object has to be exposed in x-ray radiation several times. That is a serious drawback especially for medical applications.

Based on the above analysis, we have developed a new method of phase retrieval with two-images. The basic idea is to utilise the information of self-image of phase grating without object and gain information of object images for the phase retrieval. First, at two positions $\chi = \chi_1$ and χ_2, the two interferograms without the object are as follows

$$I_1^{\rm p} = \kappa N p_2 \left[\gamma + \frac{1}{\pi}\cos\left(\gamma\pi + \alpha_0\right)\sin\left(\gamma\pi\right)\right], \quad (8)$$

$$I_2^{\rm p} = \kappa N p_2 \left[\gamma - \frac{1}{\pi}\cos\left(\gamma\pi + \alpha_0\right)\sin\left(\gamma\pi\right)\right], \quad (9)$$

where $\alpha_0 = 2\pi\chi_1/p_2$, and χ meets the condition $\chi_2 = \chi_1 + p_2/2$. At the same places, the two images with the object are

$$I_1^{\rm o} = \kappa N A_m^2 p_2 \left\{\gamma + \frac{1}{\pi}\cos\left[\gamma\pi - \frac{2\pi}{p_2}\psi_m + \alpha_0\right]\sin\left(\gamma\pi\right)\right\}, \quad (10)$$

$$I_2^{\rm o} = \kappa N A_m^2 p_2 \left\{\gamma - \frac{1}{\pi}\cos\left[\gamma\pi - \frac{2\pi}{p_2}\psi_m + \alpha_0\right]\sin\left(\gamma\pi\right)\right\}. \quad (11)$$

From Eqs. (8)–(11), the following result can be deduced

$$A_m^2 = \frac{I_1^{\rm o} + I_2^{\rm o}}{I_1^{\rm p} + I_2^{\rm p}}, \quad (12)$$

$$\psi_m = \frac{p_2}{2\pi}\left[\cos^{-1}\left(\frac{\gamma\pi}{\sin(\gamma\pi)}\frac{I_1^{\rm p} - I_2^{\rm p}}{I_1^{\rm p} + I_2^{\rm p}}\right) - \cos^{-1}\left(\frac{\gamma\pi}{\sin(\gamma\pi)}\frac{I_1^{\rm o} - I_2^{\rm o}}{I_1^{\rm o} + I_2^{\rm o}}\right)\right]. \quad (13)$$

By the simple one-dimensional integration along x, phase shift φ can be retrieved from ψ_m.

The above four images can be obtained as follows. $I_1^{\rm p}$ and $I_1^{\rm o}$ are obtained without and with the object at position χ_1 respectively one after another. Along the direction of the period of the interference fringes, the phase grating moves to χ_2; $I_2^{\rm p}$ and $I_2^{\rm o}$ can be obtained with and without the object respectively, where $\chi_2 = \chi_1 + p_2/2$. So the phase grating only moves once in the imaging process.

3.2. The measurement of duty ratio

It is almost impossible to ensure the uniformity of duty ratio for the whole scintillator screen because of the limitation of state of the art fabrication. So the measurement of duty ratio for every visible light pixel is necessary.

The intensity signal of every pixel will oscillate with χ. Without the object, the curve of oscillation has maximum and minimum values expressed as

$$I_{\max} = \kappa N p_2 \left[\gamma + \frac{1}{\pi}\sin\left(\gamma\pi\right)\right], \quad (14)$$

$$I_{\min} = \kappa N p_2 \left[\gamma - \frac{1}{\pi}\sin\left(\gamma\pi\right)\right]. \quad (15)$$

Thus the ratio $\frac{\gamma\pi}{\sin(\gamma\pi)}$ can be solved

$$\frac{\gamma\pi}{\sin(\gamma\pi)} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}. \quad (16)$$

Corresponding to the maximum and minimum values, the positions of phase grating are denoted as $\chi_{\max}$ and $\chi_{\min}$, which can be measured by nanometer displacement setup; the periodicity of interference fringes is

$$p_2 = 2|\chi_{\min} - \chi_{\max}|. \quad (17)$$

Utilising the result of Eqs. (15) and (16), we can calculate the phase of the object.

The integration in Eq. (7) is deduced with the assumption that the width of visible light pixel is an integer multiple of period of fringes, which is difficult to realise. Usually, L will deviate from the integer multiple with $L = Np_2 + d$. Thus the oscillation will have an additional item

$$\varepsilon = \kappa N p_2 \left[\frac{d}{p_2} + \frac{1}{\pi}\cos\left(\frac{d}{p_2}\pi + \alpha_0\right)\sin\left(\frac{d}{p_2}\pi\right)\right]. \quad (18)$$

Fortunately, the additional item does not influence the solutions to Eqs. (12), (13) and (15)–(17). That is to say, the relationship between the period of fringes and the pixel size of visible light detector does not influence the result of phase retrieval. In fact, the choice

of pixel size of the visible light detector depends on the total beam size of the x-ray source in order to obtain optimal spatial resolution of the whole imaging system.

4. Conclusion

Using the technique of photo-electrochemical etching of silicon in hydrofluoric acid solution, the structured scintillator screen can be realised. The fabrication process is described as follows: (i) pore arrays are made in silicon wafer, (ii) a layer of SiO_2 is formed on the wall of pores with wet-thermal oxidation, (iii) the crystals of CsI(Tl) are filled in pores. We have realised the scintillator screen and carried out relative experiments.

In conclusion, a new method of detecting interferogram on the basis of the structured scintillator screen with a specially designed structure has been proposed. The new scintillator screen has the dual functions of detector and analyser grating. The use of this kind of scintillator screen has the following merits: In the imaging system the difficulty to fabricate the absorption grating can be avoided. The problem that the absorption grating with low contrast causes the decrease in visibility for interference fringes can be overcome. On the basis of the analysis of oscillation, the optimal structure of scintillator screen is presented. A new phase retrieval with two-images is proposed. Compared with the method of two-step phase shift suggested by Zhu group[20] which has the special requirement of position of absorption grating, the new algorithm we proposed can be applied with arbitrary initial position of phase grating. According to our proposition the duty ratio and grating period can be worked out by measuring the intensity oscillation curve.

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