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Development of the grating phase neutron interferometer at a monochromatic beam line

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ABSTRACT

Recently, it has been demonstrated that a shearing type interferometer, using precision silicon gratings, enables one to image the gradient of neutron phase shift through an object and retrieve the phase via a simple one-dimensional integration of the gradient. To fully explore this new technique for potential future cold neutron imaging stations at the National Institute of Standards and Technology and the Korea Atomic Energy Research Institute, we have developed a prototype phase imaging station at a monochromatic cold neutron beamline in the NCNR neutron guide hall. We have designed the silicon gratings for a neutron wavelength of 0.44 nm and fabricated them using the state-of-the-art nanofabrication facility at the NIST Center for Nanoscale Science and Technology. Here we will discuss the experimental apparatus, as well as the recent experimental results obtained with this prototype apparatus. We will also present the data analysis method used for the phase retrieval, and discuss the accuracy of the method as well as the measurement sensitivity obtained using this method.

1. Introduction

While conventional absorption contrast radiography measures the intensity variation resulting from the neutron interaction with an object, phase contrast radiography utilizes the phase shift induced by the object. The phase shift mechanism can be described by the interaction between the incident wave of radiation and the potential that the wave experiences within the object. The phase sensitivity is usually much higher than the absorption contrast and it is estimated that it has up to three orders of magnitude higher phase sensitivity than the absorption contrast given the same intensity is utilized for both techniques. In the case of neutrons, the particle wave of neutron is known to be shifted by nuclear potential, magnetic potential, etc. [1].

There has been no way to directly measure the phase of the neutron and all the methods till date are based on converting the wave into a measurable quantity, which is an interference pattern on a detector. The crystal interferometer is the oldest and possibly most accurate method. It has been used for accurate neutron coherent scattering length measurements and for the fundamental nuclear study [1]. However, it is not suitable for imaging because of the geometrical limitation within the crystal interferometer and its long measurement time. The propagation method uses a neutron beam with high spatial coherence for the wave to be diffracted strongly especially on the edges of an object [2]. By measuring the pattern behind the object at multiple positions, it is possible to retrieve the phase using the transport-of-intensity equation. However, this method suffers from a loss of intensity when it forms the spatially coherent beam as the typical pinhole size used is on the order of several hundred micrometers or less as compared to that of the typical transmission radiography which uses apertures of order 1 cm in diameter. Moreover, phase retrieval accuracy is limited by detector resolution and polychromatic nature of the beam. A new grating-based neutron phase imaging was reported by Pfeiffer et al. in 2006 [3], which was modified from a grating-based imaging using X-rays [4]. The neutron modification made use of a source grating to generate spatial coherence and intensify the Talbot self-imaging patterns whereas with synchrotron X-rays this is not necessary due to the inherent high coherence of these sources.

Since this new technique is promising for general applications in the future planned cold neutron imaging facilities at the KAERI and the NIST, we have developed a prototype phase imaging system, based on the newly emerged grating methods, at the NG-7 neutron interferometer and optics facility (NIOF) of the NCNR to fully explore and further improve the technique. We intend to utilize this prototype for feasibility tests at the monochromatic beam line to gain experience and to add new ideas for the optimal design of the user instrument. A full and systematic description on the work and the performance of the system is reported in this paper.

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In Section 2, the description of the system at the monochromatic beam line is given in Section 2.1 together with the system parameters chosen. A summary on the grating fabrication at the nanofabrication facility of the NIST follows in Section 2.2 providing a few essential tips during the fabrication. System alignment procedure and instability of the system are analyzed in Section 2.3 and the data analysis methods are described in Section 2.4. In Section 3, the representative images from the system are presented to show preliminary performance of the system, phase sensitivity, and nuclear phase shift. The work has been summarized and the future plan is foreseen in Section 4.

2. Materials and methods

2.1. The phase imaging system

The phase imaging system with gratings has been built at the NIOF in the cold neutron guide hall of the NCNR. The schematics of the system and the photo are shown in Figs. 1 and 2. The beamline is originally designed for the crystal neutron interferometer and the beam is extracted by the pyrolytic graphite (PG) (0 0 2) monochromator. The wavelength of the neutron is chosen at 4.4 Å, which is near the peak of the spectrum of the cold neutron guide. The aperture size of 2 cm and the distance to the sample of 3.5 m determines the resolution of the beam called L/D. The measured neutron fluence rate near the front end of the experimental table was $7.67\times10^{4}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The maximum length of the flight path was about 3.9 m. The system parameters and the grating parameters were designed to best utilize these conditions. The key components of the system are the gratings and the main parameters of the system are summarized in Table 1. The source grating creates the spatial coherence at the sample and the multiple slits intensify the beam intensity as a multiple slit. The phase grating induces a π-phase shift and generates the interference pattern called Talbot self-image at a particular distance (Talbot Distance), which is related to the grating period and the neutron wavelength. When a phase object is introduced in front of the phase grating, it induces the phase shift in the object

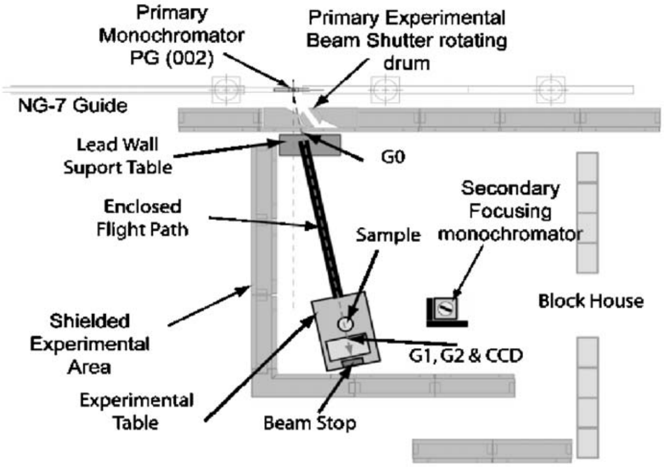

Fig. 1. Diagram of the phase imaging system.

Table 1
Main design parameters of the system.

Grating	Parameter	Value
Source grating	Period	773.98 μm
	Duty cycle	0.4
	Height of the Gd absorption line	10 μm
Phase grating	Period	7.96 μm
	Depth of the trench	34.39 μm
	Distance from the source	3.50 m
Analyzer grating	Period	4.00 μm
	Height of the Gd absorption line	2.8 μm

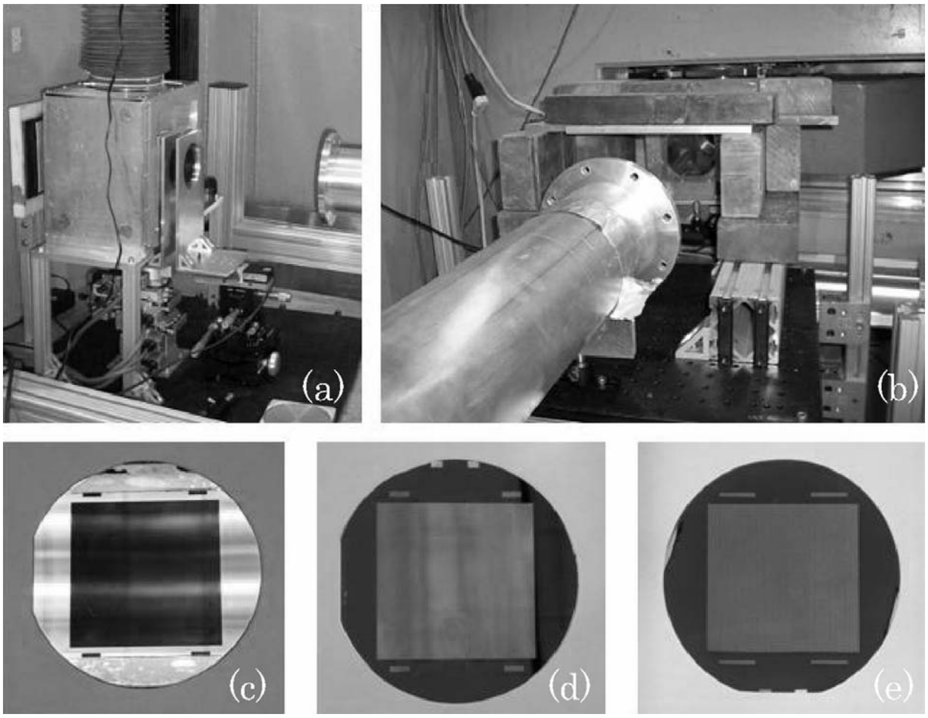

Fig. 2. Picture of the phase imaging system: (a) G1, G2 and the detector, (b) G0, (c) G2, (d) G1, and (e) G0.