Demonstration of optical thickness measurement using multilayer cold neutron interferometer

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Abstract. We have measured the optical thickness of a phase object for the first time using multilayer cold neutron interferometer. The measured phase shift of $15.1 \pm 1.9$ wavelength agreed with the expected value of $17.4 \pm 0.7$ wavelength due to an about 600-\textmu m-thick silicon plate. This demonstration reconfirmed that two paths in our new interferometer were completely separate, and showed its applicability into various precise measurements.

1. Introduction
The multilayer mirror, which can reflect cold and very cold neutrons, is one of powerful neutron optical devices for interferometry. In addition to utilization of the long-wavelength neutrons, accurate alignment of multilayer mirrors with a large distance makes it possible to increase interaction time of neutrons with external potentials in the interferometer. Such a multilayer interferometer will be more sensitive in phase detection than the conventional silicon single-crystal interferometers, and contribute to precise measurements of small interactions.

We have recently developed a new type of multilayer neutron interferometer \cite{1}. The multilayer interferometer consisted of a pair of beam splitting etalons (BSEs) (Figure 1) \cite{2} with an air gap of 189 \textmu m in spacing. Two paths of the interferometer were completely separated with a center-to-center distance of 328 \pm 9 \textmu m at an incident angle of 0.99 \pm 0.05 degrees, while the previous multilayer interferometers had almost overlapped paths. Clear interferograms with maximum contrast of 67 \% were also successfully observed.

This progress enables us to carry out experiments in more various configurations than before. As one of the configurations, we demonstrated the optical thickness measurement of a phase object inserted into the one-side path using the multilayer interferometer.

2. Experiment and discussion
The experimental setup is shown in Figure 2. A Jamin-type interferometer consisted of a pair of BSEs. In the interferometer, the incident neutron waves were firstly converted to superposition of the spin-up and spin-down states by the polarizer and the first $\pi/2$ RF spin flipper: $1/\sqrt{2} (|\uparrow\rangle + |\downarrow\rangle)$. The superposition state was then split spatially by the first BSE. For the symmetric geometry,
Figure 1. Schematic view (left) and photograph (right) of a beam splitting etalon (BSE). The BSE separates the incident spin superposition state into two parallel paths with the spin-up and the spin-down states.

Figure 2. Experimental setup. A weak magnetic field of about 10 G was generated vertically by a guide coil all over the beam (omitted in the figure). The distance between two BSEs was 300 mm.

each spin state was reversed by the $\pi$ RF spin flipper: 
\[
\frac{1}{\sqrt{2}} (|\uparrow\rangle + |\downarrow\rangle) \rightarrow \frac{1}{\sqrt{2}} (|\downarrow\rangle + e^{2i\chi_{\pi}} |\uparrow\rangle),
\]
where $\chi_{\pi}$ is the phase of oscillating magnetic field in the $\pi$ RF spin flipper relative to the other $\pi/2$ RF spin flippers, and the phase factor $e^{2i\chi_{\pi}}$ is due to the spin state transition [3]. After the spin reversal, the spatially separate paths were recombined by the second BSE. Finally, the spin state from each path was converted to the spin-up state by the second $\pi/2$ RF spin flipper and the analyzer: 
\[
\frac{1}{2} (|\uparrow\rangle + e^{2i\chi_{\pi}} |\uparrow\rangle).
\]
The interferograms were obtained by scanning the relative phase $\chi_{\pi}$. The change of $\chi_{\pi}$ of 180 degrees gave a interferograms of one cycle. For the present measurement, a solenoid as a phase-shifter-coil was arranged behind the second BSE. The experiment was carried out at the monochromatic cold neutron beamline MINE2 [4] of Japan Research Reactor No.3 (JRR-3) in Japan Atomic Energy Agency (JAEA). The mean wavelength of the beam was $\lambda_0 = 0.88$ nm with a bandwidth of 2.7% in full width at half-maximum.

As verified in the previous studies [5, 6], the contrast of interferograms in the multilayer interferometer is proportional to the coherence function $\Gamma(\sigma_k, L_0)$ as
\[
\Gamma(\sigma_k, L_0) = \exp \left[ -\frac{1}{2} (\sigma_k L_0)^2 \right],
\]
when we use semi-monochromatic beam with a mean wavenumber $k_0$ and the standard deviation $\sigma_k$ of Gaussian distribution. $L_0$ is the optical path difference between the two paths and $L_0$ of zero makes an “echo point”, that is, the maximum contrast point.
In the case of the present demonstration, $L_0$ is expressed as

$$ L_0 = L_B + L_b + L_i . $$  \hspace{1cm} (2)

$L_B$ was provided by the phase-shifter-coil. The phase object inserted into the one-side path caused $L_b$. $L_i$ arose from the shift of relative angle between two BSEs. $L_B$ was proportional to the current $j$ supplied to the phase-shifter-coil as

$$ L_B = -\alpha_B j . $$ \hspace{1cm} (3)

The coefficient $\alpha_B$ of the coil, which was also established in the previous studies [6], was $9.1\lambda_0/A$. The insert was a silicon plate with the thickness $D_{Si}$ of $600 \pm 25$ nm. $L_b$ is therefore expressed as

$$ L_b = -(n(k_0) - 1) D_{Si} \hspace{1cm} (4)$$

$$ \approx \frac{2\pi\nu b}{k_0^2} D_{Si} , \hspace{1cm} (5)$$

where $n$ is the refractive index of the material for slow neutrons, $b$ is the neutron scattering length of the nucleus, $\nu$ is the average number density, and $k_0$ is the neutron wavenumber.

The phase-shifter-coil induced the optical path differences $L_B$ of $0$, $9.1\lambda_0$, $18\lambda_0$, $27\lambda_0$, and $36\lambda_0$, corresponding to the currents of $0$, $1$, $2$, $3$, and $4$ A, respectively. These optical path differences affected the contrast of interferograms according to Equation 1. Four times measurements of interferograms at each current were carried out iteratively with/without the silicon plate. The sequential change of the contrast are shown in Figure 3 and 4. The transition of average contrast for each data set is shown in Figure 5. These transitions were fitted to Gaussian curves with a common $\sigma_k$ and maximum contrast. The fitting gave the common $\sigma_k$ of $0.079 \pm 0.008$ nm$^{-1}$, which reproduced well the wavelength dispersion of $0.082$ nm$^{-1}$ at the MINE2 beamline. The optical path difference $L_b$ of the inserted silicon plate caused an echo-point-shift. The observed echo-point-shift was $15.1 \pm 1.9$ nm. Within the margin of error, this shift was consistent with the expected value of $17.4 \pm 0.7$ nm calculated by using the number of density $\nu$ of $5.00 \times 10^{22}$, and the scattering length $b$ of 4.15 fm.

3. Conclusions

We have succeeded in measuring the optical thickness of the phase object inserted into the one-side path for the first time using the multilayer neutron interferometer. This measurement demonstrated the functional feature of completely separate paths in our new interferometer. With improved phase stability we can advance this pilot experiment into precise measurements, for example, measurement of neutron scattering lengths [7] for the study of many-body-force between nucleons. Cold neutron interferometers have a great advantage in measuring scattering lengths because the phase shift due to the nuclear interaction is proportional to the square of neutron wavelength as shown in Equation 5.

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Figure 3. Transition of interferograms due to additional optical path differences induced by magnetic field of the phase-shifter-coil. No phase object was inserted into any paths of the interferometer. All the data were fitted by sine curves with the cycle fixed at 180 degrees.

Figure 4. Transition of interferograms due to additional optical path differences induced by magnetic field of the phase-shifter-coil. A silicon plate was inserted into the one-side path of the interferometer. All the data were also fitted by sine curves with the cycle fixed at 180 degrees.
Figure 5. Variation in average contrast of four times measurements. Solid circles and open triangles indicate the case of Figure 3 and 4, respectively. Observed shift of echo point corresponds to optical thickness of about 600-μm-thick silicon plate for 0.88-nm neutrons.

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