Realization of an X-Ray Fabry-Perot Resonator

The idea of using multi-plate crystals to confine incident hard X-rays in a closed loop by means of multiple reflections was proposed more than thirty years ago. The simplest two-crystal plate cavity has been investigated mostly theoretically based on the dynamical theory of X-ray diffraction. A variety of experiments in realizing X-ray cavity resonance have also been proposed. With the advent of synchrotron radiation, high resolution and time resolved experiments have been conducted and experimental attempts to observe cavity resonance fringes have been pursued. Here we report the first direct observation of resonance fringes inside the energy gap with the total-reflection range of the (12 4 0) back reflection from monolithic two silicon crystal plates of 25—150 μm thickness and a 40—150 μm gap using synchrotron radiation with energy resolution of 0.36 meV at 14.4388 keV. Thus a Fabry-Perot resonator for hard X-rays and near gamma-rays could be realized. The cavity resonance results from the coherent interaction between the X-ray wave fields generated by the two plates with a gap smaller than the temporal X-ray coherence length. This finding may open up new opportunities for high-resolution X-ray scattering/diffraction, phase-contrast X-ray imaging, and X-ray optics.

An X-ray Fabry-Perot resonator consists, in principle, of two crystal plates as reflecting mirrors. Cavity resonance occurs when an incident X-ray beam is reflected back and forth coherently between the two plates, thus generating interference fringes. Each reflection is a back diffraction from a set of atomic planes with a Bragg angle very close to 90°. Although there have been many theoretical studies of X-ray cavity resonance reported in the literature, the difficulty in realizing X-ray resonators with observable resonance fringes arises mainly from the required experimental conditions on coherence being not easily attainable. In this study, we considered both the temporal and spatial coherence of incident X-rays in relation to the effective crystal gaps and designed the following experiments: Several two- and multi-plate crystal cavities with a plate thickness ranging from 25 to 150 μm and a gap of 40—150 μm between them were prepared from a four-inch Si (001) crystal wafer by using a microelectronic lithography process. The width and height of the crystal plates are 800 and 200 μm, respectively. Cavities with plate numbers up to 8 were manufactured. Meanwhile, a Si (111) double-crystal mono-chromator and a four-crystal ultrahigh resolution monochromator were used to yield an energy resolution of $\Delta E/E = 2.5\times10^{-8}$ at 14.4388 keV, such that the longitudinal coherent length is much longer than the crystal gap. The required longitudinal coherence for cavity resonance is therefore fulfilled. The transverse coherence determined by the photon emittance was retained very close to normal in-cidence.

The experiment was carried out at the Taiwan undulator beamline, BL12XU, at the SPring-8 synchrotron radiation facility in Japan. The storage ring is operating at 8 GeV and 100 mA. The incident radiation, monochromatized by the two monochromators mentioned above, impinged on one of the cavities, which was sat at the center of an eight-circle diffractometer. Energy scans were performed by tuning together the Bragg angles of the four-crystal monochromator with a minimum step of 0.005 arcsecond, equivalent to 58.548 μeV in energy. The crystal cavity can be rotated by adjusting $\Delta\theta_v$ and $\Delta\theta_h$ around the vertical and horizontal directions, respectively, with a minimum step of 0.0005°.

The (12 4 0) reflection of silicon was chosen as back diffraction. Both the forward-transmitted (000) and the back-reflected (12 4 0) beams were monitored by a pin-diode detector and an ion chamber, respectively. A 24-beam simultaneous diffraction, including those from (12 4 0) and (000) reflections occurred. This means that 24 reciprocal lattice points (r.l.p.s) lie simultaneously on the surface of the Ewald sphere, thus generating 24 diffracted beams from the center of the Ewald sphere towards the 24 r.l.p.s. Fig. 1 shows $\Delta\theta_v$-scans of (a) the forward-transmitted (000) beam and (b) the back-reflected (12 4 0) beam. The two-plate cavity of 70 μm thickness and 100 μm gap was set at ΔE = 9 meV off the exact energy of 14.4388 keV with 0.002° per step. Fig. 1c shows the energy E scan. According to the dynamical theory of X-ray diffraction, the angular $\Delta\theta_v$ and $\Delta\theta_h$ scans of the forward transmitted beam (000) show broad dip profiles with an averaged flat bottom (see Fig. 1a) at the photon energies close to the exact 14.4388 keV. The region of broad width is the total reflection region, which corresponds to the energy gap in the energy scans. The minimum intensity in Fig. 1a is due to the 24-beam diffraction. Distinct interference fringes attributed to the cavity resonance are clearly observed. The expected cavity resonance fringes in the energy-scans are also noticeable. The energy range of about 10.4 meV is the energy gap (Fig. 1c). The fringe spacing E_d, is about 3.60 meV, in agreement with the theoretical value of 3.65 meV calculated from the relation E_d= hc/2d, where d = d_g+t with d_g being the gap and t the crystal-plate thickness. E_d is the so-called free spectral range of a cavity. This result is also consistent with calculations based on the dynamical theory. The effective resonance distance d = d_g+t can be considered as the distance between two electric fields, the so-called X-ray wave fields, generated by each crystal plate in one back-and-forth reflection. Also, $2(d_g + t\ n_x) \cong 2dn_x \cong 2d$ is the optical path length of X-rays which gives a phase shift of 2π with n_x being the X-ray index of refraction and $n_x = 1-\delta$ with the correction $\delta = 2.3\times10^{-6}$. The spectral width Γ = 1.60 meV of the fringes gives the finesse $F = E_d/\Gamma$ = 2.3, which is less than the designed value of F = 4.0 due to crystal surface roughness and inclination, small lattice distortions and thermal expansion effects.

Figure 2 shows the intensity distributions of the resonance interference at ΔE = 12 meV off the exact photon energy: (a) Angular $\Delta\theta_v - \Delta\theta_h$ distribution of the transmitted (000) intensity I_T of the two-plate crystal cavity in a linear scale; (b) Two-dimensional contour map of Fig. 2(a); (c) Calculated map of (b) without angle and energy integrations. The 3-dimensional plot, Fig. 2a, reveals the interference intensity distribution. The 2-dimensional fringes in Fig. 2b show concentric rings of alternating maxima and minima and the straight lines are due to the coplanar diffractions denoted as Lines L1 - L9.

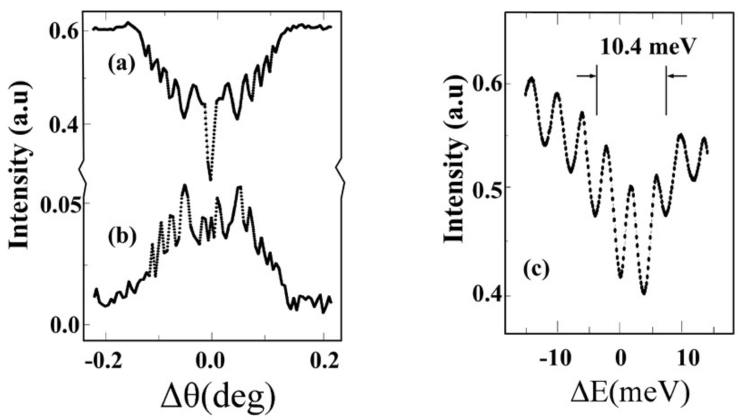

Fig. 1: Angle-scans of the forward-transmitted (a) and back-reflected beams (b); (c) Energy scan.

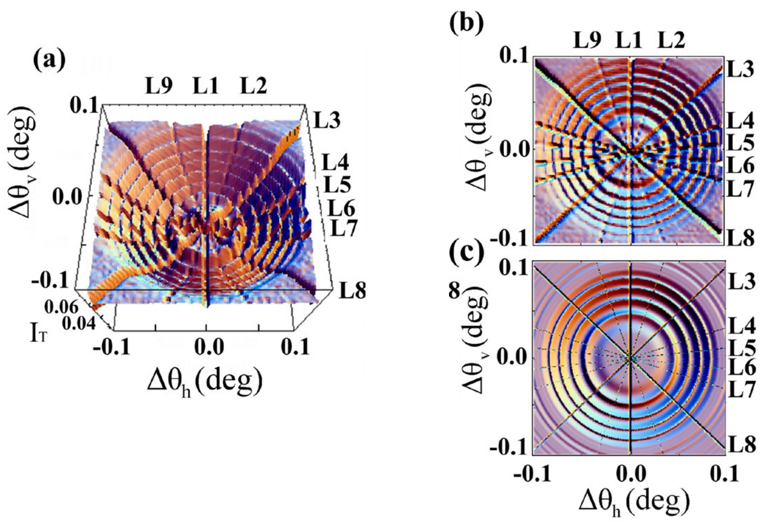

Fig. 2: Intensity distributions of resonance interference: (a) three-dimensional, (b) two-dimensional, and (c) calculated two-dimensional maps.

For different photon energies, different back diffraction together with different multiple reflections may be considered. In principle, the presence of multiple diffractions is not problematic. Slight angular detuning of the crystal cavity from the multiple-beam positions is always possible without losing the resonance condition. Since there is a fixed phase relation between the forward-transmitted beam and the back-reflected beam and the X-rays from the cavity can provide narrow energy and angular widths, this crystal cavity can be utilized for phase-contrast and high-resolution X-ray optics. Those can then be used in high-resolution X-ray scattering/ spectroscopy and phase-contrast microscopy. Also, the Fourier transform of the energy scans, which provides time-structures for the X-ray cavity re-sonance, facilitates the investigations of dynamics in solids, liquids, and biomolecules. Furthermore, crystal cavities of better quality may be useful for the development of hard X-ray (or gamma-ray) lasers, if suitable lasing materials can be developed.

BEAMLINE
SP12U Inelastic X-ray Scattering Beamline

EXPERIMENTAL STATION
Eight-circle diffractometer

AUTHORS
S.-L. Chang, Y.-R. Lee, and W.-H. Sun
Department of Physics, National Tsing Hua University, Hsinchu, Taiwan

Y. Stetsko and M.-T. Tang
National Synchrotron Radiation Research Center, Hsinchu, Taiwan, R.O.C.

M. Yabashi
SPring-8/JASRI, Hyogo, Japan

T. Ishikawa
SPring-8/RIKEN, Hyogo, Japan

PUBLICATIONS

- S.-L. Chang, Y. P. Stetsko, M.-T. Tang, Y.-R. Lee, W.-H. Sun, M. Yabashi, and T. Ishikawa, Phys. Rev. Lett. **94**, 174801 (2005).

CONTACT E-MAIL
slchang@phys.nthu.edu.tw