Microscopes, spectrometers, interferometers, and other high-resolution optical devices are indispensable in natural sciences. Invented by Fabry and Pérot [4] the interferometers known under their names have been used for more than a century to explore the visible spectral region of the electromagnetic radiation. They are used for high-precision wavelength measurements in atomic spectroscopy, in astrophysics, and many other physical as well as life sciences [1, 10]. They are used as interference filters and resonators in laser physics. High resolution instruments of this kind would be extremely useful for research with x rays. X-ray Fabry-Pérot interferometers (or resonators) could be used as interference filters with micro-eV spectral resolution [9] for studying dynamics of solids, liquids, and macroscopic biological molecules. They could be used for phase-contrast imaging of nanometer-scale objects. A combined optical-x-ray Fabry-Pérot interferometer could bridge the optical and x-ray domains by measuring directly the x-ray to visible light wavelength ratios. X-ray Fabry-Pérot interferometers present an exciting and challenging problem.

![Diagram of an x-ray Fabry-Pérot interferometer](image)

Figure 1: Top: schematic of an x-ray Fabry-Pérot interferometer with $\alpha$-Al$_2$O$_3$ mirrors as in Fig. 2 separated by a gap of $d_g = 50$ mm. Center and bottom: the appearance of the Fabry-Pérot resonances on the x-ray energy scale in reflection (left), and transmission (right). The central parts on an expanded scale are shown in the bottom graphs.

The main components of the simplest Fabry-Pérot interferometer are two highly reflecting low absorbing parallel mirrors (Fig. 1). The system becomes transparent despite the high reflectivity of each mirror when the gap $d_g$ between the mirrors is an integer multiple of half of the radiation wavelength as then the resonance condition for standing wave formation in the gap is fulfilled. The energy separation between two successive transmission resonances - the free spectral range $E_f = h\nu/2d_g$ - is a constant independent of the incident photon energy. The spectral width of the transmission resonances $\Gamma = E_f/F$ is smaller the higher the finesse $F = \pi\sqrt{R/(1 - R)}$, or equivalently, the higher the mirror reflectivity $R$ [1]. With a reflectivity of $R = 0.85$ ($F = 19.3$) and

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Figure 2: Energy dependence of the reflectivity (a)-(b), and transmissivity (a')-(b'), of x rays at normal incidence to the (0 0 0 30) atomic planes of α-Al₂O₃ single crystals used as the interferometer mirrors: (a)-(a'): mirror 1, \( d_1 = 63.0(1) \ \mu m \); (b)-(b'): mirror 2, \( d_2 = 58.6(2) \ \mu m \) thick. \( E_0 = 14.315 \) keV. Red lines are theoretical fits by using the dynamical theory of x-ray diffraction in exact backscattering. In the fit, the 2 meV energy width of the incident radiation is taken into account.

a gap of 50 mm, the width of the transmission resonances is in the sub-micro-eV range. Physically, such a small spectral width is due to interference of a large number \( \approx F \) of coherent waves arising from multiple reflections.

Steyerl and Steinhauser [9] have pioneered the idea of a Fabry-Pérot-type interference filter for x rays proposing the replacement of the optical mirrors by Bragg back reflection from parallel-sided silicon single crystals. The theory of such devices was propounded by Caticha et al. [3, 2]. A revised theory taking also into account possible imperfections of the x-ray Fabry-Pérot interferometers was given by Kohn et al. [5], see also [6, 7].

The results, which we are reporting here, were obtained at the undulator beamline ID3 at the synchrotron radiation facility APS (ANL, Argonne). Many-years preliminary studies were carried out at the wiggler beamline BW4 at HASYLAB (DESY, Hamburg). The results presented here were published in [8].

The (0 0 0 30) Bragg reflection in α-Al₂O₃ single crystals was used to reflect 14.315 keV x-rays backwards. The energy dependence of reflectivity and transmissivity in exact backscattering for two α-Al₂O₃ crystal plates picked out for the interferometer mirrors is shown in Fig. 2. The measurements were performed with x rays monochromatized to a bandwidth of 2 meV, and directed normal to the mirrors with an accuracy of 5 \( \mu rad \). The dependences for the mirror 1 in Fig. 2(a) and mirror 2 in Fig. 2(b) look very similar. The peak reflectivities are almost the same: \( R = 0.84(2) \). Still, a slightly different period of oscillations on the wings can be observed. The oscillations are due to the interference of the waves reflected from the front and the rear crystal surfaces. The period is \( E_d = hc/2d \). This simple relation allows one to directly ascertain the crystal thicknesses to be \( d_1 = 63.0(1) \ \mu m \) and \( d_2 = 58.6(2) \ \mu m \) for the mirrors 1 and 2, respectively. The small difference \( \delta d = d_1 - d_2 = 4.4 \ \mu m \) in the mirror thicknesses will become important in the experiment, which proves the functioning of the interferometer (Fig. 4). A Fabry-Pérot interferometer built with these mirrors should have a finesse of \( F = 18(3) \).

Figure 1 shows simulations of the reflectivity and transmissivity of an x-ray Fabry-Pérot interferometer with such mirrors. The theory [5, 6, 7] was applied. The mirrors in the interferometer are at a distance of \( d_g \approx 50 \) mm chosen for reasons of the accessible time resolution, which is discussed
The left panels in Fig. 3 show the measured time response of the interferometer in transmission. The right panels show the energy dependence of the mirror reflectivity and the spectral distribution of the incident x-ray photons. The Bragg reflectivity of the mirrors changes with the energy of the incident radiation. Far from the reflectivity maximum the incident radiation pulses traversed the cavity practically without interaction, as in Fig. 3(a). Apart from a few very weak just arising multiple-reflection signals, this plot actually shows the instrument’s time resolution function.

The closer the energy of x rays is to the reflectivity maximum the more significant changes occur. Multiple-reflection signals reappearing every $358(1)$ ps with descending strength are observed. These evenly spaced signals appear as a result of x-rays bouncing back and forth between the
Figure 4: Energy dependence of the reflectivity - (a),(b), and transmissivity - (a’),(b’), of the two-crystal interferometer. X rays are at normal incidence to the first crystal. (a)-(a’): The atomic planes of both crystals are adjusted parallel to better than 0.35 µrad. The solid red lines are theoretical spectra calculated by the theory of x-ray Fabry-Pérot interferometers [5, 6, 7] and averaged over the 2 meV bandwidth of the incident radiation. The dashed line in (a’) is the product of the transmissivities through the mirror 1 and 2, i.e., describes the transmissivity through a system of two noninteracting mirrors in Bragg backscattering. (b)-(b’): The mirror 2 is tilted by 3 µrad from the parallel state. The red solid line in (b’) is the same as in (a’). Vertical dashed line indicate the nodes of beatings in (a).

mirrors. When the x-ray energy coincides with the reflectivity maximum, a train of more than 30 peaks is observed due to ≃ 60 reflections, see Fig. 3(c). Such a long train of pulses is observed not only due to a high reflectivity of the mirrors. Also, the reflecting atomic planes of the mirrors should be set parallel. The longest decay time measured was τ ≃ 0.86(1) ns. Such a decay time corresponds to an energy width of Γ ≃ 0.76(1) µeV for the transmission resonances. By using \( t_f = 358(1) \) ps, one derives for the finesse of the interferometer \( F = \frac{2\pi\tau}{t_f} \approx 15 \).

About \( F \) interfering beams are sufficient to obtain an almost perfect interference pattern with sharp Fabry-Pérot resonances [6, 7]. We observe ≃ 30 periods, i.e., twice of this. One has to be, however, sure that these beams interfere. The next experiment demonstrates interference of the beams reflected from the mirrors.

Figure 4 shows the energy dependence of the reflectivity - (a),(b), and transmissivity - (a’),(b’), of the interferometer. Experimental data are shown by the circles connected with the dotted lines. In case of Fig. 4(a)-(a’), the atomic planes of the both crystals are adjusted parallel to better than 0.35 µrad. The period of the thickness oscillations fits perfectly to that of the theoretical curve in Fig. 2(a). While the period fits perfectly, the theoretical curve in Fig. 2(a) does not agree with the experimental data in Fig. 4(a) in other respects. An additional periodical modulation - a beat-pattern - of the thickness oscillations with four nodal points is observed. Furthermore, the measured reflectivity in the antinodes of the beat-pattern is two times higher than expected from single crystal reflectivity. Already these two features clearly demonstrate that a two-crystal interferometer is realized. The energy separation between the nodal points \( \delta E_d = 140(3) \) meV corresponds to a quantity of length \( \frac{\hbar c}{2\delta E_d} = 4.4(2) \) µm, which agrees with the difference in the mirror thick-
nnes \( \delta d = d_1 - d_2 \) obtained from the fits of the spectra in Figs. 2(a) and 2(b). Therefore, the beat pattern appears due to a slightly different thickness of the crystal mirrors. The observed beating demonstrates unequivocally the interference of the waves reflected from the two mirrors.

The measured spectra in Fig. 4(a)-(a') agree almost perfectly with the spectra evaluated by the theory of x-ray Fabry-Pérot interferometers [5, 6, 7]. The red solid lines in Fig. 4(a)-(a') present the spectra calculated for monochromatic x rays (as in Fig 1) and then averaged over the 2 meV bandwidth of the incident radiation. No free parameters were used. All the details, i.e., the beat-pattern in the reflection spectrum, the transmissivity of the system, are described by the theory. The transmissivity is higher than that of two independent mirrors - shown by the red dashed line in Fig. 4(a') - as it should be for a Fabry-Pérot interferometer.

The beat-pattern in Fig 4(a) can be easily destroyed by tilting the second crystal. Tilting by an angle of \( \approx 3 \mu \text{rad} \) is enough to blur the nodes closest to the reflectivity maximum, as shown in Fig 4(b). With increasing tilt the beat-pattern disappears, and the reflectivity of the two-crystal system transforms to that of the first mirror, as in Fig 2(a).

The reported experimental result bears direct evidence of the successful performance of the used two-crystal x-ray interferometer. This brief discussion illustrates that the present design of the x-ray Fabry-Pérot interferometer can be implemented in physical experiments. In this respect, it is important to note, that sapphire is transparent for visible light. This opens up a possibility to realize combined optical-x-ray Fabry-Pérot interferometers, as optical mirrors can be fabricated by thin film metalization of the sapphire x-ray mirrors.

References


