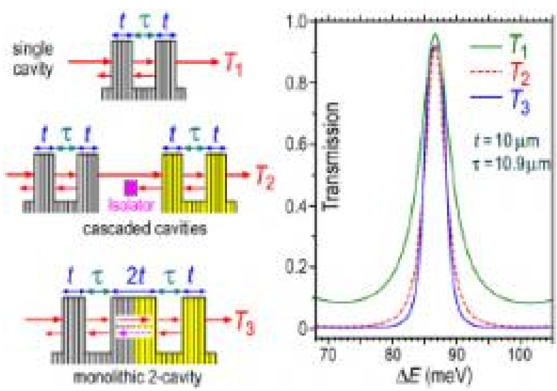
Multiple crystal cavities for unlimited X-ray energy resolution and coherence

August 23 2012



Fabry-Perot resonance spectra (right) of a single-cavity resonator, two cascaded resonators, and a monolithic two-cavity resonator, respectively. Note the significant background of T1 as the Bragg reflectivity from a 10-μm diamond plate is only 59%. By comparison, spectra T2 and T3 are very similar, both having sharp tails and extremely low background. Diamond 224 back reflection (E = 8.5146 keV, Dawin range 67 ≤ ΔE ≤ 106 meV).

(Phys.org)—The Fabry-Perot (FP) interferometer is one of the most fundamental and important optical instruments used for accurate measurements and control of the wavelength of light, and for making lasers. It is typically made of two parallel mirrors that successively reflect light back and forth in a cavity to create resonance.

However, this scheme does not work for hard x-rays, such as those produced by the Advanced Photon Source (APS), because there are no specularly reflecting mirrors (which reflect light from a single incoming direction into a single outgoing direction) for hard x-rays at large incidence angles.

A solution to this problem is to use Bragg back reflections (a Bragg angle close to 90°) from two parallel crystal plates to produce x-ray FP resonance, as has been proposed and explored for many decades.

A primary motivation to pursue x-ray FP resonators is that the energy resolution of conventional crystal-based, high-resolution x-ray optics has reached the physical limit (for example, a few milli-electron volts for medium energies, approximately 10 keV), which is far from being able to meet the demanding requirements of frontier research using modern synchrotron light sources and free-electron lasers.

Therefore, tremendous efforts have been made in recent years to develop new concepts and schemes to surpass this limit. X-ray FP resonance is one such scheme for achieving almost unlimited energy resolution because the bandpass is determined by the cavity width instead of the Bragg-reflection Darwin widths.

Implementation of x-ray FP resonance has been very difficult. Previous experiments showed that single-cavity resonance has extremely low finesse (i.e., low Q factors corresponding to wide resonance peaks), low efficiency, and significant background, indicating that such resonators could hardly be used for practical applications.

Now, researchers from Argonne National Laboratory, Brookhaven National Laboratory, and Nanjing University have demonstrated the principles of a novel and advanced design of x-ray FP resonators, which consists of multiple cavities separated by crystal plates with specific thickness ratios. These resonators were illustrated to have extremely high finesse, sharp tails, and ultralow background (i.e., ultrahigh contrast), which can achieve unprecedented high resolution and (temporal) coherence.

The low finesse of a single cavity surrounded by two thin crystal plates is due to the intrinsically low Bragg reflectivity of the plates (particularly for highly absorbing crystals). If one sequentially cascades two identical single-cavity resonators, the spectral background can be remarkably suppressed because the combined transmissivity is the product of the transmissivities of the two individual resonators.

Because cascading two resonators in experiments requires stringent alignment, isolation, and control of temperature and stability, a much simpler scheme is to merge the two resonators into a monolithic two-cavity resonator with the thickness of the middle plate twice those of the two outer plates.

Based on rigorous dynamical theory calculations, the researchers illustrated that such a monolithic two-cavity resonator is equivalent to the cascading of two single-cavity resonators. Furthermore, this principle can be extended to an arbitrary monolithic N-cavity resonator, which is equivalent to the cascading of N separate single-cavity resonators. This is an extremely interesting property that is unique to X-ray diffraction.

Based on this mechanism, one can design multiple equal-width cavities (but with specific plate thicknesses) to sharpen the FP peaks and lower the background to any desired extent. In particularly, the multi-cavity resonator can be designed to have a single resonant peak within the Darwin width by choosing a specific cavity width. Combined with a pre-monochromator, such resonators can be used as high-resolution monochromators for white beams. It is also possible to design multi-cavity resonators with different cavity widths to eliminate undesired resonance orders so as to achieve unprecedented ultrahigh finesse and energy resolution.

Fabrication of multi-cavity structures from a silicon crystal by microelectronic lithography has already been demonstrated. But diamond crystals are superior for multi-cavity x-ray FP resonance due to their much lower absorption. Recent progress in diamond structuring technologies may also allow the fabrication of similar structures from diamond crystals.

This study opens exciting possibilities for making multi-cavity monochromators with nearly unlimited energy resolution (at least up to μmeV in principle).

In the future, such inline monolithic mini-monochromators could revolutionize the conventional crystal optics for modern versions of ultrahigh-resolution x-ray spectroscopy, coherent diffraction, phase contrast imaging, etc.

Next, the researchers plan to experimentally test silicon-based multi-cavity FP structures utilizing a number of double cavities already fabricated at Brookhaven National Laboratory with well-controlled cavity parameters and flat cavity walls.

Fabrication and development of diamond-based FP resonators have also been discussed within the diamond x-ray optics community, and with diamond crystal growers and manufacturers.

More information: X. R. Huang, D. P. Siddons, A. T. Macrander, R. W. Peng3, and X. S. Wu, "Multicavity X-Ray Fabry-Perot Resonance with Ultrahigh Resolution and Contrast," *Phys. Rev. Lett.* 108, 224801 (2012). DOI:10.1103/PhysRevLett.108.224801

Provided by Argonne National Laboratory