X-Ray Waveguiding in Resonance with a Periodic Structure

Novel X-ray waveguides are designed based on the concept of photonic crystals. The waveguides consist of a pair of claddings sandwiching a core with a periodic structure. X-rays that undergo multiple interference are confined in the core by total reflection at the core-cladding interfaces to form a characteristic waveguide mode whose field distribution matches the periodicity of the core. Because the propagation loss in this mode, which is in resonance with a periodic structure, becomes distinctively low, substantial single-mode propagation of X-rays can be achieved. This concept will open up new fields in X-ray optics.

Collimated X-ray beams with high spatial coherency have attracted much attention because of their remarkable advantages in analytical and diagnostic applications. X-ray waveguides (WGs) using one- or two-dimensional nano-scale gaps, which enable the propagation of X-rays on individual discrete modes, have been proposed. However, the width of the gaps in the direction of X-ray confinement needs to be extremely small to achieve the formation of a coherent X-ray beam by satisfying the single-mode propagation conditions. Here, we propose a novel X-ray WG based on the physics of photonic crystals in the X-ray regime [1].

The structure of the WG and the underlying concept are schematically shown in Fig. 1. The WG consists of a core with a periodic structure and a pair of claddings sandwiching the core. The X-rays undergoing multiple interference in the periodic core can be confined by total reflection at the core-cladding interfaces, when the Bragg angle for the periodic structure is sufficiently smaller than the total reflection angle. The periodicity-resonant WG mode is resonant with both the total thickness and the periodicity of the core. The electric field profile of this resonant mode has fine fringes with the same periodicity as that of the core, and the antinodes of the field are located in the layers with a lower absorption coefficient, as shown in Fig. 1. On the other hand, the shape of the envelope shows that the field is concentrated in the center of the core. Because of these two features of the formed fields, the resonant mode achieves an exceptional low propagation loss.

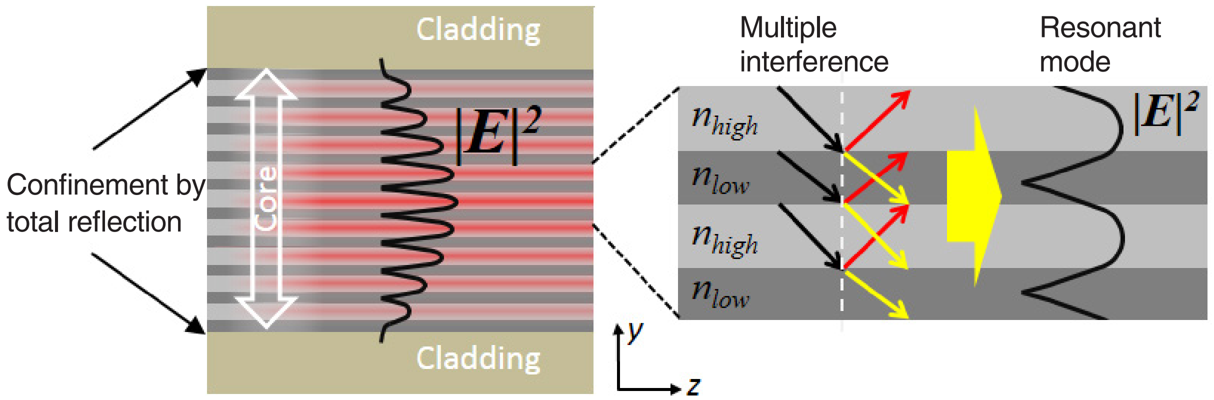

Figure 1: The concept of the periodicity-resonant X-ray waveguide.

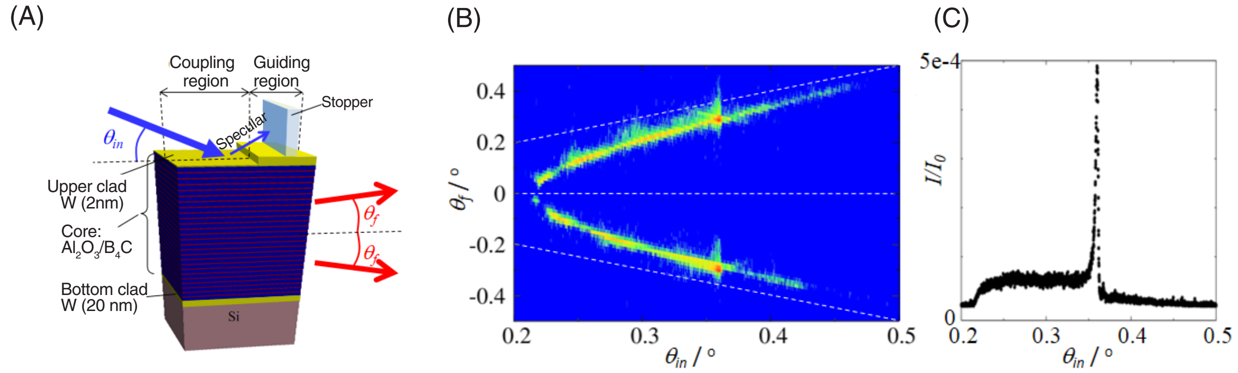

Figure 2: (A) The structure of the waveguide and the measurement geometry, (B) dependence of the far-field pattern on the incident angle θ_{in}, (C) dependence of the normalized X-ray intensity on θ_{in}.

The structure of the waveguide used for the experiment is schematically shown in Fig. 2(A). The core is an Al_2O_3/B_4C multilayer, which is sandwiched by a pair of tungsten claddings. The thickness of the Al_2O_3 and B_4C is 3 nm and 12 nm, respectively, and the number of pairs is 100. The thickness of the claddings is 20 nm except for the coupling region with a ~2 nm thickness. The experiments for the waveguide were performed at the BL-4A using X-rays with 10 keV, which was monochromated using a Si (111) double-crystal monochromator. The beam was shaped into 150 μm height x 1000 μm width. The divergence angle and the energy band width $\Delta E/E$ of the beam were ~0.002° and ~2×10^{-4}, respectively. The X-ray beam was impinged on the coupling region of the waveguide at a grazing angle θ_{in}, and the spatial distribution of the emitted X-rays, the far-field pattern, was recorded using a 2D detector.

The dependence of the far-field pattern on the incident angle is graphically shown in Fig. 2(B). A pair of symmetric bright lines with respect to θ_f (emission angle) = 0° is observed, which are caused by the 0^{th} order Fraunhofer diffraction originating from the near-field distribution of the waveguide modes. As shown in Fig. 2(B), a pair of spots with large intensity is observed at an incident angle slightly smaller than the Bragg angle for the multilayer. These are formed by the X-rays propagated on the periodicity-resonant waveguide mode. The origin of this resonant mode is multiple interference in the periodic core, which makes the consequent X-ray beam spatially coherent. The X-ray beam created by this novel waveguide will find various innovative applications in X-ray optics using its unique spatial coherency as well as small divergence angle.

REFERENCE

[1] K. Okamoto, T. Noma, A. Komoto, W. Kubo, M. Takahashi, A. Iida and H. Miyata, *Phys. Rev. Lett.* **109**, 233907 (2012).

BEAMLINE

BL-4A

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