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Diamond X-ray refractive lenses with high acceptance

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Abstract

During the last years X-ray refractive lenses with various design have been manufactured from mono-crystalline diamond by laser ablation with ultra-short laser pulses. The present paper shortly reviews diamond lenses with high acceptance which are intended for transportation of radiation at high-power X-ray accelerator sources. Planar, linear and two-dimensional lenses with parabolic or spherical shape were manufactured and tested at laboratory and synchrotron X-ray sources in focusing and imaging modes. Surface morphology and material quality were also analyzed both with X-ray and conventional methods. Considerations on ways to improve the quality of surface and shape are presented.

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Keywords: X-ray optics; X-ray refractive lenses; beam conditioning; diamond; laser ablation;

1. Introduction

During the last decade, several projects on creation of cyclic accelerator X-ray sources of new generation have been approved and funded. NSLS-II and recently built MAX-IV synchrotron sources will be followed by an upgrade of European Synchrotron Radiation Facility, which pushes a world-wide trend of reaching the maximal X-ray brightness we have ever seen. These X-ray sources of new generation are called Ultimate storage rings [1], which means that generated radiation has almost circular shape with a size of few tens of microns, very low emittance and very high power of light. A light with such properties will "enable the study of materials that we use today and

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improve them beyond the performance that we know." It "will allow scientists to develop new materials and products that we cannot even imagine today, such as medications with better and more precise functions and fewer side-effects, nanoparticles for diverse areas of application, including paints, catalysis or computing, or lighter and stronger packaging materials for the future", says the web-site of MAX-IV [2]. Then, a big issue arises – what are the X-ray optical elements and materials that are suitable to withstand high thermal and radiation loads while transporting X-radiation from its source to a sample with maximal efficiency and preservation of its properties.

If we consider optical instrumentation for ultimate storage rings, first of all we should pay attention to refractive optical elements as they have proven to be compact; in-line; stable; easy aligned; and coherence-preserving optics for micro- and nano-beam focusing at third-generation synchrotron radiation sources. X-ray refractive lenses were introduced in 1996 [3] as drilled rows of cylindrical holes in bulk aluminum which has successfully focused X-radiation. Since that moment they have made a big evolutionary change. To date, lenses have a variety of shape and design solutions – either planar [4] or two-dimensional [5] with spherical [3], parabolic [6] or kinoform [7] profile. Al, Be, C, Ni, Si or even SU-8 photoresist may be used as lens optical materials, allowing one to focus a high-energy radiation down to micro- and nano-dimensions which has been applied in many of experimental techniques (x-ray nano-interferometry [8-11], high-resolution microscopy and tomography [12-23], standing-wave microscopy [24], high-resolution diffraction [25], high-pressure XANES and XMCD [26] and so on). X-ray optical materials with minimized absorption and high thermal stability, maximized refractive power and high acceptance are of interest to the new sources. If we put a ratio of a refractive index decrement δ to the total linear attenuation coefficient, μ, to describe the optical performance of the material, we will see that Al, C and Be are the best in the energy interval from 5 to 50 keV. Such energy interval is a typical region of interest for a big part of experiments with X-ray radiation. Beryllium here is the top low-Z material for production of 2D parabolic lenses of highest quality which are suitable both for X-ray imaging and focusing down to 10^{-7} m scale. However, the biggest disadvantage of beryllium is its polycrystalline material structure which limits a lens resolution in X-ray imaging and microscopy modes. As highly spatially coherent X-ray beam is intended for investigation of the nano-scale material structure, it easily sees the inner grain structure of a lens, leaving absolutely no chances to avoid appearance of "speckles" in a transmitted beam. Therefore, single-crystalline carbon in a form of diamond could be more applicable. As it is a perfect single crystal, radiation should not "feel" any material structure. Optical properties (δ/μ) of diamond rank second whereas the refractive efficiency, δ, is double that of beryllium, cutting twice the number of lenses in the experimental scheme. Diamond has already shown excellent thermal and X-radiation stability in high heat load monochromators [27-30], Bragg mirrors [31], monochromators for self-seeding XFELs [32, 33], and beam-multiplexing monochromators for XFELs [34]. The last fact is not least as beryllium lenses require powerful cooling to avoid recrystallization of material grains and degradation of the lens profile in high-heat flux X-ray beams [35].

Diamond has been already used in manufacturing of refractive optical elements. In the very first research, planar refractive lenses were manufactured either by combination of electron-beam lithography and reactive-ion etching [36], or transfer molding technique [37, 38]. Such approach was not very encouraging as processed polycrystalline lenses had very modest depth and aperture (~ 30 microns in [39]) which is much less than typical size of a synchrotron beam (500 - 1000 μm). Besides, thin diamond films grown on the silicon mold typically consist of nanocrystals (~50 nm) or small microcrystals (1-2 μm) that results in a reduced thermal conductivity in comparison with single-crystalline diamond (~30 W/cmK) and also causes a noticeable scattering of X-rays. However, during the last decade in diamond processing technology a special attention has been giving to use of ultra-short laser pulses (<10 ps), which ensures low ablation threshold (even in IR and visible spectral range), negligible thermal diffusion and reduced thickness (<50 nm) of graphitized layer [40] on the ablated diamond surface. The positive effect of applying of ultra-short pulses to precise diamond processing was verified with regard to high-aspect-ratio drilling and cutting [41], micromachining of diamond tool tips [42, 43], 3D surface profiling [44, 45] and submicrometer-scale surface structuring [46]. Basing our research on the laser technology, we employed laser ablation of a single-crystalline diamond to processing of stacked planar [47], individual linear [48, 49] and two-dimensional [50, 51] refractive lenses with a significantly increased quality and aperture of almost one millimeter. In the present paper we would like to show together and briefly compare all types of lenses that have been manufactured. They have been tested both at synchrotron radiation and conventional laboratory X-ray sources.