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Ray-tracing simulations for the ultra-lightweight X-ray optics toward a future jupiter exploration mission

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Abstract

To investigate a feasibility for in situ X-ray imaging spectrometer JUXTA (Jupiter X-ray Telescope Array) onboard a Japanese Jupiter exploration mission, we demonstrated the ideal performances, i.e., angular resolution, effective area and grasp, of our original, conically-approximated Wolter type-I MEMS-processed optics, by extending the previous ray-tracing simulator. The novel simulator enables us to study both on- and off-axis responses for our optics with two-stage optical configurations for the first time. The on-axis angular resolution is restricted to ~13 μm corresponding to ~10 arcsec on the detector plane without considering the diffraction effect and dominated by the diffraction effect below ~1 keV (e.g., 13 arcsec at 1 keV). Si optics can achieve effective area of >700 mm^2 and grasp of >1600 $\mathrm{mm}^2\,\mathrm{deg}^2$ at our interesting energy of 600 eV. Larger effective area and grasp can be attained by employing Ni as a substrate material or Ir as a reflecting surface material. However, other factors produced in the fabrication processes such as the waviness on the mirror surface and the deformation error cause the significant performance degradation. Thus, we concluded that MEMS-processed optics can satisfy all the requirements of JUXTA only if the manufacturing accuracy can be controlled.

Keywords: X-ray; Optics; MEMS; JUXTA

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1. Introduction

Since collecting X-rays refractively is difficult, grazing-incidence optics are often utilized in X-ray astronomy. A typical critical grazing incidence angle is about several degrees or less at 1 keV, which requires typically tens to thousands of mirrors to gain a large effective area. Thus, mass is one of the most important factors for X-ray optics to realize large effective areas and a wide field of view in a tight weight limit to reduce launch costs. Angular resolution is also needed to provide good imaging quality.

We have been developing our original X-ray optics (Ezoe et al., 2006, 2008a,b, 2010, 2012a,b; Mitsuishi et al., 2009, 2010a,b, 2012) which are made by MEMS (Micro Electro Mechanical Systems) technologies. Thus, hereafter in this paper, we define our optics as MEMS-processed X-ray optics. MEMS-processed optics, ten-micrometer scale small mirrors in a hundred-micrometer scale thin and deformed wafer with a small radius of curvature, make it possible for us to realize the lightest and compact optics. The curvilinear pore structure

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and the accurate deformation can achieve high angular resolution at the same time in principle even though a contribution of diffraction is not negligible especially below 1 keV (∼13 arcsec at 1 keV). To date, we verified an X-ray focusing by using a single-stage MEMS-processed optic for the first time (Ezoe et al., 2012a). Therefore, as a next step, we have started designing and fabricating two-stage MEMS-processed optics to complete the conically-approximated Wolter type-I optical system. Thanks to advantages on its mass and compactness, MEMS-processed optics are baselined as one of key components of a unique instrument named JUXTA (Jupiter X-ray Telescope Array) (Ezoe et al., 2013) for the future Japanese exploration mission of the Jupiter's magnetosphere. The mass and power limits of the instrument system including a detector and an optic, are 10 kg and 10 W, respectively. Therefore, simulation studies are essential to clarify the ideal performances for our original optics and optimize the design for the JUXTA X-ray optics. It should be emphasized that this simulator can be applied for a better understanding of experimental data and provide us with useful suggestions to achieve target performance.

A ray-tracing simulator for MEMS-processed optics was firstly established (Ezoe et al., 2010) assuming a single planar plate type configuration for an ideal point X-ray source as a grand application of microanalysis. However, not only on-axis but also off-axis responses for the final configuration, i.e., deformed two-stage conically-approximated Wolter type-I optical system, have not been investigated so far. A novel ray-tracing simulator for deformed two-stage MEMS-processed optics should take into account additional configuration parameters which were not included in the previous simulator such as an interval between the two optics and a radius of curvature and a number of light paths to estimate a contribution of stray light especially at larger off-axis angles. In this paper, the expected capabilities for both on- and off-axis photons are shown for the first time by building the novel ray-tracing simulator for conically-approximated Wolter type-I MEMS-processed optics. Finally, we discuss implications for the JUXTA.

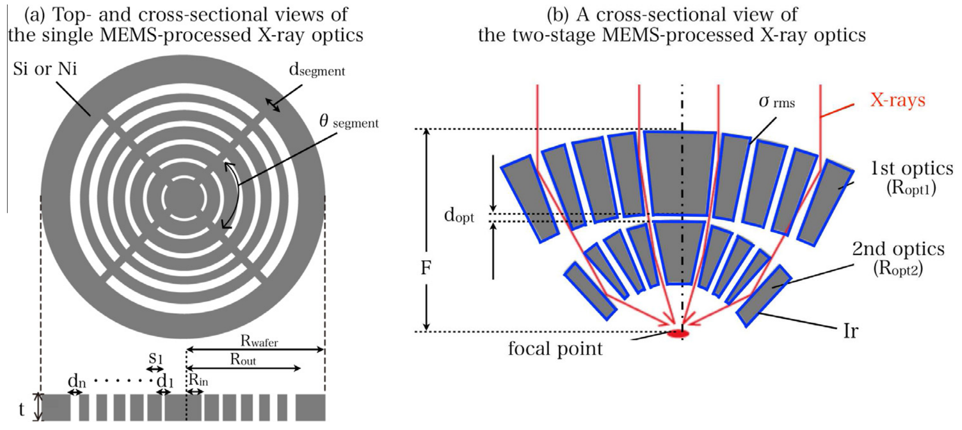
2. Ray-tracing simulations

2.1. Geometry and configuration parameters

To evaluate the ideal performances of our two-stage MEMS-processed optics, a novel simulator was constructed. The configuration parameters used in the ray-tracing simulations are defined as Fig. 1 and summarized in Table 1. The X-ray mirrors are arranged from an inner radius of R_{in} to an outer radius of R_{out} on a wafer with a radius of R_{wafer} and thickness, t. The 1st optic is located a focal length (F) away from a detector and the focal length should be 1/4 of a radius of curvature of the first optic (R_{opt1}) in the two-stage optical system. R_{opt2} should be 1/3 of R_{opt1} because an inclination of 3 θ is needed at the second optic to realize an incident angle of θ for a reflection vector with a reflection angle of 2 θ at the first optic. θ corresponds to an incident angle at the first optic. d_{m} and s_{m} correspond to the width of the mth pore and an interval between mth and $(m+1)$ th pores. Thus, the radial distance from the wafer center of the mth mirror is expressed by

$$R_{\text{in}} + d_1 + \sum_{i=1}^{m} (d_{i+1} + s_i). \tag{1}$$

d_{segment} and θ_{segment} show an interval between segments and an azimuthal angle of neighboring two segments. d_{opt} means the space between 1st and 2nd optics. σ_{rms} and E exhibit an rms surface roughness of reflecting mirrors and the energy of incident X-ray photons. The typical rms surface roughness of the mirror in our optics is about 1 nm (Ezoe et al., 2012a) as measured by atomic force microscope measurements. In this paper, we assume that σ_{rms} is independent of position on the wafer and d_{opt} is 0 as an ideal condition. Three sorts of optics,


(a) Top- and cross-sectional views of the single MEMS-processed X-ray optics

(b) A cross-sectional view of the two-stage MEMS-processed X-ray optics

Fig. 1. Configuration parameters of the MEMS-processed X-ray optics in the ray-tracing simulations.