Characterization of Micro-Structured Optical Arrays

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Abstract. Characterization methods for grazing-incidence reflecting channel arrays are discussed. Characterization of single-reflection, unactuated micro-structured optical arrays is required to evaluate their performance as focusing elements. Numerical simulations allow the contribution of the x-rays reflected by the channel walls to be distinguished from the overall transmitted signal, and are applied to axial sources. Experimental results are also shown to support the simulations by translation of the channel structure parallel to a detector plane, allowing separation of reflected and transmitted x-rays through the array on the detector.

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MICRO-STRUCTURED OPTICAL ARRAYS

Micro-structured optical arrays (MOAs) are currently in development by the UK Smart X-ray Optics consortium as x-ray focusing devices [1-3]. MOAs use grazing-incidence reflections from an array of channels all contributing to a focus spot, as shown in Fig. 1(a). The anisotropic etching process currently used to create MOAs produces an array of parallel, linear channels etched through a silicon wafer, with very small roughness on the sidewalls of each channel (~1.2 nm RMS) [4], to reduce scattering effects.

FIGURE 1. (a) Cross section of an unactuated MOA illuminated by x-rays from a point source on the optical axis. The x-rays are reflected by the array of channels, and converge at a focus in a shadowed region behind the central stop. Typical dimensions are $L=100–200 \ \mu m$, $\delta=10 \ \mu m$. (b) Schematic of a single-reflection actuated MOA with the central active area of etched linear channels and piezoelectric actuator strips bonded to the surface.
The active area of an MOA for which x-rays can contribute to a focus is limited by the critical angle for grazing-incidence reflection and is typically etched into a 2 mm × 2 mm central square on the wafer. In addition to this, the surface of the MOA wafer can be actively curved (Fig. 1(b)) using piezoelectric actuators bonded to the surface, allowing control of the focal length of the MOA. In practice it is advantageous to use a pair of MOAs in series [3], either to produce 2-D focusing or to control aberrations.

Both simulation and experimental characterization results are presented below for a single-reflection unactuated MOA, to gain information about reflectivity and imaging performance of the 1-D channel array.

SIMULATION OF A SINGLE-REFLECTION MOA

Routines have been developed to simulate the action of a single-reflection, unactuated MOA structure. These routines project light from a point source through the MOA channel structure onto a detector plane (Fig. 1(a)). Radiation from an on-axis source point at a distance $S_1$ from the MOA is reflected towards a common point at a distance $S_2 = S_1$ from the MOA, resulting in an approximate focusing effect. For actuated MOAs, similar focusing behavior can be produced, with $S_2 \neq S_1$.

Figure 2 shows the ray paths emerging from the exit surface of the MOA as the detector plane is moved away from the MOA, and confirms the existence of a narrow beam crossover on the optical axis in the shadow of the MOA’s central stop. Extended sources could also be considered, by adding the contributions to the detected intensity from source points displaced above or below the optical axis.

**FIGURE 2.** Results of simulation show the change in intensity distribution through focus where $S_1 = 165$ mm (see Fig. 1(a)). Transmitted (blue) and reflected (red) radiation can be shown separately.

Figure 2 shows the focusing effect from a point source with the array of channels symmetrically distributed to either side of the $y$–$z$ plane. The region of transmitted radiation overlaps the focused radiation everywhere except for the shadowed region downstream of the central stop of the MOA, making direct comparison of simulated reflected intensity distributions with experimental measurements difficult for an axial source. By translating the MOA
channels from a symmetric distribution about the optical axis by a perpendicular displacement $T$, it is possible to separate the reflected and transmitted radiation at the detector plane, as shown schematically in Fig. 3.

**FIGURE 3.** Translation of the MOA channels results in separation of the reflected (red) and transmitted (blue) x-rays at the detector plane.

The simulated effect of displacing the MOA channels is shown in Fig. 4. For each displaced position in the range $-10 \text{ mm} \leq T \leq 10 \text{ mm}$ the distribution at the detector plane of rays transmitted or reflected by the channel array is plotted. A vertical line section taken at $T = 0$ in Fig. 4, where the reflected and transmitted ray patterns overlap, corresponds to the line section at $S_2 = 265 \text{ mm}$ in Fig. 2. This shows the case where the channels are symmetrically distributed on either side of the source position. A clear separation of the intensity distributions is seen after translation of the channels by a few mm in either direction.

**FIGURE 4.** Simulation showing translation of the MOA channels across the source plane, for a point source at distance $S_1 = 165 \text{ mm}$, and a detector plane at $S_2 = 265 \text{ mm}$.

**EXPERIMENTAL CHARACTERIZATION OF SINGLE-REFLECTION MOAS**

Experimental characterization has been performed using a micro-focused electron bombardment source with an aluminium target, producing a small-sized broadband x-ray source. X-rays with energies up to 10 keV from this source illuminate the active area of an MOA, and the resulting image is projected onto a CCD. Translation of the MOA parallel to the CCD plane has been examined for $S_1 = 165 \text{ mm}$, $S_2 = 265 \text{ mm}$.

Figure 5 shows the comparison between experimental results and the simulated model for $T = 2.15 \text{ mm}$. The relative intensities do not match and cannot be directly compared, since the micro-focus source has a finite source size and the broadband illumination results in a continuous distribution of reflectivities within MOA channels that is not perfectly smooth. The experimental x-ray distribution on the detector will be broadened compared to the simulation, which has assumed a point source and uniform reflectivity within the MOA channels. Despite these...
differences, when the position of the central stops have been aligned (at 0 pixels), the small peak in the scattered intensity measured experimentally is consistent with the single reflection peak predicted by the simulation for $T = 2.15$ mm.

![Graph](image)

FIGURE 5. Comparison between simulated (black) and experimental (red) intensity distributions. The simulation corresponds to a channel displacement of $T = 2.15$ mm from the optical axis. The peak at around 500 pixels corresponds to the position of the x-rays reflected by the channel array.

CONCLUSIONS

MOAs have been identified as a large-aperture focusing optics for soft x-rays. Linear channel arrays are currently in development and can be bonded to piezoelectric actuators in order to provide active control of the focal length of the MOA. Simulations of single-reflection, unactuated MOAs show the focusing effect for axial point sources. Experimental characterization can be carried out more easily when the MOA is displaced off-axis, so that the relative contribution of the reflected and transmitted radiation can be distinguished. The characterization of individual channel performance can be examined from an out-of-focus intensity distribution.

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