Development of multilayer mirror based soft X-ray polarimeter

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Multilayer mirror consists of a periodic repetitions of a low and high atomic number materials coated alternatively. It works on the principle of the Bragg’s law. Thickness of a single layer pair is called the period of bi-layer.

\[ m\lambda = 2 \ d \sin \theta \]

- Narrow band reflection possible by tuning coating parameters
- Fabrication over a wide range in d spacing possible
- Larger \( d \ (> 1 \text{ nm}) \) possible where natural crystals are not available
Why multilayer mirrors

- d-spacing (1.20 nm – 7 nm) corresponding to (600 eV – 100 eV).
- Almost 100% modulation index at Brewster’s angle
- Good spectral resolution.

- Narrow band-pass (~ 20 eV).
- Low reflectivity (~10%).
Instrument design
**Instrument Design**

- Instrument primarily consists of three major sub-systems:
  - Soft X-ray concentrator.
  - Multilayer mirror placed at $45^\circ$ with respect to the optical axis of the concentrator.
  - Soft X-ray detector positioned at the Nasmyth focus of the instrument.
**X-ray concentrator**

- A concentric shell of conic section grazing incidence mirrors
- Geometric area of 630 cm²
- Effective area = energy dependent reflectivity profile for each shell times the geometric area

<table>
<thead>
<tr>
<th>Sl.No</th>
<th>Parameter</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Number of shells</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>Focal length</td>
<td>110 cm</td>
</tr>
<tr>
<td>3</td>
<td>Inner most shell radius</td>
<td>5 cm</td>
</tr>
<tr>
<td>4</td>
<td>Outer most shell radius</td>
<td>15.06 cm</td>
</tr>
<tr>
<td>5</td>
<td>Axial length of each mirror</td>
<td>10 cm</td>
</tr>
<tr>
<td>6</td>
<td>Inner most shell ‘θ’</td>
<td>1.27°</td>
</tr>
<tr>
<td>7</td>
<td>Outer most shell ‘θ’</td>
<td>3.84°</td>
</tr>
<tr>
<td>8</td>
<td>Coating</td>
<td>Ni</td>
</tr>
<tr>
<td>9</td>
<td>Substrate</td>
<td>0.2 mm thick Al foil</td>
</tr>
</tbody>
</table>
Multilayer mirrors

- Single multilayer mirror has a very narrow band response.
- Hence 5 different multilayer mirrors are used one after the other (on a rotating wheel) to cover the wide range of X-rays from 200-800 eV.

<table>
<thead>
<tr>
<th>Mirror ID</th>
<th>Coating</th>
<th>Period of bi-layers (nm)</th>
<th>Position of 1\textsuperscript{st} Bragg peak (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>W-Si</td>
<td>1.5</td>
<td>587</td>
</tr>
<tr>
<td>M2</td>
<td>Ni-Si</td>
<td>1.8</td>
<td>490</td>
</tr>
<tr>
<td>M3</td>
<td>Ni-Si</td>
<td>2.3</td>
<td>384</td>
</tr>
<tr>
<td>M4</td>
<td>Co-C</td>
<td>2.9</td>
<td>306</td>
</tr>
<tr>
<td>M5</td>
<td>Co-C</td>
<td>3.5</td>
<td>254</td>
</tr>
</tbody>
</table>
**Effective area estimation**

- The converging beam from the concentrator results in a range of angles from 37 to 53 incident on multilayer mirrors.
- Results in a reduction in peak reflectivity and increase in spectral width of reflection.
- Also, reflectivity profile of the concentrator varies as a function of its Y-axis. This is because of change in incident of X-rays on the concentrator.
Effective area estimation

- Overall effective area of the concentrator is estimated.

\[ EA = \int_{y=-15}^{y=+15} R_{\theta(y)}^{ml}(e) \times A(y) dy \]
Modulation index of the instrument

- Modulation index of a polarimeter is given by,

\[ \mu = \frac{S_{max} - S_{min}}{S_{max} + S_{min}} \]

- Overall modulation index over a band is given by,

\[ \mu = \frac{G_S - G_P}{G_S + G_P} \]
Modulation index

<table>
<thead>
<tr>
<th>Mirror ID</th>
<th>band of operation (eV)</th>
<th>$G_S \text{ (cm}^2\text{eV)}$</th>
<th>$G_p \text{ (cm}^2\text{eV)}$</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>520-685</td>
<td>405</td>
<td>6</td>
<td>0.97</td>
</tr>
<tr>
<td>M2</td>
<td>435-570</td>
<td>327</td>
<td>5</td>
<td>0.97</td>
</tr>
<tr>
<td>M3</td>
<td>340-450</td>
<td>407</td>
<td>8</td>
<td>0.96</td>
</tr>
<tr>
<td>M4</td>
<td>270-360</td>
<td>660</td>
<td>16</td>
<td>0.95</td>
</tr>
<tr>
<td>M5</td>
<td>220-300</td>
<td>1030</td>
<td>17</td>
<td>0.96</td>
</tr>
</tbody>
</table>
Instrumental contribution to polarization by the concentrator

- Since the concentrator is circularly symmetric, the overall instrumental polarization gets cancels out at the detector.
- Muller matrix on integration to $360^\circ$ results in a diagonal matrix and hence there is no cross talk in the system.

$$M = 0.5(1 - \epsilon^2) \times \begin{bmatrix} A + B & 0 & 0 & 0 \\ 0 & A & 0 & 0 \\ 0 & 0 & A & 0 \\ 0 & 0 & 0 & A - B \end{bmatrix}$$

$$A = |R_s + R_p|^2, \quad B = |R_s - R_p|^2$$

$\epsilon$ is the central obscuration ration of the inner and outer radii of the annular aperture
**Instrumental polarization of the concentrator**

- Residual instrumental polarization is given by,
  \[ IP = \frac{(R_s - R_p)^2}{(R_s + R_p)^2} \]

- At grazing angles \( R_s \sim R_p \).
Instrument Sensitivity

• MDP is the smallest polarization that can be detected at a 99% probability.

\[
MDP = \frac{4.29}{\mu r} \times \sqrt{\frac{r + b}{t}} = \frac{4.29}{\mu} \frac{1}{\sqrt{N}} \sqrt{1 + \frac{b}{r}}
\]

• MDP is different for different bands as the instrument sensitivity and source flux varies.

• For example, MDP of a blazer PKS 2155-304 is estimated for this instrument at 10% detector quantum efficiency and for 100 ks integration time (25 ks per band).

<table>
<thead>
<tr>
<th>Mirror ID</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy band (eV)</td>
<td>520-685</td>
<td>435-570</td>
<td>340-450</td>
<td>270-360</td>
<td>220-300</td>
</tr>
<tr>
<td>MDP for 100 kS</td>
<td>1.4</td>
<td>1.35</td>
<td>1.04</td>
<td>0.64</td>
<td>0.57</td>
</tr>
</tbody>
</table>
Developmental efforts
Development status

- Fabricated a set of W/B4C multilayer mirrors with d ranging from 1.5 nm to 5.5 nm and number of layers as high 300.
- Tested the performance stability with time.
- Underwent thermal cycling and pre and post performance evaluation.
- Concentrator prototype fabricated with flight spare gold coated grazing incidence mirrors from astronomy mission ASTROSAT.
Long time performance of mirrors

D-1.9 nm
Inferences:

- Density of the top layers is changing possibly due to the oxidation or contamination layers.
- Peak reflectivity at first Bragg peak reduces initially and tends to remain constant over time.
- Larger period mirrors are more stable over time than short period mirrors.
- Bragg peak broadens over time. This can be explained due to interlayer diffusion of the layers.
Effects of thermal cycling on multilayer mirrors

- **D=1.5 nm**
  - Before cycling: $R_{b1}=13.8\%$, $\theta_{b1}=2.75^\circ$
  - After cycling: $R_{b1}=13.12\%$, $\theta_{b1}=2.75^\circ$

- **D=3.2 nm**
  - Before cycling: $R_{b1}=22\%$, $\theta_{b1}=1.37^\circ$
  - After cycling: $R_{b1}=20.3\%$, $\theta_{b1}=1.37^\circ$

- **D=4.4 nm**
  - Before cycling: $R_{b1}=38.7\%$, $\theta_{b1}=1^\circ$
  - After cycling: $R_{b1}=33.14\%$, $\theta_{b1}=1^\circ$

- **D=5.5 nm**
  - Before cycling: $R_{b1}=22.5\%$, $\theta_{b1}=0.85^\circ$
  - After cycling: $R_{b1}=20.4\%$, $\theta_{b1}=0.85^\circ$

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Summary

- Soft X-ray polarimeter for soft X-rays (<0.9 keV).
- High modulation factor (~0.9).
- Spectral resolution decided by the multilayer rather than detector.
- Small size and constant period multilayers (easy to fabricate).
- Design allows scale up and scale down without major modifications.
- Rotation of the instrument is needed during observations.
- Short term changes over a broad band cannot be observed.