Sliced multilayer gratings (SMG) as dispersive elements for the soft X-rays


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http://xrays.msk.ru/index.html

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The plan of the presentation

- Sliced multilayer gratings (SMG) and their history
- Production, testing and possible applications.
- Asymmetrical crystals. Their physical likeness to SMG and possible applications.
The main types of X-ray spectral elements

- **Ruled gratings.** The number of grooves up to 5000 grooves/mm. They can be coated with a multilayer structure. Spectral range $\lambda > 3-4$ nm.

- **Holographic etched multilayer gratings.** Spectral range $\lambda > 0.5$ nm.

- **Sliced multilayer gratings (SMG).** Spectral range 4.4-30 нм.
Sliced multilayer gratings

- They are produced by cutting a multilayer structure containing hundreds or thousands period at some angle.
- Their advantages rest upon properties of the initial multilayer.
The scheme of the SMG

- $\alpha$ is slicing angle, $\phi_0$ is incident angle, $\phi_{-1,1}$ are diffracted angles for the first and minus first orders
- N number of periods
- Slicing angle is usually 5-10°
The brief history of SMG

- The first gratings based on $MoSi_2/Si$ multilayer coatings were created in 1993.
- They were used for the spectroscopy of Al laser plasma in P.N. Lebedev Physical Institute.
- Their main parameters were

<table>
<thead>
<tr>
<th></th>
<th>SMG 1</th>
<th>SMG 2</th>
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</thead>
<tbody>
<tr>
<td>d, nm</td>
<td>35.4</td>
<td>19</td>
</tr>
<tr>
<td>N</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>$\alpha$, deg.</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Range, nm</td>
<td>12.5-25</td>
<td>12.5-20</td>
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A photo of a SMG mounted in the holder
An electron microscopic image of a $Mo/Si$ SMG
An example of $Al$ plasma spectrum

Spectrum obtained in 1994 using SMG1 ($Mo/Si$)

Several spectral line were identified including:

$Al$ V-VI 13-13.1 nm
$Al$ VII 24 nm
$O$ VI 12.2-17.3 nm
New Mo/Si SMG gratings

The spectrum obtained with recently fabricated Mo/Si SMG.

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The transition into the new spectral range
4.4-5 nm

- This spectral range near the K edge of carbon is very promising for the material science, biology and astrophysics.
- We chose a new pair of materials namely Co/C multilayer structure.
- The number of periods is up to 4000. Thus the essential improvements in spectral resolution and sensitivity are possible.
Short wavelength SMG recently produced

- Multilayer coating Co/C. Spectral range 4.4-5 nm

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<th>SMG 2</th>
<th>SMG 3</th>
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<tbody>
<tr>
<td>d, nm</td>
<td>11</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>N</td>
<td>1000</td>
<td>4000</td>
<td>8000*</td>
</tr>
<tr>
<td>α, deg.</td>
<td>10</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>θ, deg.</td>
<td>23</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>R%</td>
<td>20</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

* doubled number of periods
Testing of SMG gratings for 4.4-5 nm

- Measurements with a carbon X-ray tube - SMG1
- Spectroscopic measurements with Al micropinch plasma source - SMG3 (doubled)
Our setup for the testing with an X-ray tube

- V - vacuum chamber
- EG - electron gun
- T - carbon target
- S1 - entrance slit
- G - goniometer
- SL - SMG
- S2 - exit slit
- PC - flow proportional counter

Basic pressure $10^{-5}$ torr. The time of a single measurement $1s$ gives $10^3$ counts in the PC.
Measurements

- We used a new technique based on a flow proportional counter.
- The monochromatisation wasn’t used because it’s unnecessary.
- As a source a carbon X-ray tube was used.
- The scheme provides high sensitivity and short time of measurements.
The results for the SMG 1 (Co/C)

- Experimental results (filled circles) match with calculations (solid line)
- The subtraction of background (filled triangles) improves the similarity
- All curves were normalized to unity, since it was impossible to measure absolute efficiency
The micropinch source of soft X-rays

1 - vacuum chamber, 2 - cathode, 3 - additional electrode, 4 - anode, 5 - capacitor
The source image

The size of the source was about 200 μm

100 μm
The spectrum of the Al plasma taken with a high resolution spectrometer

<table>
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<tr>
<th>4.8297 nm</th>
<th>5.2299 nm</th>
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<tbody>
<tr>
<td>4.8338 nm</td>
<td>5.2446 nm</td>
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Two close duplets were chosen for SMG testing. Also their third order repetitions are shown.

Two close duplets were chosen for SMG testing. Also their third order repetitions are shown.
The scheme of measurements with the micropinch source


The minus first order was used. The film was used as a detector.
The results of the measurements for SMG3

Two duplets remained unresolved
The experimental results for the SMG3 (doubled)

- The spectral resolution: $\lambda/\Delta\lambda \sim 100$
- Linier dispersion 0.6 nm/mm
- The dispersion range $\Delta\lambda \sim 0.1$ nm
- Optimum focus 23.5 mm

It's possible that the misalignment in the SMG caused the decrease in spectral resolution
A SMG with a slight ($\gamma \sim 10^{-8}$) period gradient will function as a cylindrical lens. The focus distance is:

$$f = -\frac{D^2}{n\lambda\gamma} \left[ 1 - \left( \sin \phi + \frac{n\lambda}{D} \right)^2 \right]$$

$$D = \frac{d}{\sin \alpha}$$

The focusing was confirmed in the earlier and recent spectral measurements.
The prospects of SMG gratings

- The creation of Co/C SMG gratings with a number of periods 10000 and more.
- Transition to the spectral range of 1-3 nm. The possible multilayer structures are $W/\text{Si}$ or $W/B_4C$.
- The continuation of production of SMG based on $\text{Mo}/\text{Si}$ coatings for the range 12.5-25 nm.
Symmetrical (SC) and asymmetrical (AC) crystals

- **SC**
  - Crystal planes are parallel to the surface
  - The reflection band width determines resolution
  - Bragg condition $\alpha=0$
  - The full equivalent of multilayer mirror

- **AC**
  - Crystal planes are at the angle $\alpha$ to the surface
  - The parallel beam is dispersed
  - The reflection band width determines dispersion range
  - The full equivalent of SMG
AC as a diffraction grating

- AC is a diffraction grating with a period $D = d / \sin \alpha$
- The spectral resolution is determined by the number of crystal planes on the surface $N = L / D$
- The diffraction angle is $\varphi_n = \varphi + 2 \alpha$, the grating equation $D (\cos \varphi_n - \cos \varphi) = n \lambda_0$. 

\[ D (\cos \varphi_n - \cos \varphi) = n \lambda_0 \]
On possibility of high resolution spectrometers based on AC

- It possible to use AC as a high resolution spectral element
- To achieve resolution $\frac{\lambda}{\delta \lambda} \approx 10^7$ a crystal with the size $L \approx \frac{(\lambda/\delta \lambda)D}{r}$ is necessary
- The length of the spectrometer $L_s \approx \frac{(\lambda/\delta \lambda)r}{r}$, $r$ – the size of the exit slit
Conclusions

- In many applications of soft and hard X-rays a high resolution about $\sim 10^3$-$10^7$ is required.
- The existing types of gratings often can’t be used to achieve this goal.
- The use of SMG is a good option to achieve high dispersion for soft X-rays while maintaining high diffraction efficiency and spectral resolution.
- AC can be used to create single crystal high resolution spectrometers for the hard X-rays if one uses its dispersion properties.