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长春光机所软X射线-极紫外波段光学研究

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摘要：综述了我所软X射线-极紫外波段关键技术的研究进展。描述了软X射线-极紫外波段光源技术，研制了工作波段为6～22 nm的微流靶激光等离子体光源；介绍了光子计数成像探测器技术，研制出了有效直径为25 mm，等效像元分辨率为0.3 mm的极紫外波段探测器；开展了超光滑表面加工、检测技术的研究，研制了超光滑表面抛光机，加工出高面形精度的超光滑表面，面形精度为6 nm(RMS值)，表面粗糙度达0.6 nm(RMS值)；进行了软X射线-极紫外波段多层膜技术的研究，研制出13 nm处反射率为60%的多层膜反射镜，150 mm口径反射镜的反射率均匀性优于±2.5%；最后，讨论了软X射线-极紫外波段测量技术研究，研制出该波段反射率计，其测量范围为5～50 nm，光谱分辨率好于0.2 nm，测量重复性好于±1%。在上述关键技术研究基础上，研制出了极紫外波段成像仪和空间极紫外波段太阳望远镜，这些仪器在我国空间科学研究项目中发挥了作用。

关　键　词：空间光学；软X射线；极紫外
中图分类号：O434.1；O434.2　　**文献标识码：**A

Soft X-ray and extreme ultraviolet optics in CIOMP

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Abstract: Some key technologies on soft X-ray and Extreme Ultraviolet (EUV) optics developed at CIOMP are reviewed in this paper. The technology for laser-produced plasma sources is described and a laser-produced plasma source with a liquid target worked at wavelength range of 6～22 nm has been developed. Soft X-ray and EUV photon-counting imaging is introduced and a two-dimensional photon-counting detector with position sensitive anode is fabricated. The active area of the detector is 25 mm in diameter and the resolution is 0.3 mm. The technology of super-smooth mirror fabrication is studied and a polishing machine has been developed to fabricate the super-smooth surface mirrors with the roughness and the figure of 0.6 nm (RMS) and 6 nm (RMS), respectively. Soft X-ray and EUV multilayer film technologies are coverd also in the paper and a number of mutilayer coating mirrors have been deposited for some space science projects. These multilayer mirrors show their reflectivity of 60% at 13 nm and the uniformity better than ±2.5% across a 150 mm diameter. The soft X-ray and EUV radiometric technologies are studied and a reflectometer, with operational wavelength range of 5～50 nm, spectrum resolution of 0.2 nm and repeatability better than 1% has been set up. Based on a

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cutting-edge technology, an EUV imager and a space EUV solar telescope are developed, these imaging instruments have played an important role in a number of scientific projects.

Key words: space optics; soft X-ray; EUV

1 Introduction

Since the early 1980's, the studies of soft X-ray and extreme ultraviolet (EUV) optics have been implemented in Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP). So far, the research systems for soft X-ray and EUV optics have been established, including light sources, detectors, calibrations, optical testing and machining of super smooth mirrors and fabrication of multilayer film mirrors. Based on the above technologies, we have designed and developed soft X-ray and EUV optical instruments, such as a space EUV solar telescope and an EUV imager.

2 Key technologies for soft X-ray and EUV optics

2.1 Laser produced plasma source[1]

For the applications of soft X-ray and EUV calibration and lithography, we have developed a series of Laser Produced Plasma (LPP) sources, which hve metal, cryogenic, gas-puffed and liquid targets. Here we describe the latest LPP source with a liquid target developed in CIOMP.

The LPP source is driven by a Q-switch Nd: YAG laser (Continuum 9100) operating in single shot mode, delivering up to 1.5 J per pulse at 1 060 nm. The laser beam is focused through a glass paraboloidal lens with a 100 mm focal length. The liquid target arrangement is shown in Fig. 1. The setup incorporates a standard General Valve Corporation series 9 stainless steel solenoid valve. A copper gasket seal and a Kel-F poppet are used during high-pressure cryogenic operation to minimize leakage and poppet deformation. A supersonic nozzle with a 0.5 mm orifice and 5° expansion half angle is attached to the valve body. The valve is controlled using a high speed single shot pulse with a minimum valve opening time of 100 μs. A close fitting copper cooling jacket surrounds the valve body. The jacket clamps around a stainless steel coolant carrying tube, which is fed by an automatically pressurized liquid nitrogen-filled Dewar. The valve temperature is finely controlled by copper filament heaters encased in the copper jacket. An external circuitry allows the power to the heaters to be varied continuously from 0 to 60 W. The valve temperature is measured through a small cylindrical thermocouple which controls the heaters in an on/off mode. Oscillations in temperature around the user-selected given point are minimized by careful adjustment of the heater current. The combination of these heating and cooling elements allows continuous control of the valve temperature between 100 and 300 K. At any given set point, the temperature remains stable within ±0.5 K. The valve is mounted on a vacuum flange that provides the necessary liquid nitrogen, gas, thermocouple and electrical feedthroughs. For sufficiently high background pressure and low temperature, the valve reservoir gas can undergo a gas-to-liquid phase transition. Upon valve pulsing, the liquid is ejected into a vacuum and breaks up into micron-sized droplets. The spectra from the Kr and

Xe liquid target plasma are shown in Fig. 2. The LPP source can produce high-intensity soft X-ray and EUV radiation from 6 nm to 22 nm.

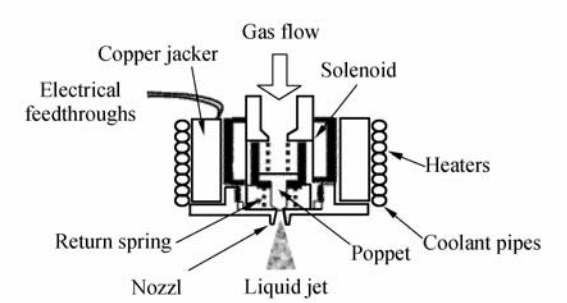

Fig. 1 Schematic diagram of the cryogenic jet valve

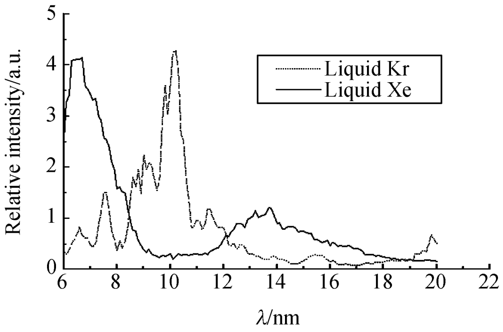

Fig. 2 Spectra from Kr and Xe liquid target plasma

2.2 Two-dimensional photon-counting detector with position sensitive anode

We arrange a photon-counting detector in soft X-ray and EUV region, as shown in Fig. 3, composed of three 25 mm-diameter micro-channel plates (MCP) and a metal wedge-and-strip or an induced charge position sensor. The anode is mounted 14 mm behind the exit surface of the rear MCP and there is no gap between the MCP pieces. A high voltage from −2 100 to −2 300 V is applied to the MCP pieces, and an acceleration voltage from −100 to −200 V is applied to the exit surface of the rear MCP and anode. The EUV images are obtained by the EUV detector. The resolution of the image is around 0.3 mm.

The wedge-and-strip anode is fabricated by lithography on a fused silica substrate chosen for its stability and low dielectric constant. The conductor pattern of the finished anode has thirty quartets with a period of 1 mm. The three conducting anodes are separated by insulating gaps of around 20 μm. The capacitances between each conductor anodes are measured as 140 pF.

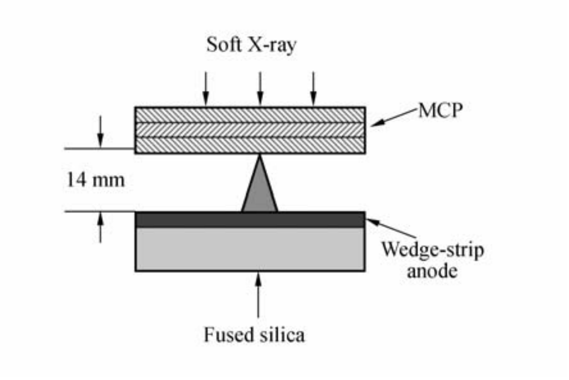

Fig. 3 Schematic diagram of the position-sensitive anode detector

The front end circuit for the detector is arranged, as shown in Fig. 4. The circuit consists of charge-sensitive preamplifiers (CSP) for each of the three anode electrodes, shaping amplifiers (SA) with 100 ns shaping time, passive delay lines and peak detectors. Each shaping amplifier signal is divided into two portions. A portion is fed into a sample/hold circuit, meanwhile another is used to generate TTL signals for triggering the sample/hold circuit and 16 bit A/D converter card. Finally the images are displayed on a PC.

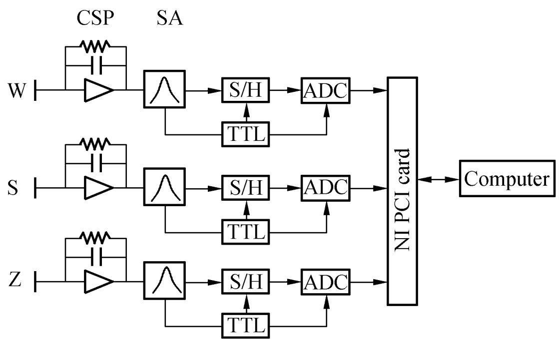

Fig. 4 Schematic diagram of the front end circuit

2.3　Super-smooth surface mirror fabrication

The history of the precision mirror manufacturing is around 30 years in CIOMP. Before 1990 we machined the precision surface only through means of traditional grinding and polishing methods. To obtain the super-smooth surface, a float-polishing technology invented by Professor Namba has been studied for many years. By the float-polishing machine, we have obtained super-smooth surface with the roughness of 0.3 nm (RMS). However, the float-polishing technology only can polish a plane suppersmooth surface.

In order to meet the demands of soft X-ray and EUV applications, we have been developing a micro-jetting fluid (MJF) nano-precision polishing technology for a concave super-smooth surface. Now a prototype machine has been developed as shown in Fig. 5 and Fig. 6. This polishing machine consists of five parts comprising main axes, small polishing tool, guiding rail, polishing fluid supplying system and computer-control system. The movements of the main axes and the small polishing tool are controlled by the computer. In the course of fabrication, the polishing fluid is forced out of holes on the end of the small polishing tool. The gap between the small polishing tool and the workpiece is around 10 μm. Nano-size particles contained in the polishing fluid are ejected to remove atoms by the spinning of the small polishing tool. As the wiping rate is very low, we can obtain the super-smooth concave surface of high contour precision without any undulations.

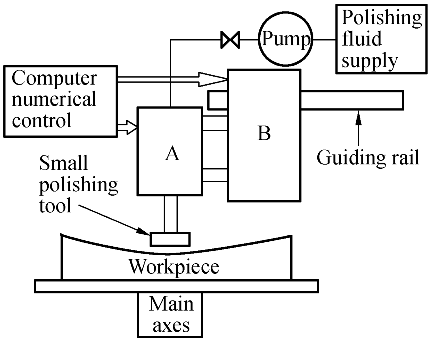

Fig. 5　Schematic diagram of the MJF nano-precision polishing system

We have succeeded in polishing the concave surface by the machine to be super-smooth with roughness below 0.6 nm (RMS) and contour precision below 6 nm. The maximum size of the workpiece is several hundred millimeters. Some of super-smooth surface mirrors have been fabricated and applied to a space EUV solar telescope and an EUV imager.

Fig. 6　Prototype of the MJF nano-precision polishing system

2.4　Soft X-ray and EUV multilayer film technology[2]

Soft X-ray and EUV multilayer film mirrors are key components for imaging instruments in this region. In China, the first soft X-ray and EUV multilayer film mirror was developed by use of magnetron sputtering and ion beam sputtering technologies in CIOMP. We designed and constructed an ion beam sputtering coating machine and a magnetron sputtering coating machine in the early 1990′s. Material pairs such as Mo/Si, Mo/BN, Mo/B_4C, W/C and W/Si have been deposited on silicon, glass and zerodur substrates using coating machines developed in CI-

OMP. The reflectivity is over 60% at 13 nm. The uniformity is better than ±2.5% across 150 mm diameter. Now the multilayer film mirrors have been applied to many fields such as X-ray laser studies, ICF research, space soft X-ray and EUV imaging instruments and synchrotron beam lines. We are developing high quality multilayer film mirrors with large diameters over 300 mm, high stability and high uniformity to meet the needs of space projects.

2.5 Soft X-ray and EUV reflectometer[3]

In order to improve multilayer performance (i.e. normal incidence reflectance) a soft X-ray and EUV reflectometer is necessary. It can provide a immediately measurement on the optical performance of the multilayer coatings. We have designed and constructed the soft X-ray and EUV reflectometer shown in Fig. 7, which consists of a LPP source, a monochromator, a high vacuum sample chamber, a vacuum pumping system and an electronics unit shown in Fig. 8. The soft X-ray and EUV radiation is generated from the LPP source. Then the soft X-ray and EUV are collected and the mono spectrum narrowed using the high resolution grazing-incidence monochromator. The emerging monochromatic beam is incident on the multilayer sample located in the sample chamber. The sample and the detector motion are controlled by a stepping-motor. Reflectance is measured versus wavelength by scanning monochromator, or versus incidence angle by rotating the sample and the detector.

We have measured a large number of multilayer film samples, the results indicating that the reflectometer has a measurement repeatability better than ±1%, for an operation wavelength range from 5 nm to 50 nm and the spectrum resolution is 0.2 nm. The performances of the soft X-ray and EUV reflectometor can satisfy the needs of the reflectance measurements on multiplayer film mirrors.

Fig. 7 Soft X-ray and EUV reflectometer

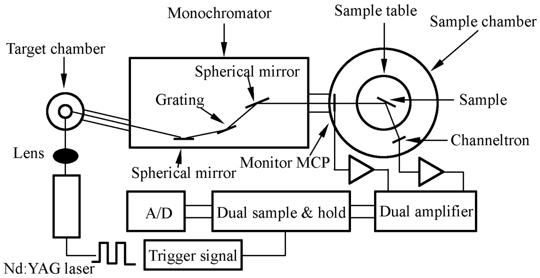

Fig. 8 Schematic diagram of the soft X-ray and EUV reflectometer

3 Applications

3.1 Space EUV solar telescope[4-5]

Based on our fundamental technologies, we have developed a space EUV solar telescope to achieve high-resolution solar EUV images in space, which is composed of four EUV telescopes. Each telescope consists of an aluminum filter, a multilayer film for normal incidence Cassegrain optics, a secondary mirror controlling unit, a EUV detector, a mechanical structure and a vacuum chamber shown in Fig. 9. The specifications of the telescopes are shown in Tab. 1. When the EUV radiation enters the telescope, radiation over 60 nm is blocked by the aluminum filter. The EUV radiation is focused on the active surface of the EUV detector through the multilayer film normal incident optics. The photon-electron signal is recorded and the EUV image is obtained. We have measured the 17.1 nm wavelength for the four telescopes using our UV and EUV testing system. The testing results are shown in Fig. 10, indicating that the angular resolution of the 17.1 nm telescope is 0.8″.

Tab. 1　Specifications for the space EUV solar telescope

Items	Parameters
Operating wavelength (nm)	13.0, 17.1, 19.5, 30.4
Field of view	8.5′×8.5′
Angular resolution	0.8″
Focal length(mm)	7 040

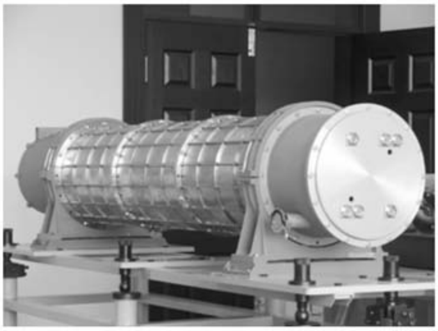

Fig. 9　Space EUV solar telescope

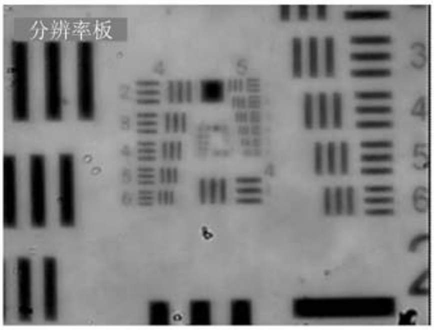

Fig. 10　Testing result of the EUV telescope

3.2　EUV imager

In additional, we have developed a prototype EUV imager for the purpose of imaging the earth's plasmasphere, which is composed of an aluminum filter, a spherical multilayer film mirror, a two-dimensional photon-counting position-sensitive detector with curved surface microchannel plates (MCP) and their mechanical support structures. When the EUV imager is running, the EUV radiation from the earth's plasmasphere and background are go into the entrance pupil of the EUV imager. Radiation below 50 nm arrives at the detector through the EUV filter and higher wavelengths are blocked out. The EUV radiation is focused on the surface of the two-dimensional photon-counting position-sensitive detector by the spherical multilayer film mirror. Finally the EUV images are received by the EUV detector. The prototype of the EUV imager is shown in Fig. 11 with specifications in Tab. 2.

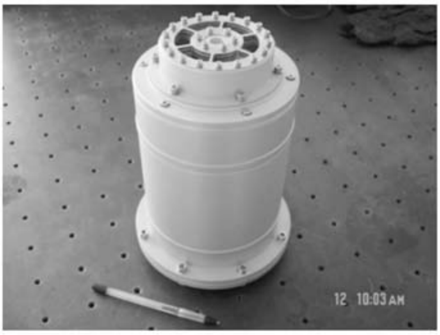

Fig. 11　EUV imager

Tab. 2　Specifications for the EUV imager

Items	Parameters
Operating Wavelength	30.4 nm
Bandwidth	5 nm
Field of view	15°
Angular resolution	0.08°

4　Conclusions

We have developed cutting-edge technologies such as the laser produced plasma source, a

two-dimensional photon-counting detector, super-smooth surface mirror fabrication, soft X-ray and EUV multilayer films, and a soft X-ray and EUV reflectometer. The equipment and optical components have been developed using technologies in CIOMP. We have applied these technologies to space instruments and have also developed an EUV imager and a space EUV solar telescope for space projects.

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