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Space solar telescope in soft X-ray and EUV band

CHEN Bo†, LIU Zhen, YANG Lin, GAO Liang, HE Fei, WANG XiaoGuang & NI QiLiang

State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130022, China

In this paper we have reviewed our achievements in soft X-ray and extreme ultraviolet (EUV) optics. Up to now, the research system of soft X-ray and EUV optics has been established, including light sources, detectors, calibrations, optical testing and machining of super smooth mirrors, and fabrications of multilayer film mirrors. Based on our achievements, we have developed two types of solar space telescopes for the soft X-ray and EUV space solar observations. One is an EUV multilayer normal incident telescope array including 4 different operation wavelength telescopes. The operation wavelengths of the EUV telescope are 13.0, 17.1, 19.5 and 30.4 nm. The other is a complex space solar telescope, which is composed of an EUV multilayer normal incident telescope and a soft X-ray grazing incident telescope. The EUV multilayer normal incident telescope stands in the central part of the soft X-ray grazing incident telescope. The normal incident telescope and the grazing incident telescope have a common detector. The different operation wavelengths can be changed by rotating a filter wheel.

space solar telescope, soft X-ray, EUV, optics

1 Introduction

Space weather is an emerging field of space science. The activities of the sun such as solar flares, and coronal mass ejections have tremendous influence on the earth's environment[1,3]. The strong soft X-ray and EUV radiation are produced following these solar activities which then can be forecasted by analyzing the changes of the solar images in the soft X-ray and EUV region. A series of studies on the solar physics are carried out with the help of soft X-ray and EUV images.

In order to obtain soft X-ray images, a German physicist Wolter designed a two-mirror system of Wolter type which can produce two dimensional imaging in the soft X-ray region. Wolter optical systems include three types: Wolter Type-I, TypeII and Type III. Up to now, Wolter type-I telescope has been used successfully in astronomical observation tasks in several satellites such as the European Exosat observatory, the Germany Rosat satellite, the US Advanced X-ray Astrophysics Facility (AXAF), the European XMM Mission and US GOES SXI system3, and the Japanese Solar-A and Solar-B Missions. The less effective collecting area and the worse angular resolution along with the larger field of view remain major problems in this kind of telescope system[2]. In order to obtain high resolution soft X-ray and EUV images, in the 1970's Eberhard Spiller successfully applied multilayer mirrors to the normal incident optical systems such as Cassegrain configuration, and Ritchey-Chretien telescope after he found them useful for optical instruments in the soft X-ray and EUV regions[2].

Now Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Science is confident of developing space solar imaging instruments. Here studies on soft X-ray and EUV optics began in the early 1980s. As a result, the research system of soft X-ray and

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†Corresponding author (email: bochen2000@yahoo.com.cn)
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EUV optics, including light sources, detectors, calibrations, optical testing and machining of super smooth mirrors, fabrications of multilayer film mirrors, has been established. In addition to the achievements made, we have also developed two types of space solar telescope.

1.1 Fabrication of the super-smooth surface mirror[3]

About thirty years ago, we started the fabrication of precision mirror and until 1990 our method was the traditional grinding and polishing. At present in order to meet the requirements of soft X-ray and EUV applications, we have developed a prototype machine which combines a computer numerical controlling (CNC) polishing for high surface accuracy, and non-contacting polishing for low roughness. The polishing machine contains five main parts, a CNC system, main axes, a small polishing tool, a guiding rail, and a polishing fluid supplying system.

The movements of main axes and the small polishing tool are controlled by the CNC system. The polishing fluid is forced to jet out from a number of holes on the end of the small polishing tool while the machine works. The gap between the small polishing tool and the workpiece is around 10 μm. Nanometer size particles contained in the polishing fluid are driven to wipe off the atoms by the spinning of the small polishing tool. We can obtain the super-smooth concave surface of high contour precision without any wave (quivering), because of the low wiping rate. We have succeeded in polishing the concave surface to be super smooth with the roughness below 0.6 nm (RMS) and the contour precision below 6 nm by the machine. The maximum size of the workpiece is several hundred millimeters.

1.2 Soft X-ray and EUV multilayer technology[3,4]

Soft X-ray and EUV multilayer film mirrors are the key components of the imaging instruments in this project. The first piece of soft X-ray and EUV multilayer film mirror in China was fabricated by ion beam sputtering technique in CIOMP. In the early 1990s, we designed and constructed an ion beam sputtering coating machine and a magnetron sputtering coating machine. Many material pairs such as Mo/Si, Mo/BN, Mo/B_4C, W/C and W/Si can be deposited by our machines on the silicon wafer, glass and zerodur substrates. The reflectivity is over 60% at 13 nm and the uniformity is better than ±2.5% across a 150 mm diameter. Now the multilayer film mirrors have been extensively used in many fields such as X-ray laser studies, ICF research, space soft X-ray and EUV imaging instruments and synchrotron beam line. To meet the needs of space projects, we are working on high quality multilayer film mirrors with much larger (over 300 mm) diameter, high stability and high uniformity by magnetron-sputtering system.

1.3 Soft X-ray and EUV reflectometer[3,5]

In order to improve the performance of the multilayer mirror, a soft X-ray and EUV reflectometer becomes necessary, that can directly measure the optical performance of the multilayer coatings. Fortunately we have completed such a soft X-ray and EUV reflectometer which consists of a laser produced plasma (LPP) source, a monochromator, a high vacuum sample chamber, a vacuum pumping system and an electronics unit. The soft X-ray and EUV radiation are emitted from the LPP source, then collected and monochromatized by the high resolution grazing-incidence monochromator. The emerging monochromatic beam is incident on the multilayer sample located in the sample chamber. The stepping-motor controller unit controls the motion of the sample and the detector. Reflectivity is measured versus wavelength by scanning monochromator or versus incidence angle by the rotation of the sample and the detector.

We have measured plenty of multilayer film samples whose results indicate that the reflectometer has measurement repeatability better than ±1%, the operation wavelength ranges from 5 nm to 50 and the spectrum resolution, 0.2 nm. The performance of the soft X-ray and EUV reflectometer meets the standard of the reflectivity measurements on multiplayer film mirrors.

2 Space EUV normal incident solar telescope[2,3]

Our space EUV solar telescope, made up of four EUV telescopes, is developed to get high-resolution solar EUV images in the space. Each of the four telescopes is composed of a piece of aluminum filter, a multilayer film normal incidence Cassegrain optics, a secondary mirror controlling unit, an EUV detector, an optical bench and a vacuum chamber. The operating wavelengths of the space EUV solar telescope are 13.0, 17.1, 19.5 and 30.4 nm, the field of view is 8.5′×8.5′, and the focal length is 7040 mm. When the EUV radiation enters the telescope, wavelength beyond 60 nm radiation is blocked by the aluminum filter. Then the EUV radiation focuses on the active surface of the EUV detector by the multilayer film normal incident mirror. The photon-electron signal is recorded and the EUV image is obtained. We have measured the 17.1 nm telescope using our UV testing system. The testing result is shown as Figure 1. The grid used as testing object has the period of 58 microns and the line width, 20 microns. The testing results indicate that the angular resolution of the 17.1 nm telescope is 0.8".

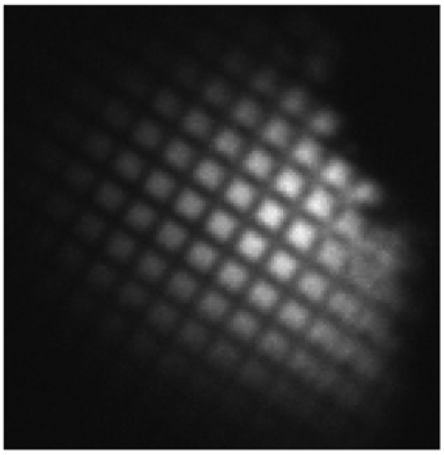

Figure 1 The testing result of the telescope in the UV wavelength range.

3 Complex space solar telescope

We have been working on a complex space solar telescope to observe the sun in much wider wavelength range. The conventional Wolter type I telescope is composed of two mirrors: a paraboloid and a hyperboloid mirror, which are co-axial and confocal to fulfill the Abbe sine rule. There is much interspace in the central section of the Wolter type I optics, and otherwise the Cassegrain optical system has the much shorter axial length and compact configuration at the same effective focal length and the same aperture compared. Therefore it is possible to integrate the Wolter type-I and Cassegrain configuration with a complex telescope. The schematic of the complex grazing incidence and normal incidence telescope configuration is showed in Figure 2. The two configurations use only one common detector[2].

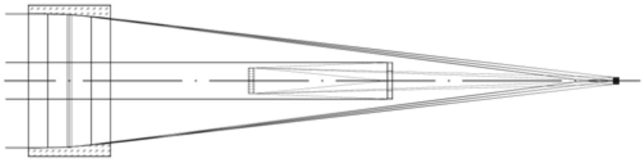

Figure 2 The schematic of the complex telescope configuration.

3.1 Normal incidence telescope[2]

A series of double mirror optical systems can be used for imaging in the EUV region: Sphere-Sphere, ellipsoid-sphere (Dall-Kirkham), paraboloid-hyperboloid (Cassegrain), and hyperboloid-hyperboloid (R-C) configurations. In spite of better resolution possibly obtained by the classical Cassegrain telescope because of reduced coma, it is hard to fabricate the two aspherical mirrors with both high quality of figure and super smooth effect. Because the resolution demand of the normal incidence telescope in this design is not too high, less than 2 arc second, the sphere-sphere pseudo-Cassegrain telescope is the best choice, as the sphere surfaces are more easily fabricated and tested. To satisfy the requirements, only one common detector is used by two optical systems, and the flux of photons to the detector is identical to the greatest extent. The relationship of the flux of two optical systems can be expanded as

$$\frac{\int_{\lambda_1}^{\lambda_2} I_1(\lambda)R_1(\lambda)T_1(\lambda)\mathrm{d}\lambda}{\int_{\lambda_3}^{\lambda_4} I_2(\lambda)R_2(\lambda)T_2(\lambda)\mathrm{d}\lambda} \approx \frac{A_2}{A_1},$$

where $I_1(\lambda)$, $R_1(\lambda)$, $R_1(\lambda)T$ represent the radiation intensity, reflectivity and transmission ratio at the soft X-ray wavelength bands respectively, and $I_2(\lambda)$, $R_2(\lambda)$, $T_2(\lambda)$ represent the radiation intensity, reflectivity and transmission ratio at the EUV wavelength bands respectively. From the above formula, we can calculate the parameters of the normal incident telescope. The focus of the normal incident telescope is designed as the optical bench requirement of the grazing incident telescope. If the focal length is 2713 mm, the resolution of the normal telescope is 2″ across full FOV.

3.2 Grazing incidence telescope[2]

Theoretically, the grazing incidence configuration is very simple. Wolter Type I optical system is preferably used to image the solar soft X-ray radiation. Many new designs to improve on the original Wolter Type 1 which consists of a paraboloid mirror and a hyperboloid mirror have been made, but with limited success. What we did was to use the original Wolter type I grazing incidence system and confirm the optical mirrors parameters by referring to the previous designs.

We entered these parameters into the popular optical design program ZEMAX and traced ray to give through focus spot diagrams across the full field. The optical ray trace result is showed in Figure 3. At the same time, we chose an effective focal of 2713 mm. Then the angular resolution is 2.0″ across FOW of 32′ and 2.5″ across full FOW of 35′.

4 Conclusions

After years of research we have understood the key technology for developing space soft X-ray and EUV telescope and have succeeded in accomplishing such a mission. A more complex telescope in soft X-ray and EUV for the space solar observation is being developed.

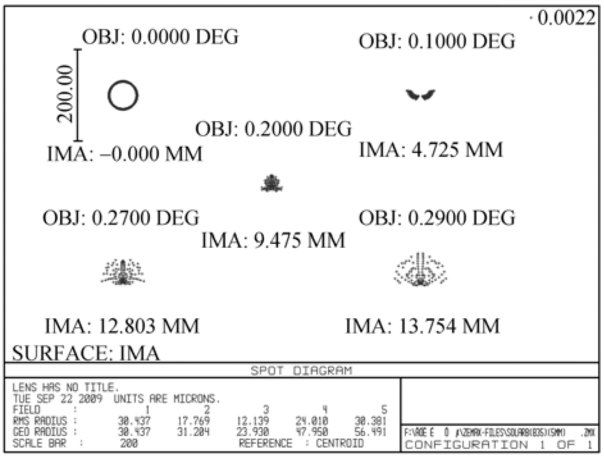

Figure 3 Grazing incident telescope spot diagram.

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