THE EXPERIMENTAL RESEARCH OF THE SR-FEL CAVITY MIRRORS AT 355nm AND 248nm*

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Abstract

The cavity mirrors of the SR-FEL at 355nm and 248nm central wavelengths are developed experimentally with the fused silica substrate and "HfO2/SiO2+Al2O3/SiO2+M-SiO2" optical coatings. The electron-beam evaporation and ion-beams sputtering are used as the deposition technologies. After heating condition at 400^{o}C×4hrs, the absolute reflectance and wavelength-tunable range is measured with VARIAN-Cary-5000 spectrophotometer. The experimental results show that R=99.45% and $\Delta\lambda$(R≥99.00%) =75nm at 355nm for the broadband mirror. For the mirror with the dual-central wavelength at 355nm/248nm, R= 99.69% and $\Delta\lambda$(R≥99.00%)=59nm at 355nm, and R=98.21%, $\Delta\lambda$(R≥99.00%)=9nm and $\Delta\lambda$ (R≥98.00%) =51nm at 248nm.

INTRODUCTION

Storage-Ring Free-Electron Laser (SR-FEL) is a wavelength-tunable, high power, short pulse light source. With the optical resonator, SR-FEL will generate a laser radiation with the best spatial and temporal coherences, tunable wavelength and harmonic radiations, simultaneously [1-3]. It is also the best seed light for generating HGHG, X-ray laser and γ-ray laser with new FEL schemes [1-11]. All of these light sources have a potential application in the nuclear physics, atomic physics, molecular physics, bioscience and medicine. But the high power UV/DUV free electron laser and the synchrotron radiation will induce the mirror reflectance degradation or direct damage. These will limit the laser gain and the development of the SR-FEL toward to the shorter wavelength, shorter pulse and higher power in the UV/DUV region [1-3,8,12-13]. Thus, it's very important to develop the resonator mirror with the lowest absorption, highest absolute reflectance, needed wide wavelength-tunable range, highest damage threshold and the best resistance to reflectance degradation [1-13]. In this paper, report the progress on the experimental research of the SR-FEL resonator mirrors at 355nm and at 355nm/248nm.

PHYSICAL DESIGN TO MIRROR COATING

The physical design of the mirror coatings is based on the experimental results in the Inertial Confinement Fusion (ICF) driven by high energy laser and Storage-Ring Free Electron Laser (SR-FEL) researches from 1982 to 2006, so that it can integrate the all advantages of different physical designs, deposition technologies, film-growing parameters, post-deposition conditions, and so on. Here, a compound mirror coating is designed for the broadband mirror coating at 355nm central wavelength and the dual-band mirror coatings at 355nm and 248nm central wavelengths. It is "HfO2/SiO2+Al2O3/SiO2+M-SiO2", where Sub is the material of the mirror substrate, fused silica is chosen because of its stable physical characteristics. HfO2/SiO2 and Al2O3/SiO2 are two coating stacks, M=6 the layer number of the SiO2 top layers. Because the HfO2/SiO2 coatings has the largest bandwidth and Al2O3/SiO2 coatings has the highest damage threshold in the UV/DUV region, as found by LANL, LLNL, CIAE scientists in the research of ICF driven by high-energy laser [13-18]. And the top-layer SiO2 has an evident effect to increase the damage threshold of the mirror coating as found by above researchers [13-18], and to resist the reflectance degradation induced by the synchrotron radiation and the UV/DUV FEL as found by the ELETTRA scientists [8,12]. The theoretical design are listed in table.1, where H is HfO2, H` is Al2O3, L and L` are SiO2. Since the damage threshold of the Al2O3/SiO2 mirror coatings is higher than that of the HfO2/SiO2, the absorption coefficient of Al2O3 material is lower than that of HfO2 materials, and the laser intensity of the coherent standing-wave electric field in the topmost layers of mirror coating is higher than that in the inner. Thus, the Al2O3/SiO2 coating stack is set above the HfO2/SiO2, the top-layers SiO2 is put on the HfO2/SiO2 coating stack. The basic structures of the mirror coatings are "Sub.-LL-(0.5H-L-0.5H)[12-pair]/ 355nm-(0.5H`-L-0.5H`)[25-pair]-LL-4L`/320nm" for the broadband mirror at 355nm and "Sub.-LL-(HL)[11-pair] /355nm-H-(LH)[11-pair]/248nm-H`-(LH`)[20-pair]-LL-4L/212nm" for the dual-band mirror at 355nm/248nm.

DEPOSITION TECHNOLOGY AND PARAMETER

The past experiment research has shown that, for an optimized mirror coating design, the deposition technology and parameters have a strong and direct affection to the realization of the physical design. As found by LLNL scientists in ICF research, a mirror coatings will have a higher damage threshold when

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deposited by electron-beams evaporation (EBE) than by ion-beams sputtering (IBS) deposition [14]. But, as found by ELETTRA scientists in the SR-FEL research [8,12], when deposited by IBS technology, the oxide coating of the resonator mirror will have resistance to the reflectance degradation induced by FEL and synchrotron radiation. Thus, in our experimental research, the "HfO2/SiO2+Al2O3/SiO2+2-SiO2" part of the mirror coatings is deposited by EBE technology with LEYBOLD-APS-1104 machine; the rest 4-SiO2 film layers are deposited by IBS technology with VECCO-SPECTRA-IBS machine, so that these cavity mirror will have high damage threshold to laser radiation and resistance to synchrotron radiation, simultaneously. The deposition parameters are listed in table 2.

In Table 1, the leaked oxygen is used to re-oxide the dissociated oxygen molecular to increase the damage threshold of coatings further, as found by IECAS scientists in ICF and FEL researches [13]. Finally, the fresh sample is conditioned at 400°C×4hrs to decrease the absorption of the mirror coating and increase the absolute reflectance and damage threshold together. The step-size of temperature increase is 70°C/1hr. After 4-hour continuous treatment, the mirror sample will cool down naturally to room temperature. Then, they are measured.

Table 1: deposition technology and parameters for SR-FEL mirror coatings.

Deposition technology	Deposition parameter	
Electron-beams evaporation	V(HfO2)	0.5nm/s
	V(Al2O3)	0.5nm/s
	V(SiO2)	0.6nm/s
	T	185°C
	P(O2)	1.5×10[-4]mbar
Ion-beams sputtering	V(M-SiO2)	0.3nm/s
	T	120°C
	P(O2)	4.0×10[-4]mbar
Heating condition	400°C×4hrs	

EXPERIMENTAL RESULT AND DISCUSSION

The spectral performance of the SR-FEL mirror coatings is measured with the spectrophotometer VARIAN-Cary-5000. The parameters include the absolute reflectance at the central wavelength and the bandwidth corresponding to the absolute reflectance higher than 99.00%, i.e., the top width of the reflectance spectrum.

Broadband Mirror Coatings at 355nm

In Fig.1 was shown the spectra of the absolute reflectance for the broadband mirror coatings at 355nm before and after heating condition. The top width with the reflectance higher than 99.00% is listed in Table2. From Fig.1 and Tab.2, it shows, after heating condition, that the absolute reflectance at 355nm central wavelength is R(355nm)=99.45%, the wavelength-tunable range is from 406nm to 331nm, i.e., Δλ(R≥99.00%)=75nm. Relative to the R\` and Δλ\` of the fresh mirror sample without heating treatment, the average increases of the absolute reflectance and the wavelength-tunable range in the top region are ΔR= 0.39% and Δλ*=7nm, where ΔR and Δλ* are defined as

$$\Delta R = \frac{1}{N}\sum_{j=1}^{N}\left(R(\lambda_j) - R`(\lambda_j)\right)$$

$$\Delta\lambda^* = \Delta\lambda - \Delta\lambda`$$

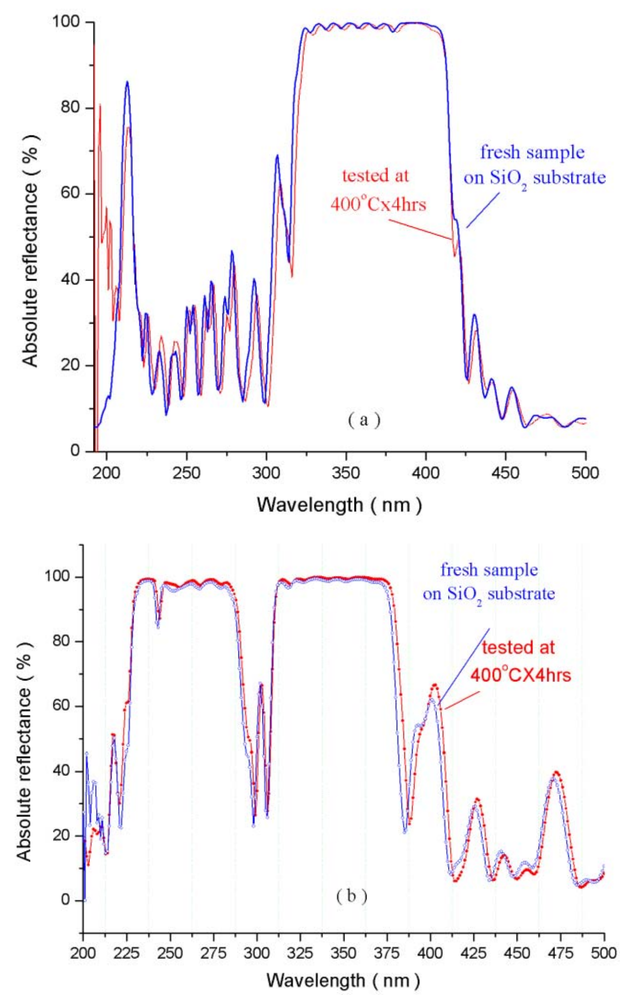

Figure 1: The spectral performances of the broadband (a) and dual-band (b) SR-FEL mirror with heating condition at 400°C×4hrs and without for the fresh samples. They are measured with varian-cary-5000 spectrophotometer.

Dual-band Mirror Coatings at 355nm/248nm

In the Figure 1 was also shown the spectra of the absolute reflectance for the dual-central wavelength mirror coatings at 355nm/248nm on fused silica substrate. The absolute reflectance higher than 99.00% is listed in Table 3. From these experimental data, it can be seen that, for the mirror coatings after heating condition, all the characteristics of the first band at 355nm is similar to that in Fig.1. It has a perfect shape. At the central wavelength 355nm, the absolute reflectance and wavelength-tunable range are R=99.69% and Δλ(R>99.00%)=373nm-314nm=59nm; Relative to the experimental data (R` and Δλ) in the Fig.1 for the fresh sample without heating treatment, the average increase of the absolute reflectance and wavelength-tunable range are ΔR= 0.73% and Δλ*=26nm, defined as above.

In the second band at 248nm for the sample with heating condition, the absolute reflectance is less than 99.00% at most of the wavelengths. The reflectance at 248nm central wavelength is only R(248nm)=98.21%. Only in the wavelength ranges of (275-272)nm and (240-234)nm, the absolute reflectance is higher than that 99.00% and Δλ(R≥99.00%)= (275-272)nm+(240-234) nm=9nm. At most of the wavelengths, the absolute reflectance is ranged from 98.00% to 99.20%, its corresponding wavelength-tunable range is Δλ(R≥98.00%) =33nm. Relative the optical spectrum of the fresh mirror coatings without heating treatment, its average increase of the absolute reflectance and wavelength bandwidth are ΔR(R≥98.00%)=1.04% and Δλ*(R≥98.00%)=9nm.

Table 2: The absolute reflectance and wavelength-tunable range of the SR-FEL broadband mirror at 355nm

λ/nm	406	405	401	400
R/%	99.02	99.10	99.55	99.67
R`/%	97.89	98.02	99.01	99.25
λ/nm	341	333	332	331
R/%	99.73	99.67	99.64	99.38
R`/%	98.65	99.02	98.53	97.73
Δλ/nm	Δλ (R>99.00%)=406nm–331nm=75nm, Δλ`(R`>99.00%)=401nm–333nm=68nm			

Table 3: The absolute reflectance and wavelength-tunable range of the SR-FEL mirror at 355nm/248nm.

λ/nm	373	364	363	355	330
R%	99.17	99.73	99.79	99.69	99.46
R`/%	97.54	98.83	99.01	99.14	99.04
λ/nm	323	322	316	314	283
R%	99.30	98.97	99.09	99.07	98.22
R`/%	98.87	98.77	97.81	98.39	96.45
Δλ/nm	Δλ(R>99.0%)=(373-314) nm=59nm, Δλ`(R`>99.0%)=(363-330) nm=33nm				
λ/nm	275	272	271	270	248
R/%	99.19	99.12	98.8 79	98.49	98.21
R`/%	98.16	98.42	98.19	97.88	97.01
λ/nm	241	240	234	233	232
R%	98.83	99.17	99.12	98.82	98.09
R`/%	93.61	98.11	98.53	97.98	96.72
Δλ/nm	Δλ (R>98.0%) = (283-259)+(241-232)=33nm Δλ`(R`>98.0%) = (275-271)+(240-234)=10nm				

In additional, the highest reflectance is up to 99.19% at 275nm. The shortest wavelength with reflectance R≥99.00% is at 234nm. The shortest wavelength with reflectance R≥98.00% is at 232nm, its reflectance is 98.09%. The spectral breaking at 244nm may be induced by the bandwidth narrowing in the DUV region. Thus, it's necessary to improve the spectral continuity at 244nm further.

From the experimental results for tow types of the mirror coatings, we can get the following conclusion. (1) Heating condition to the fresh mirror coatings has an evident influence on increasing mirror's absolute reflectance and expanding spectral bandwidth. It implies that absorption coefficient of the mirror coatings have reduced after heating treatment. It's very important to develop the RS-FEL mirror toward the shorter wavelength and higher power output. (2) These resonator mirrors have get the designed absolute reflectance and spectral bandwidth. Thus, it can be used as the SR-FEL resonator mirror.

CONCLUSION

Today's experimental results show that it's possible to develop the SR-FEL cavity mirror with an absolute reflectance higher than 99.00% and wavelength-tunable range from 10nm to 75nm in the UV/DUV region. It is very effective to develop the SR-FEL mirror coatings with a compound optical design, a combined deposition technologies of electron beams evaporation and IBS, oxygen-leaked method, and heating treatment.

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