Fabrication of broadband antireflection coatings using broadband optical monitoring mixed with time monitoring*

Qi-Peng Lv(吕起鹏)[1,2], Song-Wen Deng(邓淞文)[1], Shao-Qian Zhang(张绍骞)[1], Fa-Quan Gong(公发全)[1], and Gang Li(李刚)[1,†]

[1] *Key Laboratory of Chemical Lasers, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian* 116023, *China*
[2] *School of Materials Science and Engineering, Dalian University of Technology, Dalian* 116024, *China*

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Multi-layer optical coatings with complex spectrum requirements, such as multi-band pass filters, notch filters, and ultra-broadband antireflection coating, which usually contain very thin layers and sensitive layers, are difficult to be fabricated using a quartz crystal monitoring method or a single wavelength optical monitoring system (SWLOMS). In this paper, a broadband antireflection (AR) coating applied in the wavelength range from 800 nm to 1800 nm was designed and deposited by ion beam sputtering (IBS). Ta_2O_5 and SiO_2 were chosen as high and low refractive index coating materials, respectively. The optimized coating structure contains 9 non-quarter-wave (QW) layers totally with ultra-thin layers and sensitive layers in this coating stack. In order to obtain high transmittance, it is very important to realize the thickness accurate control on these thin layers and sensitive layers. A broadband optical monitoring mixed with time monitoring strategy was successfully used to control the layer thickness during the deposition process. At last, the measured transmittance of AR coating is quite close to the theoretical value. A 0.6% variation in short wavelength edge across the central 180 mm diameter is demonstrated. A spectrum shift of less than 0.5% for 2 continuous runs is also presented.

Keywords: broadband optical monitoring, time monitoring, ultra-thin and sensitive layer, broadband antireflection coatings

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1. Introduction

Optical coatings with complex spectrum requirements, such as multi-band pass filters, notch filters, and ultra-broadband antireflection (AR) coatings[1,2] with ultra-thin and sensitive layers, are very difficult to be controlled accurately by a quartz crystal monitoring method[3] or a single wavelength optical monitoring system (SWLOMS)[4] due to their intrinsic defects and limitations.[5–9] To surpass the limitation of these methods, great efforts have been made on improving the broadband optical monitoring (BBOM) technique for decades. The BBOM is an available method and has many advantages, such as error self-compensation, higher monitor precision, adaptation to non-quarter-wave, and sensitive film deposition. The transmission spectrum of the coating during the deposition process can be acquired *in-situ* using a charge coupled detector (CCD) spectrometer,[10] which is equipped in the deposition chamber. The machine-installed software fits the acquired spectrum immediately, based on which the deposition process is terminated when the value of merit function meets the target. However, ultra-thin layers can hardly be monitored only by using BBOM due to small value change in transmittance at monitored layers. Thus, time monitoring is preferable because of the stable deposition rate of IBS.

In this paper, a broadband AR coating applied in the wavelength range from 800 nm to 1800 nm was designed and then deposited by IBS. Ta_2O_5 and SiO_2 were chosen as high and low refraction coating materials, respectively.[11] The optimized structure contains 9 non-quarter-wave layers totally with ultra-thin layers and sensitive layers. In order to obtain high transmittance, the most important thing is to realize the thickness accurate control of these thin layers and sensitive layers. A broadband optical monitoring mixed with time monitoring strategy was successfully used to control the layers thickness during the deposition process.

2. Experiment

2.1. Equipment

The broadband AR coating was fabricated by dual ion beam sputtering (DIBS),[12–15] as shown in Fig. 1. Ta_2O_5 and SiO_2 were used as high and low refractive index coating materials, respectively. The physical deposition rate of Ta_2O_5 was ~ 0.62 nm/s and that of SiO_2 was ~ 0.39 nm/s. The coating machine was equipped with a 2 planet 425 mm diameter planetary fixture and a BBOM system using intermittent transmission monitoring through the center of one of the planets. The monitoring wavelength range is only from 450 nm to 1000 nm. Various materials can be used as monitoring witness substrate. In this paper, BK7 was chosen as the monitoring and deposition substrate. The diameter of sample substrates is 25.4 mm.

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†Corresponding author. E-mail: lig@dicp.ac.cn
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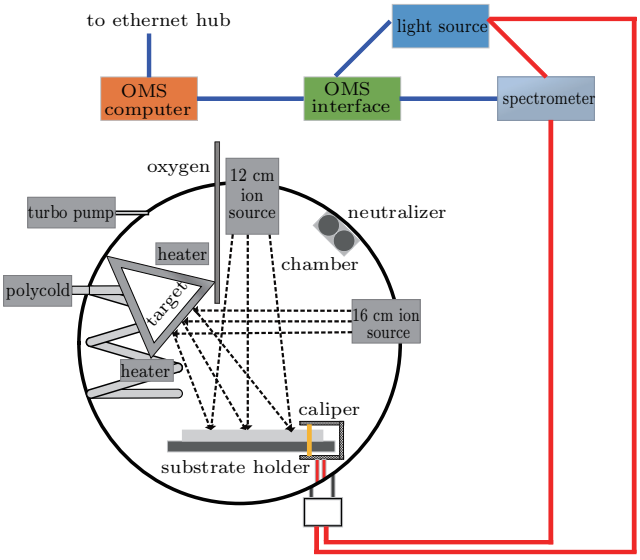


Fig. 1. (color online) Scheme of the Spector-HT system, which contains vacuum system, bake-up system, deposition system, and optical monitoring system.

2.2. Design

Optilayer was employed to design broadband AR coatings in the range from 800 nm to 1800 nm. The refractive indices of Ta_2O_5 and SiO_2 are shown in Fig. 2 and obtained by fitting the transmission spectrum of the pre-coated single layers measured by a well-known matrix method. The refractive indices of Ta_2O_5 and SiO_2 were described by the well-known Cauchy formula:

$$n(\lambda) = A_0 + A_1/\lambda^2 + A_2/\lambda^4. \quad (1)$$

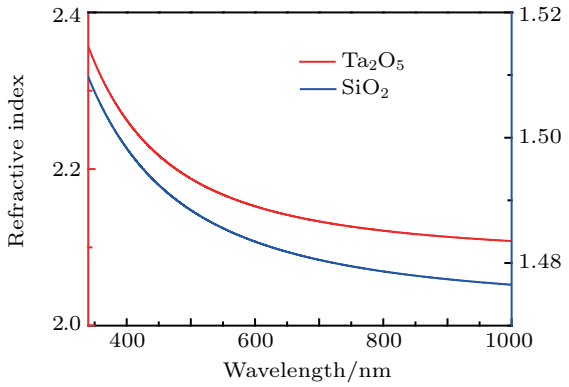


Fig. 2. (color online) Refractive indices of materials. Red line represents the Ta_2O_5 layer and blue line represents the SiO_2 layer.

The average transmittance of the optimized design coating is more than 99.5% (without considering reflection of backside) in the wavelength range from 800 nm to 1800 nm. The initial design was based on a standard quarter-wave stack which contained 9 layers and provided enough optimizable variables to realize high transmittance (99.5%). However, it is difficult to avoid introducing ultra-thin layers when the film design is optimized. The theoretical transmission spectrum without considering backside reflection and the stack structure of the final optimized design coating are shown in Figs. 3(a) and 3(b), respectively. From Fig. 3(b), it can be seen that the 2nd and 7th layers are ultra-thin layers. It is a great challenge to control the thicknesses of these ultra-thin layers accurately by SWLOMS due to a very small transmission value change during deposition.

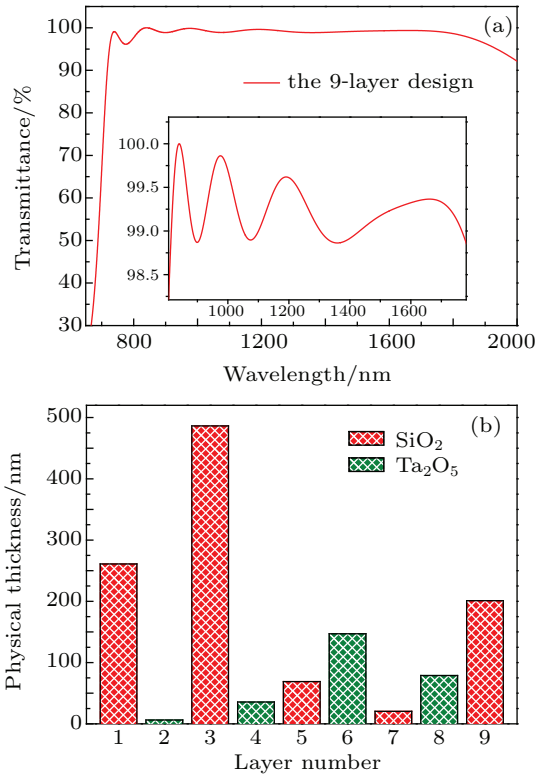


Fig. 3. (color online) The theoretical design results of broadband AR coating. (a) Theoretical transmission spectrum in the range from 800 nm to 1800 nm. (b) Design thickness of broadband AR coating.

2.3. Broadband optical monitoring method

The optical monitoring software provides a superior solution for optical end point detection of optical multi-layer coatings produced by the Spector-HT system. The Quest OMS contains a variety of algorithms for controlling quarter-wave and non-quarter-wave coatings, using *in-situ* measurements of the transmission spectrum of the monitoring witness. The operator-friendly software offers fully automatic operation incorporating real time[16] and historical deposition analysis capabilities. Many control schemes are employed to control the layer thickness, such as average rate (range) module, initial optical rate module, quarter-wave scaling end point module, and transmission fit module. The transmission fit module contains three fitting strategies, which are introduced to monitor the optical film deposition process as candidates, i.e., Control to Thickness, Single Wavelength, and Control to Spectrum.

In this paper, the BBOM system is employed to control the layer thickness. The BBOM system is a real time method related parameters (e.g., deposition rate and refractive index) calculated by fitting the real time measured transmission spectrum by a well-known matrix method to calculate a stop time

prediction that most closely matches the target thickness for this layer. It contains a variety of algorithms for controlling quarter-wave and non-quarter-wave coatings, using *in-situ* measurements of the transmission spectrum of the monitoring witness. When the BBOM is used, the transmission spectrum of each layer *in-situ* measured by broadband optical monitoring system is fitted, the real time refractive index and deposition rate can be obtained. Then the stop time is calculated based on the chosen thickness. The deposition time is determined by

$$t_{\text{stop}} = \frac{\text{Th}_{\text{film}}}{n_{\text{fit}} v_{\text{fit}}}, \tag{2}$$

where t_{stop} is the deposition time, Th_{film} is the optical thickness of each layer, n_{fit} is the fitted refractive index, and v_{fit} is the fitted deposition rate.

3. Results and discussion

Figure 4 shows the relative sensitivity of each layer in the broadband AR coating calculated by the Optilayer analysis module. It is obvious that the 3rd and 6th layers are much more sensitive than other layers. Thickness control accuracy of the sensitive layers is also a challenge for a BBOM system. In this paper, those sensitive layers can still be controlled by our monitoring strategy very well.

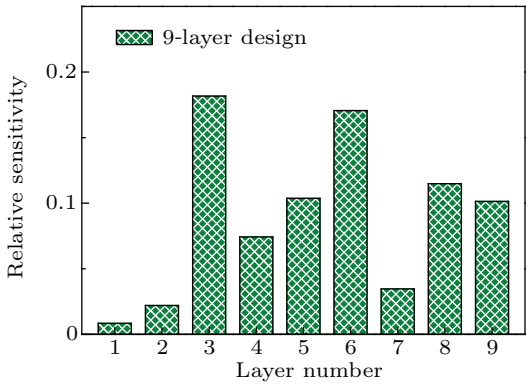


Fig. 4. (color online) Relative sensitivity analysis of the broadband AR coating.

From Fig. 3, we know that the 2nd and 7th layers are ultra-thin and the 1st layer is SiO_2 material whose refractive index is close to BK7 witness. It is difficult to monitor these layers thicknesses using the BBOM strategy due to a very small change in the transmission spectrum at the present layer. Thus, time monitoring is a suitable strategy that will generate a layer's stop time only using the initial physical deposition rate and index specified in the general material parameters.

As a comparison, two monitoring methods were given for this broadband AR coating. Table 1 shows the monitoring strategy of each layer in detail. The thicknesses of the 2nd and 7th layers are controlled by time monitoring and the BBOM strategy is employed to control the other layers. The only difference between methods 1 and 2 is the 1st layer monitoring strategy which changes from the BBOM strategy to time monitoring. The transmission spectrum of the broadband AR coatings is given in Fig. 5. It can be found that the deviation between the theoretical and measured transmission spectrum by monitoring method 1 is rather larger than by monitoring method 2. It can be concluded that in the case of this broadband AR coating, BBOM mixed with the time monitoring strategy is well used, as can be seen from Fig. 5. The measured transmission spectrum monitored by using BBOM mixed with the time monitoring strategy meets the theoretical design and only 0.4 nm shift of short wavelength edge can be found.

Table 1. The monitoring strategy of each layer.

Layer numbers	Monitoring method 1	Monitoring method 2
1	BBOM	Time monitoring
2	Time monitoring	Time monitoring
3	BBOM	BBOM
4	BBOM	BBOM
5	BBOM	BBOM
6	BBOM	BBOM
7	Time monitoring	Time monitoring
8	BBOM	BBOM
9	BBOM	BBOM

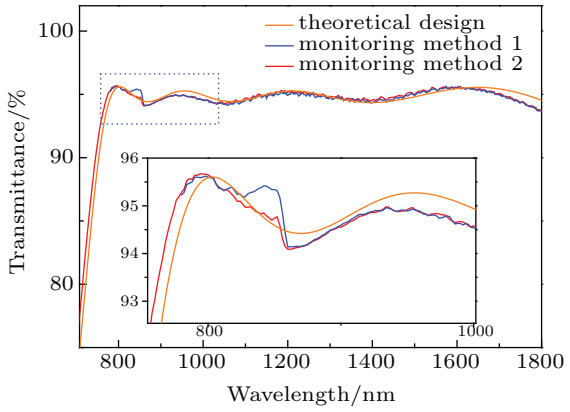


Fig. 5. (color online) Transmission versus wavelength of broadband AR coatings. Orange line represents the theoretical transmission spectrum. Red line represents the measured spectrum by monitoring method 1. Blue line represents the measured spectrum by monitoring method 2.

The broadband optical monitoring system uses intermittent transmission monitoring through the center of one of the planets. Only a small part of a planet can be monitored during the deposition. In order to obtain large aperture optical components with the same performance as the monitoring witness, uniformity is a truly important factor, which can directly affect optical and mechanical performance of high precision optical coatings. It is necessary to control the coating thickness distribution over the coated substrates. A static mask and a rotary accurate mask were designed and introduced to realize

accurately layer thickness control during deposition. Generally, the static mask is used for uniformity coarse adjustment to limit the variation in the short wavelength edge to a small range and it should never be modified again after generation. The rotary accurate mask can be generated and reshaped using many times iteration for several consecutive runs until the variation in the short wavelength edge is small enough and meets the requirement. Figure 6 shows the measured relative coating thickness uniformity. A $\pm 0.05\%$ variation for both Ta_2O_5 and SiO_2 materials in the short wavelength edge across the central 150 mm diameter was obtained. This result can satisfy the demand of depositing the broadband AR coatings on large aperture optical components.

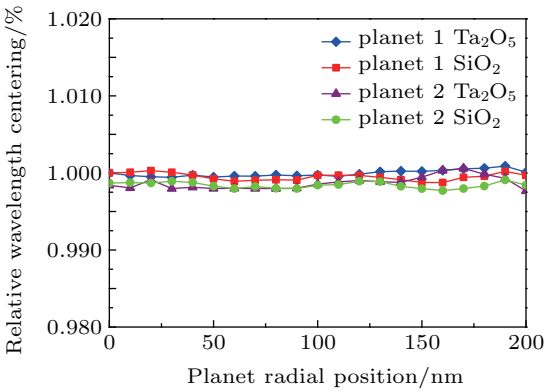


Fig. 6. (color online) Measured relative coating thickness uniformity. Blue line represents Ta_2O_5 material for planet 1 (monitoring planet). Purple line represents Ta_2O_5 material for planet 2 (accompanying planet). Red line represents SiO_2 material for planet 1. Green line represents SiO_2 material for planet 2.

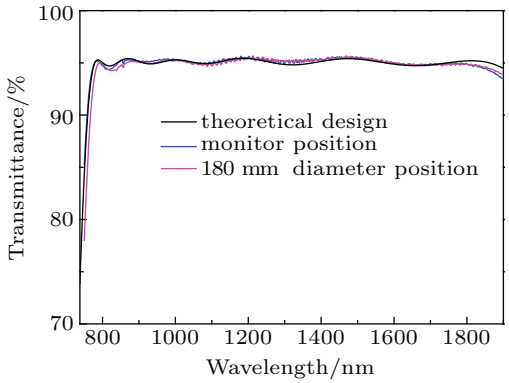


Fig. 7. (color online) Transmission versus wavelength of the broadband AR coatings. Blue line represents the measured design deposited on the monitoring position. Purple line represents the measured design deposited on the 180 mm diameter position.

Figure 7 shows the variation in the short wavelength edge across the central 180 mm diameter for one run. It can be known that radial thickness variations on the planetary fixture lead to the variation in short wavelength edge. Before the broadband AR coating was deposited, thickness uniformity of less than $\pm 0.1\%$ across the central 180 mm diameter was obtained by reshaping the shadow mask shape. The results show that the relative variation of the short wavelength edge shift is about 0.6%. The maximum deviation in centering of 6 nm from the design wavelength can be found.

Repeatability, which can never be ignored in batch production, is also an important performance factor for an optical film coater. Thus, experiments for 2 continuous runs were executed. Figure 8 shows the repeatability of 2 runs of the broadband AR coating. The relative variation of the short wavelength edge shift for 2 runs is about 0.5%. The results show that we can obtain repeatable results at the monitoring position from run to run because of the stability of the BBOM system.

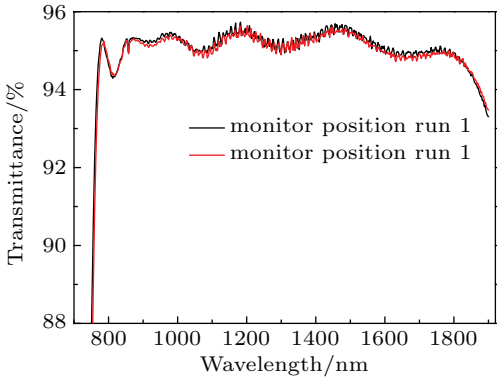


Fig. 8. (color online) Transmission versus wavelength of broadband AR coatings for 2 continuous runs. Black line represents run 1 deposited on the monitoring position. Red line represents run 2 deposited on the monitoring position.

4. Conclusion

In this paper, broadband AR coatings in the range from 800 nm to 1800 nm were designed by Optilayer and deposited by IBS. Broadband optical monitoring mixed with time monitoring was employed to monitor the layer thickness during the deposition process. Results show that broadband AR coatings can be successfully fabricated by IBS using BBOM and time monitoring strategy during the deposition process. A 0.6% variation in the short wavelength edge across the central 180 mm diameter is demonstrated. A wavelength shift of less than 0.5% for 2 continuous runs is also presented.

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