Design and preparation of a large size laser protective coating for solar arrays on spacecrafts

Zhenfeng Shen (申振峰)

Key Laboratory of Optical System Advanced Manufacturing Technology, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

Corresponding author: zf_shen@163.com

Received August 11, 2013; accepted October 15, 2013; posted online March 25, 2014

In this letter, we introduce the project of multilayer dielectric film based on conventional optics to design laser-protective coating. A desired material with an ideal refractive index is used to optimize the design results. Two film-thickness masks are designed to improve the uniformity of large-size coatings. Experimental results show that the average spectral transmittance from 400 to 1000 nm is higher than 85%, the attenuation of high-energy laser at both 532 and 1064 nm is larger than 98% in the range of ±20°, and the film uniformity of large area is more than 98.2%. The coating performance observed meets the requirements of both utilization of solar energy and laser protection.

OCIS code: 350.1260.

doi: 10.3788/COL201412.S13501.

In the future war, the role of spacecrafts, such as satellites, becomes increasingly important. It can be realized by means of satellites, such as reconnaissance, communications, navigation, and other important functions. Space control is the key factor in determining the outcome of the future war, so the satellite will become one of the important goals of enemy's attack. With the high-speed development of laser-blinding weapons, the threats against solar arrays on spacecrafts are also growing. America and Russia began to research in laser anti-satellite weapons in 1960s and have successfully conducted series of laser anti-satellite tests since 1990s. Meanwhile, they have specially focused on the researches on satellite laser protection and have mastered considerable protective measures[1–6]. Solar array is an equipment that transforms the energy of solar radiation into electrical energy, and it is sure to maintain a spacecraft running in orbit. Strong irradiation of high-energy laser to solar cell can destroy photovoltaic device and makes the spacecraft ineffective. To ensure reliable operation and improve the viability of the spacecraft during wartime, solar arrays must be effectively protected.

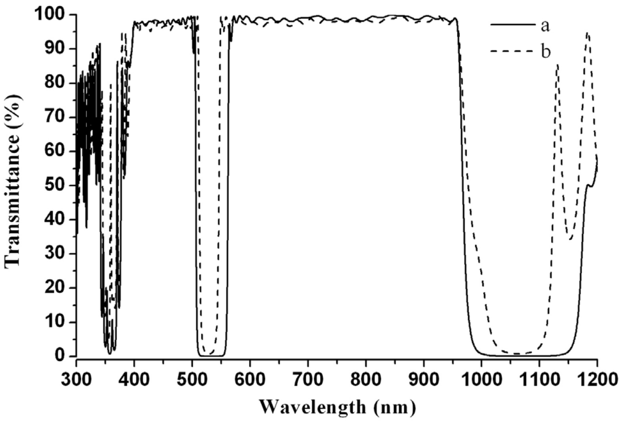

Fig. 1. Solar radiation spectrum of upper atmosphere.

The function of solar array is to transform the energy of solar radiation into electrical energy. So, when the protective film provides protection against high-energy laser damage, it must ensure the full utilization of solar radiation. Figure 1 shows the solar radiation spectrum of upper atmosphere[7]. The energy of solar radiation centralizes mainly in the visible waveband (wavelength: 0.4–0.76 μm), and then in the near-infrared waveband (wavelength: 0.76–1.4 μm) and ultraviolet waveband (wavelength: 0.3–0.4 μm).

Solar array of spacecrafts is assembled by silicon solar panels and its working band is from 380 to 1100 nm. Laser-protective objectives of this project in the working band of solar array have the high laser radiation at the wavelength of 532 and 1064 nm. Therefore, by considering the above aspects, the performance requirements of this designed protective coating ensure a higher spectral transmittance in the waveband from 400 to1000 nm and to cut down the high intensity of 532- and 1064-nm laser. The coating must also have a laser damage threshold as high as possible. In order to increase the protective effect, it should be ensured that the coating gives effective protection in a wide incidence angle range of about ±20°.

In general, there are three main ways to prepare the laser-protective coatings[8–10]. The first one is multilayer dielectric film based on traditional optics. It is advantageous because the preparation technique is reliable and the coating can obtain a higher laser damage threshold. But, its protection performance is poor under larger incident angle and it is also possible to hinder the useful signal at the same waveband when protecting against high-energy laser damage. The second one is the protective coating based on the principle of nonlinear absorption. The most mature one is C_{60}, which

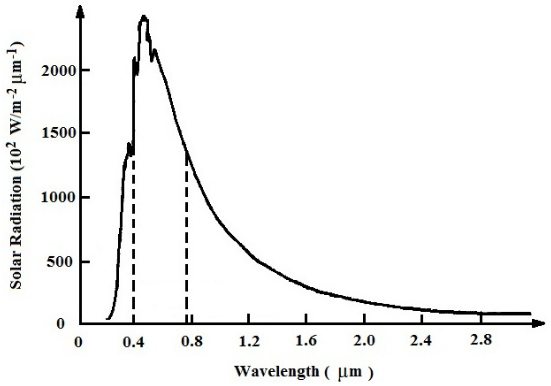

Fig. 2. Transmittance curves of the protective coating design.

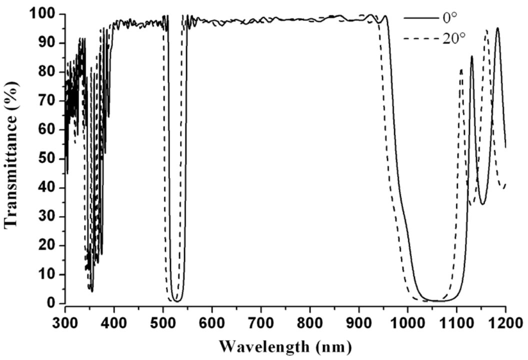

Fig. 3. Transmittance curves at 0° and 20° incidence of the improved design.

is characterized by fast response. However, its laser damage threshold is low and the attenuation of high-energy laser radiation is insufficient. The third one is the protective coating based on phase transition theory delegated by VO_2 coating. It helps in both signal reception and laser-protection function, and furthermore, it has not only a wider protective waveband, but also a large protective incident angle. Unfortunately, its laser damage threshold is not high enough.

Although the protective performance of VO_2 coating is relatively good, its transmittance in visible range is too low, the average is less than 40%[8,9], which cannot meet the requirements of the utilization of solar radiation. So, VO_2 coating is not suitable for the application in this program.

Considering the double demands, e.g., utilization of solar radiation and laser protection for the solar array, it is concluded that only the multilayer dielectric film based on the traditional optics is more appropriate compared to other two kinds of coating; and furthermore, it is more suitable to facilitate the practical engineering applications. Therefore, in this project, we introduce the program of multilayer dielectric film for protective coating design.

To ensure a higher utilization of solar radiation for laser-protective coating of the solar array, 400–800 nm waveband followed by 800–1000 nm waveband is selected as the main waveband, which should have the transmittance as high as possible. At the same time, high laser intensity at 532 and 1064 nm must be cut down. SO_2 and ZrO_2 are selected for coating design because of their high laser damage threshold and mature preparation techniques. A 56-layer coating design is obtained after optimization. The optical transmittance of coating design is shown in Fig. 2 (curve a). It can be observed that the cut-off bands at 532 and 1064 nm are relatively wide. Although this helps ensure an effective attenuation to high-energy laser in a larger incident angle range, it prevents a few parts of the solar radiation and reduces the utilization of solar radiation, especially the solar radiation near 532 nm. So, the width of cutoff band should be reduced appropriately.

Formula used to calculate reflective bandwidth of multilayer dielectric reflective film in the classical film theory is express as

$$\Delta g = \frac{2}{\pi}\sin^{-1}\left(\frac{n_H - n_L}{n_H + n_L}\right),$$

where, n_H and n_L are the refractive indices of two materials. This formula indicates that the reflective bandwidth relates only to refractive index (n). If the difference in n is larger, the reflective bandwidth changes are wider. The width of cutoff band in this design is also determined by this formula. Owing to the large difference ‘n’ of ZrO_2 (n = 2.05) and SiO_2 (n = 1.46), the width of the cutoff band is relatively wide. To reduce the cutoff bandwidth, difference ‘n’ of the two materials should be decreased. According to the theoretical analysis and calculation, it was found that better results are obtained if a material with the refractive index of 1.75 is used as a substitute for SiO_2 in the film design. The curve (b) in Fig. 2 represents the optical transmittance spectra of an optimized design by using a material with n = 1.75. It can be observed that the cutoff band width is significantly reduced. Figure 3 shows the optical transmittance of 0° and 20° incidence under the optimized design. In both the cases, the transmittance at 532 and 1064 nm is less than 2%. The results of the optimized design not only realize an effective attenuation to high-energy laser in ±20° incident angle

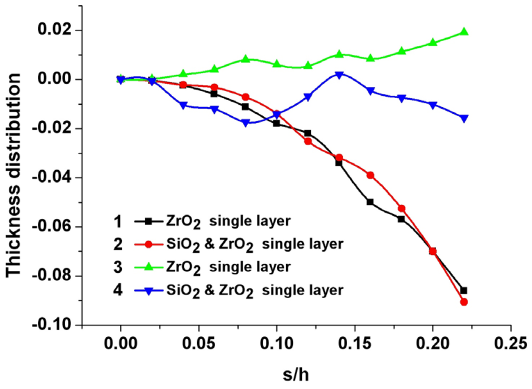

Fig. 4. Thickness distribution curves of the related materials.

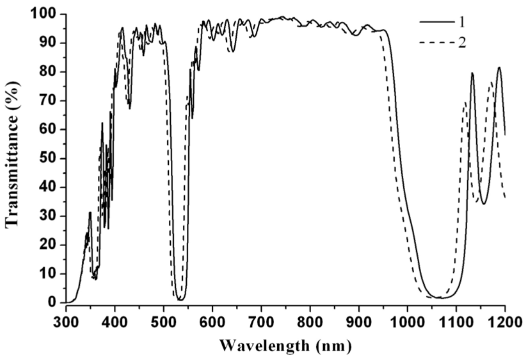

Fig. 5. Transmittance test curves at 0° and 20° incidence of the protective coating.

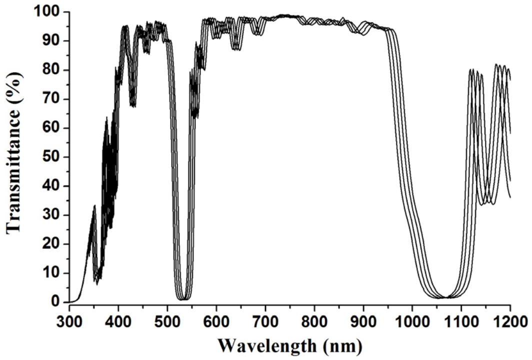

Fig. 6. Performance uniformity test curves of the protective coating.

range, but also ensure the solar energy utilization ratio as high as possible.

The results obtained from the previous section indicate that results will be better if a material with the refractive index of 1.75 is used as a substitute for SiO_2 in the film design. In addition, in order to avoid the damage from high-power laser, this material should also have a high laser damage threshold. But in fact, materials available for this purpose are limited.

It is difficult to find an ideal material with the refractive index of 1.75. In order to obtain such a material with an ideal refractive index, we developed a method to prepare mixed materials, e.g., ZrO_2 and SiO_2. ZrO_2 and SiO_2 are mixed in a certain quantity, which resulted in a mixed material coating, for which the refractive index (n = 1.75) is between that of ZrO_2 and SiO_2. Furthermore, it has a high laser damage threshold. Subsequently, better experimental results are obtained with this mixed material in the preparation of laser-protective coating.

In order to obtain adequate supply power for spacecraft, large surface area of solar array is necessary. This requires a laser-protective coating with uniform thickness in a large area. Mathematical analysis and fitting method are used to establish the models of evaporation characteristics of the materials and film thickness uniformity to ensure a better uniformity of the protective coating in a large area. Film thickness masks for evaporation are designed using different materials, and therefore the coating uniformity is improved by optimizing the corresponding assistant means of preparation technology.

Figure 4 shows the thickness distribution curves of the film materials within Φ400 mm area; curves 1 and 2 represent the thickness distribution of ZrO_2 and ZrO_2 and SiO_2 mixed material prepared by ion-assisted deposition method. The nonuniformity is about 9%. Curves 3 and 4 represent the thickness distribution after applying film thickness mask technology. The nonuniformity is 1.6% and 1.9%, respectively. It can be concluded that the material uniformity has been significantly improved after the application of film thickness mask and it can meet the requirement of large area coatings.

Curves 1 and 2 in Fig. 5 represent the optical transmittance experimental results of the same laser-protective coating sample at 0° and 20° incident angles, respectively, which show that the average spectral transmittance at 400–1000 nm waveband is greater than 85%, and the attenuation of high-energy laser at 532 and 1064 nm is more than 98% in incidence angle range of ±20°. Figure 6 shows the optical transmittance experimental curves of four samples, which are evenly distributed from the center to the edge of a 400-mm radius. The test results show that the film thickness uniformity in Φ800 mm range is greater than 98.2%.

A kind of solar array laser-protective coating is designed and fabricated by using the multilayer dielectric film based on the traditional optics and the techniques of ion-assisted deposition method. Experimental results show that the protective coating meets the dual requirements of solar energy utilization and high-energy laser protection at 532 and 1064 nm. Furthermore, it meets the relevant requirements of engineering applications. However, the number of studies on the protective wavelength is limited, therefore further studies are needed. The protection at large incident angles (> ±20°) is insufficient, this needs further protection using optical baffle technology.

References

1. W. H. Chi and S. Z. Zhu, Natl Defense Sci. Technol. **3,** 13, (2011).
2. X. D. Weng, J. Xu, and W. M. Zhou, Lasers Optoelectron. Progress **40,** 22 (2003).
3. M. Xu, Y. C. He, and Q. Y. Li, Mod. Defense Technol. **29,** 43 (2001).
4. Y. Cui, H. B. He, Z. X. Fan, and J. D. Shao, Laser Optoelectron. Progress **43,** 10 (2006).
5. Y. Sun, J. S. Ren, and Y. Shen, Electro-Opt. Technol. Appl. **21,** 14 (2006).
6. B. L. Liu, J. M. Shi, X. C. Yan, and Z. D. Lin, Infra. Laser Eng. **38,** 470 (2009).
7. Y. M. Xu, H. N. Liu, and G. Y. Xu, *Introduction to Atmospheric Sciences* (Nanjing University Press, Nanjing, 2000).
8. L. J. Qin and Z. K. Li, Spacecraft Recov. Remote Sens. **33,** 99 (2012).
9. W. P. Wang, Y. Q. Luo, D. Y. Zhang, and F. Luo, Appl. Opt. **45,** 3378 (2006).
10. Y. Q. Du, Proc. IEEE Conf. Photon. Optoelectron **1,** (2010).