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Investigation of thermal radiation effect on optical dome of sapphire coated yttrium oxide

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Abstract Compared to traditional optical domes, domes of sapphire coated with films can effectively reduce emissivity and increase transmittance. The purpose of this work is to investigate the thermal radiation effect on sapphire optical dome coated with yttrium oxide by a radio frequency magnetron sputtering method. The emissivity of sapphire coated with Y_2O_3 films is studied by both numerical and experimental methods. The results indicate that the emissivity of sapphire substrate is reduced effectively with increasing the thickness of the Y_2O_3 film. In addition, a finite element model is developed to simulate the radiation intensity of the optical dome. The thermal responses indicate that the maximum temperature is reduced apparently compared with the uncoated sapphire as Y_2O_3 film thicknesses increase. The average irradiance distribution at different film thicknesses with time shows that the self-thermal radiation disturbance of sapphire optical dome delays 0.93 s when the thickness of Y_2O_3 film is 200 μm, which can guarantee the dome works properly and effectively even in a harsh environment.

Keywords Yttrium oxide · Sapphire substrate · Apparent emissivity · Thermal radiation effect

1 Introduction

Infrared technologies including infrared imaging and infrared guidance are very important strategic and tactical approaches in the area of modern national defense. Infrared windows and domes are essential devices in these technologies [1, 2]. The optical dome is subjected to severe aerodynamic heating and fierce pressing during spacecraft flies at a hypersonic speed in the atmosphere [3]. Temperature increase of an optical dome will cause an increase of the thermal stress and strain, and even a thermal damage, which will cause a complete structural failure of the material [4, 5]. It has to protect infrared radiation sensor and sensing photo units from material structure failure and guarantee the imaging qualities of photoelectric sensor at the same time, so requirements to the materials of optical domes are quite strict [6, 7]. Single crystal sapphire is a kind of important material for mid-wave infrared-transmitting domes on high-speed missiles and aircrafts due to its impressive optical and mechanical properties. However, the properties of sapphire are limited by the quality and manufacturing technique [8, 9]. Meanwhile, the dome is heated by the atmosphere around whose temperature increases due to the thermal radiation, while part of the thermal radiation is accepted by the infrared sensor which results in a radiated interference [10, 11]. The thermal radiation of the dome increases with the increase of the temperature, which produces a sharp increase in background radiance and reduces the detection capability and the traceability of detectors. Some severe cases even lead to saturation of infrared detector, which will cause a material function failure [12, 13]. Therefore, it is necessary to improve the transmission of optical dome so as to guarantee it working properly and effectively even in a harsh environment [14, 15].

Film deposition is one of the processing technologies that can effectively enhance the optical and mechanical

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properties of optical domes. Film materials usually have better optical and mechanical properties than the substrate [16]. In recent years, studies on optical property enhancement and invalidation of the optical dome material have attracted many researchers' attention. Feng and Liu [17] investigated the optical properties of sapphire dome coated SiO_2 films. Song et al. [18] studied the effect of Ag-doping on microstructural, optical and electrical properties of sputtering-derived ZnS films. Y_2O_3 is also a rapidly developing material for coating films owing to its perfect optical and mechanical performance, such as low thermal diffusion coefficient, low specific heat and high transmittance [19]. Therefore, Y_2O_3 can be a good choice for film material deposited on sapphire substrate. However, there is little research on the thermal radiation failure mechanism of sapphire optical dome. And the materials and properties of films and substrates have not been fully exploited by coating technology as its functional mechanisms of resistance to thermal radiation failure are still unclear.

In this work, the emissivity of sapphire coated with Y_2O_3 films by radio frequency magnetron sputtering method was studied experimentally in detail. Subsequently, the apparent emissivity of the coated sapphire was simulated for different film thicknesses at different temperatures. Meanwhile, a finite element model was developed to simulate the radiation intensity of the optical dome.

2 Experimental

An energy method is employed to measure the spectral emissivity of the semi-transparent medium at different temperatures, as shown in Fig. 1. The emissivity measurement system mainly includes a Fourier transform infrared spectrometer, a diaphragm, rotating reflector, a specimen, a furnace, a light source, a blackbody furnace, and a data processing system. The two sides of the furnace containing heating rods and thermocouples are transparent. The specimen is set on one side of the furnace. Part A of the system is to test the emissivity of the specimen and part B for the blackbody furnace. The experimental procedures are described below:

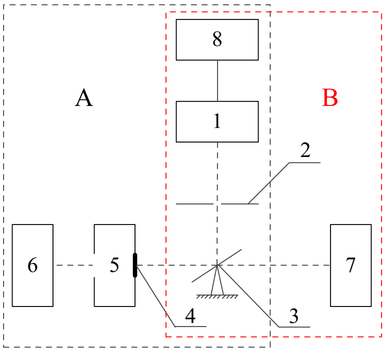

Fig. 1 (Color online) Skeleton drawing of emissivity measurement system for semi-transparent material: 1—Fourier transform infrared spectrometer; 2—diaphragm; 3—rotating reflector; 4—specimen; 5—furnace; 6—light source; 7—blackbody furnace; 8—data processing system

(1) Take away the specimen, shut down the furnace, and turn on the light source. Then measure the spectral radiation signal of 6, recorded as S_1;
(2) Take away the specimen, shut down the light source, and turn on the furnace heating to the setting temperature. Then measure the spectral radiation signal of 5, recorded as S_2;
(3) Put into the specimen, shut down the light source, and turn on the furnace heating to the setting temperature. Then measure the spectral radiation signal of 4 and 5, recorded as S_3, $S_3 = S_2\tau + S_s$. τ is the transmittance of the specimen and S_s is the spectral radiation signal of the specimen;
(4) Put into the specimen, turn on the light source and furnace heating to the setting temperature. Then measure the spectral radiation signal of 4, 5 and 6, recorded as S_4, $S_4 = (S_1 + S_2)\tau + S_s$;
(5) Using part B, heat the black furnace to the setting temperature. Then measure the spectral radiation signal of 7, recorded as S_b.

Hence, the spectral emissivity of the specimen at the setting temperature is

$$\varepsilon(\lambda) = \frac{S_s}{S_b} = \frac{S_3}{S_b} - \frac{S_2(S_4 - S_3)}{S_1 S_b}. \tag{1}$$

Main technical index of the Fourier transform infrared spectrometer is shown as below: (1) wavenumber region: 15,000–350 cm^{-1}, (2) resolution: 0.022–40 nm, (3) SNR (signal to noise ratio): 25,000:1, (4) scanning frequency: 20 Hz, (5) testing temperature: 300–1000 K.

The uncertainties of the experimental system consist of three parts: the uncertainty of the Fourier transform infrared spectrometer, the blackbody furnace, and the thermocouples in the furnace.

For the Fourier transform infrared spectrometer, the uncertainty of the nonlinear responses and the noise curve are 0.32 % and 0.35 %, respectively.

For the blackbody furnace, the uncertainty of emissivity and temperature are 0.1 % and 0.4 %, respectively.

For the furnace, the indicated temperature fluctuates by 1 K and the error transfer formula of the emissivity measurement introduced by the temperature is

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{C_2/(\lambda T)}{\exp[-C_2/(\lambda T)] - 1}\frac{\Delta T}{T}. \tag{2}$$