Design of highly reflective film for smart radiation device

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Abstract. Smart radiation device (SRD) based on the asymmetrical Fabry-Perot cavity automatically tune its IR emittance depending on the ambient temperature, making it an ideal choice for thermal control system of spacecrafts. The low solar absorption is desirable for SRD to prevent the spacecraft from overheating by sun light. In this paper, a multilayer highly reflective film with ($LH)^k$ stacking layers is designed to reduce the solar absorptance ($A_o$) of the Ag/Al₂O₃/VO₂ structured SRD. The reflective film achieves a high reflection band in ~220 nm bandwidth from 460 nm to 680 nm, which results in a reduction of the solar absorptance by 25.56 % for SRD working at low temperature and 24.27 % at high temperature as the stacking factor $k = 5$. The simulation results indicate that an economic reflective film with $k = 3$ can achieve effective suppression of $A_o$ of SRD, demonstrating the promising potential of the proposed reflective film in thermal control application of spacecrafts.

Keywords: smart radiation device (SRD), Fabry-Perot cavity, highly reflective film, solar absorption, emittance.

1. Introduction

In space environment, radiation is the only way to exchange heat between spacecraft and external space [1]. The emittance devices, a key part of the thermal control system, are designed to radiate heat produced by electronic systems. The variable emittance devices have been attracting extensive attention because of its bi-functionality that achieves heat preservation at low-temperature and heat dissipation at high-temperature [2]. The smart radiation device (SRD) based on thermochromic materials can automatically adjust the emittance depending on temperature, achieving low-emittance at low temperature and high-emittance at high temperature [3]. Furthermore, the SRD does not need accessories as the traditional variable emittance devices, such as motorized shutters,[4] which require components involving thermal sensors, actuators, power supplies and circuit systems, resulting in the addition of load and volume to the spacecraft as well as the risk of damage. Thus, the SRD is a promising technique opening up horizon for satellite thermal control.

Benkahoul et al. reported the first fabrication of the VO₂-based SRD by depositing VO₂ film on the strongly reflective Al substrate, taking use of the thermochromic property of VO₂ in infrared region [3]. VO₂ undergoes a metal-insulator transition at ~68 °C ($T_c$), [5-8] and is transparent to visible and infrared (IR) light as $T < T_c$, and becomes strong IR reflective as $T > T_c$, leading to the IR transmittance modulation more than 70 % [9, 10]. Hendaoui et al. [11] designed and fabricated Au/SiO₂/VO₂ structure devices to achieve an intense high-temperature emittance ($\varepsilon_H$) of 0.8 and a large emittance modulation ($\Delta \varepsilon$) of 0.46. Wang et al. reported a Ag/HfO₂/VO₂ three-layer SRD which realized a $\Delta \varepsilon$ of 0.55 [12]. Beaini et al. studied the effect of individual layers on the SRD performance, and achieved a large $\Delta \varepsilon = 0.66$ by selecting BaF₂ as the optical medium layer [13]. However, those works did not involve the investigation on solar
absorption ($A_s$).

In space environment, the sunlight can heat the spacecraft surface up to ~150 °C, the low solar absorption rate is essential for the thermal control surface to avoid overheating of solar radiation. Therefore, a low solar absorption SRD is desirable for the integral thermal control system of microsatellites. The surface micro- and nano-optical structure can realize the low solar absorption surface [14, 15]. However, the micro- and nano-processing suffers from harsh experimental techniques and difficulty of preparing large area surface. In this paper, we propose an ideal of depositing reflective film on the surface of SRD to achieve the low solar absorption, and do not damage the IR emittance of the devices. The reflective film is designed to alternatively stack low refractive index layer ($L$, Al$_2$O$_3$) and high refractive index layer ($H$, TiO$_2$) on the Ag/Al$_2$O$_3$/VO$_2$ device. The optical simulation demonstrates that the optical design reduces the $A_s$ by ~25% while slightly improves the $\Delta\varepsilon$ by the $(LH)^k$ stacking with $k = 5$.

2. SRD and reflective film design

2.1. SRD structure

As shown in Fig. 1, the SRD structure is composed of VO$_2$ film (50 nm), optical medium Al$_2$O$_3$ film (1500 nm) and highly reflecting Ag film (200 nm). Optical constants of VO$_2$ film in cold and hot states are from [16]. At low temperature, VO$_2$ is a semiconductor, transparent to the IR light, so the IR radiation can easily pass through the VO$_2$ and Al$_2$O$_3$ layers and reflected by the Ag layer. At high temperature, VO$_2$ works as an IR reflector, together with Al$_2$O$_3$ layer and Ag layer to form an asymmetric Fabry-Perot cavity (F-P cavity), which can realize interference extinction for IR light around 10 μm, resulting in high IR emittance.

![Fig. 1. Illustration of structure and tunable emittance of SRD, a) for insulating VO$_2$ at low temperatures, b) metallic VO$_2$ at high temperatures](image)

According to Kirchhoff’s law, the optical absorptance ($\alpha$) of an object is equivalent to its emittance ($\varepsilon$) under thermal equilibrium conditions, namely $\varepsilon(\lambda) = \alpha(\lambda)$. The IR emittance at a certain temperature $\varepsilon_{IR}(\lambda)$ is an integral value calculated using Eq. (1) [17]:

$$\varepsilon_{IR}(\lambda) = \frac{\int_{\lambda_1}^{\lambda_2} \alpha_{IR}(\lambda)B_{IR}(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} B_{IR}(\lambda)d\lambda}$$

(1)

where $B_{IR}(\lambda)$ is the blackbody spectral radiation at the desired temperature given by Planck’s law.

2.2. Reflective film

The highly reflective film is fabricated by alternatively stacking of high refractive layer and low refractive layer, whose optical thickness $n\lambda$ ($n$ denotes the refractive index) is $\lambda_0/4$. As shown in Fig. 2, the high refractive index material is TiO$_2$ ($n = 2.38$ at 550 nm) and the low refractive index material is Al$_2$O$_3$ ($n = 1.62$ at 550 nm).
The model structure can be represented by the following expression:

\[ GLHLHLH...LHA = G(LH)^kA. \]  

\[ \text{(2)} \]

\( G \) denotes substrate, in this case, it is SRD device; \( A \) is air; \( L \) and \( H \) represent the low refractive layer and high refractive layer, respectively; \( k \) is the stacking factor, and \( k = 1 \) means a couple of \( L \) and \( H \) layers.

For a single-layer optical film with \( \lambda_0/4 \), the reflectance is:

\[ R = \left( \frac{n_0 - n_1^2/n_2}{n_0 + n_1^2/n_2} \right)^2, \]

\[ \text{(3)} \]

where \( n_0 \) is the refractive of air, \( n_1 \) is the refractive of optical film, \( n_2 \) is the refractive of substrate. Eq. (3) can be expressed as Eq. (4) by taking \( n_1 = n_2^2/n_2^2 \):

\[ R = \left( \frac{n_0 - n_2^2/n_2}{n_0 + n_2^2/n_2} \right)^2, \]

\[ \text{(4)} \]

where \( n_1 \) is defined as the equivalent refractive index of the optical structure constructed by the \( \lambda_0/4 \) \( n_1 \) layer covering the \( n_2 \) substrate, namely the \( n_1/n_2 \) structure is equivalent to a \( n_1 \) medium. In this way, the equivalent refractive index \( n_{2k} \) of the \((LH)^k\) stacking film is:

\[ n_{2k} = \left( \frac{n_H^2}{n_L^2} \right)^k n_2, \]

\[ \text{(5)} \]

and the reflectivity of the \((LH)^k\) film becomes:

\[ R_{2k} = \left( \frac{1 - n_0/n_{2k}}{1 + n_0/n_{2k}} \right)^2. \]

\[ \text{(6)} \]

As \( k \) increases, \( n_{2k} \) becomes much larger than \( n_0 \) according to Eq. (5), then \( R_{2k} \) tends to be 1. The highly reflective films are obtained.

For SRD, the strong reflecting Ag layer determines the transmittance \( T(\lambda) \) of SRD is 0, then \( \alpha(\lambda) = 1 - R(\lambda) \) according to \( \alpha(\lambda) + R(\lambda) + T(\lambda) = 1 \) [10]. The solar absorption \( A_s \) of the devices can be calculated using the equation:

\[ A_s = \frac{\int_{\lambda_1}^{\lambda_2} (1 - R_{sol}(\lambda)) \varphi_{sol} d\lambda}{\int_{\lambda_1}^{\lambda_2} \varphi_{sol} d\lambda}, \]

\[ \text{(7)} \]
where $\varphi_{sol}$ represents the solar radiation spectrum corresponding to an atmospheric mass of 1.5 (according to the sun standing 37° above the horizon).

3. Results and discussion

Optical simulation results of the VO$_2$/Al$_2$O$_3$/Ag three-layer SRD are shown in Fig. 3. In the visible region, the SRD working at low temperature and high temperature has the similar reflectance value as shown in Fig. 3(a). However, in the NIR (800-3000 nm) region, the reflectance at low temperature is obviously higher than that at high temperature. This is because the M-phase VO$_2$ is transparent to both visible and IR light but the R-phase VO$_2$ is highly reflective to IR light while retains transparent to visible light. The calculated solar absorptance $A_s$ of the SRD is 33.29% at low temperature and 45.52% at high temperature, as shown in Fig. 3(c). The infrared emittance spectra of the SRD is shown in Fig. 3(d). The device achieves the high emittance at high temperature and low emittance at low temperature. The emittance modulation $\Delta \varepsilon$ is up to 0.71 with $\varepsilon_L = 0.12$ and $\varepsilon_H = 0.83$, indicating the Fabry-Perot cavity works well. However, the solar absorptance of the device is unsatisfactory due to the high values in Fig. 3(a-c), especially for that of high temperature.

![Simulation results of VO$_2$/Al$_2$O$_3$/Ag three-layer structured SRD: a) UV-VIS and b) NIR reflection spectra of M- and R-phase VO$_2$; c) Integral solar absorptance $A_s$ of M- and R-phase VO$_2$; d) The emittance spectra of M- and R-phase VO$_2$. The $\varepsilon$ values in d) are the integral emittances (5-15 $\mu$m) of M and R phases](image-url)
Fig. 4. a) Calculated reflection spectra of the reflective films with different stacking factors $k$, b) integral reflectance in the 300-800 nm range

Fig. 5 shows the calculated reflection spectra of the highly reflective film coated SRD in the solar spectral range. The highly reflective coating renders SRD the quite high reflectance in the wavelength range of 460-680 nm, and has less impact on other bands. The solar spectral reflectance of SRD rises up with the increase of stacking factor $k$. The integral solar absorptances of the devices are calculated and listed in Table 1. As $k = 5$, the reflective film coated SRD has the lowest $A_0$, 24.78 % for low-temperature (M-phase VO$_2$) and 34.47 % for high-temperature (R-phase VO$_2$), corresponding to a reduction of 25.56 % and 24.27 % with respect to the bared SRD, respectively. Considering economy and feasibility, the $k = 3$ film can also do good work on reducing the solar absorption of SRD as shown in Table 1.

Table 1. Calculated integral solar absorptance $A_0$ of SRD with highly reflective films

<table>
<thead>
<tr>
<th>VO$_2$</th>
<th>$k$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>M phase</td>
<td>33.29 %</td>
<td>30.96 %</td>
<td>27.12 %</td>
<td>26.64 %</td>
<td>25.19 %</td>
<td>24.78 %</td>
<td>25.51 %</td>
<td></td>
</tr>
<tr>
<td>R phase</td>
<td>45.52 %</td>
<td>40.06 %</td>
<td>36.27 %</td>
<td>34.71 %</td>
<td>35.5 %</td>
<td>34.47 %</td>
<td>36.12 %</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. Simulated solar reflection spectra of SRD devices with highly reflective films, a), b) for M-phase VO$_2$, c), d) R-phase VO$_2$.
The IR emittance of the highly reflective film coated SRD is calculated to find out whether the addition of the reflective film injures the emittance performance of SRD. Fig. 6 shows the calculated emittance spectra of SRD with highly reflective films. The IR emittance modulation $\Delta \varepsilon$ of SRD is enhanced by increasing $k$. What it is that the emittance of SRD at high temperature is increased and decreased at low temperature in the 5-16 $\mu$m range with the increase of $k$. The improvement of $\Delta \varepsilon$ is mainly ascribed to the broadening and enhancing of the IR absorption band at high temperature as shown in Fig. 6.

![Fig. 6. The emittance spectra of SRD devices with highly reflective film for VO$_2$ in M/R phase](image)

4. Conclusions

The highly reflective film was designed with the classical $(LH)^k$ stacking model to reduce the solar absorptance of SRD. The $(LH)^k$ stacking layers with $k = 5$ performed the most effective reduction of $A_s$ by 25.56 % as SRD works at high temperature and 24.27 % at low temperature. Meanwhile, the highly reflective film can enhance the high-temperature emittance and suppress the low-temperature emittance in the 5-16 $\mu$m range, as a result, improve the IR emittance modulation of SRD. In the view of economy, the reflective film of $k = 3$ can bring about the effective reduction of the solar absorptance of SRD, making the proposed highly reflective film feasible.

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References


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