Optimization Design of a Multilayer Structure for Broadband and Direction-Selective Emissivity

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Abstract

Micro-nano structures for broadband and direction-selective emission have long been a scientific and engineering challenge. In this work, based on the emissivity distribution of three silver-coated dielectric media, including silicon dioxide (SiO₂), silicon monoxide (SiO), and aluminum oxide (Al₂O₃), a multilayer structure was designed for broadband and direction-selective emissivity. The structure's emissivity varying with wavelength and emission direction was analyzed. Effects of different arrangement modes of the dielectric media and the thickness of each dielectric layer on the multilayer structure's emissivity were examined for design optimization. The optimal multilayer structure exhibits a strong direction-selective emissivity within a broadband wavelength of 8.0-11.0 μm which covers the spectral emission peak of an object maintained at ~ 300 K, and thus has potential applications in infrared camouflage.

Keywords: Broadband radiation characteristic; Direction-selective emissivity; Multilayer structure; Infrared camouflage.

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1. Introduction

According to the Stefan-Boltzmann law, any object at a temperature higher than 0 K radiates energy in the form of electromagnetic waves. Thus, thermal radiation is a ubiquitous phenomenon and now witnesses essential applications in several domains, such as infrared imaging,^[1] remote-sensing detection^[2], and energy conversion and utilization.^[3-8]

In general, natural objects are isotropic, and the outward-emitted thermal radiation shows no pronounced directivity. On the other hand, with the development of science and technology, many application fields have set a higher requirement on the direction selectivity of the thermal radiation, and simultaneously, thermal structures with direction selectivity have now attracted a significant amount of attention. Early in 1967, Tien *et al.*^[9,10] from the University of California, Berkeley, discovered the micro-scale radiation effect of the thermal impact on actual engineering. Afterward, investigations on the manipulation of radiation characteristic via micro-structures began to raise broad concerns. In recent years, tremendous micro-/nano- structures, including

multilayer slabs,^[11-15] nanoparticle/nanowire-doped coatings,^[16-20] micro-nano humps, holes and rods,^[21-25] and their combined photonic crystals,^[26-30] have been prepared for spectral-selective emission of a thermal surface.

In addition to spectral regulation of the radiation emission, controlling the angular emission via sub-wavelength structure is also of great importance in scenarios where radiation in unwanted directions should be suppressed, such as privacy screens, stealth coatings, radar-like detectors. Compared with the fast development of spectral-selective thermal emitters, micro-/nano- designs towards achieving direction-selective thermal emission have been far less prepared. Greffet *et al.*^[31,32] found that some planar sources have an in-plane spectral coherence length much larger than a wavelength and can be quasi-monochromatic in the near-field. Wolf *et al.*^[33,34] first predicted the spatial coherence emission of a carefully designed microstructure. The work of Greffet *et al.*^[31,32] and Wolf *et al.*^[33,34] paves the way for the construction of a thermal source that could radiate light within narrow angular lobes. Greffet *et al.*^[35] prepared silicon carbide (SiC) periodic optical gratings and they observed strong direction-selective emissivity in the wavelength at around $\lambda = 11.0 \mu\text{m}$. The highly directional coherent thermal emission therein^[35] is due to the diffraction of surface phonon polaritons which can convert surface waves to propagating waves.^[35-37] Based on surface plasmons, Laroche *et al.*^[38] and Dahan *et al.*,^[39] respectively, designed one-dimensional periodic grating

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Fig. 1 (a) Sketch of the sDM structure. Emissivity distributions of the sDM structure composed of a 0.2 μm -thick dielectric medium of (b) SiO_2 , (c) SiO , and (d) Al_2O_3 .

structures by using tungsten and silicon dioxide, and achieved intensive direction selectivity in the infrared range. A two-dimensional grating structure with both direction selectivity and spectral selectivity was designed by Costantini *et al.* [40] for applications in infrared light source and gas detection systems. Recent developments on direction-selective emitters can be found in the comprehensive review work on thermal radiation control by Baranov *et al.* [36] and Wang *et al.*, [37] respectively.

Planck's law demonstrates that thermal radiation emitted from an object at a specific temperature naturally distributes in a broad waveband. Investigating the structure with direction-selective emissivity in a wide wave range is of great relevance to energy conversion and management. [41–45] Wu and Fu [46, 47] designed a multilayer structure for broadband absorption by carefully stacking the tilted hexagonal boron nitride slabs [46] and silicon nanowire doped polymethyl pentene slabs, [47] respectively. By preparing a two-port system with a graphene layer deposited on a two-dimensional photonic crystal slab, Xiao *et al.* [48] achieved a manipulation of maximum absorption bandwidth from ultra-narrowband (< 0.5 nm) to broadband (> 50 nm). Despite all efforts, the above-reported micro-nano structures can only achieve the direction selectivity of the emissivity at a particular wavelength or in a

quite narrow waveband, or broadband emissivity without angular selectivity. Structures with direction-selective emissivity in a broad waveband are far from perfect, [49–51] the existing structures are usually complicated and the optimal designs have been rarely reported.

Thin films composed of epsilon near zero (ENZ) material [52] can couple the electromagnetic modes to the propagation free-space modes, and have been recently verified to have the ability of exhibiting direction-selective emissivity. [53–57] But the previous work is still limited to narrow-band. The objective of this study is to fill the gap of simple structure for obtaining direction-selective emissivity within a broad wave range that covers the wavelength of $\lambda \sim 9.6$ μm which is the emission peak of a blackbody maintained at the room temperature of ~ 300 K, by using low-cost ENZ materials.

By carefully checking the optical constant of common oxides, [58] we found that for the materials of SiO_2 , SiO , and Al_2O_3 , the real part n and the imaginary part k of the refractive index satisfies $n \approx k < 1.0$ and supports near-zero epsilon phenomenon at specific wavelength (8.0, 8.5, 11.0 μm for SiO_2 , SiO , and Al_2O_3 , respectively) near 9.6 μm . We, therefore, spontaneously select these three oxides as the dielectric media for the broadband and direction-selective emitters. The rest of this article is organized as follows. The

emissivity distributions of a silver-coated dielectric medium are analyzed in Section 2. In Section 3, a multilayer structure composed of three dielectric media was designed for broadband direction-selective emissivity, and optimized for a better performance. Section 4 summarized the main conclusions of this work.

2. Single-dielectric-medium structure

Firstly, the emissivity characteristics of the slab structure with a single dielectric medium were investigated. As shown in Fig. 1(a), a silver (Ag) layer with a thickness of $0.1 \mu\text{m}$ was first deposited on the silicon substrate, and a dielectric medium with a thickness of d was then coated onto the Ag layer. The rigorous coupled wave analysis (RCWA) method,^[59-61] which is based on semi-analytical solutions of electromagnetic fields and has been well developed for calculating the emissivity/absorptivity of photonic crystals,^[62-65] is applied to calculate the emissivity of the single-dielectric-medium (sDM) structure in this work. Figs. 1(b)-(d) plot the emissivity as a function of wavelength and direction of the sDM structure

composed, respectively, of different oxides, *i.e.*, the selected SiO_2 , SiO , and Al_2O_3 . When SiO_2 is used as the dielectric material, the emissivity of the prepared sDM structure shows significant direction selectivity at the wavelength of $\lambda \sim 8.0 \mu\text{m}$. As shown in Fig. 1(b), the emissivity is relatively low in the small-zenith-angle directions (near the wall surface's vertical axis) and high in the large-zenith-angle directions. When the dielectric layer is, respectively, selected as SiO and Al_2O_3 , the sDM structure shows significant direction selectivity at $\lambda \sim 8.5 \mu\text{m}$ and $\lambda \sim 11.0 \mu\text{m}$, as shown in Fig. 1(c) and (d), accordingly.

For the planar thin film-based structures, the thickness of the dielectric medium significantly influences its emissivity as the in-plane electric field is a function of the medium thickness.^[60] The emissivities of the sDM structure with different thicknesses of $d = 0.1, 0.2$, and $0.3 \mu\text{m}$ are calculated for two selected directions of $\theta = 20^\circ$ and $\theta = 80^\circ$, and they are presented in Figs. 2(a)-(c) for the medium of SiO_2 , SiO , and Al_2O_3 , respectively.

Fig. 2 Emissivities of the sDM structures composed of different dielectric media: (a) SiO_2 , (b) SiO , and (c) Al_2O_3 . (d) Emissivity of the different sDM structures composed of a $0.2 \mu\text{m}$ -thick dielectric medium and standardized spectral emission intensity of the black body at 300 K, $I_{b\lambda}/I_{b\max}$, where $I_{b\lambda}$ and $I_{b\max}$ are the spectral emission intensity and its maximum, respectively.

It is observed from Figs. 2(a)-(c) that the emissivity differs greatly in the two directions, and the difference is tightly correlated with the thickness of the dielectric layer. When the thickness of the SiO₂ dielectric layer is 0.1 μm , the emissivity peak of the sDM slab reaches a maximum at 80° and, simultaneously, a minimum at 20°. That is to say, the emissivity difference in these two directions is the greatest when the thickness of the dielectric layer is designed as $d = 0.1 \mu\text{m}$. As the thickness of SiO₂ increases to 0.2 μm or 0.3 μm , the emissivity peak in the direction of 80° drops while the peak in the direction of 20° rises. In other words, the difference of the emissivity along the two directions drops, suggesting a weakening of the direction selectivity performance. For the structure in which the dielectric layer is composed of SiO or Al₂O₃, the peak emissivities in the two directions increase steadily with the increase of the dielectric thickness, as shown in Figs. 2(b) and 2(c). For the sDM structures composed of the same thickness $d = 0.2 \mu\text{m}$ but different dielectric media, the spectral emissivities are plotted together in Fig. 2(d) for the two selected directions. The standardized emission intensity $I_b/I_{b\text{max}}$ of a blackbody maintained at 300 K is also plotted in the main body and inset of Fig. 2(d). Here, I_b denotes the spectral emission intensity of a blackbody determined by Planck's law, and $I_{b\text{max}}$ denotes the maximum of the blackbody spectral emission intensity. Together with the spectral distribution of the standardized blackbody emission, it is noted in Fig. 2(d) that the peak wavelengths of these three structures exhibit a cross-distribution within the wave range covering the peak wavelength of the blackbody emission. This provides a theoretical reference for designing broadband directional-selective emitters at room temperature.

3. Three-dielectric-medium structure

In this section, by selecting SiO₂, SiO, and Al₂O₃ as the dielectric materials, a multilayer structure with three dielectric

layers was designed. The multilayer is sketched in Fig. 3 and referred to as three-dielectric-medium (tDM) structure in the following. Due to the impedance mismatch, *i.e.*, the dielectric constant difference between the adjacent dielectric media, different arrangements of the three dielectric media have vital influence on the emissivity of the tDM. Therefore, the arrangements of the three dielectric media are first optimized for the desired performance of broadband direction-selective emissivity.

The spectral emissivities of the tDM structure with six different arrangements are shown in Fig. 4(a) where the thickness of each dielectric layer is fixed at 0.2 μm . A significant emissivity difference is observed among these structures at $\theta = 20^\circ$ and $\theta = 80^\circ$. In order to quantitatively compare the direction-selective performance of different tDM structures, the relative emissivity difference along the two selected directions is defined as

$$\delta = \frac{\varepsilon(\theta=80^\circ) - \varepsilon(\theta=20^\circ)}{\varepsilon(\theta=80^\circ)} \times 100\% \quad (1)$$

Fig. 3 Sketch of the three-dielectric-medium structure.

Fig. 4 (a) Emissivities and (b) relative emissivity difference of the tDM structures with different dielectric medium arrangements (the order of the dielectric media listed in each legend entry is from top to bottom).

Fig. 5 (a) Emissivities and (b) relative emissivity difference of the tDM structures with equal-thickness dielectric layers.

The emissivity differences of the different structures were compared in Fig. 4(b). When the dielectric medium is composed, from top to bottom, of Al_2O_3 , SiO , and SiO_2 layers, the relative difference of emissivity along the two directions exceeds 65%, suggesting a good direction selectivity of the emissivity within the wavelength range of $\lambda = 7.5\text{--}11.5\ \mu\text{m}$. The emissivity difference for tDM structures with other dielectric medium arrangements is found to be lower in some wavelength ranges. Therefore, in order to design tDM structures with an evident direction selectivity of the emissivity in a wide waveband, the dielectric media composing the structure are designed as Al_2O_3 , SiO , and SiO_2 from top to bottom, the SiO film between the Al_2O_3 and SiO_2 films is separated from the air environment to avoid its oxidation. In the following, this tDM structure with Al_2O_3 , SiO , and SiO_2 films from top to bottom is referred to as Al_2O_3 - SiO - SiO_2 -based (ASSb) structure.

In the following, effects of the dielectric thickness on the ASSb structure's emissivity are examined. The scenarios where all dielectric layers have the same thickness were analyzed first. Fig. 5(a) compares the emissivity distributions of the designed structures with three selected dielectric layer

thicknesses of $d = 0.1, 0.2$, and $0.3\ \mu\text{m}$ ($d = d_1 = d_2 = d_3$, where d_1, d_2 , and d_3 are the thicknesses of Al_2O_3 , SiO , and SiO_2 , respectively). It is found that as the thickness increases, the ASSb structure's emissivity at $\theta = 20^\circ$ increases significantly while the emissivity at $\theta = 80^\circ$ drops at most wavebands. Therefore, when all layers have the same thickness, the direction selectivity performance of the ASSb structure's emissivity drops with increasing the dielectric layer thickness, as shown in Fig. 5(b).

It is noted from Fig. 2 that the emissivity at $\theta = 80^\circ$ increases with the dielectric layer thickness for the sDM structure with Al_2O_3 or SiO as the dielectric layer. Therefore, the effects of the dielectric layer thickness on the ASSb structure's emissivity are further examined for the scenarios where the dielectric layers have different thicknesses. Fig. 6(a) displays the emissivities of the structure containing three dielectric layers where two layers remain at $0.1\ \mu\text{m}$ and the left layer is increased to $0.3\ \mu\text{m}$ thick. In contrast with the results of the case whereby $d_1 = d_2 = d_3 = 0.1\ \mu\text{m}$, the emissivity at $\theta = 20^\circ$ is found to increase, no matter which one of the dielectric layers is increased to $0.3\ \mu\text{m}$.

Fig. 6 (a) Emissivities and (b) relative emissivity difference of the tDM structures with different-thickness dielectric layers.

Fig. 7 (a) Emissivities of the slabs composed of multiple dielectric layers with a different-thickness first layer at $\theta = 20^\circ$ and 80° , and (b) relative difference of the emissivity in the two directions.

When the thickness of the SiO₂ dielectric layer increases, the ASSb structure's emissivity at $\theta = 80^\circ$ increases slightly in the waveband of $\lambda = 7.5\sim 7.8$ μm while drops pronouncedly in other wavebands. Similarly, when the thickness of the SiO layer increases, the emissivity at $\theta = 80^\circ$ increases slightly in the waveband of $\lambda = 8.2\sim 9.7$ μm while drops significantly in other wavebands. Regarding the emissivity at $\theta = 80^\circ$ of the structure where the thickness of the Al₂O₃ layer is increased to $d_1 = 0.3$ μm, despite the slight decrease in the waveband of $\lambda = 7.5\sim 9.0$ μm, a dramatic increase is found in the waveband of $\lambda = 9.5\sim 11.0$ μm, especially at the wavelength of $\lambda = 10.0\sim 10.8$ μm, as shown in Fig. 6(a).

Fig. 6(b) compares the emissivity difference of the ASSb structures with different layer thicknesses. It can be concluded that the emissivity of the structure maintains a favorable direction selectivity when the thickness of the Al₂O₃ layer is set as $d_1 = 0.3$ μm. While the direction-selective performance of the tDM structure is distinctly suppressed if the thickness of the SiO₂ or SiO dielectric layer is increased to 0.3 μm.

To further study the influence of the Al₂O₃ thickness on the emissivity of the ASSb structure, Fig. 7(a) compares the emissivities of the ASSb structures with different Al₂O₃ thicknesses $d_1 = 0.1, 0.2, 0.3, 0.4, 0.5$ μm, under the condition where the thicknesses of the SiO and SiO₂ remains unchanged as $d_2 = d_3 = 0.1$ μm. At the low zenith angle of $\theta = 20^\circ$, the emissivity of the ASSb structure increases steadily as the thickness of the Al₂O₃ dielectric layer increases from 0.1 μm to 0.5 μm. At the high zenith angle of $\theta = 80^\circ$, the emissivity drops in the waveband of $\lambda = 7.5\sim 9.0$ μm, but increases in the waveband of $\lambda = 9.5\sim 10.5$ μm with increasing the Al₂O₃ thickness. Fig. 7(b) plots the difference of the spectral emissivity at the two directions for the ASSb structures with different Al₂O₃ layer thicknesses. It can be seen that, as the thickness of the Al₂O₃ dielectric layer increases, the ASSb structure shows a performance loss of the direction-selective emissivity. By conjunctively considering the emissivity in Fig. 7(a) and the emissivity difference in Fig. 7(b), it can be concluded that, when the thickness of the top Al₂O₃ layer

Fig. 8 The optimal ASSb structure's emissivity (a) as a function of wavelength and zenith angle, (b) along four selected wavelengths $\lambda = 8.0, 9.0, 10.0$, and 11.0 μm as a function of the emission zenith angle.

increases from 0.1 μm to 0.3 μm , the spectral emissivity along the direction of $\theta = 80^\circ$ increases significantly, and the emissivity difference along the two directions maintains higher than 80%. Results in Fig. 7 suggest that the ASSb structure with a 0.3 μm -thick Al_2O_3 dielectric layer shows good emission power and good performance of direction-selective emissivity. Thus, the ASSb structure with a 0.3 μm -thick Al_2O_3 , 0.1 μm -thick SiO , and 0.1 μm -thick SiO_2 , was chosen as the optimal structure in this work.

The emissivity of the optimal ASSb structure as a function of wavelength and zenith angle is shown in Fig. 8(a). The emissivities at four selected wavelengths $\lambda = 8.0, 9.0, 10.0$, and 11.0 μm , are plotted in Fig. 8(b) as a function of the emission zenith angle. From the results in Fig. 8, it is seen that the designed structure exhibits a remarkable direction selectivity in the broad wave range of $\lambda = 8.0\sim 11.0 \mu\text{m}$: the emissivity is high within the zenith angle of $\theta = 75^\circ\sim 85^\circ$, while relatively low within the zenith range of $\theta = 0^\circ\sim 30^\circ$.

The work presented in this paper presents a general strategy for designing and optimizing the performance of a multilayer film for broadband and direction-selective emitter. The high emissivity of the optimal ASSb structure in broadband wavelength enables substantial radiation energy dissipating, and the direction selectivity can suppress radiation emission to the near-normal directions of the surface. Thus, The optimal ASSb structure in this work has potential applications in infrared camouflage and stealth.

4. Conclusions

Based on the narrow-band direction-selective emissivity of the silver-coated dielectric medium of SiO_2 , SiO , and Al_2O_3 , a multilayer structure composed of three dielectric media was designed and optimized for broadband direction-selective emissivity. The optimal structure shows a remarkable performance of direction-selective emissivity within a broad wave range of $\lambda = 8.0\sim 11.0 \mu\text{m}$ which covers the emission peak of a blackbody at $\sim 300 \text{ K}$. The emissivity is high at a large zenith angle while low at a small zenith angle. The emissivity difference at two directions ($\theta = 20^\circ$ and 80°) of the optimal ASSb structure is higher than 80% in a broad waveband. The designed multilayer structure can significantly reduce infrared emission in the direction perpendicular to the interface while maintaining sustainable outward radiation energy, thereby exhibits important application in many prospects, such as infrared camouflage and stealth.

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Supporting information

Not applicable

Conflict of interest

There are no conflicts to declare.

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