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Optimized thin film coatings for passive radiative cooling applications

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ABSTRACT

Passive radiative cooling is a very interesting method, which lays on low atmospheric downward radiation within 8–13 μm waveband at dry climates. Various thin film multilayer structures have been investigated in numerous experimental studies, in order to find better coatings to exploit the full potential of this method. However, theoretical works are handful and limited. In this paper, the Simulated Annealing and Genetic Algorithm are used to optimize a thin film multilayer structure for passive radiative cooling applications. Spectral radiative properties are calculated through the matrix formulation. Considering a wide range of materials, 30 high-potential convective shields are suggested. According to the calculations, cooling can be possible even under direct sunlight, using the introduced shields. Moreover, a few water-soluble materials are studied for the first time and the results show that, a KBr substrate coated by a thin CaF_2 or polyethylene film can is very close to an ideal coating for passive radiative cooling at night.

1. Introduction

The inlet radiative heat flux on the earth's surface comprises the solar and atmospheric radiation. About 95% of the solar heat flux is limited to the 0.3–2.4 μm waveband, and the atmospheric radiation is almost negligible outside of 4–85 μm waveband. It is known that, if humidity is not too high, atmospheric radiation will be very low in the 8–13 μm waveband which is called the atmospheric window. The atmospheric radiation is very close to a Planck distribution at about 300 K elsewhere. Passive radiative cooling is based on the fact that the sky acts as a heat sink within the atmospheric window. Therefore, cooling can be possible without any energy consumption if the energy transfer is limited to this waveband [1]. The most common applications are food or medicine storage, roof cooling [2,3], cooling down of solar cells to increase their efficiency [4], and condensation of atmospheric moisture [5–7].

The maximum cooling power can be achieved by placing a black body under the sky at night. However, the heat convection with air will increase the temperature of the black body as it cools down to return it back to thermal equilibrium with its surrounding and only a temperature drop around 10–20 °C would be feasible [8]. The convective heat transfer coefficient can be lowered by using a convective shield, which can substantially increase the maximum possible temperature drop. The convective shield has different spectral radiative properties than air, which results in a decrease in cooling power. For an ideal convective shield for night cooling, the transmittance must be one at the atmospheric window and zero elsewhere. Additionally, there is a strong solar heat flux at the 0.3–2.4 μm waveband during day, which makes the passive radiative cooling very difficult. Therefore, an ideal convective shield for day cooling must have a high reflectance within the 0.3–2.4 μm waveband and a high transmittance within the atmospheric window.

Spectral selective shields have been widely investigated in the last 3 decades to maximize the temperature drop. Using pigments of high solar reflectance materials on a foil with high atmospheric window transmittance is one of the methods to fabricate an effective shield. For instance, ZnS, ZnO and TiO_2 pigmented polyethylene foils have been proposed by Nilsson et al. [8,9] and Dobson et al. [10]. ZnS and TiO_2 pigments were reported to be more effective. Another method is to use gas slabs. C_2H_4, C_2H_4O and NH_3 slabs backed by Al, were investigated by Eriksson et al. [11] and a mixture of C_2H_4 and C_2H_4O was reported to be the most desirable gas slab. The most studied method is using thin film multilayers as a convective shield. This is due to the fact that, the radiative properties of these structures can be easily altered by changing the thickness or the material at each layer. SiO, Si_3N_4 and silicon oxynitride thin films on Al coated glass were studied by Eriksson et al. [11], Granqvist et al. [12], and Diatezua et al. [13]. The polyethylene foil has a high transmittance in both solar and atmospheric wavebands. Engelhard et al. [14] showed that by deposition of a Te thin film on polyethylene, the solar transmittance will be lowered significantly, but there will be a slight decrease in the

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Table 1
Previously introduced convective shields with their mean radiative properties.

Convective shield	Reference	T_{sol}	A_{sol}	T_{8-13}
Polyethylene (50 μm)	[10,14]	0.891	0.031	0.813
MnO/Polyethylene	[14]	0.725	0.102	0.801
Te/Polyethylene	[14]	0.047	0.83	0.652
ZnS pigmented Polyethylene(50 μm)	[10]	0.346	0.114	0.641
ZnO pigmented Polyethylene (50 μm)	[10]	0.403	0.168	0.582
PbSe (200 nm)/Polyethylene (50 μm)	[10]	0.09	0.636	0.508
PbS (200 nm)/Polyethylene (50 μm)	[10]	0.168	0.364	0.741
PbS (150 nm)/Polyethylene (50 μm)	[10]	0.138	0.49	0.642
PbS/ZnS pigmented polyethylene	[10]	0.04	0.629	0.488
PbS/ZnO pigmented polyethylene	[10]	0.03	0.684	0.406
Si (1 mm)/CdTe (9.7 μm)	[16]	0.3	0.42	0.58
CdTe (9.7 μm)/Si (1 mm)	[16]	0.28	0.71	0.62
CdS (1 mm)	[17]	0.3	0.68	0.8
Stainless steel (45 nm)/Sn (195 nm)/Glass (3 mm)	[18]	0.01	0.591	0.012
Glass (3 mm)/Sn (195 nm)/Stainless steel (45 nm)	[18]	0.007	0.476	0.033

8–13 μm transmittance. Also, deposition of a PbS or PbSe thin film on a polyethylene substrate has the same effect [10]. The other previously proposed thin film coatings are SiO on $V_{1-x}W_xO_2$ substrate [15], CdTe on Si substrate [16], a single layer of CdS [17], glass substrate coated with a stainless steel–tin double layer [18] and PbS thin film on a pigmented polyethylene foil [10].

Some previously introduced shields with their reported mean radiative properties at the solar and atmospheric wavebands are gathered in Table 1.

One of the major interests in the previous works was providing a convective shield to make the passive radiative cooling possible under direct sunlight, which is still very challenging [19].

Most of the previous studies were pure experimental works and only a few simple theoretical optimizations with a limited range of materials have been conducted in [8,9,11,12]. Hence, a complete theoretical optimization would be highly beneficial for further experiments.

In this paper, the main focus will be the structure optimization of thin film multilayers to achieve desirable spectral radiative properties for passive radiative cooling at day and night. A wide range of materials will be considered and the thickness of layers will be optimized. 30 high-potential structures will be introduced. Water-soluble materials are also introduced for the first time, and it will be shown that some of these materials have very close specifications to an ideal convective shield for night cooling.

2. Theory

2.1. Calculation of the radiative properties of a thin film multilayer

A thin film multilayer with $N-2$ thin layers is studied here (Fig. 1). Where, d_j $(2 \le j \le N-1)$ is the thickness of each layer. The structure is in contact with the medium 1, on the upper surface and medium N, on the lower surface. The complex refractive index of each layer $(\tilde{n}_j)$ is defined in Eq. (1).

$$\tilde{n}_j = n_j + i\kappa_j \, (1 \le j \le N+1) \tag{1}$$

where n_j and κ_j are refractive index and extinction coefficient, respectively. The z-coordinate of complex wave vector $(\tilde{k}_{jz})$ in each layer is calculated by Eq. (2).

$$\tilde{k}_{jz} = \frac{2\pi}{\lambda}\tilde{n}_j \cos\tilde{\theta}_j \tag{2}$$

Complex angles are defined to make Snell's law applicable in the complex space; that means, for each i and j Eq. (3) should be valid.

$$\tilde{n}_i \sin\tilde{\theta}_i = \tilde{n}_j \sin\tilde{\theta}_j \tag{3}$$

Z_j is defined for each layer in Eq. (4).

$$\begin{cases} z_1 = 0 \\ z_j = z_{j-1} + d_j, \quad j = 2, 3, \dots, N \end{cases} \tag{4}$$

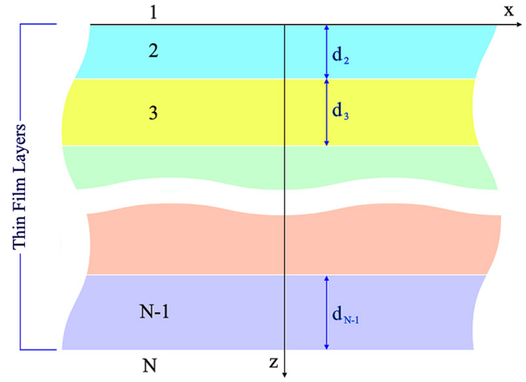

Fig. 1. A thin film multilayer structure.

By defining $\underline{\underline{P_j}}$, $\underline{\underline{D_{j,s}}}$ and $\underline{\underline{M_s}}$ matrices for an s-polarized electromagnetic beam (Eqs. (5)–(7)) and applying the Maxwell's equations, the radiative properties can be calculated, using Eqs. (8)–(10).

$$\underline{\underline{P_j}} = \begin{pmatrix} e^{-i\tilde{k}_{jz}d_j} & 0 \\ 0 & e^{i\tilde{k}_{jz}d_j} \end{pmatrix} \tag{5}$$

$$\underline{\underline{D_{j,s}}} = \begin{pmatrix} 1 & 1 \\ \tilde{k}_{jz} & -\tilde{k}_{jz} \end{pmatrix} \tag{6}$$

$$\underline{\underline{M_s}} = \begin{pmatrix} \widetilde{M}_{11,s} & \widetilde{M}_{12,s} \\ \widetilde{M}_{21,s} & \widetilde{M}_{22,s} \end{pmatrix} = \prod_{i=1}^{N-1} \underline{\underline{P_i}}\,\underline{\underline{D_{i,s}^{-1}}}\,\underline{\underline{D_{i+1,s}}} \tag{7}$$

$$\rho_s(\lambda, \theta_1) = \left| \frac{\widetilde{M}_{21,s}}{\widetilde{M}_{11,s}} \right|^2 \tag{8}$$

$$\tau_s(\lambda, \theta_1) = \frac{\mathrm{Re}(\tilde{k}_{Nz})}{k_{1z}} \frac{1}{\left|\widetilde{M}_{11,s}\right|^2} \tag{9}$$

$$\alpha_s(\lambda, \theta_1) = 1 - \rho_s(\lambda, \theta_1) - \tau_s(\lambda, \theta_1) \tag{10}$$

For a p-polarized beam, $\underline{\underline{D_{j,s}}}$ is replaced by $\underline{\underline{D_{j,p}}}$ and transmittance is calculated, using Eq. (12). The rest of calculations are similar.

$$\underline{\underline{D_{j,p}}} = \begin{pmatrix} 1 & 1 \\ \frac{\tilde{k}_{jz}}{\tilde{n}_j^2} & -\frac{\tilde{k}_{jz}}{\tilde{n}_j^2} \end{pmatrix} \tag{11}$$