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# Tailoring broadband radiative properties of glass with silver nano-pillars for saving energy

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ABSTRACT

Periodically-isolated and metallic nano-structures are shown to tailor dual radiative properties within a broadband. Embedded silver nano-pillars successfully manipulate reflectance and transmittance through glass ($SiO_2$) from the ultraviolet to near-infrared. The rigorous coupled-wave analysis and genetic algorithm are integrated into numerical programs to optimize dual property spectra for energy-saving. The performance of two examples is also quantitatively demonstrated based on ISO 9050 at the incidence of transverse electric and transverse magnetic waves. Physical mechanisms responsible for tailored spectra are explained using dispersion curves and electromagnetic field patterns.



## 1. Introduction

Advances in nano-technology have largely facilitated the development of energy-conversion and energy-saving devices [1]. They include low-emissivity (low-E) glass [2,3], solar-thermal collectors [4,5], solar cells [6,7], and thermophotovoltaic emitters [8]. The common key to their excellent performance is wavelength-selective and orientation-insensitive radiative properties generated via nanoscale engineered structures [9]. Film(s) [10], gratings [11], woodpile [12], grids [13,14], and core-shells [15] have succeeded in tailoring reflectance ($R$) or transmittance ($T$) spectrum in a broadband to satisfy applications. However, not every type of nano-structures was popular for tailoring radiative properties in a broadband. Periodically-isolated and metallic pillars were much more appealing to manipulate narrow-band properties because those structures facilitated localized resonances [16–18]. The excitation of a resonance mode usually leads to a sharp dip in $R$ spectrum, and the dip is very attractive to sensors for its high sensitivity [19]. As a result, energy-related devices using broadband tailored properties generated by metallic nano-pillars were rarely explored.

The objective of our work is to seek the possibility of tailoring broadband radiative properties using metallic pillars with uniform profile and periodic alignment. The freedom of structure dimensions will be fully exploited with our programs, which integrate an optimization method with an algorithm solving Maxwell's equations. The low-E glass [20] for office buildings in a tropical zone is selected as an energy-saving device for demonstration. The base material for tailoring radiative properties is $SiO_2$, while Ag pillars are embedded into it. $SiO_2$ and Ag are selected because they are commonly seen in commercial energy-saving glass.

Two radiative properties ($R$ and $T$) will be simultaneously tailored from ultraviolet (UV) to near-infrared (near-IR). The $R$ will be expected to low in visible (VIS) range, but it will be enlarged in UV and near-IR. On the other hand, the $T$ in VIS shall be kept high, but it will be reduced in UV and near-IR. This way, expenses for indoor illumination and air-conditioning can be saved, particularly in a hot sunny day. People and furniture will not be harmed by UV light, while outdoor drivers and passengers will not suffered from reflected stray light [21]. These wavelength-selective properties will be both plotted and quantitatively compared based on the international standard ISO 9050 [22]. Physical mechanisms contributing to unique features in spectra are going to be explained with electromagnetic (EM) field patterns and dispersion curves.

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**Nomenclature**

| | |
|---|---|
| $A$ | absorptance |
| $d$ | thickness of nano-structures, m |
| **E** | electric field vector, V/m |
| $F$ | fitness function |
| $f$ | lateral filling ratio of a material |
| $g$ | total solar energy transmittance |
| **H** | magnetic field vector, A/m |
| **k** | wavevector, $m^{-1}$ |
| $k$ | magnitude of wavevector, $m^{-1}$ |
| $m$ | dummy integer |
| $N$ | number defining Fourier terms and diffraction orders |
| $n$ | refractive index |
| $R$ | reflectance |
| $T$ | transmittance |

*Greek symbols*

| | |
|---|---|
| $\phi$ | azimuthal angle, degree |
| $\kappa$ | extinction coefficient |
| $\Lambda$ | period of nano-structure, m |
| $\lambda$ | wavelength, m |
| $\theta$ | zenith angle, degree |
| $\omega$ | wavenumber, $m^{-1}$ |
| $\psi$ | angle defining the electric field oscillation, degree |

*Subscripts*

| | |
|---|---|
| $c$ | cavity |
| e | solar direct |
| I, II, III | indices for region in space |
| IR | infrared |
| UV | ultraviolet |
| VIS | visible |

*Abbreviations*

| | |
|---|---|
| CR | cavity resonance |
| EM | electromagnetic |
| GA | genetic algorithm |
| Low-E | low emissivity |
| LSPR | localized surface plasmon resonance |
| RCWA | rigorous coupled-wave analysis |
| SC | shading coefficient |
| SPR | surface plasmon resonance |
| TE | transverse electric |
| TM | transverse magnetic |

## 2. Numerical model and design methodology

Fig. 1(a) shows sketch of the proposed nano-structure, a $SiO_2$ substrate embedded with Ag nano-pillars. Rectangular pillars are periodically aligned in the $x$- and $y$-direction. Both $SiO_2$ and Ag have the same thickness $d$. The space along the $z$-direction is divided into three regions in our numerical model. Region I and Region III are free space, whose refractive index $n$ and extinction coefficient $\kappa$ are assumed to $n = 1$ and $\kappa = 0$ as those in vacuum. Region II contains alternate Ag and $SiO_2$, whose wavelength-dependent $n$ and $\kappa$ are adopted from Ref. [23]. The top and side views of a structure period ($\Lambda$) are also shown in the figure. The lateral filling ratio of Ag is symbolized using $f$, while subscripts $x$ and $y$ specify the direction. That is, the number of nano-structure dimensions to be determined is five ($\Lambda_x$, $\Lambda_y$, $f_x$, $f_y$, and $d$) provided dimensions along $x$- and $y$-direction are uncorrelated. The orientation of incident light is defined with an azimuthal angle $\varphi$ and polar angle $\theta$. The incidence is linearly polarized with a wavevector **k**. The magnitude of **k** is $k = 2\pi/\lambda$, where $\lambda$ is the wavelength in free space. The polarization is identified with $\psi$, an angle between the electric field **E** oscillation direction and the plane of incidence.

Fig. 1(b) shows the intrinsic $R$ and $T$ spectra of a 50-nm-thick Ag and $SiO_2$ substrate at normal incidence as the wavelength $\lambda$ ranges from 250 nm to 5000 nm. The spectra serve as a benchmark for those of nano-structures shown later. The intrinsically high $R$ of Ag is opposite to the low $R$ of $SiO_2$ from VIS to near-IR. The $R$ dip of Ag film in UV comes from the plasma resonance [24]. The $R$ of $SiO_2$ film in UV remains about 0.04, lower than that of Ag. The absorptance ($A$) of both films is negligible such that $R + T \approx 1$ from VIS to near-IR (400 nm–5000 nm) based on the energy conservation [25]. The only exception is the large $A$ by Ag in UV. In reality, radiative property spectra may be modified if a supporting object is added. To remedy this practical concern, some aerogels may be excellent solutions thanks to their transparency.

Obtaining radiative properties of proposed nano-structures uses the rigorous coupled-wave analysis (RCWA) algorithm [26]. Programs based on it are able to solve Maxwell's equations for periodic structures efficiently when enough numbers of Fourier terms and diffraction orders are employed. Their numbers $(2N + 1)$ are actually identical in programs because of coupling. The number contains $N$ positive, $N$ negative, and the 0th term/order along one direction. That is, the structure profile is expanded using $(2N + 1)$ terms along one-direction, and EM fields of $(2N + 1)$ diffraction orders are numerically calculated for a 1-D periodic structure [26]. When structures are periodic along two directions, the expansion and diffraction order need two indexes. The number of them becomes product of $(2N + 1)$ and $(2N + 1)$ such that $(2N + 1)^2$ terms and diffracted waves are investigated for our proposed structure. Through a large $N$ is able to assure convergence, trade-off is exponentially growing computational cost.

Our calculation used a workstation with dual Xeon® 6C X5680 (3.33 GHz) processor and 40 GB memory. Calculation speed for data varies a little with sample geometry, wavelength, and incidence polarization. It will be specified later when radiative property spectra are discussed. Periodic structures similar to those in Fig. 1(a) are utilized to verify the sufficiency of $N$. We set $\Lambda_x = \Lambda_y = \Lambda$, $f_x = f_y = 0.5$, $\lambda = 1$ μm, and the incidence is normal ($\theta = \varphi = 0°$) for simplicity. Optical constants $n = 2$ and $\kappa = 0$ are given to pillars. Accordingly, the $A$ of pillars should be null regardless of pillar geometry. Three sets of $\Lambda$ and $d$ are input into programs to examine property convergence and energy balance. Fig. 2 plots $R$, $T$, and $R + T$ spectra of structures with $(\Lambda, d) = (1, 10)$, $(1, 5)$, and $(0.5, 5)$ in the unit of micrometer. For all of them, the energy balance ($A = 0$ and $R + T = 1$) is assured as $N \geq 3$, while the convergence takes more terms. $N = 15$ gives 5% relative error and 0.03 absolute error for the worst case $(\Lambda, d) = (1, 5)$. For convergence of various structures later, $N = 19$ will be employed to provide extra insurance. Total $39^2 = 1521$ Fourier terms and diffraction orders should be able to provide convincing results because most diffraction orders are evanescent.

Fig. 3 shows the flow chart of our programs, which integrate RCWA with the genetic algorithm (GA) [27] to effectively determine