Absorption to reflection transition in selective solar coatings

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Abstract: The optimum transition wavelength between high absorption and low emissivity for selective solar absorbers has been calculated in several prior treatises for an ideal system, where the emissivity is exactly zero in the infrared. However, no real coating can achieve such a low emissivity across the entire infrared with simultaneously high absorption in the visible. An emissivity of even a few percent radically changes the optimum wavelength separating the high and low absorption spectral bands. This behavior is described and calculated for AM0 and AM1.5 solar spectra with an infrared emissivity varying between 0 and 5%. With an emissivity of 5%, solar concentration of 10 times the AM1.5 spectrum the optimum transition wavelength is found to be 1.28µm and have a 957K equilibrium temperature. To demonstrate typical absorptions in optimized solar selective coatings, a four-layer sputtered Mo and SiO_2 coating with absorption of 5% across the infrared is described experimentally and theoretically.

OCIS codes: (350.6050) Solar energy; (310.3915) Metallic, opaque, and absorbing coatings; (310.4165) Multilayer design.

References and links

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1. Introduction

Selective solar absorbers are used in solar thermal energy systems to absorb light energy from the sun while preventing heat leakage out of the system by thermal radiation. In an ideal selective absorber, the absorption of a coating at visible and near-infrared wavelengths is 100% while the absorption further in the infrared is zero. (Note that the thermal emission is directly proportional to the absorption by Kirchhoff's Law.) In prior research, the optimal wavelength for the transition between high and low absorption has been calculated for solar

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selective absorbers using these ideal values [1–3]. However, in a real coating, there will always be some non-zero absorption at long wavelengths [1–5]. Non ideal absorption characteristics in the infrared will dramatically change the optimal transition wavelength for a real solar thermal coating. We use an experimental coating to demonstrate typical absorption levels and then generalize the current selective absorption optimization theory to handle imperfect coatings.

To begin our quantitative treatment, we use a hypothetical material that is capable of absorbing the solar spectrum of light while not emitting IR light beyond the solar spectrum. To optimize this situation we want to find the wavelength of light beyond which the coating becomes highly reflective rather than highly absorbing. Both the sun and the selective solar coating will obey Planck's law of thermal emission Eq. (1).

$$\mathrm{u}_{\lambda}^{device}\left(T\right)=\frac{2hc^{2}}{\lambda^{5}}\frac{1}{\left[\exp\left(hc/\lambda k_{B}T\right)-1\right]} \tag{1}$$

Where h is Planck's constant, c is the speed of light, λ is the wavelength, k_B is Boltzmann's constant, and T is the temperature of the black body. Multiplying Eq. (1) by a ratio of surface areas of the sun and earth's orbit will convert from energy emitted at the surface of the sun to energy incident on the earth Eq. (2).

$$\mathrm{u}_{\lambda}^{solar}\left(T\right)=\frac{2hc^{2}}{\lambda^{5}}\frac{1}{\left[\exp\left(hc/\lambda k_{B}T\right)-1\right]}\frac{r^{2}}{R^{2}} \tag{2}$$

Where r is the radius of the sun, and R is the radius of earth's orbit around the sun. According to [6,7] r is 6.96 x 10^5 km, R is 1.496 x 10^8 km, and the effective T at the surface of the sun is 5778K. The spectrum from the sun has been measured, and the standards, AM0 and AM1.5, have been developed for use in solar energy simulations. Figure 1 shows a calculated, AM0, and AM1.5 solar spectrum, as well as a blackbody at T = 700K. We use 700K to show graphically the difference of incoming solar and blackbody radiation; it is not a meant to be the optimal system temperature.

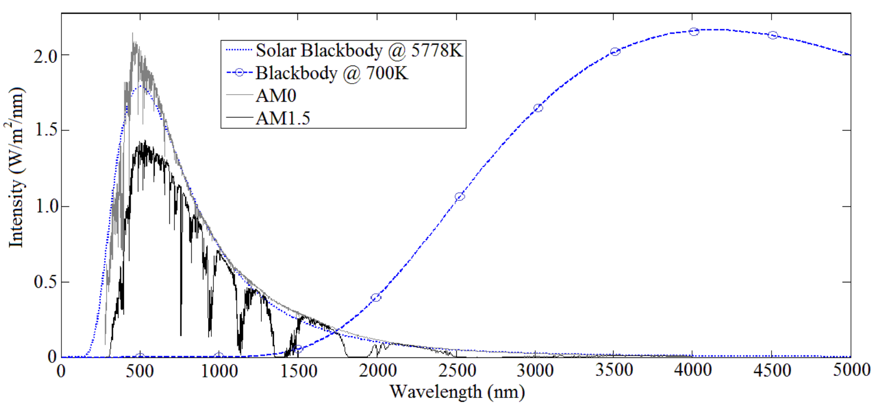

Fig. 1. Solar radiation and the thermal blackbody emission spectrums. AM0 is the solar spectrum outside of earth's atmosphere, AM1.5 is the standard spectrum used for terrestrial solar energy applications. Notice that even though the sun is at an effective emission temperature of 5778K, the peak is comparable to a 700K blackbody because of the great distance between the earth and sun.

If we were to integrate over the solar spectrum and the blackbody spectrum at T = 700K, it would be easy to see that the earth at 700K is not in thermal equilibrium with incident solar energy Eq. (3).

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$$\int_0^{\infty} u_\lambda^{device}\left(700K\right)\partial\lambda \gg \int_0^{\infty} u_\lambda^{solar}\left(5778K\right)\partial\lambda \qquad (3)$$

However at a much lower temperature near 300K the earth will be in thermal equilibrium with the incoming solar irradiation [8]. From Fig. 1 it is also apparent that we may be able to construct a solar absorber with a wavelength dependent absorption capable of absorbing the solar radiation but yet not emitting the IR radiation beyond a certain wavelength.

2. Background

Solar selective absorbing characteristics have been shown to exist for many types of structures, and there has been significant work on optimizing each for different applications [1–5]. To design an absorber for solar energy harvesting, the goal is to absorb the most amount of incoming solar radiation and efficiently convert it to useable energy. Because this type of system will be operating based on heat, the efficiency will be related to the Carnot efficiency which is dependent on the temperature difference in the system. To optimize efficiency then one would like to create the largest temperature difference possible in the system.

To achieve the highest temperature difference, much work has been done to achieve ideal solar absorption and ideal IR reflection. In reality the best integral solar absorption and infrared emissivity coefficients achieved in a coating have been a couple percent away from ideal [1–5]. For an optimized 4 layer sputtered Mo-SiO_2 coating we were able to achieve about 5% integral infrared emissivity as seen in Fig. 2. This leads to the question, what does having a non-ideal emissivity do to our optimization?

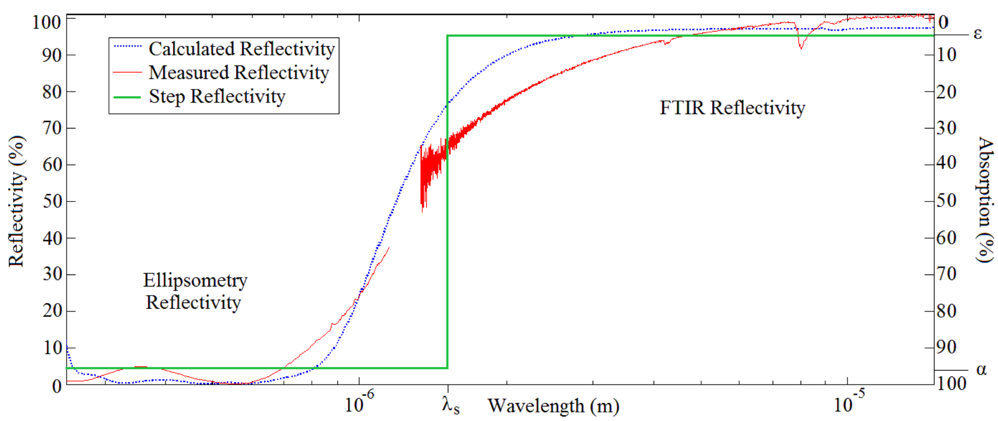

Fig. 2. Calculated and measured reflectivity of an alternating 4 layer structure of Mo and SiO_2 on a Si wafer as a function of wavelength on a log scale. Also a non-ideal step reflectivity used in further simulations. We assume no transmission so the absorption and emission are calculated as 100-R [%]. The actual reflectivity doesn't reach 100% because we used a gold reference reflector in the FTIR measurement. The dip in reflectivity around 8μm is from the high NA of the FTIR resulting in an average reflectivity over a large angle, and at large angles some light is absorbed due to the SiO_2 IR absorption peak.

3. Calculations

To find the wavelength at which we want to switch from absorbing to reflecting we need some idea of the system we want to build to give us our constraints. We will assume that a system receives solar radiation and emits radiation from the same surface area, like a tube in a parabolic reflector design [9]. Also we will assume that the system is in a vacuum and thermally isolated from its surroundings. This will be a thermal equilibrium problem so we need to integrate the two radiation spectra as in Eq. (4),(5).

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$$P_{in} = C\left(\int_0^{\lambda_s} \alpha \mathrm{u}_\lambda^{solar}(T_{sun})d\lambda + \int_{\lambda_s}^{\infty} \varepsilon \mathrm{u}_\lambda^{solar}(T_{sun})d\lambda\right) \tag{4}$$

$$\begin{gathered} P_{out} = \int_0^{2\pi}\int_0^{\pi/2}\left(\int_0^{\lambda_s} \alpha \mathrm{u}_\lambda^{device}(T_{device})d\lambda + \int_{\lambda_s}^{\infty} \varepsilon \mathrm{u}_\lambda^{device}(T_{device})d\lambda\right)\sin(\theta)\cos(\theta)d\theta d\varphi \\ P_{out} = \pi\left(\int_0^{\lambda_s} \alpha \mathrm{u}_\lambda^{device}(T_{device})d\lambda + \int_{\lambda_s}^{\infty} \varepsilon \mathrm{u}_\lambda^{device}(T_{device})d\lambda\right) \end{gathered} \tag{5}$$

Where λ_s is the wavelength where the selective absorber will transition from absorption to reflection as seen in Fig. 2, α is equal to the spectral absorption coefficient of the coating for wavelengths less than λ_s, ε is the spectral emissivity coefficient of the coating for wavelengths greater than λ_s, and C is the concentration of solar radiation. The power input term is much less complicated because we are assuming only normally incident light, whereas the radiation leaving the device is Lambertian so we need to integrate over all solid angles. Integrating turns out to only add a constant multiplier equal to π if it is assumed that the spectral absorption and emission coefficients are relatively constant as a function of θ and φ. It will also be assumed that the spectral absorption and emission coefficients are constant with wavelength over their respective solar and infrared bands as is seen in Fig. 2.

By setting the input power equal to the output power, we then have 1 equation and 4 unknowns. By setting α = 1 and ε = 0 we have the ideal case but still two unknowns, transition wavelength and equilibrium temperature. Plotting the two unknowns against each other can be can be seen in Fig. 3. However, since there is no analytical solution to integrating Planck's law with finite boundaries, the equation must be plotted numerically. The numerical solution was found by discretizing the integral over all wavelengths, and decreasing the step size Δλ, until the solution approached the analytical result with infinite boundaries. Using the same discretization, different values for emissivity, absorption, and solar spectrum can be used to get results more closely related to realistically achievable coatings Figs. 3 & 4.

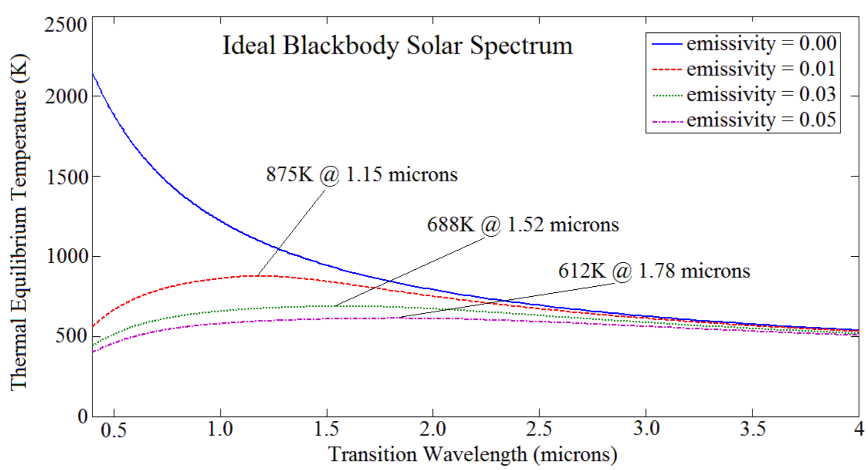

Fig. 3. (a) The ideal thermal equilibrium temperature between a selective absorber and the sun with no concentration (C = 1) as a function of transition wavelength. As the emissivity increases notice that the optimum transition wavelength for a certain operating temperature is shifted to shorter wavelengths. AM0 will have a very similar result to this case.

From Fig. 3 it is evident that the optimal transition wavelength is highly dependent on IR emissivity. It was found that non-ideal absorption coefficients in the visible spectrum only

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slightly reduced the maximum equilibrium temperature and had little effect on the shape of the curves. Emissivity in the infrared played a much more dominant role in the result of the simulations.

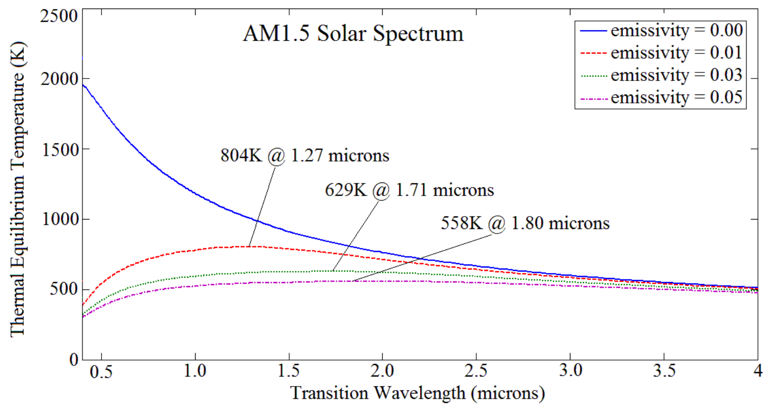

Fig. 4. Thermal equilibrium temperature as a function of transition wavelength and emissivity for the AM1.5 solar spectrum with no concentration (C = 1)

Because of the dependence on emissivity, we cannot design a system without some a priori information about the infrared emissivity of the selective solar coating to be used. This inherently makes optimizing selective solar absorbers an iterative process. We can also see from Fig. 4 that for a terrestrial selective absorber with an emissivity around 5%, equilibrium is reached at a temperature around 550K. For some solar thermal applications, like molten salt reactors, 550K may be insufficient for efficient conversion of energy [1]. It is clear then that a solar concentrator will be needed to reach higher temperatures. One remaining question, however, is what effect does solar concentration have on the optimum transition wavelength?

Again using Eq. (4), (5) we simulate the thermal equilibrium temperature as a function of transition wavelength for a variety of solar concentrations, but keep infrared emissivity constant at 5%. From Fig. 5 it is evident that the optimum transition wavelength is also highly dependent on concentration of incident solar radiation. Both increasing IR emissivity and increasing solar concentration push the optimum transition to shorter wavelengths than in the ideal case.

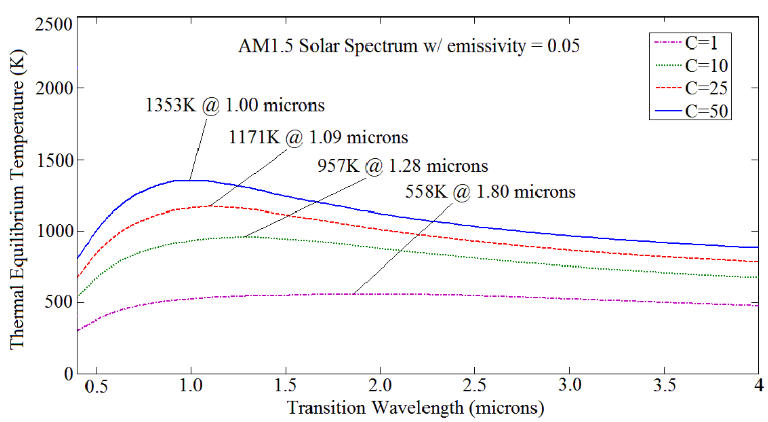

Fig. 5. Thermal equilibrium temperature as a function of transition wavelength for a selective absorber with an emissivity of 5% under AM1.5 illumination at different concentrations. The optimal transition wavelength is highly dependent on the concentration of incoming radiation.

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4. Discussion

It is apparent that both infrared emissivity and solar concentration have a large effect on the thermal equilibrium temperature of selective solar absorbers. It should be noted that the thermal equilibrium temperature is not the operating temperature of the solar thermal system. In a real system getting the energy out of the hot liquid is desired, requiring the liquid to flow. In the modeled cases the equilibrium temperature is calculated when velocity is zero and therefore no useful energy is ever removed from the system and the overall efficiency is zero. As the velocity of the liquid is increased the operating temperature will decrease, it is clear then that for a given system the optimum selective solar absorber will also be highly dependent on emissivity, concentration, and velocity, but the optimization will differ from the one presented. At infinite velocity the operating temperature will decrease to the ambient conditions and again the system will have an overall efficiency of zero. There is obviously then an optimum velocity and transition wavelength that should be matched for any given solar thermal system to maximize efficiency.

It is not the goal of this paper to optimize every solar thermal system rather just to provide a road map to improve system efficiency by optimizing the selective absorber to the given system. In prior treatises of this problem non-ideal emissivity and absorption, and solar concentration have not been included when finding the desired transition wavelength. It is found that not taking these parameters into account when designing a selective absorber could have drastic effects on overall system efficiency.

In our optimization we also assumed no solid state thermal conduction to the outside world. This is, of course, the ideal case and most systems try to minimize non-radiative conduction, but it is difficult to meet in practice. To overcome this fault in the modeling, it would be simple to add a thermal conductance term to the power out Eq. (5). Increasing solid state thermal conductivity will have the same effect on P_{out} as increasing infrared emissivity; therefore, it is safe to assume that adding a solid-state conductance term should result in a similar effect on the optimization.

In many selective solar absorber coatings, there is also thermal degradation over time. However, this is typically shown to only reduce the solar absorption but not the IR emissivity [10]. As was found earlier, absorption only plays a minimal role in the optimization result.

6. Conclusion

Much research in solar-selective absorbers has been performed to optimize solar absorption while simultaneously reducing the infrared emissivity. Because of this work solar selective coatings have reached maturity, however due to nonzero emissivity in the infrared there remains some thermal emission from these devices. By including the non-ideal infrared emissivity in the optimization it is possible to find a corrected transition wavelength for the selective solar absorber. It was found that even a small change from zero emissivity in the infrared drastically changes the optimal transition wavelength. These coatings are also affected by solar concentration, which additionally modifies the optimization away from the ideal case. Finally if thermal conduction were taken into account it is reasoned that it will also have a similar effect on the optimization as the other non-idealities taken into account. For a given system a solar selective coating can be optimized for a minimum solar concentration needed, thus maximizing efficiency.

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