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Metamaterial Window Glass for Adaptable Energy Efficiency

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Metamaterial Window Glass for Adaptable Energy Efficiency

by

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Abstract

Metamaterial Window Glass for Adaptable Energy Efficiency

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The University of Texas at Austin, 2014

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A computational analysis of a metamaterial window design is presented for the purpose of increasing the energy efficiency of buildings in seasonal or cold climates. Commercial low-emissivity windows use nanometer-scale Ag films to reflect infrared energy, while retaining most transmission of optical wavelengths for functionality. An opportunity exists to further increase efficiency through a variable emissivity implementation of Ag thin-film structures. 3-D finite-difference time-domain simulations predict non-linear absorption of near-infrared energy, providing the means to capture a substantial portion of solar energy during cold periods. The effect of various configuration parameters is quantified, with prediction of the net sustainability advantage. Metamaterial window glass technology can be realized as a modification to current, commercial low-emissivity windows through the application of nano-manufactured films, creating the opportunity for both new and after-market sustainable construction.

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Chapter 1: Introduction

The design of materials for radiant characteristics often takes into account the spectral dependence in radiative absorption and emission. For example, natural gas storage tanks are universally painted a shade of white; meant to minimize absorptivity in the visible spectrum during the day, yet maximize emission in the infrared during the night. Positive and negative photoresists are used in combination with a single wavelength of light to produce lithographic effects, and photovoltaic cells are engineered to maximize absorption near the bandgap energies of the semiconductors used. Radiative material properties are famously sensitive, however, and in some cases ill-defined, often resulting in sub-optimal application. Further, the most recent decade of research has revealed additional strong dependencies of radiative properties in the near-field, which refers to the region that is less than one wavelength away from the surface of interest. Within the near-field, bulk properties can be dramatically different based on surface structuring at the micro- and nanoscale [4-5, 7-8, 11, 15-16, 18]. The sensitivity of radiative properties is a double-edged sword, creating a difficult challenge for analytical or computational design of a nanostructured surface, yet providing the opportunity to tailor precise, coherent properties to manage radiative energy in intelligent ways. Several recent communications have demonstrated the ability to manipulate the near-field radiative properties of surfaces and meet demands for specialized applications [21-24, 29].

A large fraction of fossil fuel use is dedicated to heating and cooling structures due to seasonal variation in solar irradiation. Therefore, the radiative characteristics of common building materials represent a fulcrum through which the energy efficiency of a structure can be leveraged. A design is presented here introducing intelligent radiative properties in window glass, allowing a structure to absorb or reflect near-infrared energy to adapt to the needs of the interior. The variable emissive properties are predicted to substantially enhance the thermal efficiency of windowed structures. By building on recently presented techniques [9-10], a design for metamaterial window glass with the capability of reducing winter heating demand by up to 240 Watts per square meter of installed material has been developed. This reduction in heating demand assumes normal incidence of solar radiation, however simulations have shown that the design is relatively insensitive to incident angle, showing only a slight decrease in energy capture through a cone angle of 50 degrees. The resultant efficiency gain, relative to current high-efficiency, low-emissivity windows, is expected to create significant long-term cost-savings and reduction in fossil fuel usage for medium- to large-sized structures.

Simulations of metamaterial window glass are performed using FDTD Solutions, a finite-difference time-domain solver created by Lumerical Computational Solutions, Inc. Simulations are performed at the Texas Advanced Computing Center (TACC) on a parallel cluster of up to 1500 cores. These simulations reveal the opportunity to modify the radiative response of the glass in order to variably access a large portion of the near-infrared spectrum using a nanoscale base layer of Ag (currently used in commercially available low-emissivity window glass) with an additional, patterned, Ag layer to create a periodic, metamaterial configuration. Metamaterial window glass is capable of reflecting the near-infrared and far-infrared energy from the sun in its “summer” configuration, yet selectively absorbing solar near-infrared energy in the “winter” configuration. By tuning the radiative properties to this specific wavelength band, the glass retains its ability to reflect far-infrared energy ($\lambda > 1500$ nm) emitted by heated interior spaces, thereby maximizing the energy efficiency of the window through intelligent design. It is shown that the effect is non-trivial, representing opportunity for thermal efficiency enhancement in any windowed structure.

Chapter 2: Literature Review

Recent publications have shown the use of metamaterials, synthetic composite materials that exhibit properties not usually found in nature, to create surfaces with dramatically different bulk properties. Additionally, researchers have demonstrated the ability to tune the near-field properties based on surface structuring at the micro- and nanoscale. The capability to control the radiative properties of surfaces has resulted in the use of surface structuring and metamaterials for specialized applications, including optimization of solar photovoltaic cells and spectrally selective window glass.

Greffet and Henkel have shown that, contrary to previous understanding, the thermal radiation of a large number of substances is partially coherent when it is observed within the near-field. Furthermore, they documented that surface waves could be excited thermally and generate resonant effects within the near-field. By developing new experimental techniques, they were able to directly observe the thermally excited near-fields [7]. Additionally, Andrew and Barnes have revealed that the coupled surface waves provide effective transfer of excitation energy across metal films up to 120 nanometers thick. This result should allow for directional control of excitation energy through the use of appropriate metallic nanostructures [1]. The use of surface structuring to create materials with different bulk properties has been well documented in recent years of research. Researchers have demonstrated that by introducing a periodic microstructure into a polar material (SiC) a thermal infrared source could be fabricated. By optimizing the depth of the surface structuring, the wavelength of peak emissivity was shown to be controllable. Additionally, the near-field resonant effect caused the electric field emitted to be enhanced by more than four orders of magnitude [8]. Sheng et al. also experimentally measured the enhanced energy transfer between two surfaces at small gap sizes [24]. Further research has shown that the near-field resonant effect also caused the electromagnetic field emitted from a microstructured surface to be highly directional in the near infrared and coherent for p polarization [15]. By combining a polar material (SiC) and dielectric photonic crystal into a layered arrangement, it has been shown that it is possible to achieve coherent emission for both s and p polarization while maintaining enhanced emission due to resonant effects [16]. This body of research forms the foundation for designing surfaces with tunable radiative properties.

By varying the surface structure at the nanoscale it is possible to tune the radiative properties of surfaces. Francoeur determined that tuning of near-field radiative heat transfer via thin films that support surface phonon polaritions was possible simply by varying the structure of the system. Important parameters of the system included thickness and separation distance of the thin films [4]. Through the use of micro- and nanostructured semiconductor materials, McConnell designed two structures to selectively emit at mid- and far-infrared wavelengths. Experimental measurements demonstrated that spectrally selective absorption at the design wavelengths was achieved. Furthermore, the radiative properties were largely unaffected by a wide range of incident angles [21, 22]. Zhang and Fu determined that the cavity resonance modes and surface phonon polaritions of periodic gratings could interplay, allowing for the development of thermal emission sources to fulfill specific requirements [5]. Additionally, research has shown that by combining multiple periodic microstructures, a dual-band mid-infrared emitter could be created [18]. Other work has shown that the surface plasmon resonance peaks of indium tin oxide nanoparticles can be tuned by changing the concentration of tin doping or by electrochemical modulation [6, 13]. By studying silver nanoparticle arrays encapsulated in dielectric SiO, Jensen et al. showed that the wavelength of maximum transmittance could be tuned from 400 nanometers to 6000 nanometers [12]. Further research on films composed of silver either sandwiched or overcoated by a dielectric has shown that the ability to tune the surface plasmon response was enhanced by almost one order of magnitude simply by introducing the dielectric [28]. Additionally, through precise control of manufacturing variables, Weimar and Dyer were able to create silver island films on glass substrates with tunable surface plasmon resonance wavelengths that could be adjusted from the visible to the near-infrared regions of the electromagnetic spectrum [27]. Ye et al. have also shown by varying the SiO_2 thickness in $Ag/SiO_2/Ag$ structures, the degree of coupling between the surface plasmons of the two silver layers could be controlled. When the SiO_2 layer was thin (20 nm), the surface plasmons were coupled. This resulted in a redshift in the thermal emission peak. As the thickness of the SiO_2 layer was increased, the surface plasmon coupling became weaker and eventually disappeared [29]. By implementing micro- and nanoscale metamaterial structures, researchers have shown that the radiative properties of surfaces can be intelligently designed for specific applications.

Researchers have implemented surface structures to tailor materials' radiative properties to specialized purposes [11]. One such example is the use of plasmonics to improve the absorption characteristics of photovoltaic devices [2]. Hajimirza et al. have presented an optimization methodology for designing periodic metallic nanostructures to increase absorption efficiency in solar photovoltaic cells. Through the implementation of this optimization methodology, the authors were able to realize enhancement factors as high as 1.52 [9, 10]. Metamaterials have also been used to design building materials capable of enhancing the energy efficiency of structures. For example, Rephaeli et al. have presented a metal-dielectric photonic structure capable of daytime radiative cooling. The structure achieved a net cooling power of 100 W/m^2 by blocking solar light and emitting in the mid-infrared [23]. Researchers have also used metamaterials to enhance the energy efficiency of window glass. For example, a window composed of vanadium oxide and titanium oxide films was shown to increase luminous transmittance, the fraction of visible light transmitted, by 86%. Additionally, there was a sharp optical transition at 57.5 °C which allowed for automatic solar heat control and ultraviolet radiation blocking [26]. Other researchers have also investigated vanadium oxide nanoparticles embedded in glass-like material. The resulting composite showed decrease in the fraction of visible light absorbed and enhanced modulation of solar energy transmittance [17]. Additionally, Banerjee has designed a coating of vanadium oxide nanowires that allowed for the creation of a switchable window that allows heat through when it is cold and blocks heat when it is hot. The transition between states was achieved by passing an electric current through the material [3]. Other research on switchable window glass has focused on tin-doped indium oxide nanocrystals in niobium oxide glass. The resultant glass selectively blocked near-infrared and visible light by varying an applied electrochecmical voltage. The optical contrast was enhanced 5 times and the film retained 96% charge capacity after 2000 cycles [14, 19]. Metamaterials have provided designers with the opportunity to engineer surfaces with precise radiative properties to manage radiation in energy efficient ways.

Radiative properties are strongly dependent on the near-field in which properties can be vastly different due to surface structuring at the micro- and nanoscale. Research has revealed that it is possible to control the radiative properties of surfaces by introducing intelligently designed microstructures. This has allowed designers to create materials with enhanced radiative properties for specific applications in order to boost the energy efficiency of those processes.

Building on the research outlined above, this work seeks to converge on a design for metamaterial window glass that improves on the performance of currently available low-emissivity window glass. Through the implementation of Ag thin-film nanostructures it is possible to capture a substantial portion of solar energy, thereby increasing the energy efficiency of any windowed structure through reduction of heating demand during cold periods. In this work, the effect of various configuration parameters is quantified computationally via 3-D finite-difference time-domain simulations leading to a prediction of the net sustainability advantage of metamaterial window glass.

Chapter 3: Design and Simulation Methodology

Commercially available, high-efficiency, low-emissivity window glass was assumed to be composed of a base layer of SiO_2 glass with a 10 nm silver layer. This model for commercial low-emissivity glass was simulated for algorithm verification and baseline comparison to metamaterial glass. The finite-difference time-domain (FDTD) method solves Maxwell's curl equations at the nodes of a discretized spatial grid [25]. Maxwell's curl equations are given by equations 1, 2, and 3:

$$\frac{\partial \vec{D}}{\partial t} = \nabla \times \vec{H} \tag{1}$$

$$\vec{D}(\omega) = \varepsilon_0 n^2 \vec{E}(\omega) \tag{2}$$

$$\frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu_0} \nabla \times \vec{E} \tag{3}$$

where *H*, *E*, and *D* are the magnetic, electric and displacement fields, respectively, and *n* is the refractive index. The FDTD Solutions commercial-grade simulator by Lumerical Computational Solutions, Inc. was used for the investigation. FDTD Solutions employs the Yee algorithm to solve for both electric and magnetic field components in time and space [20]. Absorbing, periodic, and Bloch-type boundary conditions are used to simulate macroscale surfaces with small, periodic domains. Grid-independence investigations determined minimum spatial resolution for accuracy, which ranged from 2.5 Angstroms to approximately 5 nm.

FDTD simulations established baseline configurations for both standard and low-emissivity glass. Figure 1 provides a graphical schematic of standard window glass and commercial low-emissivity glass, illustrating the mechanism of IR-reflection that boosts energy efficiency in the structure.

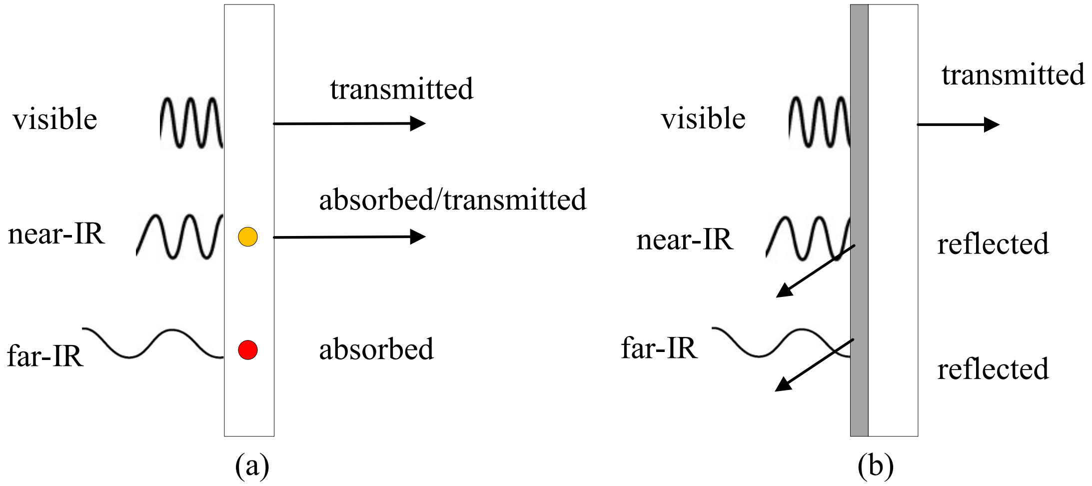


Figure 1: Solar interaction with (a) bare glass, and (b) Ag-coated glass (low-emissivity window)

While standard (bare) glass windows allow virtually all optical wavelengths and a portion of near-infrared solar energy to enter the structure, a significant portion of near- and far-infrared energy is absorbed by the window glass, which is opaque at longer wavelengths. Low-emissivity windows make use of the highly reflective properties of silver to reflect much of the non-optical, unwanted energy during mild or warm periods. Chemical vapor deposition (CVD) techniques are typically used to apply approximately 5-20 nm of silver in a uniform, thin film. The optical absorption/reflection of the thin-film is minimal, allowing the windows to appear transparent, however the Ag layer efficiently reflects near- and far-IR energy, up to > 90% beyond 1.5 µm wavelength. Figure 2 presents the reflectivity spectrum of both bare glass and low-emissivity glass (with 5 and 10 nm Ag layers) between 400 nm and 2.5 µm. The computational results presented in Figure 2 agree with curves presented by various manufacturers.

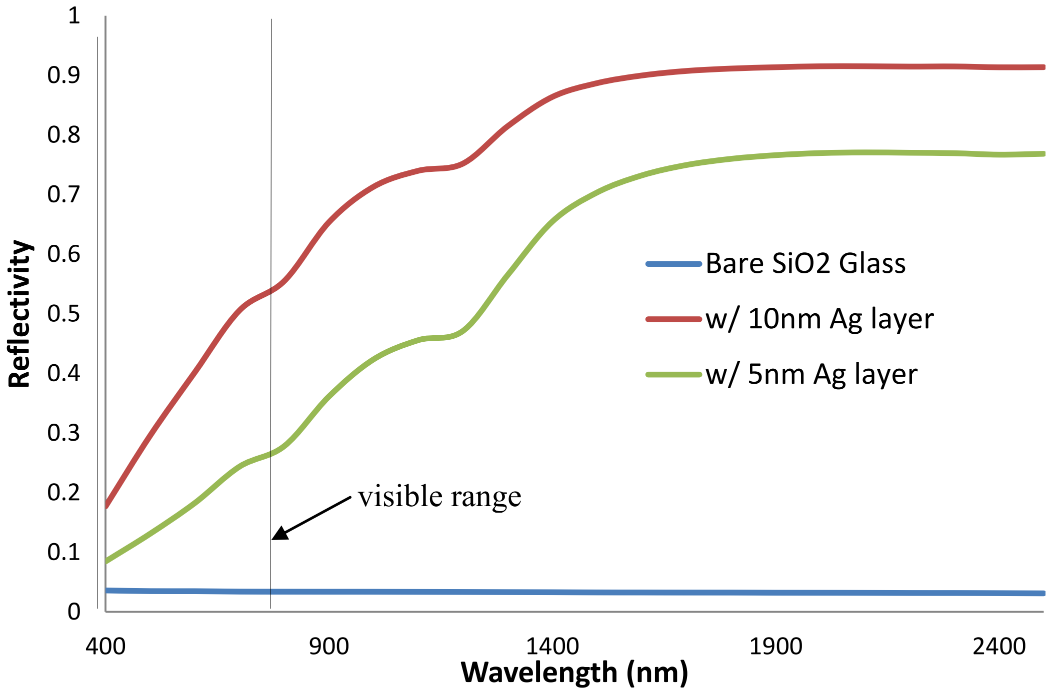


Figure 2: FDTD simulation results, illustrating IR-reflective property of 5nm and 10nm Ag films

Spectral integrations to be presented were compared to the 10nm Ag, low-emissivity baseline to determine the net advantage of metamaterial window glass designs. The opportunity for improvement lies within the near-IR band, which contains nearly 50% of all solar energy, yet virtually none of that emitted from the interior of heated structures. The reflection of near-IR energy is therefore desirable only during periods of warm external temperature, when energy is used to cool the interior of the structure. During periods of cold external temperature, commercial low-emissivity window glass reflects near-IR energy wastefully to the environment. Window glass with the ability to modify its emissive and reflective properties based on external temperature can make use of this wasted solar energy during colder conditions, thereby boosting energy efficiency by tapping into a fraction of the solar spectrum containing over 400 W/m^2.

Variable emissivity metamaterial window glass has been conceived for this purpose. The reflection of near-IR energy can be modified through the unique, near-field properties of nanostructured silver. Figure 3 presents a schematic of one metamaterial glass concept in configurations of high near-IR absorptivity (3a) and high near-IR reflectivity (3b).

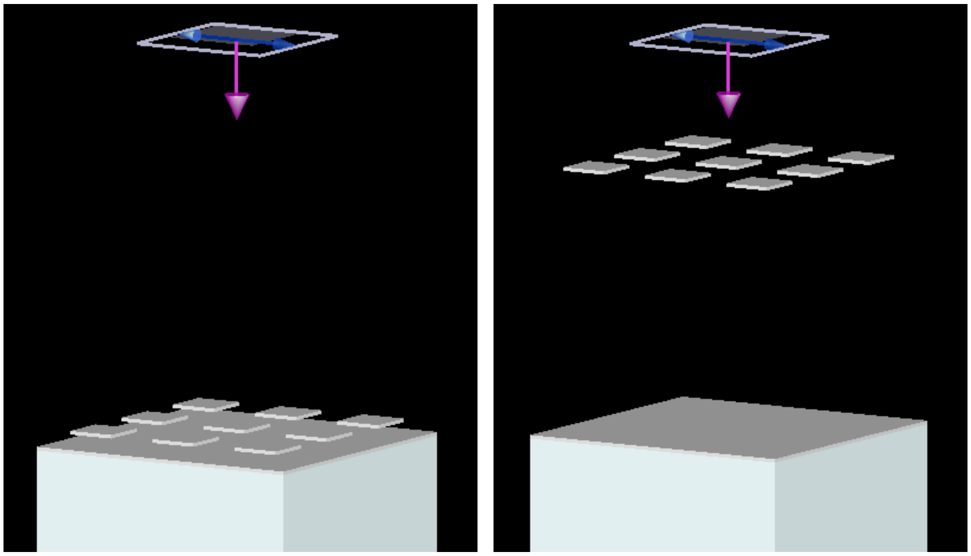
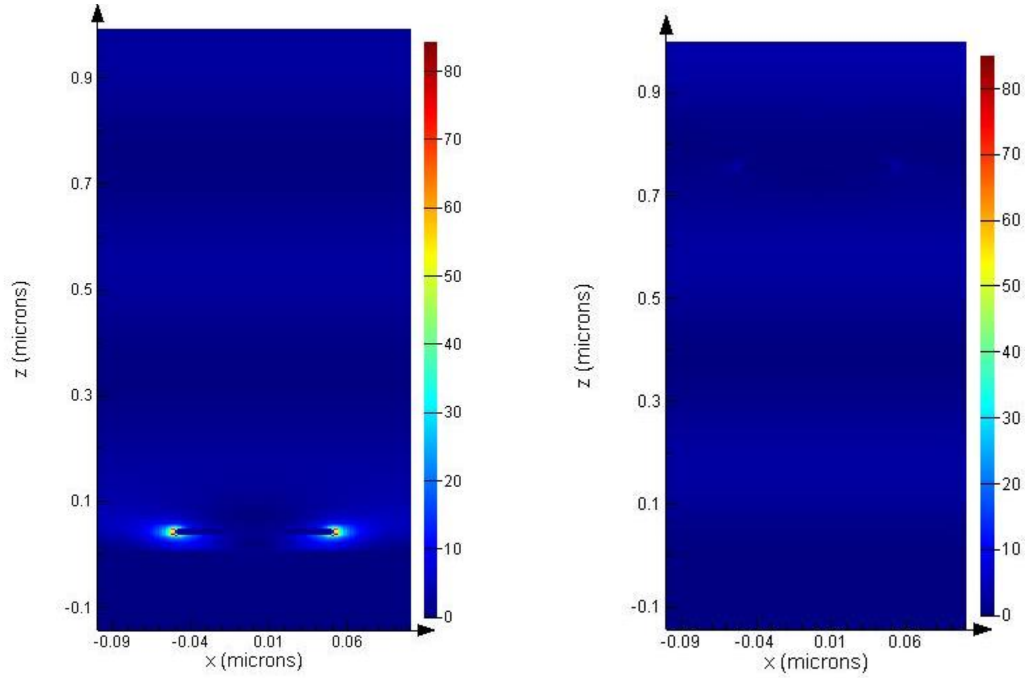

(a) (b)

Figure 3: Metamaterial window glass concept with metamaterial layer 30 nm from surface (a), and 750 nm from surface (b)

The metamaterial glass makes use of the plasmonic coupling mechanism demonstrated by nano- and micro-sized Ag objects. When two Ag structures are separated by a sufficient distance, typically larger than the characteristic wavelength of interest, no coupling effect will exist. However, if the Ag structures are moved within a few tens of nanometers of each other, a surface plasmon resonance will be achieved, generating intense local fields, sometimes referred to as anomalous absorption. It is this mechanism that is used here to capture the energy in the near-IR portion of the solar spectrum during periods of cold temperature. On a hot, sunny day, the design calls for either separation of the Ag structures or rotation of the metamaterial assembly, producing standard low-emissivity reflection performance. Figure 3(a) shows a "unit cell" of a conceptual metamaterial glass segment, in which the standard low-emissivity glass is represented by the substrate upon which a 10 nm Ag layer is deposited. This is the contemporary high-efficiency, commercial design. An additional film, designated the metamaterial layer--containing discrete 100 nm x 100 nm Ag squares of thickness 10 nm and 200 nm period is modeled and is separated from the Ag surface by a distance of 30 nm. Figure 3(b) shows the configuration with the metamaterial layer raised 750 nm above the Ag surface. The dielectric film in which the Ag metamaterial squares would be embedded is not shown for clarity.

3-D FDTD simulations were performed for both cases. Electric field profiles are shown in Figure 4 for the discrete near-IR wavelength of 800 nm. It is clear that localized coupling exists in case (a), where the metamaterial layer is in close proximity to the Ag surface. The local electromagnetic field is enhanced by more than a factor of 80. Case (b) demonstrates the lack of coupling, and hence absorption, when the metamaterial layer is moved only a short distance away. There is very little field enhancement, and the reflectivity is comparable to the case of a traditional low-emissivity window.



(a) (b)

Figure 4: EM field intensity with metamaterial layer 30 nm from Ag surface (a), 750 nm from Ag surface (b)

Simulations were performed for wavelengths between 400 nm and 2.5 µm to determine the effect of metamaterial layer presence and transition over the entire solar spectrum. These results are presented in Figure 5, indicating that the presence of the metamaterial layer only 30 nm from the base Ag layer dramatically reduces the reflectivity in the near-IR between 700-1000 nm. This additional energy would now be absorbed and convected to the interior, reducing the heating demand of the structure in which the windows are installed.

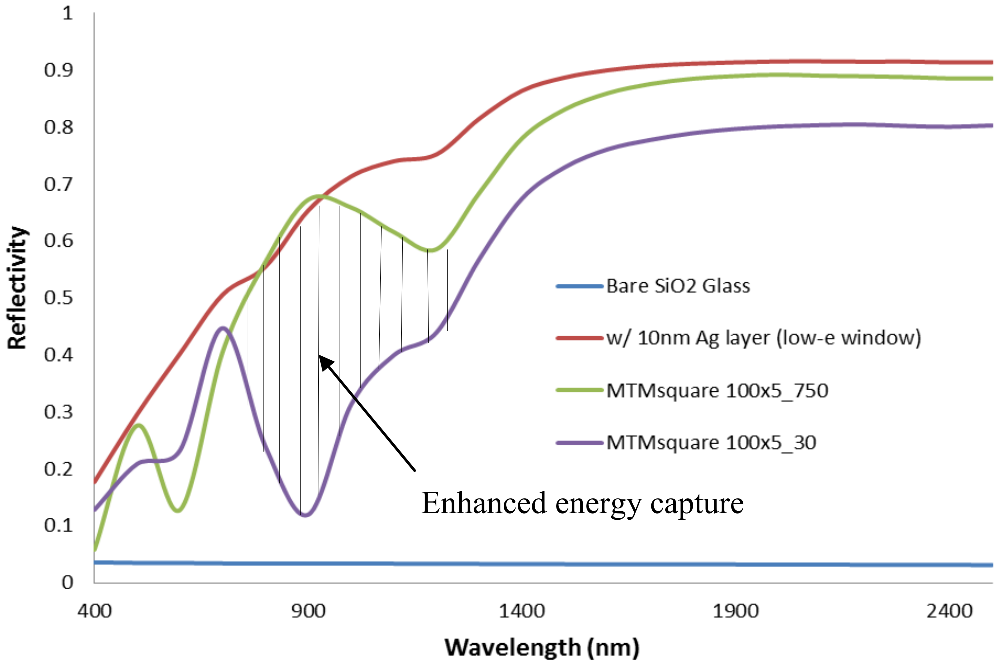


Figure 5: Spectral reflectivity comparison of standard, low-emissivity, and metamaterial window configurations

The net energy effect of a metamaterial glass design must be calculated by integrating the product of the reflectivity and the solar intensity over the wavelength range of interest. The ASTM Reference Spectra (1.5 Air Mass) Direct + Circumsolar data is used here, shown in Figure 6.

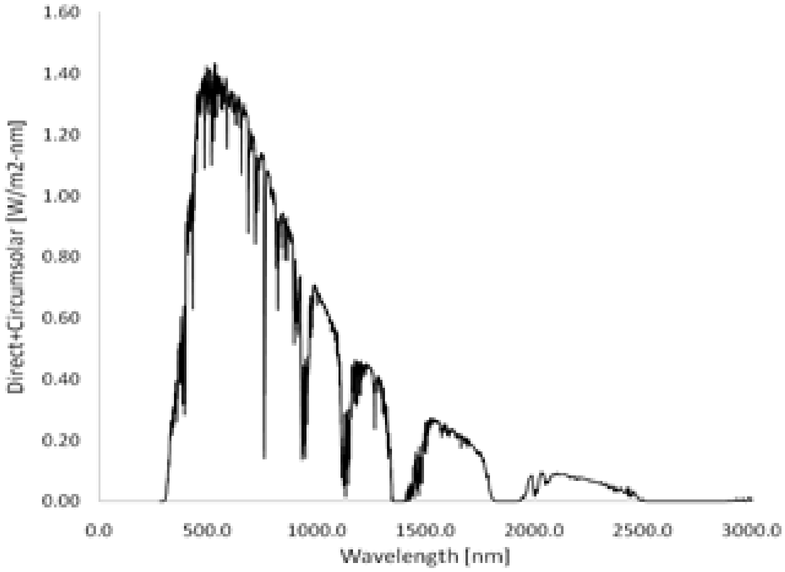


Figure 6: ASTM Solar Reference Spectra, Direct+Circumsolar

A metamaterial glass design is presented in Figure 7, consisting of a 20 nm thick Ag base layer on glass, followed by dielectric layer of width 20 nm, followed by a square checkerboard patterned Ag layer 5.0 nm thick, with square side dimension 100 nm and period of 350 nm.

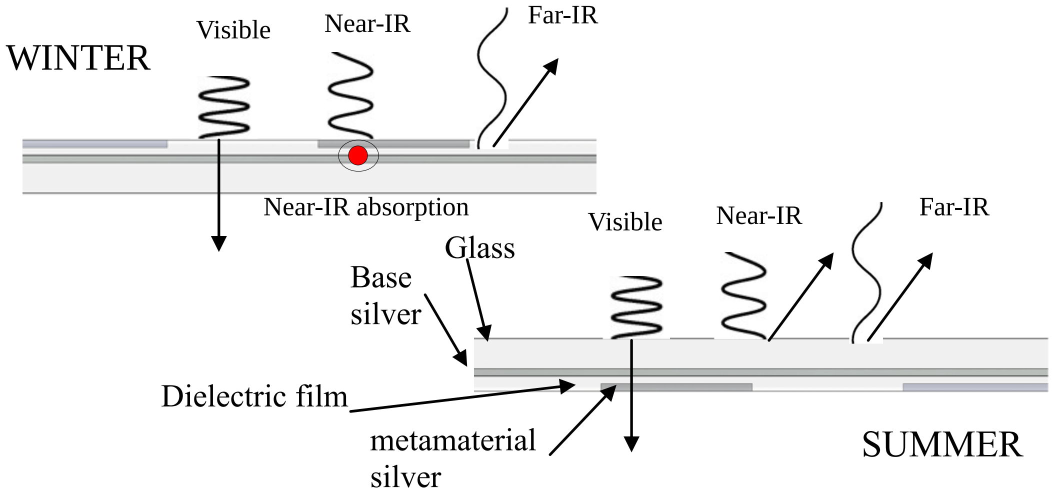


Figure 7: Metamaterial window glass orientations

As mentioned above, two options exist for transition from winter to summer configurations: rotating the window glass to present the opposite side to the exterior, or moving the Ag layers apart by a distance on the order of microns. Figure 7 illustrates the rotation of the metamaterial glass from winter to summer configuration. It should also be noted that climates that enjoy cold weather year-round may simply maintain a static configuration, which maximizes the sustainability benefit of metamaterial window glass without any transition. Figure 8 plots the product of the solar spectrum and the reflectivity values of baseline low-emissivity glass, along with that of one metamaterial window glass design in a “summer” configuration, and metamaterial window glass in a “winter” configuration, for wavelength values between 400 and 1500 nm.

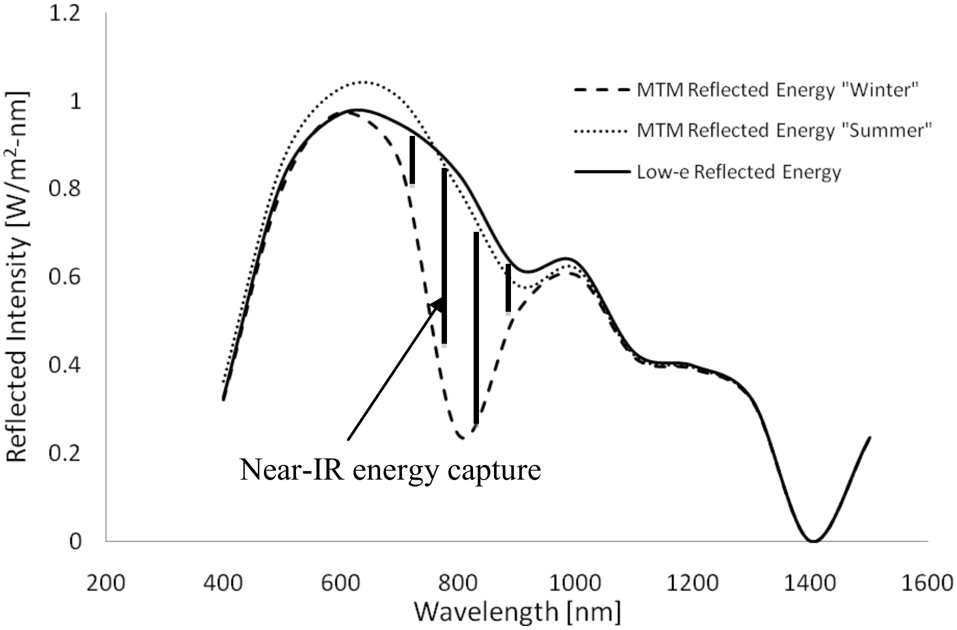


Figure 8: Reflected radiant intensity as function of wavelength for low-emissivity and metamaterial glass configurations

Figure 8 predicts very comparable performance of low-emissivity and metamaterial glass in the summer configuration. With rotation to winter configuration, however, simulations predict a dramatic absorption/transmission effect in the near-IR band. Integration of the curves reveals 94.6 W/m^2 captured by the metamaterial glass relative to the commercial low-emissivity window, for the design specified. Figure 9 gives the electromagnetic field distribution in the vicinity of the glass for both winter and summer orientations at λ=800nm, showing the interaction in the solar near-IR range with the metamaterial layers.

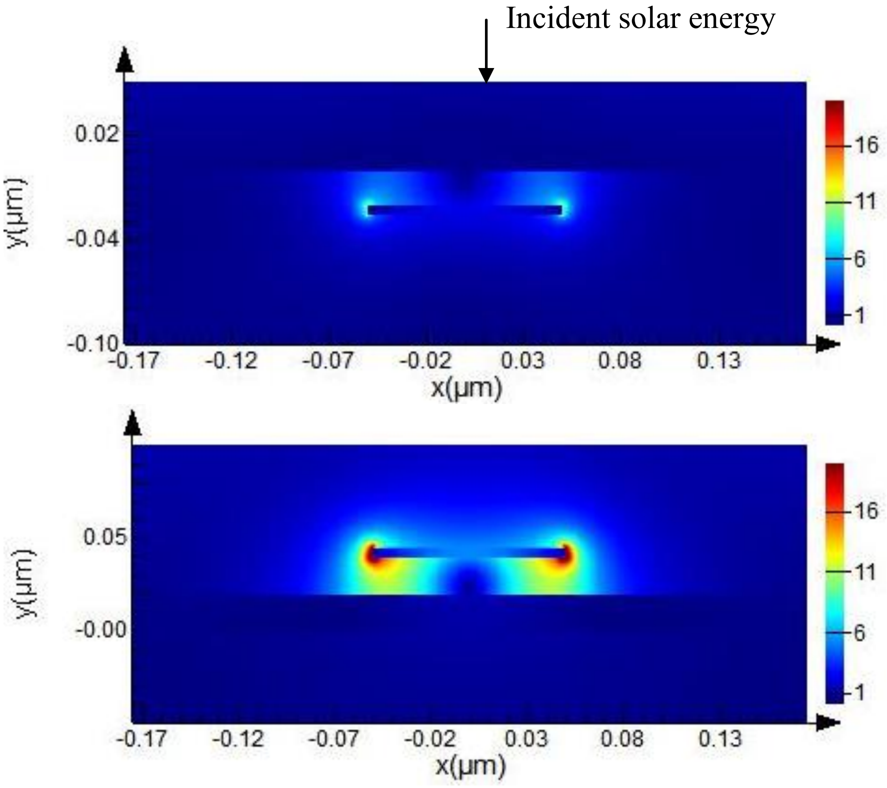


Figure 9: Electric field distribution in metamaterial glass for summer orientation (top) and winter orientation (bottom), λ = 800 nm

Simulations also imply that a tinting effect may occur in some designs due to increased absorption in the optical range, primarily at the red end of the spectrum. Therefore, an aesthetic trade exists in which the amount of change in optical transmission counters the amount of change in near-IR reflection. The metric is in part subjective, but a reasonable transmission threshold can be applied, while maximizing near-IR absorption within this constraint. Figure 10 presents the reflected spectral intensity for a metamateial design consisting of a 20 nm thick Ag base layer on glass, followed by dielectric layer of width 100 nm, followed by a square-patterned Ag layer 5 nm thick, with square side dimension 200 nm and period of 400 nm.

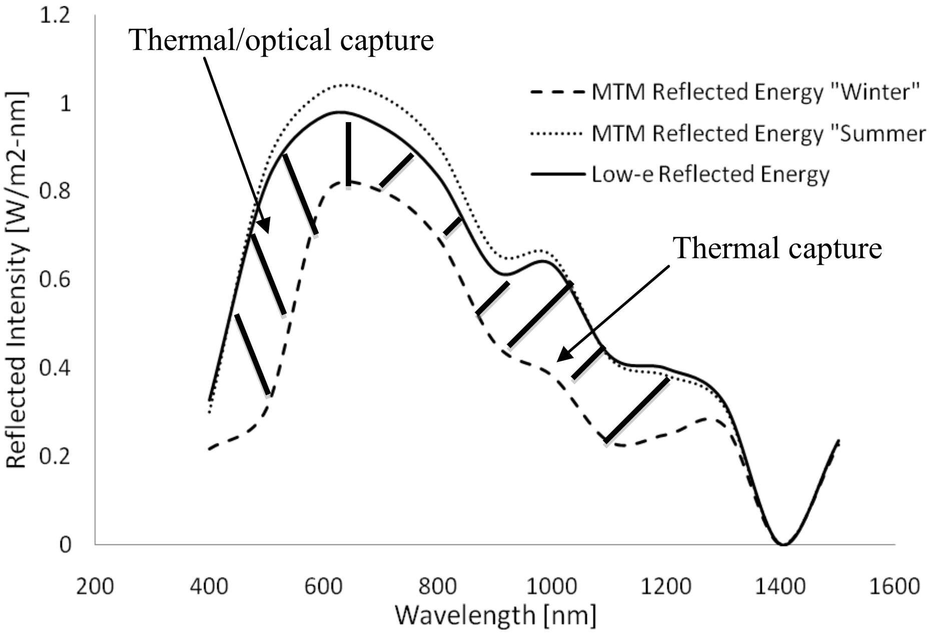


Figure 10: Reflected radiant intensity as function of wavelength for low-emissivity and metamaterial glass configurations

Again, a dramatic effect is predicted with rotation from summer to winter configurations; however, the effect is roughly consistent through the optical and near-IR. The enhanced optical absorption greatly contributes to the thermal efficiency, boosting the energy capture to 214.6 W/m^2, but reducing optical transmission to approximately 30%, not unlike a pair of sunglasses. Figures 8 and 10 combined illustrate the sensitivity of the radiative properties to small changes in design. In this case, only the distance of separation between base and metamaterial Ag layers created the strong enhancement in optical absorption, implying the possibility of commercial products that offer an entire range of adaptably efficient glass per the situational need.

This sensitivity requires an understanding of the effect as a function of relevant parameters, including metamaterial layer size, period, and spacing. Figure 11 presents a set of points predicting the energy capture of a metamaterial window in its winter configuration, as a function of metamaterial layer coverage of the Ag base layer. Metamaterial square width and thickness are held constant at 100 nm and 5 nm, respectively. A peak exists at roughly 50% coverage, with the design accessing nearly 120 W/m^2 of formerly reflected energy. Likewise, when holding the metamaterial period constant at 200 nm while varying metamaterial square width, a similar trend is observed in Figure 12, though with a notable dip at approximately 60% coverage. Depending on the optical properties desired, however, it may be preferable to shift the design off-peak to allow for increased transmission in the range of $\lambda = 400 - 700$ nm.

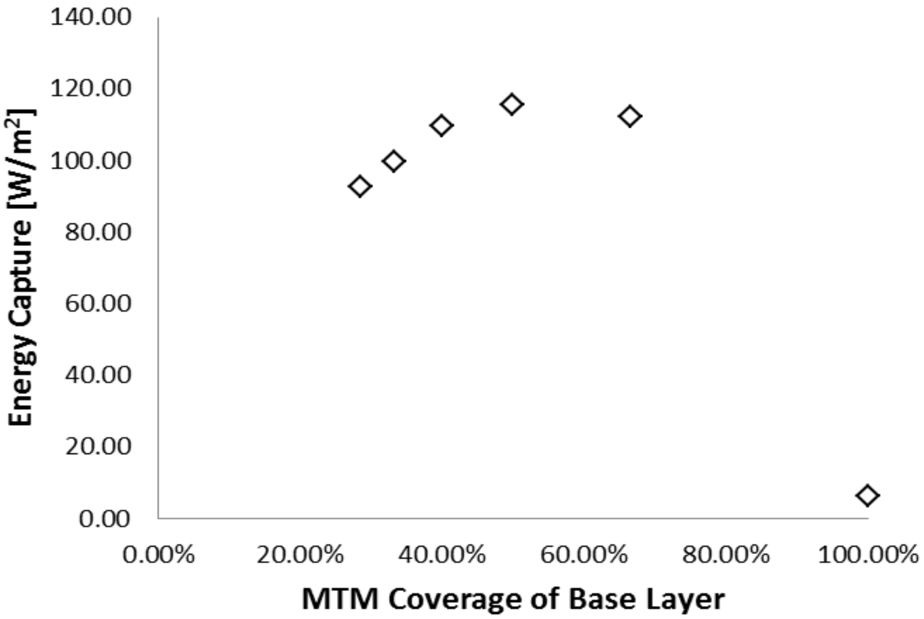


Figure 11: Energy capture as a function of metamaterial coverage of Ag base layer (constant metamaterial square width)

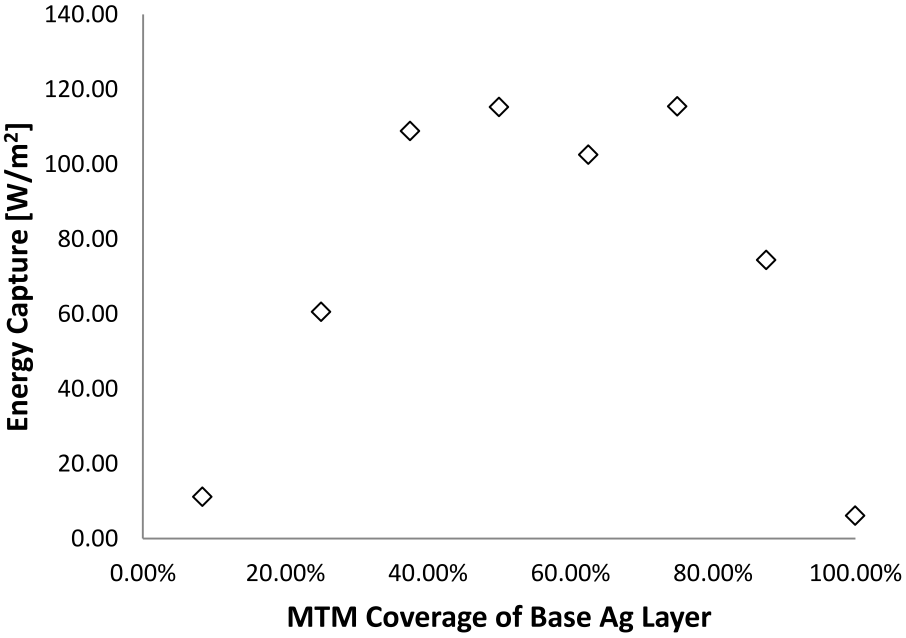


Figure 12: Energy capture as a function of metamaterial coverage of Ag base layer (constant metamaterial period dimension)

The spacing between the metamaterial and base Ag layers represents both a means for transitioning between winter and summer configurations as well as a design point. Figure 13 presents the results of simulations revealing the strong spectral dependence on this parameter. As the metamaterial layer is moved away from the base Ag layer, the enhanced absorption shifts from the near-IR into the visible range, with the total energy absorbed generally increasing. Figure 13 presents a very specific mechanism for tuning not only total energy absorbed, but the optical quality of the resultant window glass, including tint and coloration. Applications of this mechanism extend beyond improvements in energy efficiency to decorative and functional products such as stained glass and sunglasses.

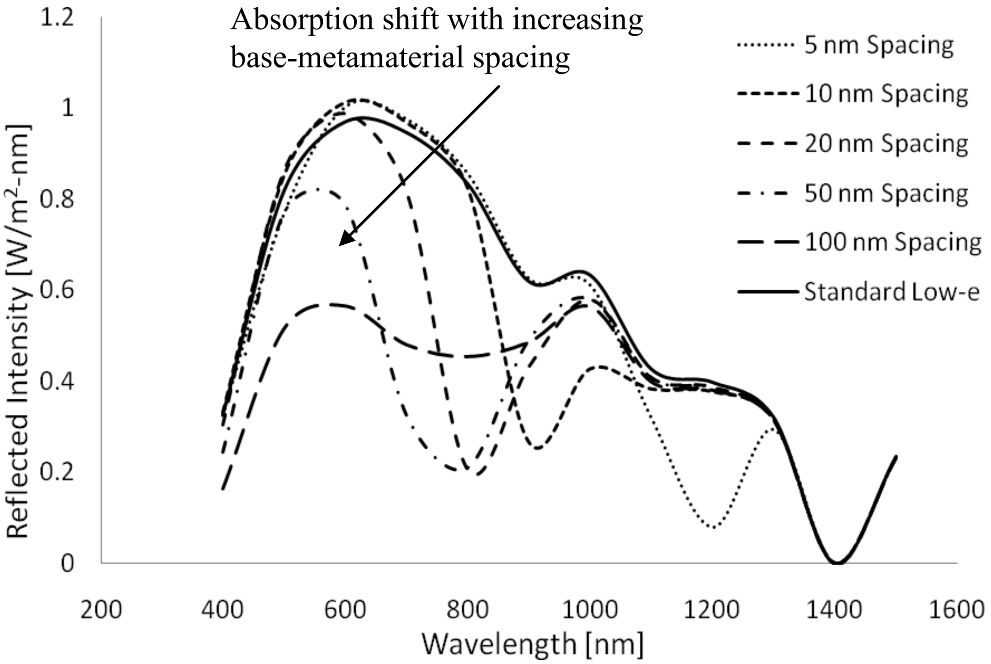


Figure 13: Absorption shift as a function of metamaterial spacing

The primary goal of this work was to converge on a design for metamaterial window glass that is optimized for maximum energy savings. The data from Figure 11 and 12 was used to determine the optimal period and metamaterial square side length. The optimized metamaterial layer is composed of an Ag checkerboard patterned surface embedded in a dielectric. The checkerboard pattern has a square side length of 100 nm, period of 200 nm, and thickness of 5 nm. The spacing between the 20 nm base Ag layer and metamaterial layer was varied to identify the spacing which yielded maximum energy capture. Figure 14 presents the energy capture versus spacing curve. The maximum energy capture of 258 W/m^2 occurred at a spacing of 110 nm. Figure 15 shows the reflected spectral intensity for the optimized design in winter and summer configurations as well as the low-emissivity baseline. Increased absorption in the optical range results in a decrease in optical transmission to approximately 30%.

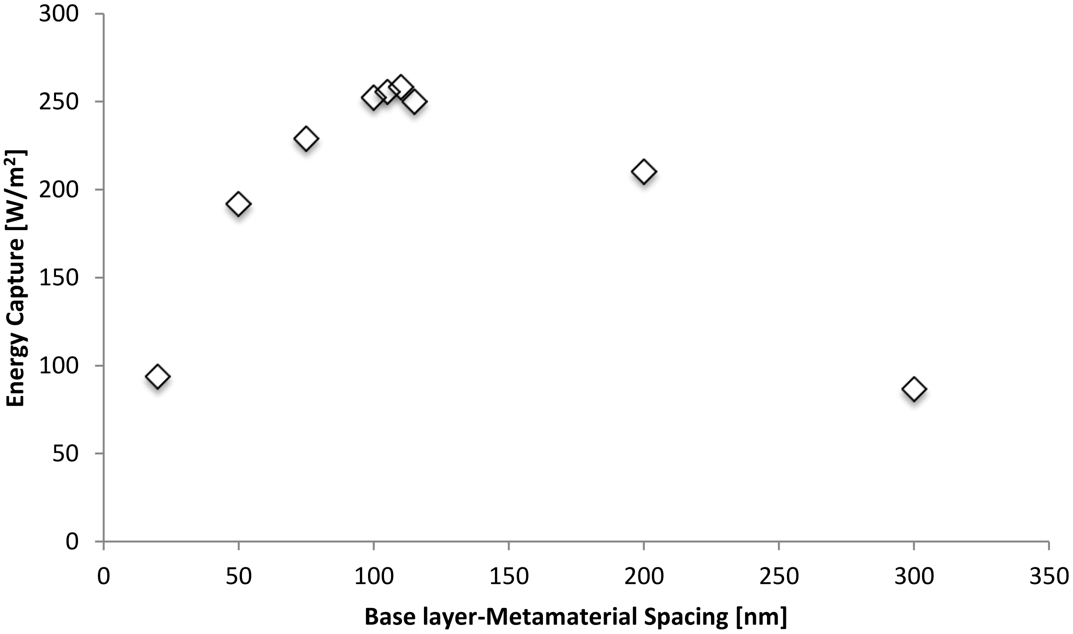


Figure 14: Energy capture versus base layer-metamaterial spacing

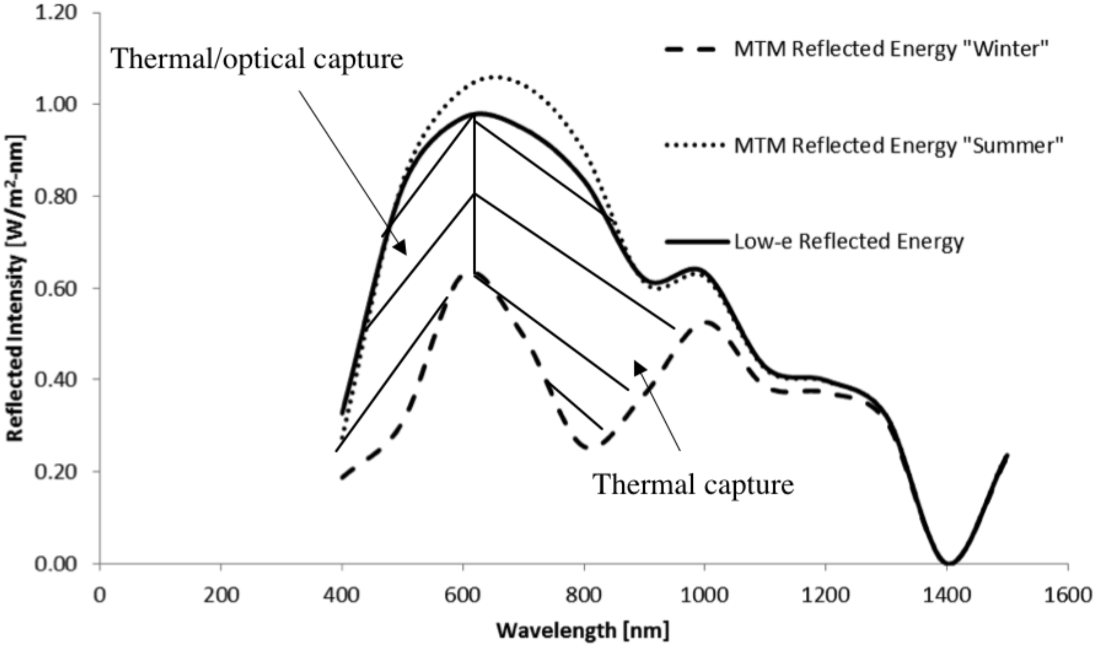


Figure 15: Reflected radiant intensity as function of wavelength for low-emissivity and optimized metamaterial glass configurations

A final important parameter of interest is the response of metamaterial glass to various incident angles, as the sun sweeps through the sky. Figure 16 shows the effect of incident angle on energy capture. The design is relatively insensitive to incident angle, showing a maximum of 27% decrease in energy capture, when compared to normal incidence, through a cone angle of 100 degrees (-50 to 50 degree incident angles), accounting for virtually all expected irradiation during the day. This is an important result, opening the door for practical application in windowed structures.

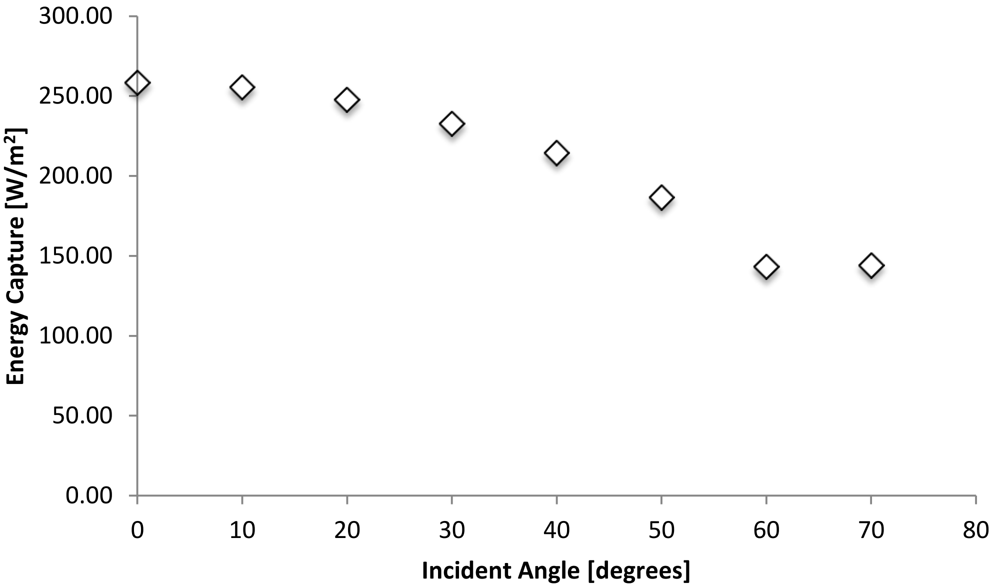


Figure 16: Energy capture versus incident angle

Chapter 4: Thermal Analysis

The net energy savings as a result of using metamaterial window glass is dependent on its specific design configuration, as noted above, and not readily understood from the spectral reflection plots. Finite-element models were built to assess this effect on energy demands in a structure with metamaterial glass installed. While a large, entirely windowed structure in a predominantly cold climate would see the most dramatic savings (e.g. a skyscraper in the northern United States), a small dwelling with conservative window coverage is considered here. A portion of the structure is modeled using ANSYS CFD/thermal software as pictured in Figure 17, wherein a small, roofed home is approximated by four fiberglass insulated walls, four 1.0 m^2 double-pane windows, a wooden door, an insulated ceiling, attic space, and roof. A cold day was simulated by applying a 1.0 m/s, 0^o F boundary condition across the home, while supplying heated air through an interior vent to maintain an average internal temperature of 70^o F. The full internal/external simulated environment contained ~1e6 finite volume elements, while individual wall segments used ~1e4 elements. Simulations performed on a single 2.2 MHz processor required 2-4 hours wall time to converge. Higher fidelity simulations resulted in negligible change to heat transfer results. The Navier-Stokes and energy equations were solved in all fluid domains, and the energy equation in all solid domains, converging on a steady-state solution of the notional environment.

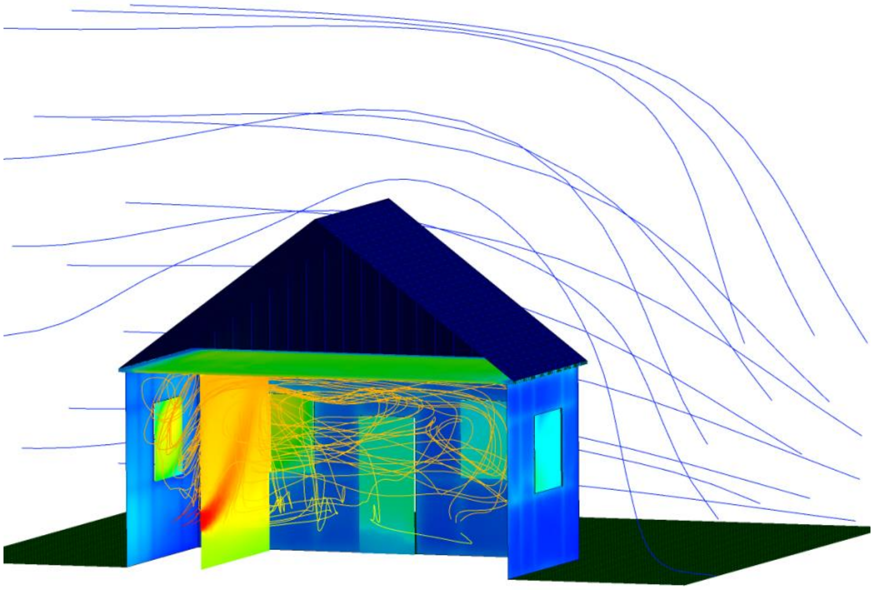


Figure 17: Navier-Stokes/Energy simulation of a small, windowed structure in a cold environment

Approximately 70% of the heat loss to the environment is predicted to occur through the windows and door using standard, double-pane windows. Simulations predict a heating demand of 376 W at the listed conditions (noting that a small, well-insulated, "half-room" is the extent of the model domain). During periods of sunlight, energy absorbed by the metamaterial window can reduce this demand. Figure 18 presents the temperature distribution in the double-pane window with a standard design, and with the metamaterial glass design with performance specified in Figure 8. The energy absorbed by the metamaterial glass raises the temperature of the inner pane by 9^{o} C, up to 31.5^{o} C (89^{o} F). Convecting this heat directly to the outside is a concern with single-pane windows, however Figure 18 shows that a typical double-pane window with a 16.0 mm thick air cavity keeps most of the energy at the inner boundary where it can be convected to the structure's interior. Thermal radiation in the cavity was not considered in the model.

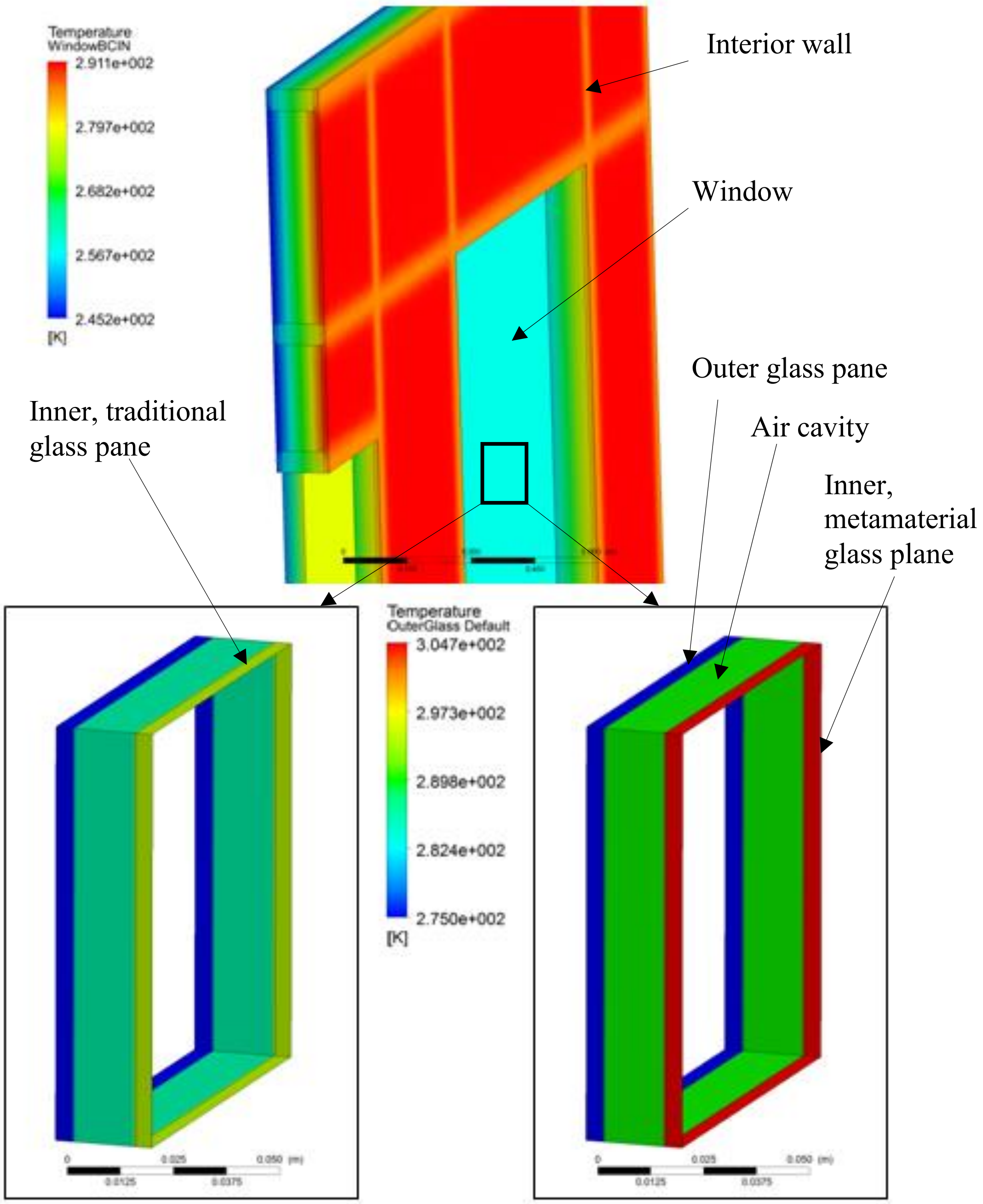


Figure 18: Temperature distributions in wall and glass segments, traditional double-pane window (left), metamaterial window glass (right)

Depending on orientation of the house to the sun, simulations predict a reduction in demand between 19 – 38% during periods of sunlight. Therefore, considering a full diurnal cycle, the installation of metamaterial window glass is predicted to reduce the total heating demand of the structure by approximately 6 – 12% on days with sun. These values are based on largely conservative assumptions (i.e. the metamaterial design used is optically transparent with moderate absorption) and are offered for the single case specified. A large structure with severe heating demands may expect to reduce this load by an even greater margin.

Chapter 5: Conclusions and Recommendations

By building on previous research that demonstrated the ability to manipulate radiative properties through the implementation of surface structuring at the micro- and nanoscale, this work presented design options for ultra-high efficiency metamaterial window glass. Commercially available, low-emissivity window glass uses a silver thin film to reflect infrared energy year-round, while maintaining optical transmission for functionality. Metamaterial window glass can increase the energy efficiency of buildings in seasonal or cold climates through a variable emissivity implementation of silver metamaterial structures. In the summer orientation, metamaterial window glass offers comparable performance to commercially available low-emissivity glass, reflecting infrared energy to reduce a structure's cooling load. Transition to the winter orientation is achieved by rotating the window so that the opposite face points outside the structure. In the winter orientation, non-linear absorption of near-infrared energy provides the means to capture a substantial portion of the incident solar radiation, thereby reducing the structure's heating load.

3-D finite-difference time-domain simulations in FDTD Solutions were used for the computational analysis presented here. The effect of metamaterial period, base layer period, and metamaterial layer to base layer spacing was quantified, which lead to a metamaterial window glass design that was optimized for maximum energy capture. The optimized metamaterial window glass design is composed of glass with a 20 nm base silver layer, followed by a dielectric layer of 110 nm, followed by a metamaterial layer. The metamaterial layer is composed of a silver checkerboard patterned surface imbedded in a dielectric. The checkerboard pattern has square side length of 100 nm, period of 200 nm, and thickness of 5 nm. The optimized design yielded an energy capture of 258 W/m^2

under normal incidence while decreasing optical transmission to approximately 30%. Additionally, angle of incidence was shown to cause only a small decrease in energy capture. Lastly, a CFD simulation of a small dwelling with metamaterial glass install was presented. The simulation was based largely on conservative assumptions, primarily that the metamaterial glass design was one with only moderate absorption coupling and high optical transmission. The simulation predicted energy savings potential of 6-12%, depending on orientation of the structure. A structure with larger window coverage area and/or a more aggressive metamaterial glass design could expect to decrease energy demands by an even greater margin.

Future work on this research can benefit from a few recommendations. First, additional simulations should be performed to obtain the full spectral transmissivity of the metamaterial window glass design. The spectral transmissivity, combined with the spectral reflectivity presented here, will enable researchers to determine what portion of the incident solar radiation is absorbed in the window glass and what portion is transmitted to the interior of the structure. Both transmitting and absorbing are effective methods for trapping solar energy for heating; however the primary benefit of transmitting over absorbing is minimization of convection losses. Convection losses will also be minimized by implementing a double pane design, as presented here. Second, detail should be given to the specific design of the mechanism for transitioning the window from summer to winter orientation. At this time, no specific design to rotate the window glass exists, however it is possible to envision a window frame that allows the entire window assembly to rotate about an axis and lock into the appropriate orientation. Third, more research on manufacturing costs should be considered. Preliminary discussions with Molecular Imprints, Inc., a world leader in micro/nanoscale patterning methods, and the NASCENT Advanced Manufacturing Lab, a pioneering engineering research center of the National Science Foundation, suggest that metamaterial window glass might be cost competitive at this time. Lastly, sub-scale samples should be fabricated in order to verify the computational results presented here. Spectrophotometer measurements focused on total hemispherical performance of the prototype samples should be performed in order to quantify the benefit of installation of metamaterial window glass experimentally.

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