Nanolayer and Micro-structure Technologies for Energy Efficiency and Sustainability

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ABSTRACT

Multilayer optical film technologies made with hundreds of nanolayers and micro-structured film technologies can be used to manage building energy while maintaining architectural aesthetics. For example, visibly transparent (invisible) infrared mirror films are useful for rejecting infrared energy from building windows and walls, to reduce air conditioning cooling energy loads by 10-30%. Rather than just rejecting infrared energy, the infrared energy can be redirected to where it may be converted to electricity, or solar thermal energy, with concentrated solar optical designs made with these transparent infrared mirror films. Infrared concentrated solar designs have been modeled, which simultaneously provide building daylighting and solar energy generation. Nanostructured and micro-structured films can be used for anti-reflection to capture more solar energy for solar panels and greenhouses. Both multilayer optical films and micro-structured films can be used to bring daylighting further into a building enabling reduced electrical energy consumption for lighting. 3M Company manufactures specular mirror films having greater than 99% reflectivity and this high reflectivity enables ducting of sunlight greater distances into a building without loss in light quality. 3M Company's precision micro-structured film technologies have been applied to windows to refract light further into a building while simultaneously reducing unwanted glare. Multilayer optical films are also useful for passive radiation cooling during the day. Previously, passive radiation cooling was demonstrated for cooling only at night, but more recently, broadband solar mirror films created with multilayer optical films has enabled passive radiation cooling in broad daylight. Multilayer optical film technologies have been applied to the creation of Ultra-Violet mirror films which are useful for providing durable long lasting film protection in outdoor applications.

Keywords: multilayer, nanolayer, microstructure, energy, sustainability

POLYMERIC DIELECTRIC MIRROR FILMS

Quarter wave constructive interference dielectric mirror films developed by 3M [1] using alternating layers of high refractive index polymers and low refractive index polymers can be used to manage solar energy incident on buildings for sustainability. Visible light transparent infrared mirror films made with hundreds of alternating layers of PET (polyethylene terephthalate) and CoPMMA (copolyethylmethylmethacrylate) reflect >90% of infrared energy in the wavelength range of 850nm to 1150nm as shown in Figure 1. When applied to building windows as shown in Figure 2, significant air conditioning energy savings can be achieved.

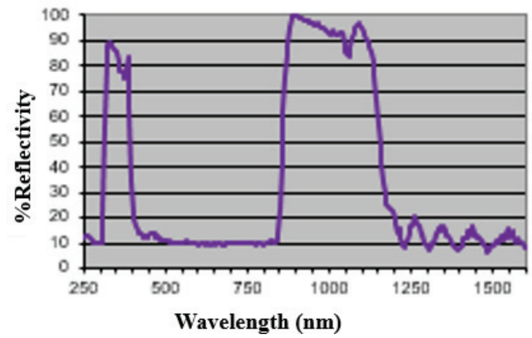

Figure 1: Infrared mirror film reflection band.

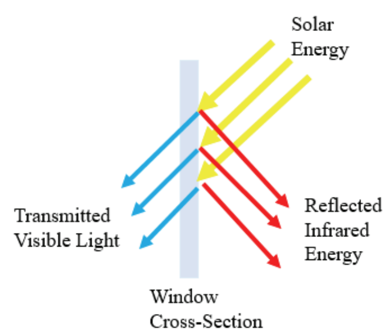

Figure 2: Illustration of window with infrared mirror film.

Rather than just reflecting the infrared energy onto the ground where it heats the ground and ambient air, the infrared energy can be redirected to where it may be converted to electricity with photovoltaic modules as shown in Figure 3. Peak spectral response of silicon photovoltaic modules shown in Figure 4 aligns with the peak reflectance wavelengths of 3M infrared mirror films.

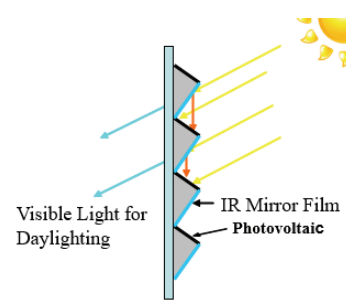

Figure 3: Illustration of infrared mirror window film reflecting near infrared energy onto photovoltaic module.

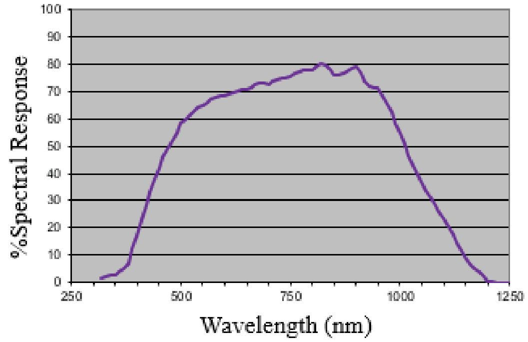

Figure 4: Spectral response of silicon photovoltaic cell.

Analogous to windows, skylight designs can take advantage of the visible light transmission of 3M infrared mirror films for daylighting while simultaneously increasing electricity generation from photovoltaic modules as shown in Figure 5.

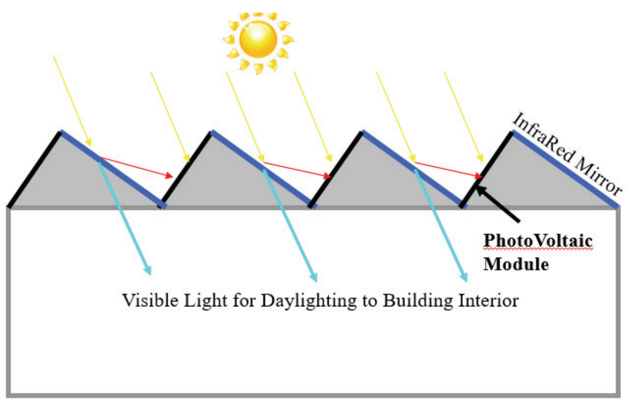

Figure 5: Illustration of Skylights with infrared mirror film redirecting near infrared energy onto photovoltaic modules.

Harmonic reflection bands are an inherent property of quarter constructive interference dielectric mirror films. The third order harmonic reflection band for standard dichroic IR mirror films is shown at 300-400nm in Figure 1. Third order harmonic reflection bands are what constrains the right reflection band of the standard dielectric IR mirror to 1200nm without introducing unwanted visible color reflection above 400nm. Novel optical designs implementing thinner anti-reflective layers with every quarter wave constructive layer pair have demonstrated suppressed third order harmonics [2]. This technical advancement in optics can be seen in Figure 6 where the infrared reflection band is shown extending beyond 1200nm without undesirable third harmonic reflection bands occurring in the 400-500nm wavelength region.

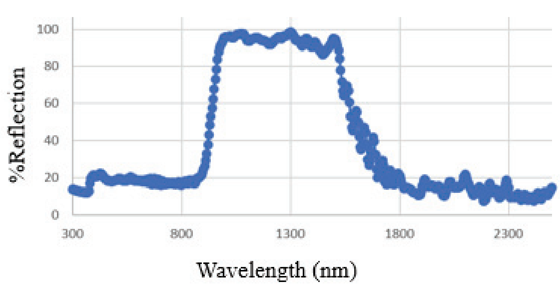

Figure 6: Extended band infrared mirror reflection band.

Extending the IR mirror reflection band beyond 1200nm is important because it can enable increasing the reflection of 17% of the total solar energy to 35% of the total solar energy. Figure 7 shows additional solar energy peaks 3 and 4 which can be reflected and Table 1 quantifies the additional solar energy reflected.

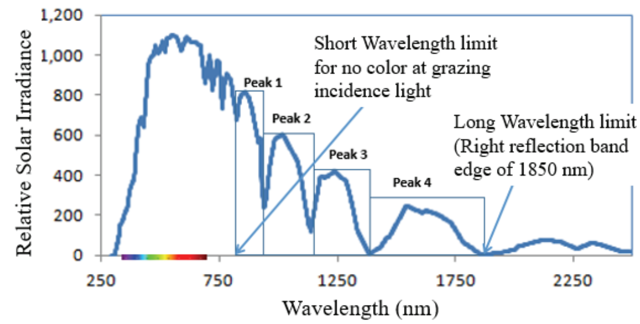

Figure 7: Solar Air Mass AM1.5 Spectrum showing solar energy peaks reflected by extended band IR mirror.

	Short Wavelength (nm)	Long Wavelength (nm)	Total Solar Weight (%)
Peak 1	870	950	6.05
Peak 2	950	1140	11.47
Peak 3	1140	1375	9.18
Peak 4	1375	1850	8.63

Table 1: Relative solar energy reflected from each solar peak in solar spectrum shown in Figure 7.

Highly reflective visible polymeric dielectric mirror films have also been applied towards ducting natural light into a building through circular tubes or square ducts. Aluminum vapor coated mirror films are typically 89% reflective. When used in a light duct, 11% of the natural light is absorbed by the aluminum coating each time the light is reflected down the light duct. Absorption of light by the aluminum coating significantly decreases the distance the natural light can be ducted into a building. Silver vapor coated mirror films typically reflect 94% of natural light and most of the absorption by silver that limits the film reflectivity is in the blue (400-500nm) region of light. When used in a light duct, the reflected light will appear more yellow the further distance it travels in the light duct. Polymeric dielectric mirror films are capable of reflecting 99% of natural visible light which enables better quality natural light to travel further through a duct into a building as shown in Table 2.

	Al Mirror	Ag Mirror	Polymeric Dielectric Mirror
Visible Light Transmitted	20%	55%	88%

Table 2: Natural light transmitted to end of a vertical light duct having a length/diameter ratio of 10:1 with solar angle at 45 degrees.

MICRO-STRUCTURED POLYMERIC FILMS

Engineered micro-structured polymeric films enable refraction of solar energy further into a building [5]. Electricity consumed by indoor light can be reduced by bringing natural daylight further into a building. Numerous studies have also shown that natural daylighting is beneficial to human health and productivity. Optical ray trace modeling was used to optimize geometry of micro-structures on a film applied to the clerestory portion of a window as shown in Figure 8.

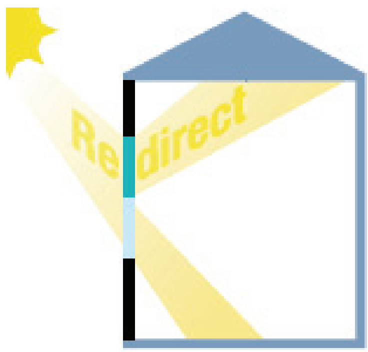

Figure 8: Illustration showing Solar Energy redirected further into building with micro-structures on window.

Optimized surface structures redirect 80% of direct sunlight upwards and as far as 35 feet into a room depending on sun angle, building location, and building orientation. For every vertical foot of micro-structured film applied to a window, the daylighting zone in a building is extended by 8 feet. An additional benefit is diffusion of direct light which reduces specular glare and thus decreases eye strain. Decreased eye strain provides improved occupant comfort and increases their productivity. Building energy modeling estimated the increase in daylighting enables interior lighting electricity energy savings of up to 52% as shown in Figure 9.

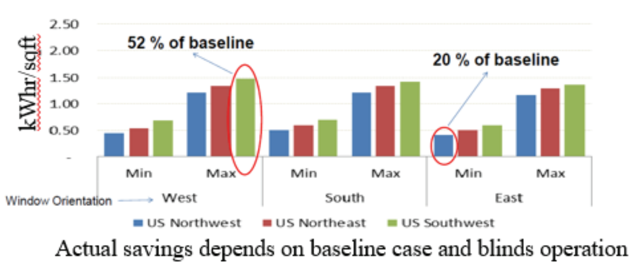

Figure 9: Modeled light energy savings.

NOVEL COMBINATIONS OF POLYMERIC DIELECTRIC MIRROR AND MICRO-STRUCTURES

Multilayer polymeric dielectric mirror films having maximum solar energy reflectivity and maximum absorption in the far infrared atmospheric window region of 8-13 microns are ideal for passive radiative cooling during the day. Solar mirror films designed for passive radiative cooling should have minimal absorption of solar energy and maximum absorption of energy in the far IR region of 8-13 microns as shown in Figure 10. Passive radiative cooling can be used to cool surfaces by radiation heat transfer to dark cold space without the need for electricity and thus can be applied to buildings to reduce the electrical energy consumed for building cooling and refrigeration when coupled to their heat pump loops.

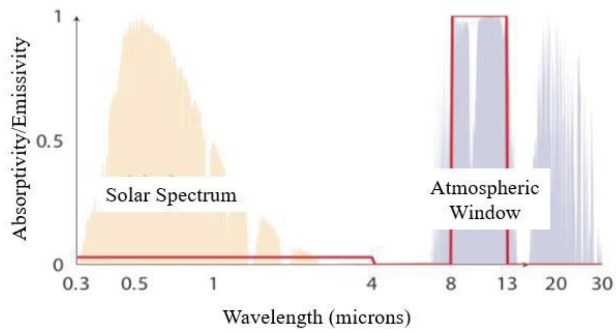

Figure 10: Illustration showing desired low absorptivity over Solar Spectrum relative to desired high absorptivity in the atmospheric window wavelengths for passive radiative cooling surface.

Advances in optical layer thickness control with improved feed block and die designs have enabled multilayer optical films made with alternating layers of PET and PVDF (polyvinylidenefluoride) / PMMA (polymethylmethacrylate) polymer blends to reflect greater than 99% of visible wavelengths of light. Historically, PET based films have been protected from UV degradation with the use of UV absorbers in a protective cap layer or coating. Since 5% of solar energy is in the UV region, a polymeric mirror film protected with UV absorbers cannot reflect greater than 94% of the solar energy. Another recent advancement in multilayer optical films is the development of UV (Ultra-Violet) mirror films made with inherently UV stable materials [3, 4]. UV mirror films can protect broadband solar mirror films from UV degradation and enable total solar energy reflection greater than 98%. The average solar irradiance on the earth's surface is 1000 watts/sqmtr. Every 1% solar energy absorption results in heating surfaces at a rate of 10 watts/sqmtr. Increasing solar mirror reflectivity from 94% to 98% will decrease solar absorption and increase passive radiative cooling power by 40 watts/sqmtr.

Fluoropolymers and acrylate polymers absorb much less UV light and thus are more inherently UV stable. Fluoropolymers require no UV protection and the UV absorption band edge of PMMA is less than 320 nanometers enabling it to be protected from UV degradation with UVAs having absorption band edges between 300 nanometers and 350 nanometers. Polymeric dielectric UV mirror films reflecting UV light in the range of 350-400nm placed over PET visible light mirrors enable an increase in total solar reflectivity from 94% to 98%. Typical reflection spectra of UV mirror film made with 150 alternating layers of PMMA and a fluoropolymer having layer thicknesses in the range of 50-100nm is shown in Figure 11.

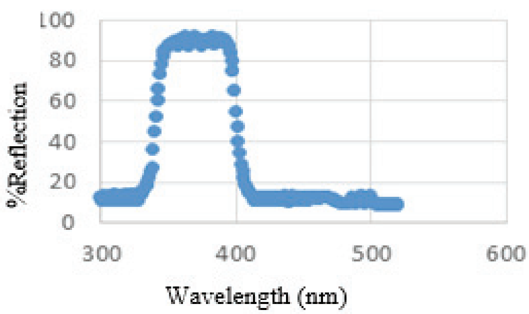

Figure 11: Modeled reflection spectra of UV mirror film made with 150 alternating layers of PMMA and fluoropolymer.

Micro-structures having the right shape and size can be replicated onto passive radiative cooling films to enhance far IR absorption in the 8-13 micron wavelength range. Metamaterial optical modeling calculates that micro-structures in the 1-10 micron size range increases far IR absorption in the 8-13 micron range. When coated with silver, or copper, to reflect near IR in the wavelength range of 1-2.5 microns, these micro-structured UV-VIS multilayer optical mirror films are capable of reflecting 98% of the total energy available from the sun while simultaneously absorbing/emitting energy in the far IR region of 8-13 microns. A cross-section illustration of metamaterial micro-structures on a polymeric dielectric multilayer broadband solar mirror film is shown in Figure 12.

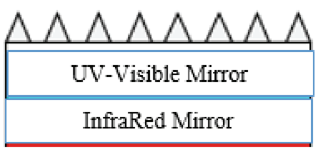

Figure 12: Illustration of passive radiative cooling film cross-section with far IR absorbing surface structures on top of broadband solar mirror film.

CONCLUSIONS

Polymeric multilayer dielectric mirror films can be applied to buildings to better manage and make use of solar energy. Polymeric dielectric mirror films absorb less light than metallized mirror films which enables polymeric dielectric mirror films to reflect more light. Micro-structured films can also be applied to building windows to redirect solar energy further into a building and thus decrease electricity consumption for artificial lighting. Unique combinations of polymeric dielectric mirror films and micro-structured surfaces can be used to cool buildings with passive radiative cooling. Since 5% of the sun's energy is in the UV region, absorption of UV light reduces the total solar reflection potential of broadband solar mirror films made with PET optical layers for reflecting the visible light. Thus, there is a strong need for UV reflecting layers made with inherently UV stable polymers that are less dependent on UVAs for protecting them from UV degradation.

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