Spectrally Selective Window Films

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INTRODUCTION

The need for energy conservation has become increasingly important over the last several decades. Several innovations have driven the growth of energy efficient glazing use in residential, commercial and automotive applications. A number of government-private joint efforts are focused on achieving even greater use of energy efficient windows [1]. Even with the high penetration of energy efficient gazing systems, a large base of existing windows will benefit from a retrofit solution. After market applied window films fit this niche very well. Several manufacturers offer a variety of window films to suit the needs of end-users. In addition to reducing passive solar gain, UV protection, low visible light reflectance and aesthetics are important to the customers. Highly reflective window films that are very efficient in reducing solar gain are popular in commercial buildings. However, in residential applications, many communities and condominiums discourage or even prohibit the use of such highly reflective films. In automotive applications, use of solar reflecting glazing can increase passenger comfort and save fuel by reducing the air conditioner workload [2]. The state laws dictate the characteristics of window films that can be used in vehicles. In general, films having high light transmission, low visible reflection and high heat rejection are preferred in many applications.

Thus, there is a tremendous demand for high solar heat rejecting window films having low reflectivity and medium to high visible light transmittance. Light-to-solar-gain (LSG) ratio, defined as the ratio of visible light transmission (VLT) to solar heat gain coefficient (SHGC), is often used to determine the effectiveness of the window film. This metric is useful in applications were in addition to reducing passive solar gain, increased interior illumination level is needed. Indeed, many utilities rebate programs are designed with a minimum LSG ratio in mind because with darker, low light transmission films, the reduction in passive solar gain may be offset by increased need for artificial lighting inside the building during daytime. There is renewed interest in improved harvesting of daylight to reduce need for artificial lighting. Sometimes, clear view to the inside is needed in commercial properties (showrooms, storefronts, etc.) necessitating the use of high LSG ratio films.

Until now, all of the window films having high LSG ratio available in the marketplace were based on tuned dielectric-silver-dielectric [3,4]. Generally, up to three silver layers are used in the design of these films and result in very high near infrared (NIR) rejection and VLT near 70%. Silver is the metal of choice due to its unique properties [5,6]. One of the drawbacks of using silver is its susceptibility to corrosion. The problem of corrosion may be reduced by the use of silver alloys instead of pure silver and also by sealing the edges of the applied films. These films are also highly conducting and often interfere with electronic toll systems, GPS, cell phones, etc. Commercial production of films based on tuned silver cavity reflectors is notoriously difficult to master since very small variation of thickness of silver layer results in significantly different color, especially when viewed in reflection. In addition, the presence of silver in the coatings necessitates the need for sealing the edges of the applied film. Improper or inadequate sealing of the edges may lead to corrosion along the edges. In automotive and commercial laminates, the edges can be cut back to effectively solve the problem of corrosion. Another drawback of applied window films based on sputtered silver/dielectric technology is that these films have very low water vapor transmission rates (WVTR). Since water is used to achieve bubble and defect-free application, removal of residual water trapped between adhesive and film is critical.

Metal-free solar reflecting films (SRF) were developed by 3M Company for use in automotive windshield [7,8]. These films were designed to be used in a laminate construction, preferably in combination with IR absorbing green glass. These films were based on a modification of polymeric multi layer mirror technology developed in the late 1960s at Dow Chemical Company [9] and later refined at 3M [10]. Since these NIR reflecting films do not contain any metal, there are no issues with RF interference and corrosion. Glass laminates have been made by laminating SRF films between PVB layers and glass showed negligible change in color upon lamination and excellent weatherability.

In this paper we present a comparison between dielectric/silver and multilayer polymeric based after market window films. Alfrey et al showed that polymeric films consisting of hundreds of layers of two materials differing in refractive index can be co-extruded to form iridescent films [9]. The bandwidth and location of band edges is determined by the thickness of each layer pair. Thickness of these layers may be chosen such that

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the primary reflection band occurs in the infrared portion of the electromagnetic spectrum. If the left band edge is positioned at approximately 900 nm and the reflection band has a bandwidth of 300 nm, a significant portion of the second order reflection will fall within the visible spectrum. However, if the thicknesses of these individual layer pairs are controlled accurately, intensity of second order spectrum may be minimized. Optical properties of NIR reflectors constructed from polymeric materials benefit from their low optical absorption, small optical dispersion, and birefringent optical constants. These films can have high visible transmission, sharp reflective band edges, and low off band ripple.

Design considerations restrict the right band edge from being placed beyond 1200 nm due to the 3rd order reflection appearing in the visible. Even though the first order spectrum can be made to be highly efficient, this restriction leaves much of the solar spectrum in the NIR beyond 1200 nm uncovered. SRF films utilize a different layer structure that does not have the same restrictions. A window film having very high visible transmission can be made with SRF films used in earlier laminates [7,8], however the solar heat gain coefficient is not low enough for some applications.

Recently, IR absorbing nanoparticles such as indium tin oxide (ITO), antimony tin oxide (ATO) and lanthanum hexaboride (LaB_6) have been used in solar control films [11,12,13]. These particles are relatively clear in the visible but strongly absorb in the NIR. They may be incorporated into PVB used as interlayer in laminated glass or an acrylic hardcoat. A significant portion of the absorption band of lanthanum hexaboride coincides with that of iron oxide present in all green glass and the overall effectiveness of the glazing and film is somewhat mitigated if it is to be applied to the interior of the glass. ITO is very expensive due to its limited supply and high demand, as it is used as transparent conductor in flat panel display products. Even though the absorption band of ATO lies further out in the IR compared to ITO and LaB_6, it may be combined with the high reflectivity of the multilayer polymeric film in the NIR to obtain a window film having high light-to-solar-gain ratio.

OPTICAL MODELING

Effective indices for birefringent materials can be used for both interfacial and phase terms in a 2x2 optical model to predict optical performance of combined stacks using birefringent and isotropic materials [10]. Using layer thickness information and measured optical constants for all components including adhesive, glass, and hardcoats, a close approximation of normal incidence measurements can be achieved. It is often simpler to use modeled results at non-normal incidence than to attempt the difficulties of non-normal measurement [14].

RESULTS AND DISCUSSION

The modeled and measured optical transmission spectra of a 224 layer polymeric multilayer film made using PET and PMMA are shown in Figure 1a. As seen from Figure 1a, almost all of the light between 850 nm and 1200 nm is reflected while there is no loss of transmission (besides air interface Fresnel losses) in the visible and IR beyond 1200 nm. With the application of an ATO coating on the interior side of this film, transmission in the visible may be adjusted to approx. 70%, and almost all of near IR between 850 and 2500 nm may be blocked (Figure 1b) while maintaining high laminate reflectivity. The thickness or the amount of ATO in the polymeric layer may be increased or decreased at will to adjust the visible light transmission. Particles such as carbon black, having absorption in the visible have been used to achieve window films having different visible light transmission [15]. It is also possible to include such particles to reduce the transmission in the visible dramatically without

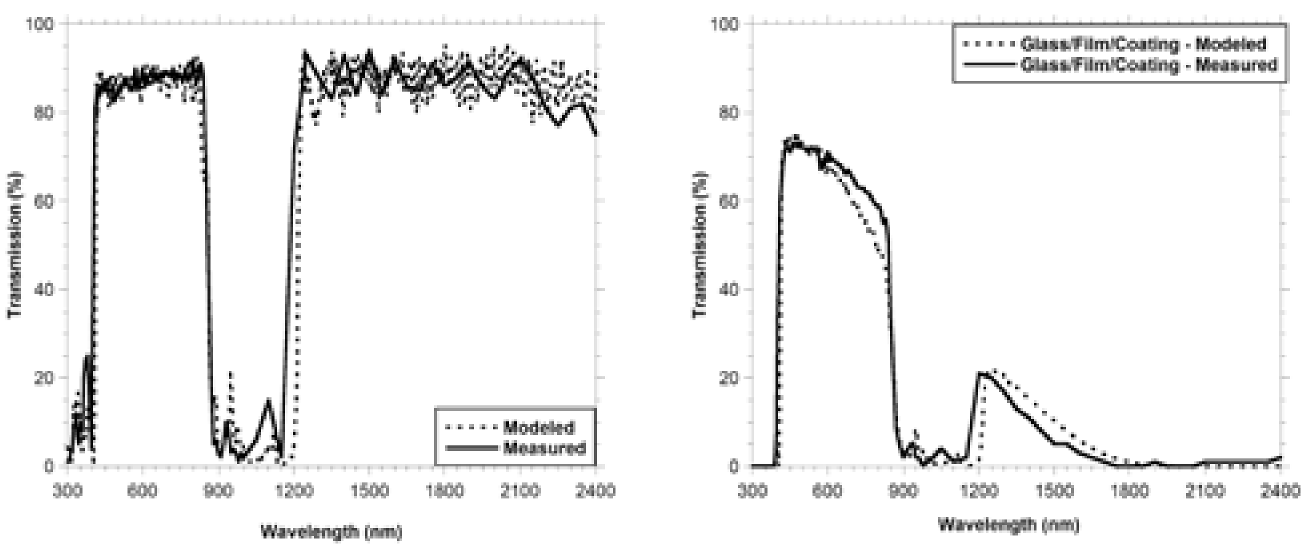


Figure 1a and 1b: Modeled and measured optical transmission spectra of uncoated polymeric multilayer film (Figure 1a) and ATO coated film (Figure 1b).

significantly altering the IR transmission or ATO concentration in the coating.

Unlike silver/dielectric sputtered films, all reflection bands based solely on dielectric components have a shift to lower wavelengths with an increase in incidence angle (away from normal incidence). This angle shift is caused by the cosine dependence of the phase difference between rays reflected from neighboring interfaces. As incidence angle increases, the centers of the s-polarized and p-polarized reflection bands move to shorter wavelengths as the effective phase thickness of the layers. A highly birefringent polymer can be used to construct dielectric mirrors that maintain or increase their reflectivity with increasing incidence angle. Additionally, for non-normal incidence, polarization effects in isotropic materials limit band edge sharpness of unpolarized light, which can greatly affect color purity. Birefringent polymers can be used to construct a mirror that has a matched short wavelength band edge at all angles for both p and s-polarized light, eliminating these difficulties.

Since the reflection band of a multilayer polymeric reflector shifts to lower wavelengths where greater amount of solar energy is present (Figure 3a), there is a rapid decrease in solar heat gain with higher incident angles. As seen from Figure 2a and 2b, this shift is considerably more with the polymeric multilayer construction compared to the dielectric/silver based window films. The optical properties of these two types of film at normal incidence and at 60 from normal (indicated as 0 deg in the table and figures) are shown in Table 1.

It must be pointed out that there are no standards for reporting of off-axis performance. Industry standard methods (see National Fenestration Research Council, http://www.nfrc.org/) and software (Window 5, available for download from http://windows.lbl.gov/software/window/window.html) do perform off-axis calculations based on material types based on an algorithm described by Furler [16], these calculations result in a poor approximation for birefringent materials. As a result, annual energy requirement calculations under-predict the savings achieved when using the multilayer polymeric window films. Furthermore, since the incident solar energy

Table 1: Solar properties of polymeric and dielectric/silver aftermarket window films.

Type	VLT (%)		VLR (%)		SHGC		UV Rejected (%)
	0 deg	60 deg	0 deg	60 deg	0 deg	60 deg	
Polymeric multilayer with ATO	69	60	8.5	13	0.51	0.42	99.9
7 layer ITO/Ag	69	62	8.0	12	0.47	0.44	99.9

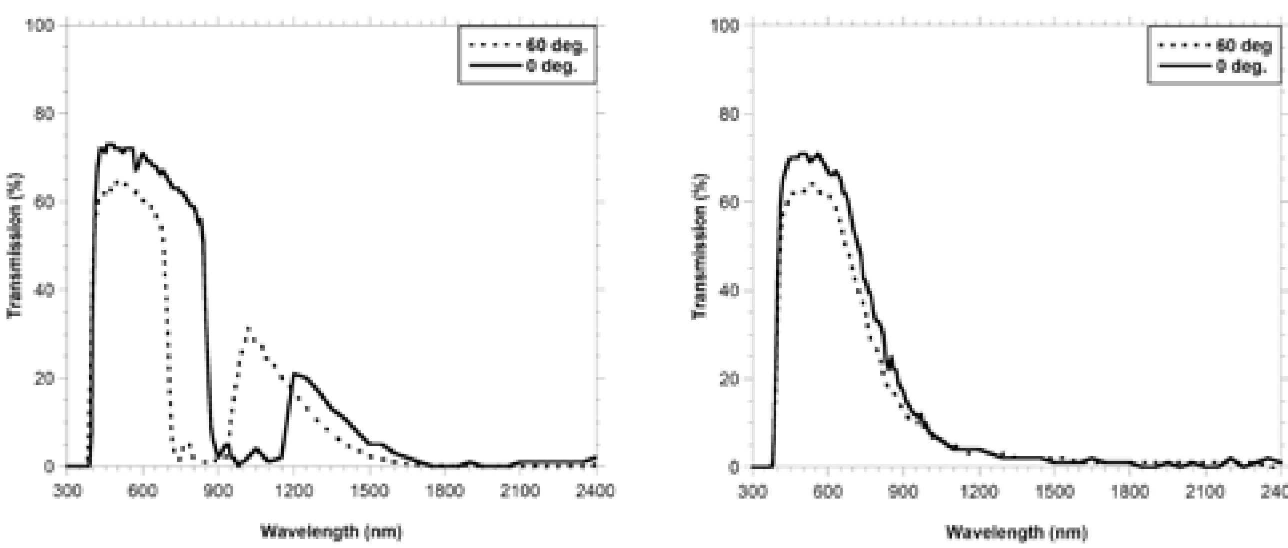
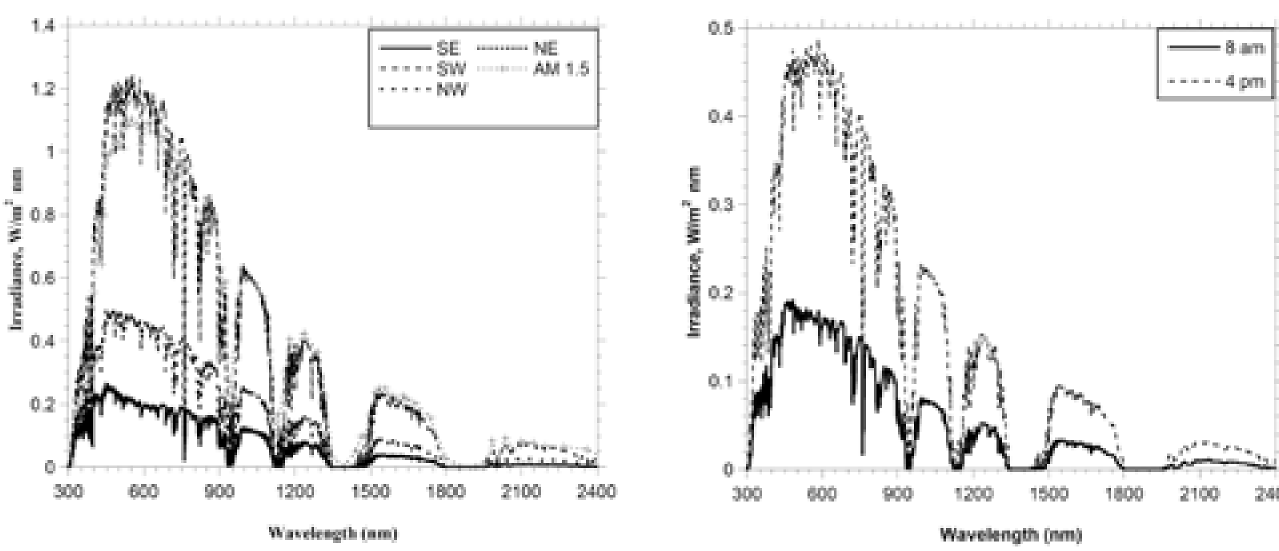


Figure 2a and 2b: Transmission of ATO coated multilayer polymeric film (Figure 2a) and 7 layer ITO/Ag/ITO film (Figure 2b) at normal incidence and 60 deg. from normal.

varies from location to location and is dependent on a large number of factors including precipitable water, ground albedo, makeup and concentration of atmospheric pollutants, among others, the solar heat gain coefficients vary depending on the shape of the incident solar spectrum. The energy and solar performance calculations made using a standard incident solar spectrum (ISO 9050 or ASTM E891) do not accurately predict the performance of these films. Incident solar irradiance spectrum also changes significantly based on the time of the day. Gueymard [17] has developed a comprehensive model for spectral irradiance. Spectral irradiance curves on four different faces of a building located in Atlanta calculated using the SMARTS model is shown in Figure 3a. Also shown in Figure 3b is the spectral irradiance on the same face at two different times of the day. As one would expect, the solar irradiances are vastly different depending on the time of the day and face of the building. Table 2 shows the total solar heat gain coefficients of sputtered stack and polymeric multilayer films for different spectral irradiance curves(calculated using SMARTS model).

Table 2: Solar heat gain coefficients of a sputtered silver-dielectric stack and polymeric multilayer optical film (MOF) at different incidence angles and spectral irradiances.

Angle of Incidence (deg)	Tvis		SHGC(AM1.5)		SHGC (SE)		SHGC (SW)		SHGC (NE)		SHGC (NW)	
	Sputtered stack	MOF	Sputtered stack	MOF	Sputtered stack	MOF	Sputtered stack	MOF	Sputtered stack	MOF	Sputtered stack	MOF
0	70.9	70.5	45.7	49.3	48.6	51.8	48.6	54.5	48.7	51.1	47.8	51.7
5	70.8	70.5	45.6	49.3	48.5	51.7	48.5	54.5	48.6	51.1	47.7	51.7
10	70.8	70.4	45.5	49.2	48.4	51.7	48.4	54.5	48.5	51.1	47.7	51.6
15	70.7	70.2	45.4	49.1	48.3	51.5	48.3	54.4	48.4	51.0	47.6	51.5
20	70.5	69.9	45.2	48.8	48.1	51.3	48.1	54.1	48.2	50.8	47.4	51.3
25	70.3	69.6	45.0	48.4	47.9	50.9	47.9	53.7	48.0	50.5	47.2	50.9
30	70.0	69.2	44.7	47.8	47.6	50.1	47.6	52.9	47.7	49.9	46.9	50.2
35	69.6	68.7	44.4	46.8	47.2	49.1	47.2	51.7	47.3	48.8	46.5	49.1
40	68.8	68.1	43.9	45.6	46.7	47.8	46.7	50.3	46.8	47.5	46.0	47.8
45	68.0	67.2	43.4	44.3	46.2	46.4	46.1	48.8	46.2	46.3	45.4	46.5
50	66.8	66.2	42.6	43.0	45.4	45.0	45.3	47.3	45.4	44.9	44.6	45.1
55	65.0	64.5	41.7	41.4	44.3	43.3	44.2	45.4	44.3	43.3	43.6	43.5
60	62.3	62.1	40.3	39.5	42.8	41.3	42.7	43.1	42.8	41.4	42.1	41.5
65	58.6	58.3	38.3	36.9	40.7	38.6	40.6	40.1	40.7	38.7	40.1	38.8
70	52.7	52.3	35.4	33.4	37.4	34.8	37.4	36.0	37.5	34.9	36.9	34.9



Figures 3a and 3b: Spectral irradiance calculated under different conditions.

CONCLUSIONS

IR reflecting polymeric multilayer films were coated with IR absorbing ATO nanoparticles to create high light transmission, high heat rejection aftermarket window films. These films were shown to have higher heat rejection at increased solar altitude angles. Since these films do not contain any sputtered layers, they have high water vapor transmission rates and are easy to install. A comparison between these films and sputtered silver/dielectric films is presented.

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