Five layer narrow band position variable filters for sharp colours and ultra low emittance

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PACS: **78.20.-e, 78.20.Ci, 78.67.Pt**

Abstract

A simplified approach to creating narrow visible and near IR transmission bands with thin films is outlined utilising just five layers on glass, three of which are thin silver. These films have very high reflection at most wavelengths except for a narrow anti-reflection band where reflectance can be very close to zero and transmittance is close to 70%. In addition these properties are combined with IR reflectance approaching 99% for a very small thermal signature. Spatial variation of narrow band colour is easily achieved and is demonstrated with production of a simple wedge filter covering the full visible spectrum. Measured CIE colour contours in transmittance and reflectance are presented and spectral data on experimental films is compared with ideal models. Potential sources of small departures from ideal models are examined to assess the scope for future improvements.

1. Introduction

Multilayer interference filters capable of transmitting a different narrow colour band across a wide range of frequencies as position on a surface varies, have been of interest since the 1960's [1]. Wedging is used to achieve this with a smooth transition as the probe moves along a surface from point-to-point and more recently such filters have been of interest for compact and low cost spectrometry [2]. They are also interesting for continuous sharp colour standards with transmitted light having colour coordinates for incident white light typically very close to the edge of the CIE colour chart. Such colour sharpness would also be of wider use including large area decorative applications, if it could be achieved in a much simpler structure than those used to date. These standard dielectric stacks also have a major technical weakness as the high levels of blocking needed at all non-transmitting wavelengths requires very large numbers of layers or additional blocking filters. If blocking can be achieved by high level near constant reflection across the non-transmitting zones then this problem is not only overcome, but it also becomes possible to have very deep narrow band anti-reflection in thin film structures. This is made possible by utilising suitable metal and dielectric combinations in a stack.

Most variable transmittance filters used to date are all dielectric with a continuous band along their length achieved by wedging all layer thicknesses. These are sometimes referred to as "Veril" filters and are commercially available. It was recently proposed that a need for extra blocking in the rejection bands might be removed and fewer layers required if a metal layer was embedded in the middle of the stack [2]. A variable transmission stack containing one wedged metal layer had been reported earlier [3] but this example had quite broad transmission bands. It is well known that reflection from a thin film metal layer can be eliminated at select wavelengths using appropriate layer or layers with matching total effective impedances on both sides of the metal layer. These impedances are achieved with dielectric stacks or sometimes just two high index dielectric layers depending on the desired bandwidth for induced transmission. Such filters are then termed induced transmission filters [4]. Even with one thin silver layer symmetrically located at the centre of a stack the total layer numbers were still above twenty for good narrow band results [2]. In this report we consider a much simpler stack structure utilising just three metal and two dielectric layers in which the five layers can achieve a reasonably narrow pass band at similar transmittance levels to some of the much larger stacks while thickness variations allow coverage of the full visible and most near infra red (NIR). These five layer structures have additional useful features not found in any of the basic filter types for this purpose so far analysed in the literature. Such structures can be considered to be a double cavity Fabry-Perot filter. Considering that window coatings for solar control [5] produced on the scale of many millions of m^2 per annum often have two or three thin metal layers and from four to seven dielectric layers these coatings could easily be mass produced for any colour or with spatially varying colours, including in a roll to roll coating system. For example by using controlled wedging of just the dielectric layers we will show that a colour gradient plus visually interesting angle of incidence dependencies are enabled. They could thus be used in a variety of applications, including glazing and position variable transmission filtering. When consideration is given to their special reflection properties in the rejection and anti-reflection bands, and in the thermal infra-red a broader range of application possibilities is apparent and with simple modification their use on opaque substrates including metal with similar spectral reflectance features is possible. Finally if surface plasmons are excited in these two or three layer silver structures in which the dielectric layer is wedged one can produce a plasmon resonance whose resonant wavelength or resonant angle of incidence varies continuously with position.

Achieving the attractive performance predicted by ideal models in practice is the final issue when thin silver layers are involved. Silver thin films at thicknesses below 50 nm can have widely varying apparent optical constants depending on deposition conditions [6] for both the silver and surrounding dielectric layers. A key source of variation is loss which can be internal to the layer and linked to grain structure and grain orientation, or external and due to interface nanostructure [7, 8]. Non-smooth interfaces can support surface plasmons SP's [9], which enhance losses and are in turn sensitive to the refractive index of the surrounding medium [10]. They become more localised as this index increases, and are not accounted for in standard thin film models, though the latter are sometimes made to fit by introducing narrow interface layers [7, 8]. It is still possible to get make films which get close to ideal model predictions, but care is needed in fitting data by adjustment of layer thicknesses rather than adjusting Ag indices, due to the issues just raised. Increased losses will degrade performance to some extent, in particular the narrowness and strength of transmission and anti-reflection bands, and hence colour selectivity, but quality control during deposition, careful choice of dielectrics and experience can largely eliminate these problems. Finally we note that multi-layers of silver and dielectric are of interest in emerging nanoscience based applications including the superlens [11] for nanoscale optical lithography, with their ability to amplify evanescent fields within their structure.

2. The silver-dielectric-silver double cavity

While the experimental data and ideal models in our Ag/oxide/Ag/oxide/Ag structures give pass bands which are not as narrow as those in the many layer stacks made entirely of dielectric, they are close to or better than those in the single silver layer system embedded in multiple quarter wave dielectric pairs [2]. These structures also have some other interesting and useful optical features related to reflectance which all-dielectric stacks lack altogether. The single silver layers in a stack have such features but at a weaker level. These will be detailed in our results, but include a very low transmittance T at all blocking wavelengths with values of T down to less than 10^{-4}, a very high infra red reflectance and hence very low thermal emittance values under 0.02, since reflectance at longer wavelengths is above 0.98, and finally a very large contrast in reflectance across the narrow AR band. In company with these spectral effects these layers can also electrically conduct quite well given the total metal thickness. The spectral reflection properties are especially interesting. We will show the surface can act as an anti-reflector with reflectance less than 0.01 on glass over a very narrow range, while at wavelengths a few 10's of nm away reflectance is above 0.96. That means for example that most white light can be strongly reflected except for a very narrow band of colour centred at any desired wavelength, which is in contrast very weakly reflected. Thus it acts as a reflector with a narrow band extraction or anti-reflection capability with very little loss at non-extracted wavelengths.

2.1 Stack structure

The stack structure we use is symmetric about the central silver layer which usually has different thickness to the two outer silver layers. The stack consists of three metal layers and two dielectric layers as shown schematically in figure 1. A single double cavity system with two silver layers but a more complex seven layer dielectric structure has been reported on very briefly [6]. It appears to have inferior performance to those we present and the broader capabilities of that system were not analysed. Ours is we believe also the first study where a double silver structure is utilised and modified to yield transmission filtering and narrow AR bands which vary continuously across any desired sample width, in our case over a few cm. While the results reported here are confined to single major pass bands it is possible in similar but asymmetric structures to have two or more strong pass bands and hence a wider variety of colours.

3. Stack deposition

All layers were sputtered, the silver metal with dc power and the alumina dielectric with rf power. Each of the films were deposited at a rate of 0.3 Å/s. Prior to deposition the chamber was evacuated to below 10^{-6} Torr. A flowing 99.99% Argon gas at a pressure of 1.6 mTorr was used as the sputter gas. The substrate is rotated for silver deposition to ensure uniformity over the full sample for all cases, whether a uniform spectral response or a graded spectral response across the full sample width. The outer silver layers are quite thin at around 20 nm while the central layer is around 50 nm thick. For a graded spectral response across the full sample width, covering the whole visible say, the visible and some NIR, or any desired range with a spatially local narrow pass band the two dielectrics have a thickness gradient. That is they are in the form of a wedge, this is achieved by stopping the rotation of the sample at a particular position such that one end is closer to the target than the other. A wedge structure suitable for the whole visible is shown schematically in figure 2 with the dielectric ranging in thickness from 75 nm to 120 nm. During deposition evolution of the reflection spectra were monitored with a fibre optic probe feed-thru attached to an external Ocean Optics spectrophotometer.

4. Spectral properties: models and data

A transmitted light colour scan across a full wedge with uniform diffuse white back light as illumination is presented in figure 3. In colour format it is clear the full visible spectrum is fully covered apart from a small violet component and that transmittance at each point and colour is quite high. An associated set of reflectance spectra is in figure 4 taken at 4 fixed points along the axis. These spectra would be slightly narrower than the 50 nm fwhm shown here had we used a smaller spot size (spot size used: 5mm x 5mm) in the spectrophotometer. The linear dispersion in these samples at the centre band is 2.6 nm/mm.

Spectral T and R data was acquired on a PekinElmer Lambda 950 spectrophotometer at normal incidence and at select angles of incidence of 8°, 20°, 40° and 60° from 300 nm to 2500 nm. For ease of viewing the figures have been limited to the range of 300nm to 800nm, with the data beyond this wavelength uniform and flat. Models and data for spectral transmittance and reflectance at two positions on the wedged sample appear in figure 5.

The ideal structures take the form of:
[Ag(20 nm) / Al_2O_3 (86 nm) / Ag(50 nm) / Al_2O_3 (86 nm) / Ag(20 nm) -500nm peak] and
[Ag(20 nm) / Al_2O_3 (100 nm) / Ag(50 nm) / Al_2O_3 (100 nm) / Ag(20 nm) - 550nm peak]
respectively.

Observing the differences between the ideal and measured transmission in figure 5 it can be seen that there is a significant reduction in transmission from the ideal. A model gives a fit to the experimental results was attained as shown in table 1. In order to account for the extra absorption in the stack a mixed medium interface layer is required. The origin of this layer could be due to either insufficient pre-sputtering of the Al_2O_3 to clean the target, or due to surface roughness in the film stack, with the former being the most likely since steps to reduce it have led to better filters. Prior films produced in this study indicated existence of mixed medium layers at other interfaces. When the pre-sputtering cleaning was carried out using a higher power pre-sputter rate to ensure more complete removal of Ag or Al_2O_3 contaminants from the opposite target, the removal of the interface layer was achieved. Modelling of the interface layer is achieved using a Bruggeman [12] effective medium approximation. The interface layer can introduced deliberately to allow a simple method for producing transmittance filters with different magnitudes of T while maintaining the sharp colour response. Combining removal of the interface layer with tight control of the layer thicknesses enables practical films with properties close to those in the ideal models. Varying the oxide to promote epitaxial silver should lead to further loss reductions and improvement in maximum T values.

Large shifts in perceived colour are also apparent as the angle of view varies for a fixed illumination source, both in reflectance and transmittance. That is there is a significant spectral shift in the transmission and anti-reflection bands as angle of incidence varies. Experimental data for select angles of incidence are shown in figure 6.

5. Discussion

The experimental results such as narrowness and strength of the pass band can approach that of the ideal model depicted in figure 7, by attention to the factors noted above, including internal silver losses and possibly interface nano-roughness or inter-mixing in the silver or dielectric, all of which could lead to the observed departures from ideality. Improved grain orientation in the silver for example should enhance properties and this is sensitive to the material used for the adjacent dielectric layers. The experimental samples shown here are still useful with performance not far from ideal model predictions. For less demanding applications such as novel decorative features combined with low emittance they are already adequate. Protection of the outer silver layer can be achieved by deposition of an extra oxide layer on the surface without significantly impacting on the optical properties.

In terms of colour coordinates and purity of colour with position along the axis of the variable filter of figure 2 the filter's contour on the CIE colour chart provides a useful indicator. Example points along the contour as one measures from one end to the other are shown in Figure 8. Example colour co-ordinates are given in table 1 along with the approximate colour in words. Narrower bands would produce a contour closer to the edge of the chart. In contrast the colour contour along the wedge for the reflected light traces around the centre of the CIE chart since the extracted band is a very small proportion of the total reflected light for white light illumination. Since this AR band can also be tuned the system might be quite useful as a special mirror. For example provision of bright white light minus the band of light which resonates with for example a fluorescent molecule or plasmon resonant nanoparticle for times or situations when the fluorescence or resonance needs to be quenched in say a sub-set of species or when two fluorescence bands are present and one needs to be removed. In some experimental situations it may be preferable to block a narrow band component of the exciting radiation rather than filter after illumination and fluorescent emission. A sequence of such mirrors with different AR bands could provide multiple controls of this type.

From observing the colour chart it can be seen that RGB filters can be formed using oxide thicknesses of 75nm, 97nm and 125nm, with a more vibrant colour response than CRT monitors. Deposition of a grid of the filter colours would be feasible using multiple rotating apertures.

5.1 IR and thermal properties

The long wavelength properties are of interest, especially in combination with the marked visible colour selection capabilities. The near IR reflectance is high and continues to rise to above 0.975 indicating that the thermal emittance (for surface temperatures up to say 100°C) will also be very low. Measurement of thermal emittance at 100°C using a Windbourn rotating cavity emissometer confirmed this with values of 0.015 and less achievable. Such surfaces will thus make excellent heat insulators and will have very small external infra red heat signatures. Thus they could be of interest in combining very bright transmitted colours with very low-e, or camouflage by appropriate mix of colours, with an almost negligible thermal signature.

6. Conclusion

Relatively simple five layer thin film multilayers with a central layer of silver and two outer silver layers and two dielectric layers, can yield a full spectrum of sharp colours in transmittance and can act as strong mirrors except for a very narrow anti reflection band. With potential improvements in stack control and losses from the silver layers the minimum reflectance of these AR bands can be very small and transmittance up to 70%. Simple axis position sensitive wedge filters are easily made and useful colour variations with position combined with very low thermal emittance are of interest. Other position sensitive applications of such layer structures with dielectric wedges are also feasible if their surface plasmon properties are exploited and these will be the subject of a future report.

Acknowledgements
Thanks to Abbas Maaroof for the suggestion that led to this work.

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Figure 2 – Schematic of double silver cavity wedged filter. (not to scale.)

Figure 3 – Transmission scan of a wedge filter, the labelled squares indicate the positions of the reflectance scans in figure 4. The white area, and corresponding sharp changes in colour, at the end is due to the clamp used during deposition masking part of the glass substrate.

Figure 4 – Reflectance at various positions along the sample depicted in figure 3.

Figure 5 – Experimental, experimental fit and ideal modelled transmittance and reflectance for two positions on a wedged filter. (a) oxide pair thickness = 86 nm, (b) oxide pair thickness = 100 nm

Figure 6 – Experimental reflectance at various angles of incidence, showing the angular shift it colour, at oxide thickness 125 nm.

Figure 7 – Ideal model [(a) reflectance, (b) transmittance] of a wedge filter. The thickness of the matched pair of oxide layers are varied, not Ag.

Figure 8 – CIE 1931 2° Observer, with theoretical coordinates shown for transmittance of various oxide thicknesses. The colour gamut is shown for displays by CRT computer monitors and lies inside the filters contour.

Table 1 – Model of Ag/Al_2O_3 multilayer

Table 2 – CIE xyz colour coordinates of ideal model.

Figure 1

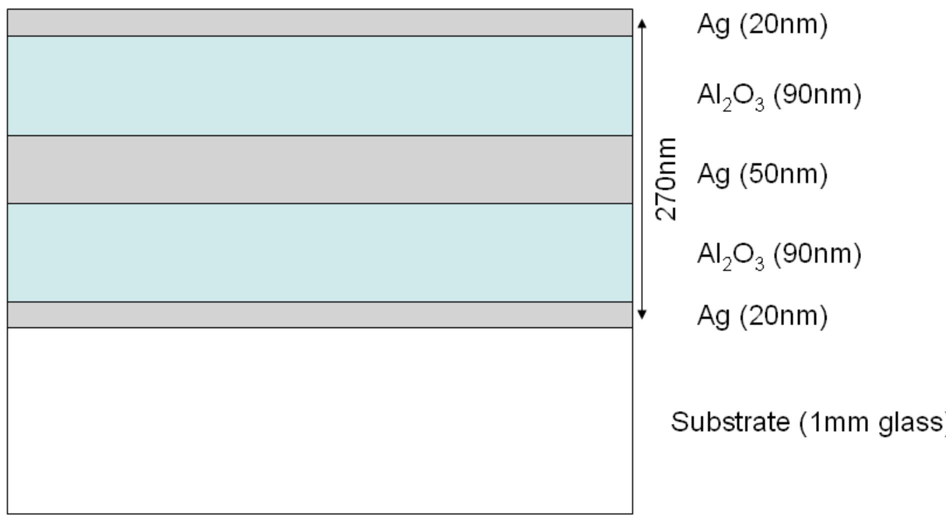
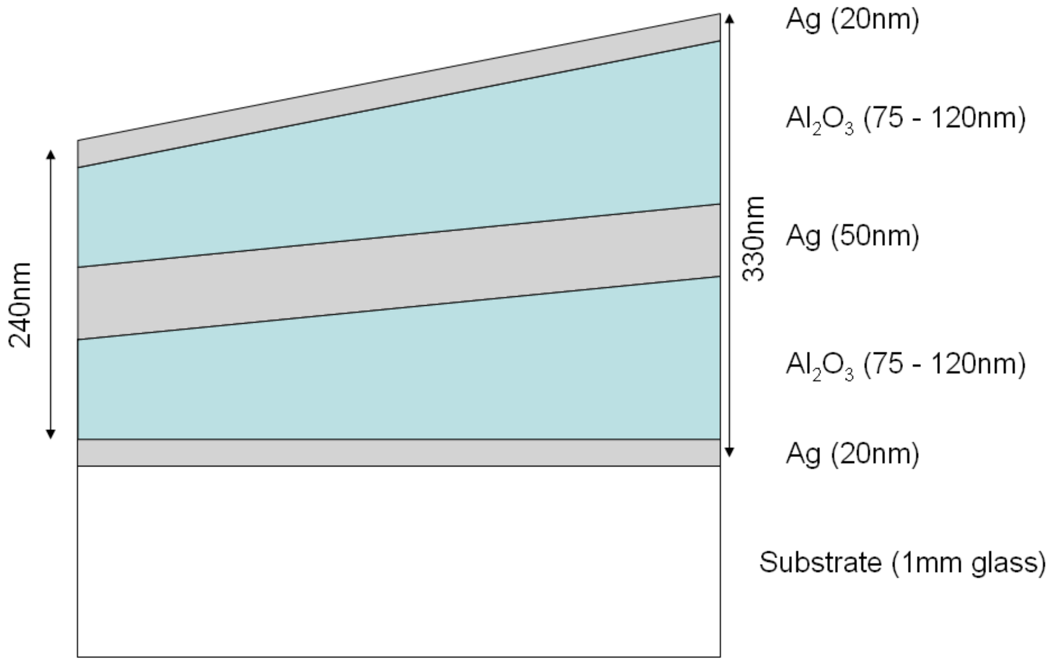

Ag (20nm)
Al2O3 (90nm)
270nm
Ag (50nm)
Al2O3 (90nm)
Ag (20nm)
Substrate (1mm glass)

Figure 2



Ag (20nm)
Al2O3 (75 - 120nm)
Ag (50nm)
Al2O3 (75 - 120nm)
Ag (20nm)
Substrate (1mm glass)
240nm
330nm

Figure 3

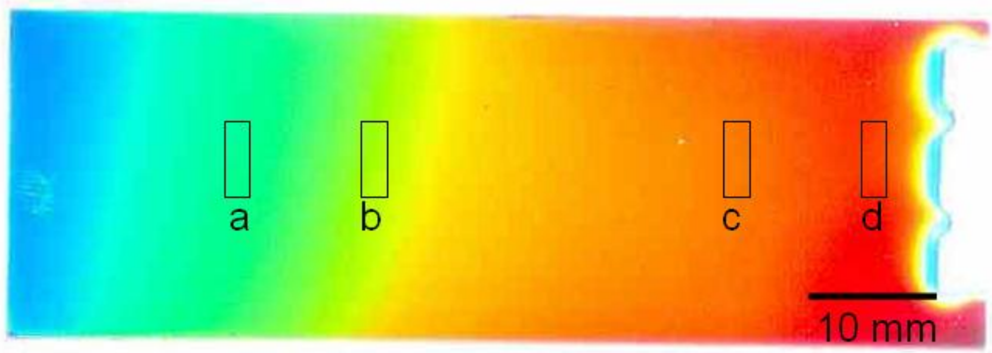
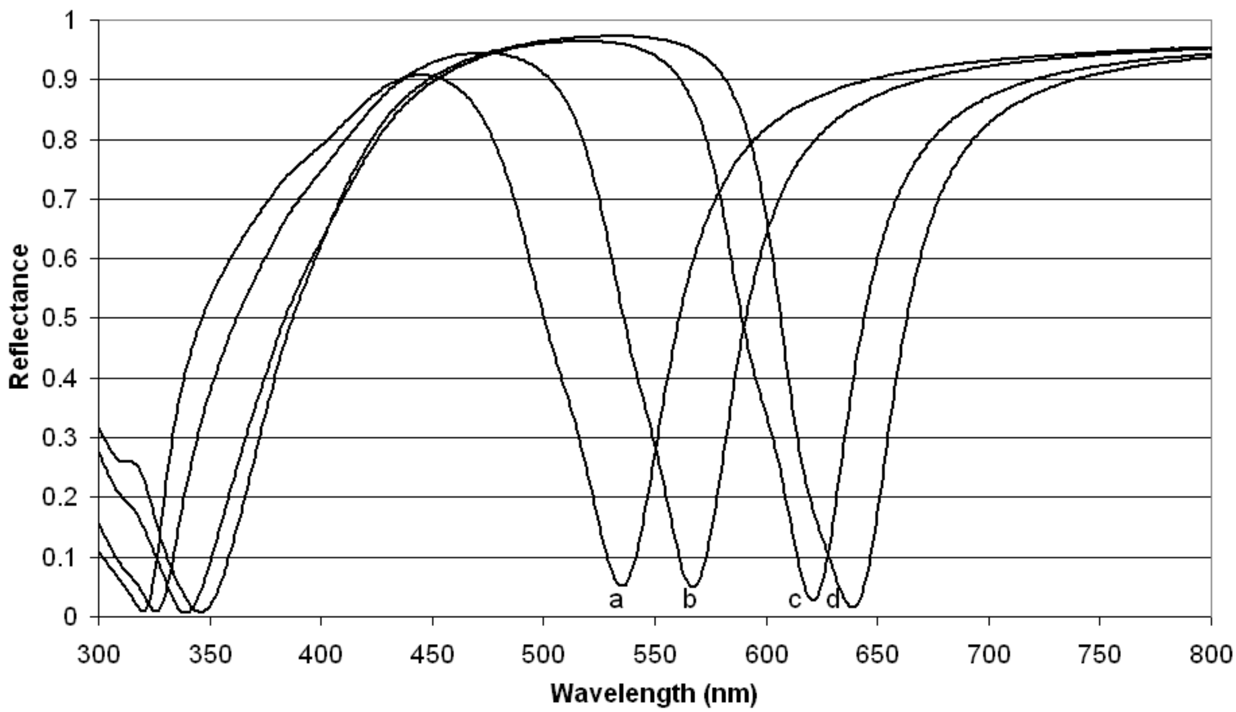
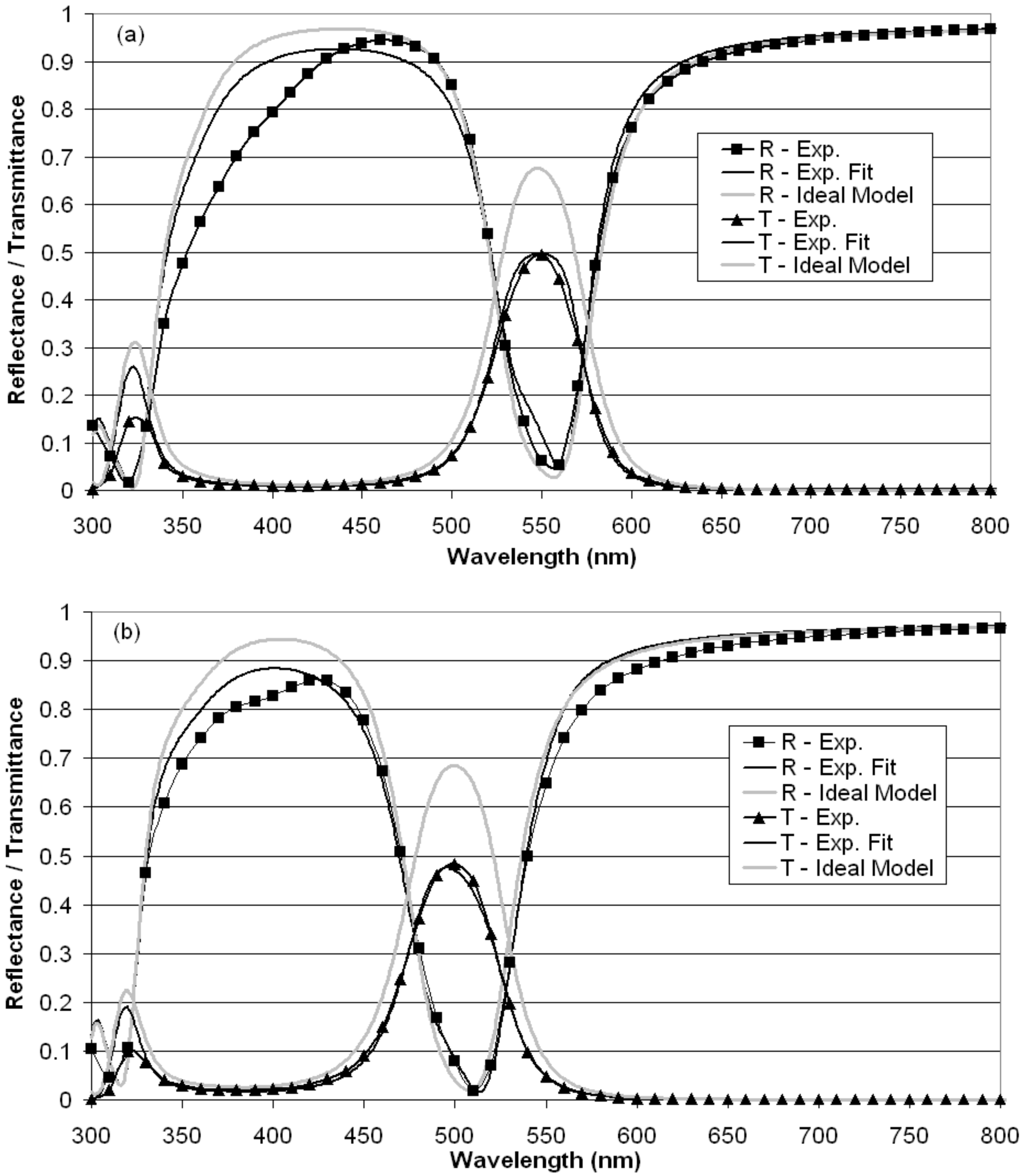


Figure 4



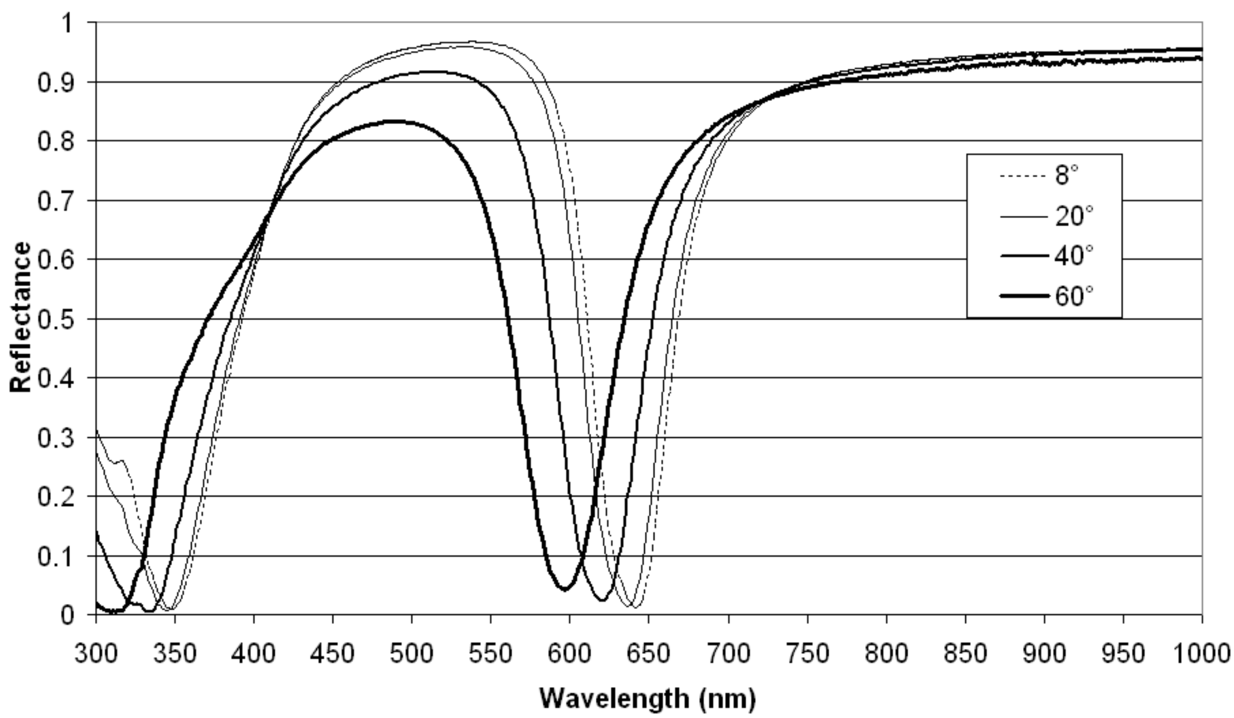
Reflectance
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
a
b
c
d
300
350
400
450
500
550
600
650
700
750
800
Wavelength (nm)

Figure 5



(a)
Reflectance / Transmittance
Wavelength (nm)
R - Exp.
R - Exp. Fit
R - Ideal Model
T - Exp.
T - Exp. Fit
T - Ideal Model
(b)
Reflectance / Transmittance
Wavelength (nm)
R - Exp.
R - Exp. Fit
R - Ideal Model
T - Exp.
T - Exp. Fit
T - Ideal Model

Figure 6



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Reflectance
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
Wavelength (nm)
8°
20°
40°
60°

Figure 7

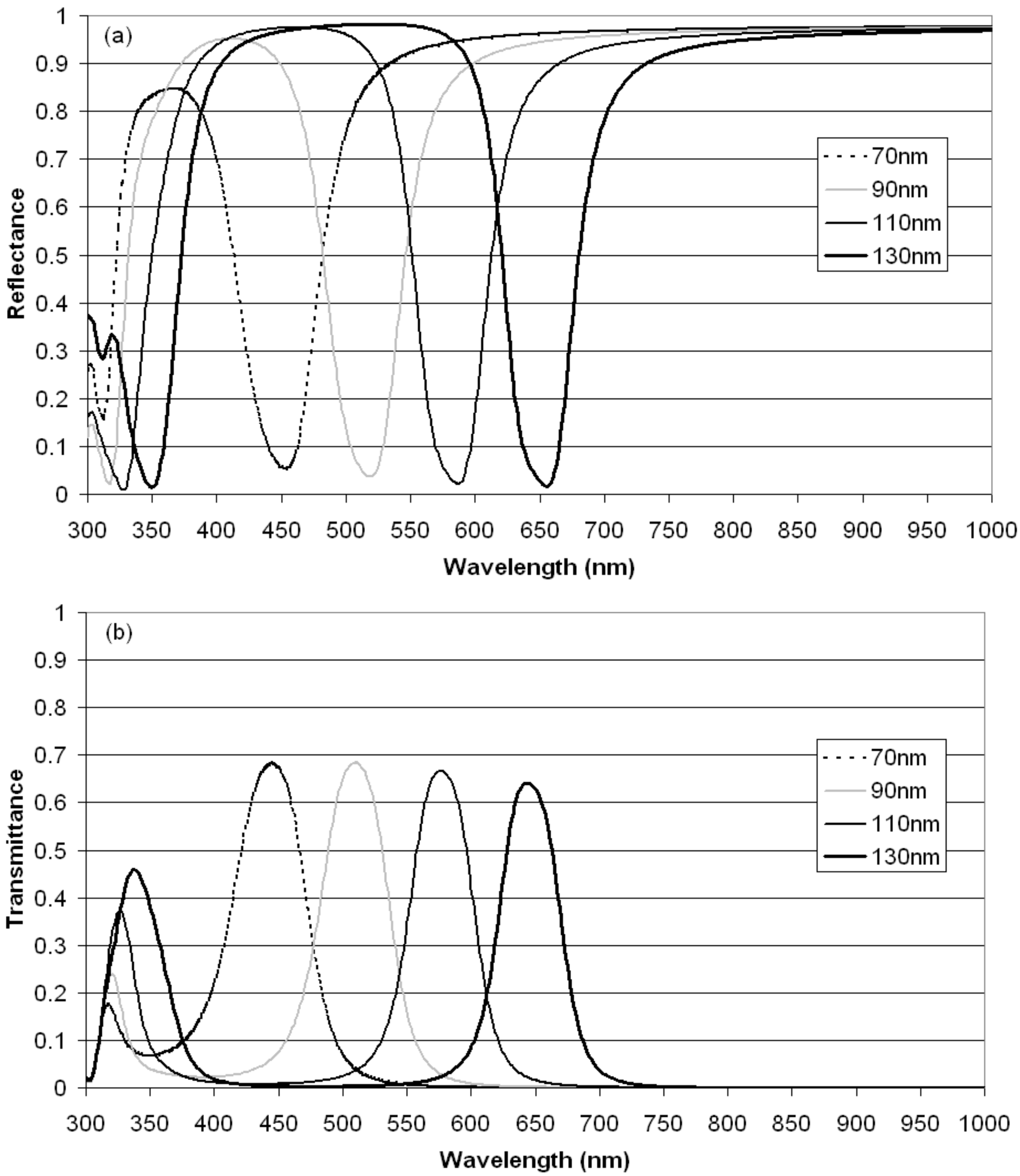
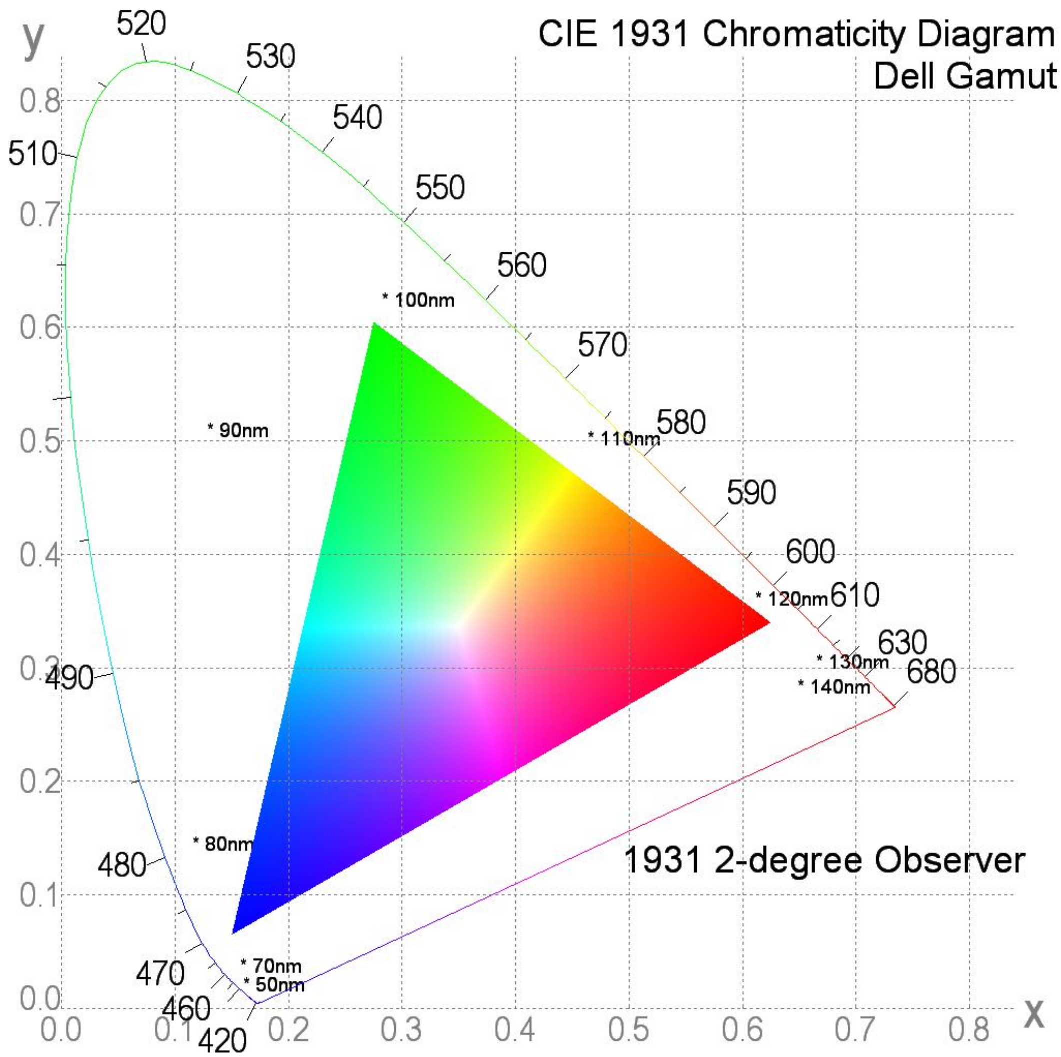

(a)
Reflectance
Wavelength (nm)
70nm
90nm
110nm
130nm
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000
(b)
Transmittance
Wavelength (nm)
70nm
90nm
110nm
130nm
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000

Figure 8



CIE 1931 Chromaticity Diagram
Dell Gamut
1931 2-degree Observer
y
x
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
520
530
540
550
560
570
580
590
600
610
630
680
510
490
480
470
460
420
* 100nm
* 90nm
* 110nm
* 120nm
* 130nm
* 140nm
* 80nm
* 70nm
* 50nm

Table 1

Layer #	Material	Material	Thickness (nm)
6	Ag		21.4
5	Al_2O_3	-	80-125
4(Br EMA)	Al_2O_3 (77.4%)	Ag (22.6%)	8.9
3	Ag		48.6
2	Al_2O_3	-	80-125
1	Ag	-	22
0	Substrate	-	1 (mm)

Table 2

nm of oxide	x	y	z	Colour
70	0.15	0.05	0.80	Aviation Blue
80	0.12	0.15	0.72	Blue
90	0.14	0.51	0.35	Aviation Green
100	0.29	0.64	0.07	Green
110	0.47	0.51	0.02	Yellow
120	0.61	0.38	0.01	Red