Designing Optical Coatings with Metal and Dielectric Materials

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ABSTRACT

Designing coatings with absorbing materials adds another parameter to the usual designs with all dielectric materials, which provides additional possibilities but also restrictions. Reflectance, admittance, and triangle diagrams add visualization and perspective to the process. The application of these tools to coating designs with illustrative examples are presented.

INTRODUCTION

A basic equation for a coating is: R+T+A = 1, where R is the fractional reflected intensity at a given wavelength, T is the corresponding transmittance, and A is the absorptance. In much of the literature, A is taken to be zero for most dielectric film studies, or at most a perturbation. However, when metals are used, A becomes an equal partner with R and T. Dobrowolski, et al.[1] have shown several examples of how and where metal layers can be employed to take advantage of the possibility to reduce the unwanted reflections which occur from the rejected bands of wide and narrow bandpass filters. They also show that such benefits can only be obtained at the expense of some reduction of transmittance in the passbands due to the inherent A. A reflection filter by Tan, et al.[2] will also be shown.

GRAPHIC TOOLS

Apfel[3,4] has described two graphic tools which are very helpful in the visualization of the relations of R, T, and A in coatings designs. These are Reflectance Diagrams (RD) and Triangle Diagrams (TD). The RD is illustrated in Figure 1 where a 3 layer coating of chromium (Cr), dielectric, Cr is deposited on a glass substrate. For the wavelength depicted, this gives a very low reflection; it would be a "black mirror" for that wavelength. With all dielectric materials and no A, we could know the transmittance of a coating also from this diagram as T = 1 - R. However, when there is A involved, we cannot readily determine this from a RD. Apfel[4] also introduced the TD to help visualize absorption effects. Figure 2 is such a diagram for the same coating as in Figure 1. The first layer starts near the top at about 96% T from the substrate with 4% R and 0% A. The second dielectric layer can only move on a locus which radiates from the 100%R point through the point where that layer starts. With the proper combination of dielectric layers it is possible to move on such a locus to the 0%R line (on the right edge between T and A). This would be an antireflection (AR) coating on the chromium layer in this case. The point of intersection with the 0%R line would show the Potential Transmittance (PT) of the first chromium layer as about 17%. This same coating is illustrated on an Admittance Diagram (AD) in Figure 3. Macleod[5] describes AD's in detail and Willey[6] discusses the pros and cons of when AD's or RD's are most useful.

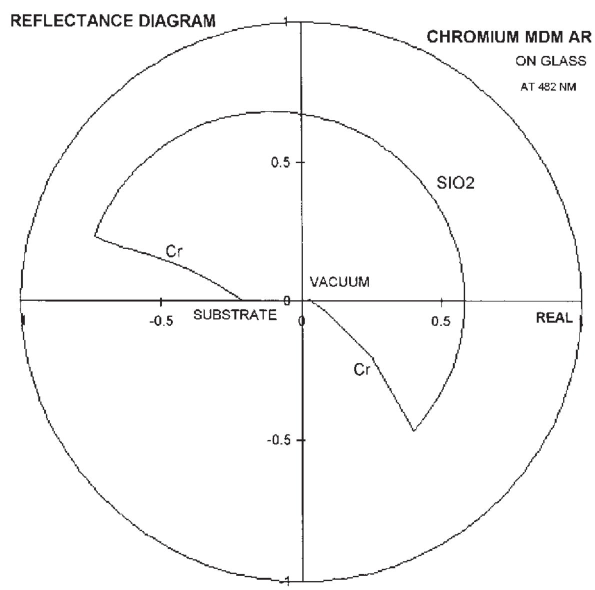

Figure 1. Apfel[3] type Reflectance Diagram (RD) of a Chromium, dielectric (SiO_2), Chromium antireflection coating evaluated at 482 nm

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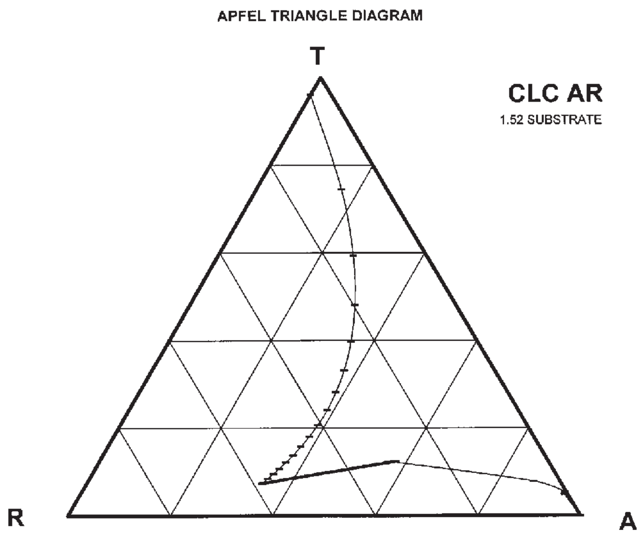

Figure 2. Apfel[4] type Triangle Diagram (TD) of same three layer coating as shown in Figure 1

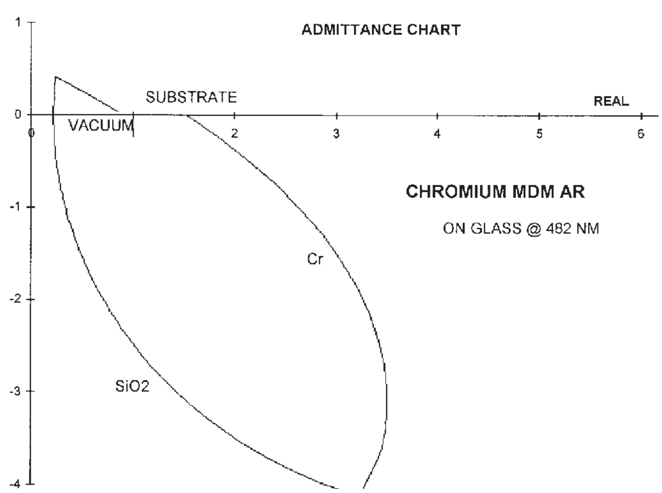

Figure 3. Admittance diagram of same coating as Figure 1

ABSORBING MATERIALS

Most of the material properties of n and k used here are derived from the compilations of Palik[7,8]. Figure 4 shows that Aluminum (Al) is generally less absorbing than Cr. The Silver (Ag) shown in Figure 5 is even less absorbing. The reflectance of a bulk material can be plotted on a RD from the Fresnel equation. Figure 6 shows lines of equal n and k on a RD. On an AD, these lines would form a rectangular grid. Figure 7 shows the opaque point or bulk reflectance of Cr as a function of wavelength. It can be seen that the distance from the origin and thereby the reflectance is fairly constant over the near UV and visible wavelengths. It then starts to climb from 2 to 3 microns and becomes a relatively high reflector at longer wavelengths. Cr has a generally neutral gray color with a little less reflectance in the blue. Ni has a similar locus but has a bit more reflection toward the blue. This is probably why Nichrome is favored for neutral density filters, the proper mix of Ni and Cr should best compensate each other to give nearly constant R and T over the visible spectrum. Figure 8 shows that Al has a fairly flat spectral reflectance except around the well known dip near 800nm. Figure 9 shows that Ag has a minimum reflectance at around 318 nm and then climbs steadily with wavelength. The semiconductor materials of silicon (Si) and indium oxide (InOx) are shown in Figs. 10 and 11. The Si has high A in the UV decreasing to none at about 1 micron. Conversely, InOx has none in the visible and starts increasing from 1 micron to longer wavelengths where it becomes a high reflector.

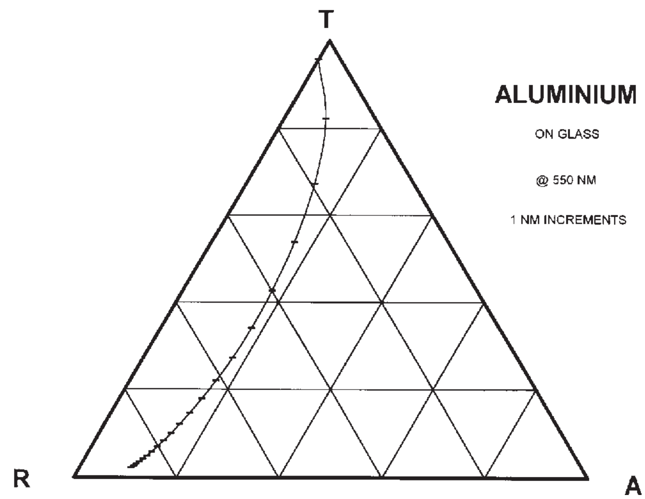

Figure 4. Triangle diagram of a thick layer of aluminum

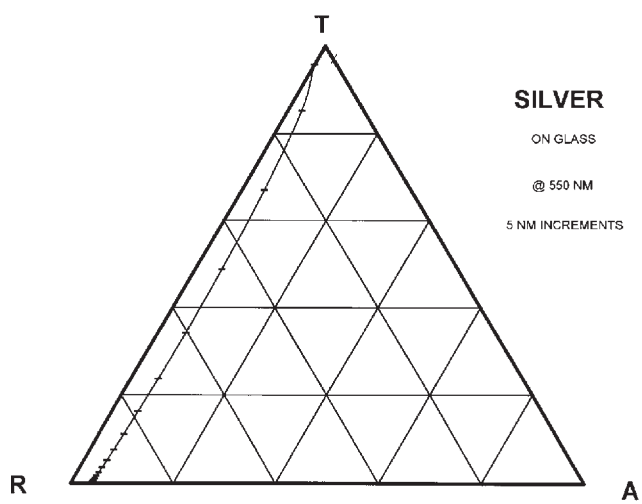

Figure 5. Triangle diagram of a thick layer of silver

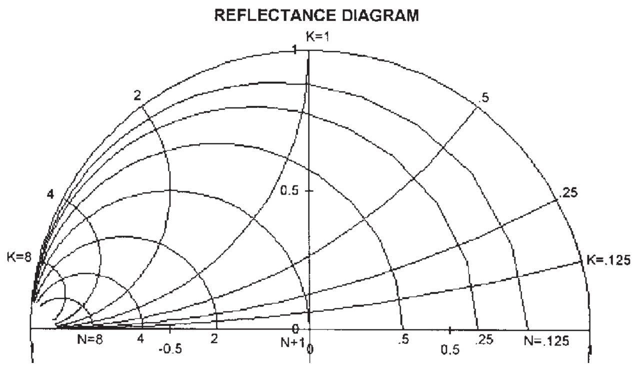

Figure 6. Constant n and k lines on a reflectance diagram

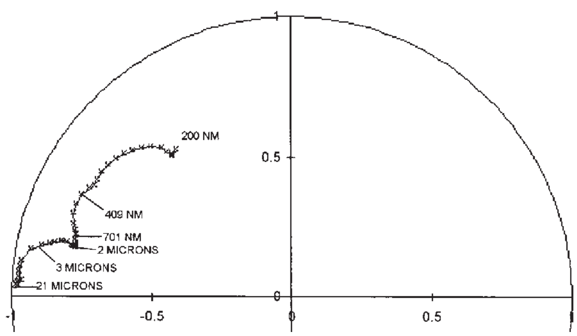

Figure 7. Reflectance of Cr opaque point versus wavelength

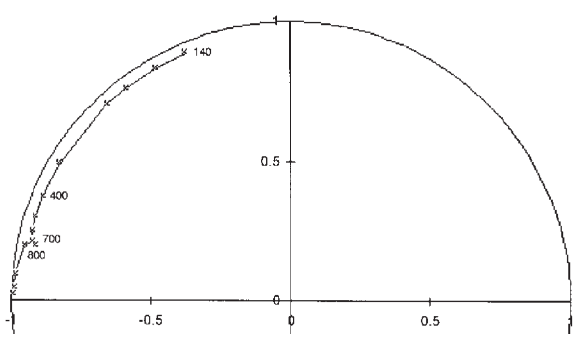

Figure 8. Reflectance of Al opaque point versus wavelength

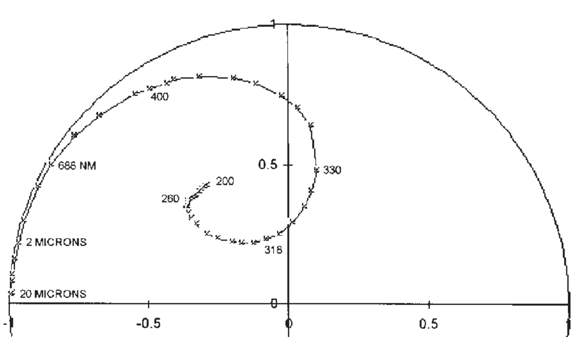

Figure 9. Reflectance of Ag opaque point vs. wavelength

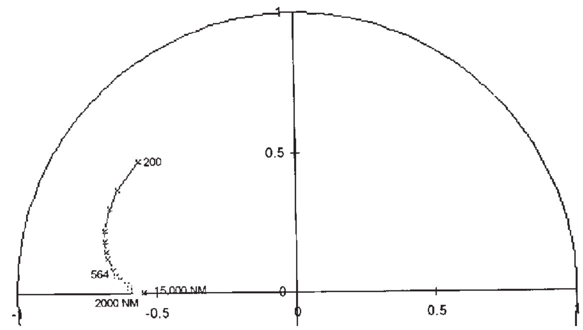

Figure 10. Reflectance of Si opaque point vs. wavelength

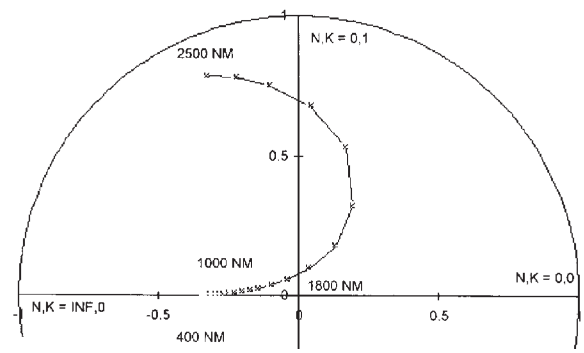

Figure 11. RD of InOx opaque point versus wavelength

Figure 12 shows the interesting thermochromic properties of tungsten doped vanadium oxide ($V_{1-x}W_xO_2$) as reported by Tazawa, et al.[9] At temperatures below the critical value of 47°C, the material has low A and looks mostly like a high index dielectric. Above this temperature, it behaves more like a metal with increasing reflectance with wavelength.

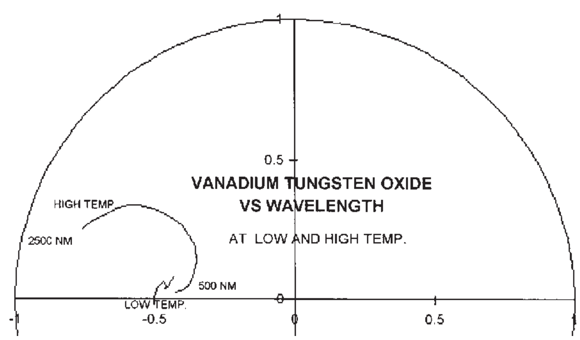

Figure 12. RD of $V_{1-x}W_xO_2$ opaque point vs. wavelength

APPLICATION EXAMPLES OF DESIGNING WITH METALS

When viewed on a RD, the locus of the reflection versus film thickness changes predictably from the starting point reflectance and phase. Figure 13, 14, and 15 show such loci for Cr, Al, and Ag. The fact that the metal loci can in some cases move almost in the opposite direction from a dielectric locus may prove useful in future designs where some A can be tolerated. An example of an induced transmission filter is taken from Figure 6 of the work by Dobrowolski, et al.[1] Figure 16 shows the transmittance of a similar design with and without suppression of the unwanted reflections shown in Figure 17. The higher reflection curve in Figure 17 is the unwanted reflection and the lower curve is the result of the reflection suppression. Figure 18 shows how this would look on a TD; the unsuppressed design at 570 nm in the passband ends near the top of the TD with about 90%T and 10%R. The suppression brings the locus to about 50%T and 2%R.

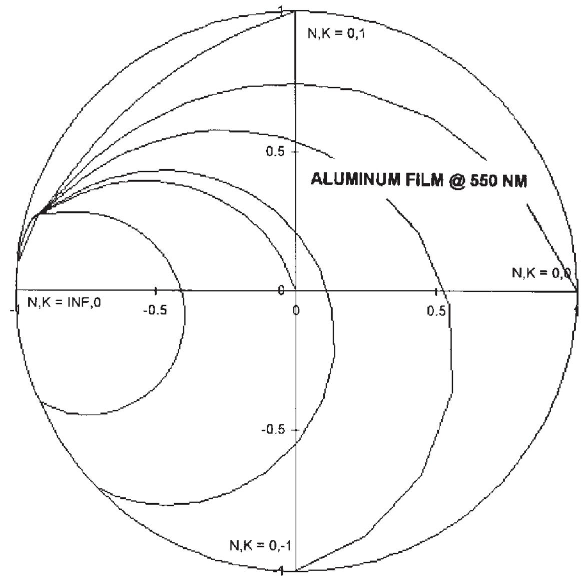

Figure 14. RD showing loci of Al from various start points

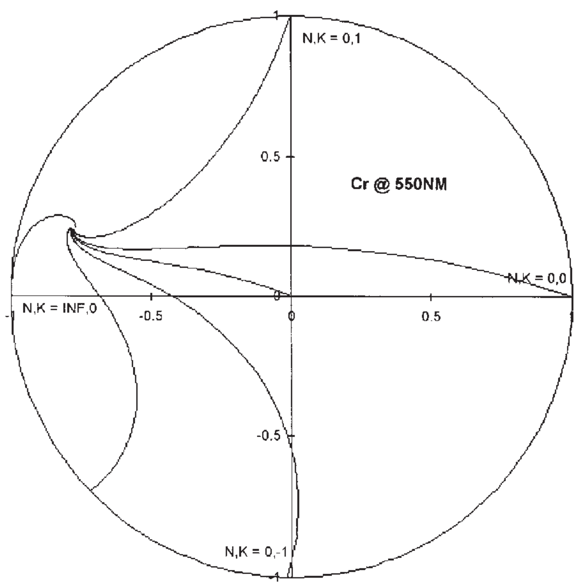

Figure 13. RD showing loci of Cr from various start points

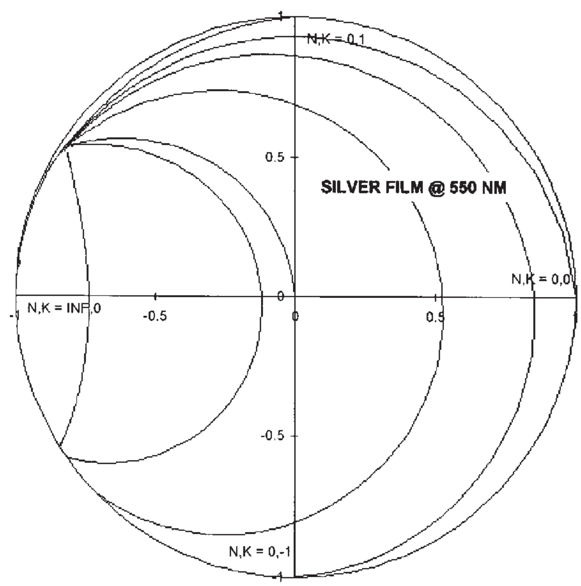

Figure 15. RD showing loci of Ag from various start points

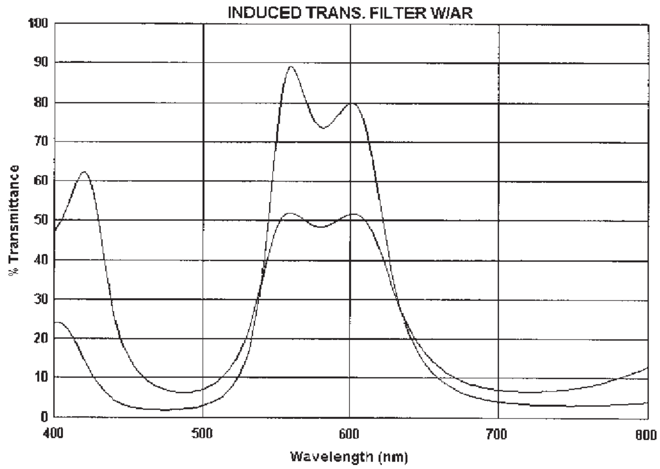

Figure 16. Spectrum of Dobrowolski[1] induced transmission design with and without suppression AR at 570 nm

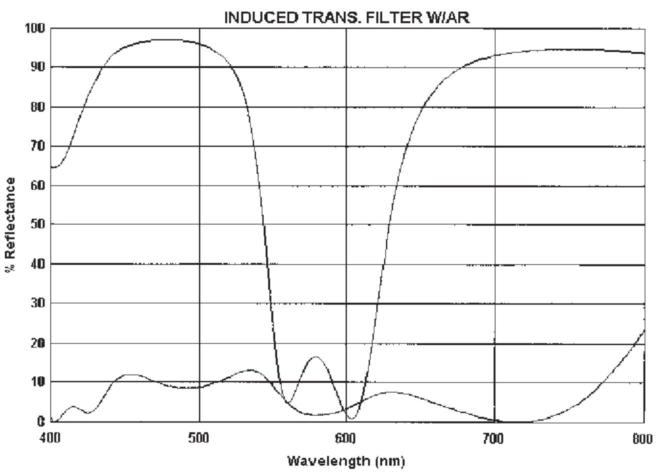

Figure 17. %R of Figure 16 designs with and without AR

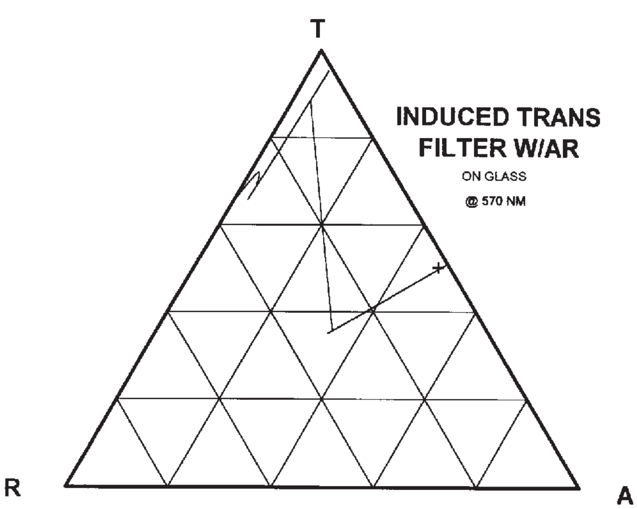

Figure 18. Triangle diagram of Figure 16 design with AR

The TD viewpoint as seen in Figure 18 is not very revealing with respect to what is happening to the R and T when the dielectric layers are deposited, just as the RD does not show what is happening to the A and T when there is A present. To overcome this limitation, I have modified the TD to make a Prism Diagram (PD) as shown in Figure 19 wherein the same TD as Figure 18 forms the base, but the values are also offset vertically with increasing thickness of the coating up to the maximum thickness at the top plane. Here, we can now see that the first five dielectric layers in the first half of the thickness oscillate in R and T in the 0%A plane. The Ag layer then adds a small amount of A at this 570 nm wavelength and the rest of the dielectrics without the AR brings the transmittance to a high %T and low %A. When the reflection suppression coating is added, the Cr layer moves the locus about half way toward the 0%T edge and then the dielectric layers antireflect this to the maximum PT near the 0%R edge at the top. This point is marked with an "X" in the figure. The shadow of this three dimensional path is seen on the base plane of the Figure 19 PD and is the same as seen in the Figure 18 TD. Figure 20 shows the same display for 700 nm wherein the coating without AR has a very high R, but with the AR it is reduced to virtually zero with a small residual %T.

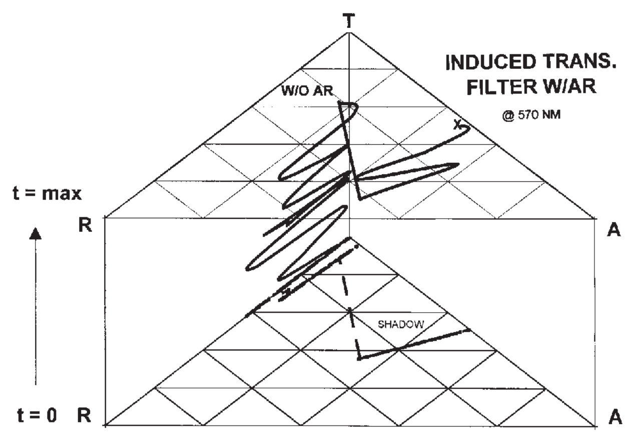

Figure 19. Prism diagram of Figure 16 design with AR

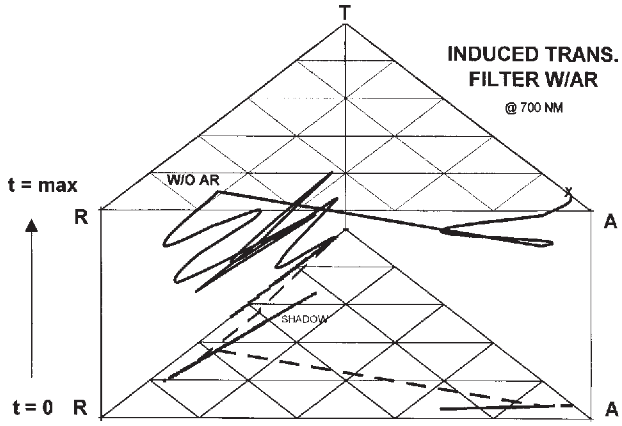

Figure 20. Prism diagram of Figure 16 design at 700 nm

Another example is from Figure 1 of the work of Tan, et al.[2] where totally opaque narrow bandpass reflection filters were studied. Figure 21 shows the reflection of the filter where there is 0%T at all wavelengths. There is basically an opaque Ag layer, a dielectric stack, and a final thin layer of Cr. The principal used here is that the stack creates a spacing such that the electric field is near zero at the thin Cr layer for the passband wavelength. Under these conditions, the Cr layer absorbs very little. As the wavelength moves either way from this, the electric field increases rapidly and causes great A in the Cr layer and thereby low reflection. Figures 22 and 23 show the PD for this filter in the passband at 520 nm and in the blockband at 600 nm. It can be seen in Figure 21 that the top of the coating ends at very high %R and low %A where there is no %T. In Figure 23, we see that A goes to 100% and thereby T and R are zero.

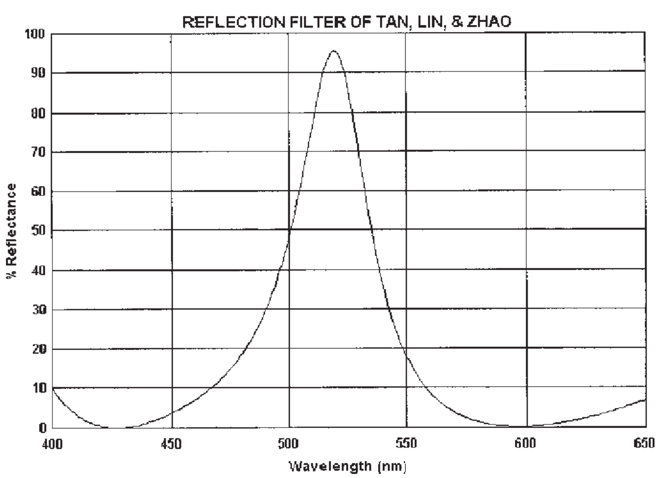

Figure 21. Reflectance of Tan[2] filter vs. wavelength

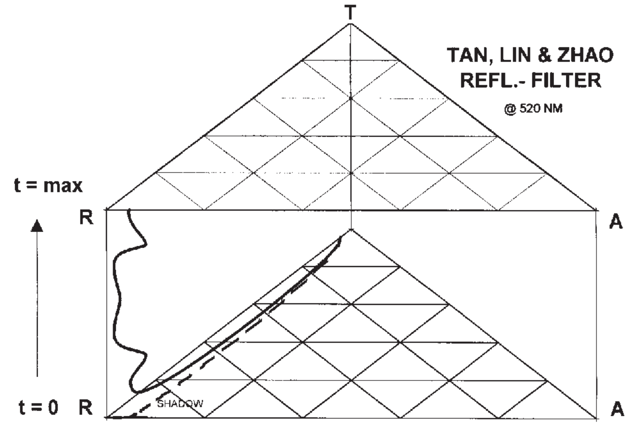

Figure 22. Prism diagram of Figure 21 design at 520 nm

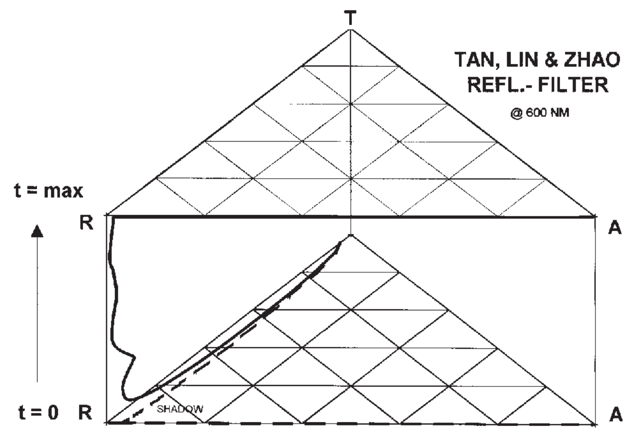

Figure 23. Prism diagram of Figure 21 design at 600 nm

SUMMARY

The design of coatings with absorbing layers adds the potential to accomplish characteristics which are not possible with only dielectric materials. Some compromise is made with the inherent energy loss due to absoption in such coatings, but the effects of these limitations can be minimized and balanced. Several ways of visualizing the behavior of such coatings have been shown which include: reflectance diagrams (RD), triangle diagrams (TD), admittance diagrams (AD), and a new prism diagram (PD). These can aid in the understanding of certain types of coatings.

REFERENCES

1. J. A. Dobrowolski, Li Li and R. A. Kemp, "Metal/dielectric transmission interference filters with low reflectance. 1. Design," Appl Opt, 34 (25) 5673 (1995).

2. M. Tan, Y. Lin and D. Zhao, "Reflection filter with high reflectivity and narrow bandwidth," Appl Opt, 36 (4) 827 (1997).

3. J. H. Apfel, "Graphics in optical coating design," Appl Opt, 11 (6) 1303 (1972).

4. J. H. Apfel, "Triangular coordinate graphical presentation of the optical performance of a semi-transparent metal film," Appl Opt, 29 (28) 4272 (1990).

5. H.A. Macleod, Thin Film Optical Filters, 2nd ed., p. 64, MACMILLAN, New York, 1986.

6. R.R. Willey, Practical Design and Production of Optical Thin Films, p. 19, MARCEL DEKKER, New York, 1996.

7. E. D. Palik, Handbook of Optical Constants of Solids, ACADEMIC PRESS, Orlando, 1985.

8. E. D. Palik, Handbook of Optical Constants of Solids II, ACADEMIC PRESS, Orlando, 1991.

9. M. Tazawa, P. Jin, and S. Tanemura, "Optical constants of $V_{1-x}W_xO_2$ films," Appl. Opt., 37 (10) 1858 (1998).