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Sensitivity to Contamination of Optical Coatings

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Summary

A simple theory is presented of the sensitivity to contamination of optical coatings, which permits prediction of performance degradation in the presence of small deposits of absorbing material. Although a major objective is the ability to compare the sensitivities of different coating types, absolute values can be made possible by adopting a standard contamination layer consisting of a 1\AA thickness of carbon. Results are quoted for a number of common thin-film coatings and filters and are sometimes surprising. The common high-reflectance coating is the quarterwave stack and, at its reference wavelength, it has very low sensitivity to contamination. Although minor constructional errors have little effect on the reflectance, they can seriously affect the contamination sensitivity. Further, the level of contamination determines the maximum reflectance it is possible to achieve, regardless of the number of layers in the coating. The admittance diagram helps in understanding the reasons for the very large variations in sensitivity between coatings with quite similar reflectance.

Abstract

Optical coatings are rarely used in an ideal environment. They are subjected to all kinds of environmental disturbances ranging from abrasion to high temperature and humidity. These cause performance degradation that mostly originates in an actual irreversible and usually visible destruction of the layers. However, performance may be degraded in a rather less spectacular way by the simple acquisition of a contaminant that may have no aggressive effect on the layers other than a reduction of the level of performance of the coating as a whole. The action of water vapor that is adsorbed by a process of capillary condensation and causes a spectral shift of the coating is well known. Here we are concerned with much smaller amounts of absorbing material such as carbon in the form of sub-molecular thicknesses either at some point during the construction of the coating or, more usually, over the surface after deposition.

Although there are many tests for the assessment of the resistance of a coating to most environmental disturbances there is no standard test for the measurement of susceptibility to contamination. Yet it can be shown [1] that the response of coatings can vary enormously, depending on many factors including design, wavelength, and even on errors committed during deposition. The reason may be that, often, careful cleaning will restore the performance but this does not avoid the degradation in between cleanings, and more frequent cleanings are required for more susceptible coatings.

Fortunately it is possible to make some predictions of coating response to low levels of contamination and, especially, to make assessments of comparative sensitivity. Electric field distribution and potential absorption are the keys to understanding the phenomenon.

The irradiance absorbed in a thin layer can be shown [2, 3] to be

$$I_{\text{absorbed}} = \frac{2\pi nkd}{\lambda} \cdot \mathcal{Y} \cdot \mathcal{E} \quad (1)$$

where the symbols have their usual meaning. Note that the losses are proportional to the *product* of n and k and the square of the electric field amplitude, \mathcal{E} . Both n and k must be nonzero for absorption to occur. The absorption will be small both for a metal with vanishingly small n and a dielectric with vanishingly small k .

But we need to find the contribution to the absorptance \mathcal{A} of the multilayer. For this we make use of the concepts of potential transmittance and potential absorptance.

The potential transmittance [4], ψ , of any element of a coating system is defined as the ratio of the output to the input irradiances, the input being the net irradiance rather than the incident. Potential transmittance has several advantages over transmittance when dealing with absorbing systems because it completely avoids any problems associated with the mixed Poynting vector in absorbing media. The potential transmittance of a complete system is simply the product of the individual potential transmittances.

$$\psi = \frac{I_{\text{out}}}{I_{\text{in}}} \quad (2)$$

$$\psi_{\text{system}} = \psi_1 \cdot \psi_2 \cdot \psi_3 \cdot \psi_4 \cdot \psi_5 \dots \psi_n$$

with the eventual overall transmittance given by

$$T = (1 - R) \cdot \psi_{\text{system}} \quad (3)$$

We return to our thin element. From the complex form of the Poynting vector

$$I_m = \frac{1}{2} \mathcal{Y} \cdot \text{Re}(Y) \cdot \mathcal{E}^2 \quad (4)$$

where Y is the admittance of the structure in free space units at the element in question, and \mathcal{Y} is the admittance of free space. Then

$$\psi = \frac{I_{\text{out}}}{I_{\text{in}}} = \frac{I_{\text{absorbed}}}{I_{\text{in}}} = 1 - \frac{2\pi nkd}{\lambda} \cdot \frac{2}{\text{Re } Y} \quad (5)$$

Potential absorptance is the complement of potential transmittance. The potential absorptance, \mathcal{A} , is defined as the ratio of what is absorbed in the element to the input irradiance.

$$\psi + \mathcal{A} = 1.0 \quad (6)$$

so that for our thin element

$$\mathcal{A} = \frac{2\pi nkd}{\lambda} \cdot \frac{2}{\text{Re } Y} \quad (7)$$

Amongst other things, this result allows interpretation of an admittance locus in terms of potential absorption.

Let us now limit ourselves to contamination on the front surface of an optical coating. The contamination receives the full irradiance that enters the multilayer and the admittance at the contamination layer determines the reflectance as well as the potential absorptance. The absorptance, A , is therefore given by:

$$A = (1 - R) \cdot \mathcal{A}$$

$$= \frac{4\pi nkd}{\lambda} \cdot \frac{1}{\text{Re}(Y)} \left\{ 1 - \frac{[y_0 - \text{Re}(Y)]^2 + [\text{Im}(Y)]^2}{[y_0 + \text{Re}(Y)]^2 + [\text{Im}(Y)]^2} \right\} \quad (8)$$

$$= \frac{4\pi nkd}{\lambda} \cdot \frac{4y_0}{[y_0 + \text{Re}(Y)]^2 + [\text{Im}(Y)]^2}$$

and equation (8) permits us to put contours of absorption due to contamination on the admittance diagram. Before we draw actual lines we need to define some of the quantities. It is simplest to use numbers that allow us to scale the diagram easily. We therefore simplify the expression by defining the quantity K for our absorbing element.

$$\frac{16\pi nkd}{\lambda} = K \quad (9)$$

Then, from (8),

$$A = K \cdot \frac{y_0}{[y_0 + \text{Re}(Y)]^2 + [\text{Im}(Y)]^2} \quad (10)$$

And if we replace Y by $x + iz$ then the equation giving the contours of constant A/K is

$$(y_0 + x)^2 + z^2 = y_0 \cdot \frac{K}{A} \quad (11)$$

that is, a circle with center at the point $(-y_0, 0)$ on the negative branch of the real axis.

To simplify matters we take the value of y_0 as 1.00. Then Figure 1 shows contour lines of constant A/K . Now to assess the sensitivity of a system to contamination we simply have to see where the admittance locus ends.

We can make some immediate general deductions from this diagram. Antireflection coatings all have loci that terminate as closely as possible to the point corresponding to y_0 , 1.0 in this case. This means that all have virtually identical sensitivity to contamination and that nothing can be done to modify it because a movement away from the point y_0 implies an increase in reflectance. High reflectance coatings, on the other hand, have a termination point that could be anywhere on an isoreflectance circle centered on the real axis. If we are dealing with a quarterwave stack that terminates with a high-index quarterwave then the termination point is at a high admittance on the real axis and therefore the sensitivity to contamination is low. A quarterwave stack that is terminated with a low index, on the other hand, has an enhanced sensitivity to contamination.

As an example of the magnitude of K we can take the values of amorphous carbon given by Palik[5, 6] that is optical constants of 2.26-i1.025 at 1000nm, and assume a thickness of 0.1nm.

A plot of K is shown in Figure 2 and over most of the wavelength region shown it is between 0.01 and 0.02.

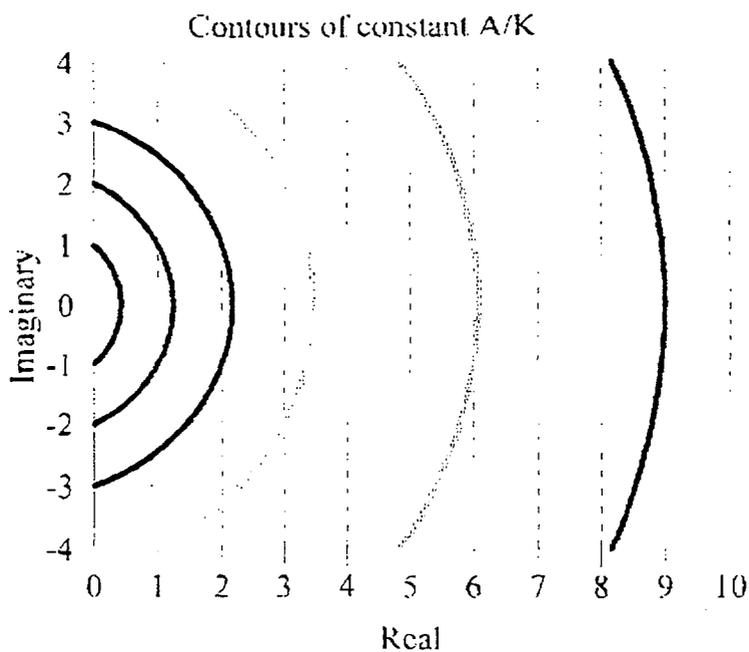


Figure 1. The contour lines of constant A/K in the admittance diagram assuming that y_0 is 1.00. From left to right (inner to outer circle) the values of A/K are 0.5, 0.2, 0.1, 0.05, 0.02, 0.01. The origin corresponds to a value of A/K of 1.00.

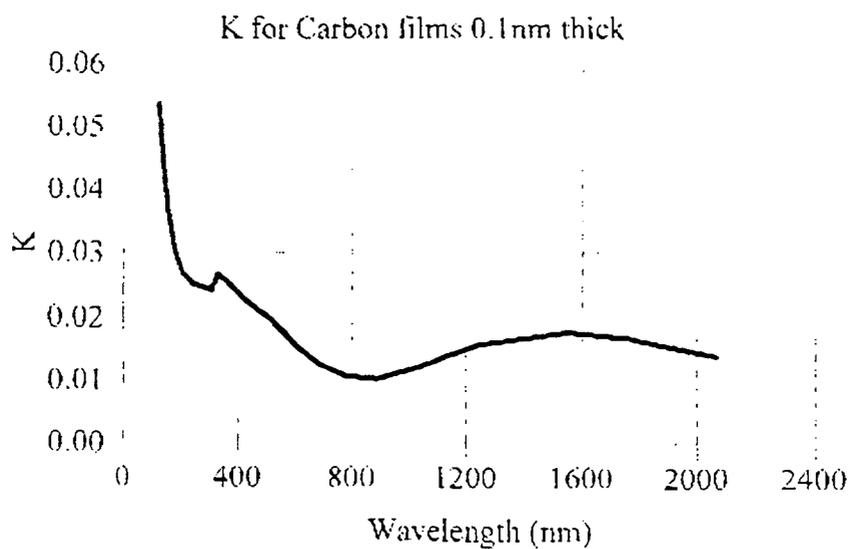


Figure 2. Plot of K against wavelength for 0.1nm thickness of carbon film.

It turns out that given a certain level of contamination there is no point in trying to increase reflectance by adding layers to a quarterwave stack. The reflectance simply stays constant. This appears to contradict the simple theory but is actually a consequence of a curious interference effect in even the very thin less than monomolecular thickness of the contaminant. Also extended-zone high-reflectance coatings have regions where the sensitivity to contamination is considerably enhanced. The halfwave protecting layer of silica over a front-surface aluminized mirror is almost the best arrangement possible from the point of view of contamination sensitivity.

These and other curious effects will be discussed. They do have quite serious implications and especially when performance levels tend towards the achievable limits.

References

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