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PHASE DISTORTION AND THICKNESS VARIATION IN THE DESIGN OF OPTICAL COATINGS

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I. INTRODUCTION

Optical coatings are widely used in space instrumentation for obtaining antireflection and high-reflection components or for filtering the incoming radiation. In most applications, only the intensity of the reflected or transmitted light is considered, however also the phase shift upon reflection and transmission can play a critical role in some instruments.

During the design of optical coatings and before making the final choice of their structure (materials, number of layers and layer thickness), it is advisable to study the stability of their performance against manufacturing conditions. Some coating features are very sensitive to thickness variations, as the transmittance of narrow-band filters, while other structures, as mirrors, are more stable. If the operating principle is based on the phenomenon of interference in thin films, the phase shift of the reflected/transmitted beams will be very sensitive to thickness variations and, in some cases, a change of a few percent in layer thicknesses will produce negligible effects in the intensity but significant changes in phase [1,2].

II. PHASE DISTORTION

In some types of coatings, if the thickness is non uniform over the surface of the coated optics, a phase distortion will occur, causing a wavefront modification similar to the sketch of Fig. 1, in which the effect of surface flatness is shown. In the case of coatings, the thickness typically changes almost monotonically over the surface from the centre to the periphery or from one border to the opposite side, depending on the production process.

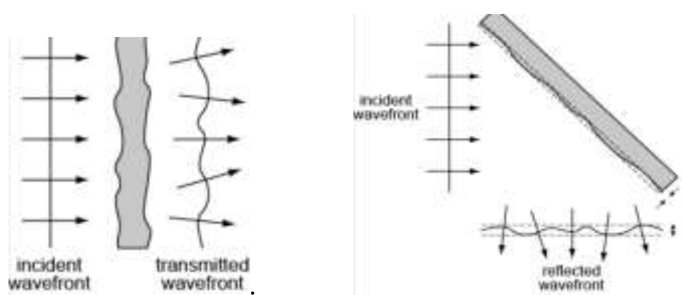


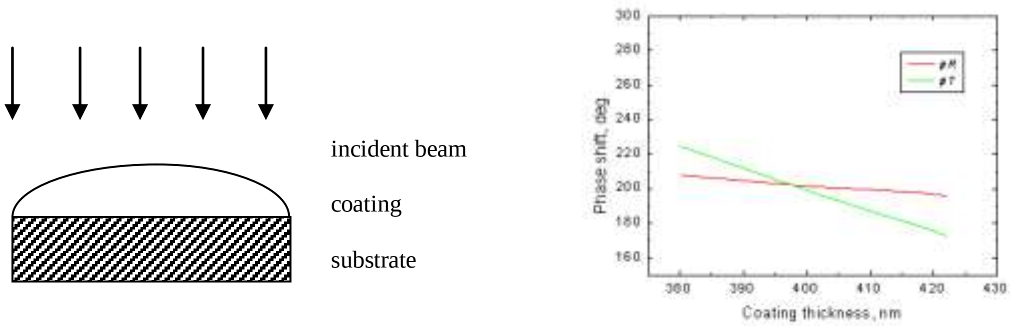
Fig. 1. Effect of surface irregularities on transmitted and reflected wavefront (from www.semrock.com**)**

To avoid undesired changes of the wavefront, care must be taken during the fabrication process to minimize the coating thickness non-uniformity and also to eliminate additional effects as stress-induced bending and other flatness changes. These elements together with interference of light contribute to the final result, when measuring the wavefront of a coated surface [3]. In addition to the optimization of the coating manufacturing process, it could be useful to make in advance a choice of the coating design in which the phase is theoretically less sensitive to variations of the coating thickness and possibly constant as function of wavelength (except otherwise requested).

For laser resonators (at single wavelength) the control of phase of shaped laser mirrors has been already analyzed in the past by the authors [4]. In that case the mirror was designed with an intentionally non uniform thickness over the surface but preserving the phase uniformity. Other papers are dedicated to the phase behaviour of optical coatings [5, 6] and to the design of coatings with control of phase derivatives as function of wavelength [7].

The aim of this work is to analyze both the phase distortion that is due to undesired spatial thickness variations and also the phase spectral behaviour.

The problem in fact becomes more complicated if a wide wavelength range performance is required. Two coatings having similar spectral intensities of reflectance/transmittance may show a quite different behaviour of the phase shift with wavelength, and chromatic aberrations may become relevant.
The two effects of spatial distortion and spectral distibution can appear in the same coating but for clarity will be examined separately. As an example a multilayer coating with five layers (two high and low refractive index materials), acting as beam splitter over the visible spectrum, has been considered and a thickness variation in the range of 10% has been introduced on all layers from the centre to the periphery of the coated surface (Fig. 2a). This variation does not induce significant changes in the transmitted and reflected intensity that, at the wavelength of 500 nm, remain equal to 35% and 65% respectively, even with the change of total thickness. The phase shift in transmittance, at that wavelength, changes from 170 to 220 degrees along the surface, as the thickness decreases (Fig. 2b); while the phase change is less pronounced in reflectance, however in that case the beam will go through an additional path in air after reflection at the surface.
The calculated phase variation caused by thickness non-uniformity could be more or less critical depending on the final use of the optical component.



a b

Fig. 2. a) coating with non-uniform thickness decreasing from the centre to the periphery, b) phase in reflection φR and transmission φT of a 5-layer beam splitter as function of coating thickness, at a fixed wavelength

Looking at the spectral behaviour of this beam splitter in the range 450-650 nm, the phase shift in transmittance undergoes a change of about 200 degrees versus wavelength, while the intensity of the transmitted and reflected beams remains almost constant in that range (Fig. 3a). A flatter behaviour of the phase as function of wavelength can be obtained using a different beam splitter, with inverted values of reflectance (35%) and transmittance (65%). The design of this coating contains only two layers (same materials of the previous example) and the result is shown in Fig. 3b. Its phase sensitivity to thickness changes is also lower compared to the previous design.
It is worth mentioning that the variation with wavelength of the phase shift in reflection is quite large in any coating having quite low reflectance. As an example two wideband antireflection coatings having the same reflected intensity, the same number of layers (four alternating layers of two materials), the same total thickness but made of different materials, are reported in Fig. 4, showing significant variations in the phase behaviour.
Another example is given in Fig. 5, in which two high-reflection dielectric coatings (about 20 layers) made with different materials are reported. Their maximum reflected intensity in the area close to the central wavelength is comparable in the two cases, while the mirror bandwidth is different. In the coating with a larger bandwidth the slope of the phase against wavelength is lower, being inversely proportional to the bandwidth.

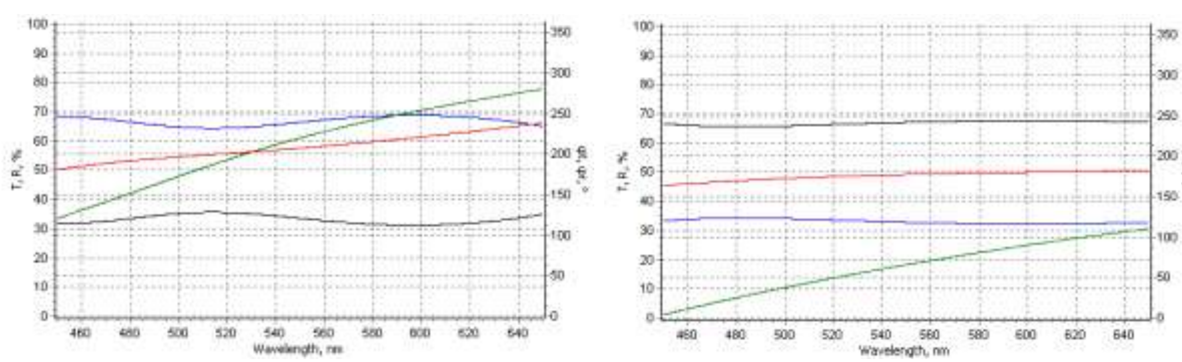


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Fig. 3. Reflected (blue line) and transmitted (black line) intensity and phase (red-reflectance, green-transmittance) of two beam splitters (a, b) containing respectively five and two layers

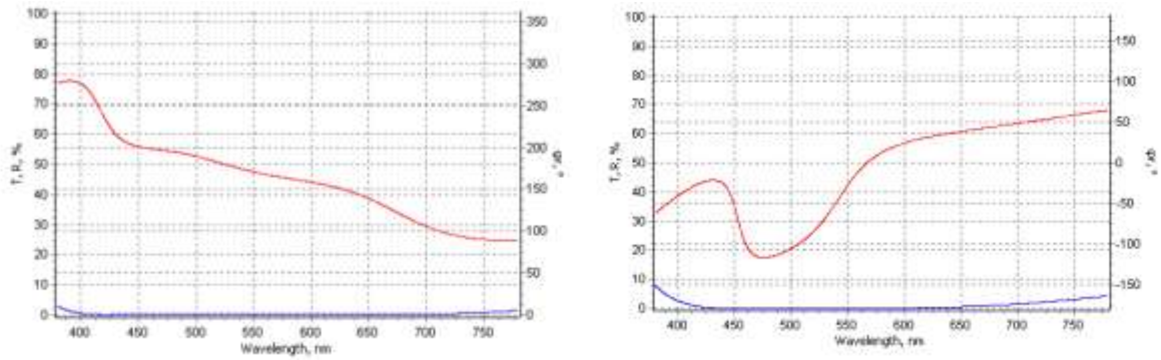

Fig. 4. Spectral reflectance (blue line) and phase shift in reflection (red line) for two wideband low-reflectance coatings, containing the same number of layers (4) with same total thickness but different materials.

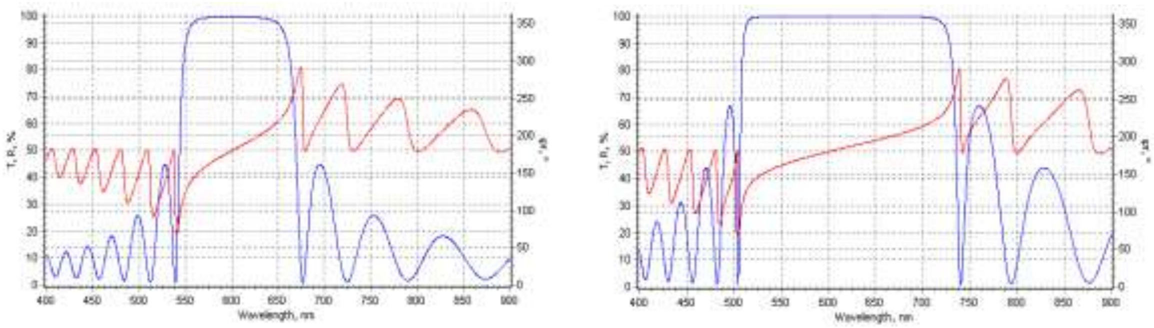

Fig. 5. Reflected intensity (blue line) and phase (red line) against wavelength of two high-reflection coatings made with different materials and number of layers (the number of layers and the total coating thickness are higher in the first case)

The phase distortion caused by possible thickness non-uniformity results also different in the above reported examples, and should be analyzed taking into account the manufacturing accuracy.
The sensitivity of the coating performance with respect to thickness variations has been investigated using the "De-sensitization" feature of the thin-film software Optilayer (www.optilayer.com), which allows the reduction of the sensitivity of a given performance (intensity and/or phase) modifying the coating structure from a starting design, by a refining procedure. A surface map of the phase values can be constructed by this software and successively used in the optical design program Zemax (www.zemax.com) to calculate the wavefront of the beam emerging from the coated component.
By comparing several coating designs, a careful choice of the coating structure can be made to minimize the effect of thickness variations on phase distortion and also to improve the phase spectral performance, preserving at the same time the spectral intensity in reflectance and transmittance of the device.

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