TECHNICAL NOTE

Dielectric thin films for maximized absorption with standard quality black surfaces

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Optical coatings deposited on rough black surfaces permit one to reduce scattering and increase absorption with broadband properties. To optimize the optogeometrical parameters (thickness, refractive index) of the coating, to obtain the best performances, it is necessary to know the refractive index of the bare surface. For this purpose we use both theoretical and experimental approaches. It is shown that with our method the total amount of scattered light from a common standard black surface can be reduced by a factor of 10. An absorption of greater than 99.5% is obtained. © 1998 Optical Society of America

OCIS codes: 290.0290, 300.1030, 310.6860, 310.1620.

1. Introduction

Reducing parasitic light with achromatic properties is a crucial problem today in many optical systems. This reduction can be done by eliminating the specular beam with metal/dielectric coatings.[1] Another solution consists of using rough black surfaces that can be found in a wide variety of optical components such as detectors, light traps, solar collectors, telescope vanes. These surfaces are of overriding importance and constitute a key to increasing the performances of many optical systems.[2] In this case finding the appropriate black coating is a crucial problem for the designer who wants to meet specific requirements. Therefore designing and producing black surfaces with maximized broadband absorption is a topical challenge.[2] Curiously enough, the study of optimal black surfaces has long been neglected. Some effective black coatings are considered as standards, but for a number of reasons (change of references, of formulas, etc.), no reliable information can be found about their optogeometric and physicochemical properties. At the moment strong efforts are being made by manufacturers and research laboratories to monitor the chemical process of polymerization of black paints that present good mechanical properties and high stability in environmental conditions. A theoretical study of the interaction between light and these randomly rough black surfaces must be performed to design the optimal surface for maximized absorption. Typically rough absorbing surfaces can be produced today with an absorption greater than 96%. The nonabsorbed light is of the order of a few percent and scattered in the whole space following a quasi-Lambertian law. Better surfaces exist but are much more difficult to find at low cost, which prompted us to do this research. Indeed we present an alternative easy-to-implement solution that allows us to produce high-performance absorbers with common black surfaces.

2. Description of the Method—Results

Our method is based on an antiscattering effect that we first calculated and measured with superpolished surfaces.[3] It consists of the deposition of a thin-film layer on a slightly rough surface. The result is minimized scattering provided that optimal thickness is designed for this purpose. This result is obtained only when the two surfaces are identical (perfect correlation), which caused destructive interferences between the waves scattered by each surface.[4] More recently we proved that scattering reduction still occurs with arbitrary rough surfaces, paving the way for the study of randomly rough multilayers.[5] In this situation the substrate can be a standard black surface, so that scattering reduction is equivalent to an increase in absorption. As a first step we used an angle-resolved apparatus to measure the bidirectional reflectance distribution function curve from a surface covered with an absorbing black paint illuminated at normal incidence at wavelength $\lambda_0 = 0.633$

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Received 23 June 1997; revised manuscript received 2 October 1997.

0003-6935/98/010103-03$10.00/0

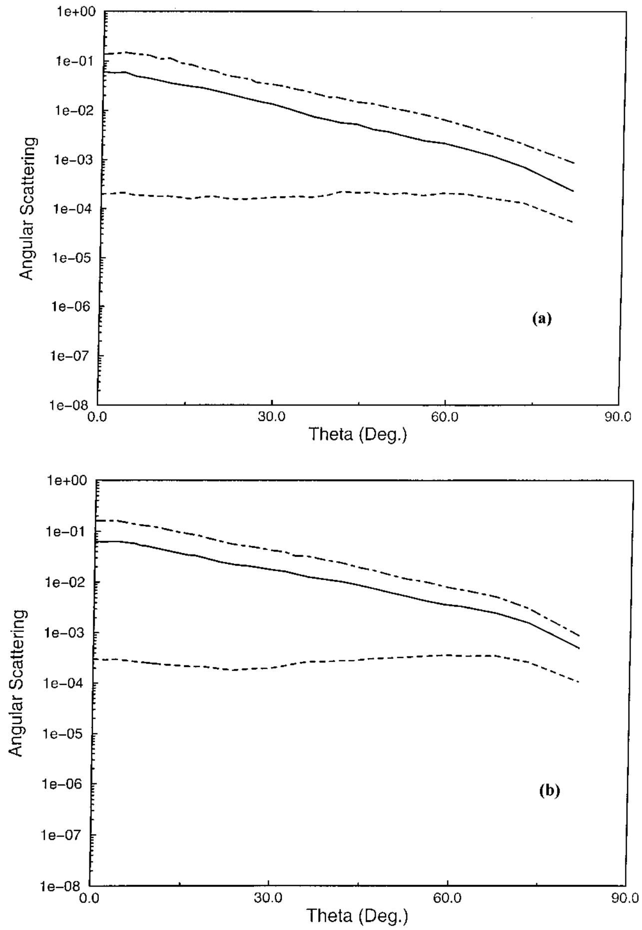

Fig. 1. Numerical results: (a) Angular scattering in different cases: $\lambda_0 = 0.633$ μm, normal incidence, incident plane wave, TE polarization. Solid curve, bare surface; dash–dot curve, black paint covered with a quarter-wave layer with $n = 2.10$; dashed curve, black paint covered with a quarter-wave layer with $n = 1.30$. (b) Same as (a) in TM polarization.

μm (see Fig. 1). Total integrated scattering (TIS) of 4.77%, which is an absorption of 95.23%, was obtained. Note that absorption occurs within the thickness of the paint, ~200 μm, so that the paint can be considered as a lossy dielectric medium. The second step consists in designing the optical thin-film layer to increase absorption. To do so, we used starting solutions calculated with two-dimensional first-order theories[6,7]; then we adjusted these solutions with a rigorous one-dimensional differential method that we recently developed.[5] This method is well suited to calculating scattering from rough interpenetrating layers, which is the case with the structures considered in this paper. However, one must know the surface profile and the refractive index of the paint in order to make the calculations. The former is determined as follows:

(1) The surface profile is measured with atomic force microscopy in the noncontact mode with different window sizes.[8] A peak-to-peak roughness of ~2 μm was found for the surface considered. The corresponding data are used in our code to compute the angular scattering from the real surface for each polarization state of the incident light.

(2) At this stage we match the numerical results with the experimental ones for different values of the substrate's refractive index n_s. In the case presented here, an agreement is obtained for a real index equal to 1.75 (see Table 1). The results for different values of n_s show the sensitivity of the method. The imaginary index of the dielectric black paint is assumed to be equal to 10^{-2}. This latter parameter has little influence on the total amount of scattered light, as confirmed by our numerical experiments; for this reason no further investigation has been made to determine its exact value.

However, the value of 1.75 should be confirmed because we use a one-dimensional code. To solve this problem, we reduce absorption and increase scattering by depositing a single quarter-wave-high index ($n = 2.10$) layer of Ta_2O_5 on the surface. The refractive index of the coating was measured simultaneously on other flat surfaces with spectrophotometric techniques, while the thickness was monitored optically. The deposition process was ion assisted to obtain the perfect replication[9,10] of the black surface by the thin-film material, which was verified with atomic force microscopy measurements of the overcoated surface. As shown in Table 1, we obtain good agreement between the theory and the experiment when the real index of the black surface is set at 1.75.

At this stage all parameters are known and allow us to design the optimal layer for maximized absorption. Because of the choice of materials, we have considered a quarter-wave layer of cryolithe (Na_3A1F_6) deposited by electron-beam deposition. The refractive index of the coating is $n = 1.30$, which is close to the classical value $n_s^{1/2}$ that gives perfect antireflection coatings. Theoretical and experimen-

Table 1. Computed and Measured TIS[a]

	TIS of the Bare Surface			TIS of the Covered Surface	
Different Approaches	$n_s = 1.52$	$n_s = 1.90$	$n_s = 1.75$	$n_s = 1.75, n = 2.10$	$n_s = 1.75, n = 1.30$
Numerical (TE)	2.7×10^{-2}	8.4×10^{-2}	4.8×10^{-2}	1.3×10^{-1}	8×10^{-4}
Numerical (TM)	2.5×10^{-2}	8×10^{-2}	4.3×10^{-2}	1.2×10^{-1}	7×10^{-4}
Experimental		4.77×10^{-2}		1.4×10^{-1}	4.8×10^{-3}

[a]The results are obtained from the curves in Fig. 1 (numerical results) and from those in Fig. 2 (experimental results).

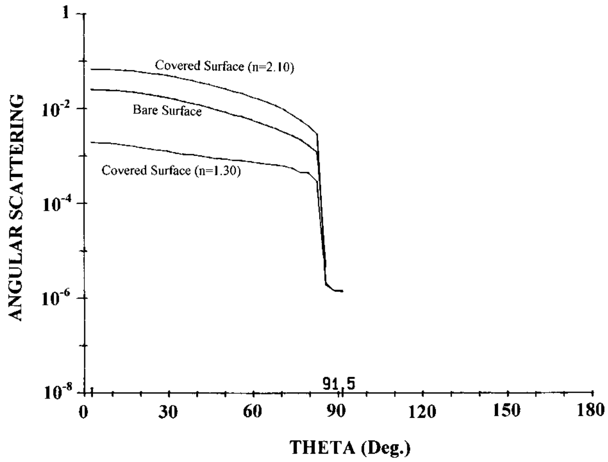

Fig. 2. Experimental results: $\lambda_0 = 0.633$ μm, spot size = 6 mm^2, normal incidence.

tal results are summed up in Table 1. The curves are satisfactory and are presented in Figs. 1 and 2. We observe that absorption has shifted from 95.23% to 99.5%, which is a significant improvement. The partial disagreement between the numerical results and the experimental ones when the black surface is covered with a quarter-wave layer of cryolithe is probably due to an imperfect replication of the bare surface by reason of the deposition technique used. Moreover the code used is only one-dimensional. Measurements at wavelengths $\lambda_0 = 0.480$ μm and $\lambda_0 = 0.514$ μm have shown that in all cases a significant reduction in scattering is obtained. These results show that our components can be used in the whole visible spectral domain. Moreover measurements at angles of incidence $i \neq 0$ have shown that absorption is greater with covered black paints than with bare ones.

3. Conclusion

Common black surfaces can be covered to produce very good candidates for light absorbers. We have shown that, even in the case of randomly rough surfaces, an antireflection coating permits one to reduce the total amount of scattered light. Note that, although rigorous theories were necessary for this study, because of the roughness of the surfaces considered, the optimal solutions are classical (antireflection layers) and identical to those of first-order theories of light scattering. We have shown that, when both an experimental approach and a numerical one are used, it is possible to determine the refractive index of a bare rough surface. This result is of great usefulness because, in the case of randomly rough surfaces, standard spectrophotometric techniques cannot be used. Very good agreement between experimental and numerical results has been found. Moreover the value of more than 99% for absorption shows that our technique leads to components with very high performances for the kind of applications considered in this paper. Our technique will be used by several companies for space applications, showing that it can become a standard procedure.

The question that arises at this stage is whether it is possible to increase the absorption of black paints further by depositing multilayer stacks. Because of the profiles of the surfaces considered, it appears that the conclusions in the domain of validity of first-order theories are not valid for black paints. Several numerical experiments have confirmed this. For this reason, the solution presented in this Technical Note appears to be the most effective for obtaining a total amount of scattered light smaller than 1% with standard black paints, i.e., surfaces whose absorption is greater than 99%.

The authors acknowledge G. Otrio and B. Cousin of the Centre National d'Etudes Spatiales for collaboration through helpful discussions.

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