Comparison of surface scattering between identical, randomly rough metal and dielectric diffusers

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A method of replicating randomly rough surfaces fabricated in photoresist has been developed, enabling comparisons of the scattered light to be made between identical diffusers made from different materials. Experimental measurements on one-dimensional metal (gold) and dielectric surfaces are presented, and some initial comparisons with numerical calculations are made.

Recent observations by Mendez and O'Donnell\textsuperscript{1,2} of enhanced backscatter and strong depolarization from two-dimensional, randomly rough surfaces has encouraged critical discussion\textsuperscript{3-8} of light-scattering mechanisms. In the development and validation of scattering phenomena the provision of such experimental data has an important part to play. In this Letter we report on observations of light scattering from one-dimensional randomly rough surfaces at a wavelength of 0.633 \(\mu\)m, comparing a metal-coated surface with a dielectric scatterer having identical surface characteristics; some preliminary numerical comparisons based on the Kirchhoff–Helmholtz integral equation\textsuperscript{7} are made for normal incidence. Few experimental results have been reported for light scattering from dielectric surfaces,\textsuperscript{9,10} least of all any that compare the surface scattering properties between different materials.\textsuperscript{11}

The requirement for producing one-dimensional surfaces, or random gratings, arose for two reasons: (1) the need to accommodate one-dimensional scattering theories and (2) the computing time and memory involved in running numerical codes for two-dimensional problems.

The surfaces are produced by using photoresist technology similar to that employed by Mendez and O'Donnell\textsuperscript{1,2} but using a thick film resist (Shipley S1400-37) to give a film thickness of \(\approx 12 \mu\)m. The coated substrates are exposed to eight uncorrelated, one-dimensional speckle patterns formed by focusing a Gaussian beam, using a large-aperture cylindrical lens onto a ground-glass diffuser. The resultant speckles are elongated in one direction; correlation lengths of the order of micrometers across the speckles and of millimeters along them are typically achieved. Once the plates are rinsed in a developer whose etching properties are linear with exposure time, the one-dimensional, randomly rough surface is completed.

In order to make accurate comparisons between the scattering properties of different materials it is preferable that the materials have identical surface characteristics. By using the etched photoresist plate as a master it is possible to reproduce the surface in certain materials by a method of replication. Two copies of plate \#39 (rms height \(1.18 \pm 0.13 \mu\)m, 1/e correlation length \(2.97 \pm 0.05 \mu\)m) were formed in clear silicone rubber (Dow Corning Sylgard 182) directly from the gold-coated master (the gold coating was applied with evaporation techniques and has a thickness of \(\approx 90 \) nm). The first copy was used to obtain scattering measurements, whereas the second copy was used to form a mold from which an epoxy resin replica of the original was cast (Araldite MY778 and hardener HY956). The resin copy thus forms a positive replica of the original surface. In order to determine how successfully the master had been replicated, we coated the resin copy with gold, and its diffuse scattering envelopes were measured and compared with those of the original surface.

The scattering equipment and geometry used are...
probability density function of the height fluctuation of an epoxy resin replica of plate #39. \( \frac{1}{e} \) correlation length \( 2.97 \pm 0.05 \mu m \), rms height \( 1.18 \pm 0.13 \mu m \).

Fig. 2. Autocorrelation function \( C(\delta) = \langle h(x)h(x+\delta) \rangle / \langle h^2(x) \rangle \) (where \( \langle ... \rangle \) represents an ensemble average) and probability-density function of the height fluctuation of an epoxy resin replica of plate #39. \( \frac{1}{e} \) correlation length \( 2.97 \pm 0.05 \mu m \), rms height \( 1.18 \pm 0.13 \mu m \).

essentially identical with those described in Ref. 2. For all scattering experiments the incident light was linearly polarized, the electric vector being either parallel (s or TE) or perpendicular (p or TM) to the grooves. The results are shown in Fig. 1 for normal incidence only, although measurements at angles as great as 60 deg have been carried out. The scattered-light envelopes exhibit the phenomenon of enhanced backscatter at 0 deg. Each measurement was normalized assuming perfect conductivity of the gold coating, integrating the total scattered radiation to unity. No depolarization, either \( sp \) or \( ps \), of the incident radiation was observed, as expected for surface roughness in one dimension only. The scattering properties of the replica show excellent agreement with those of the original surface. The slight discrepancies can be attributed to misalignment of the scattering and detection planes and possible fine-scale resolution limitations (\( \ll 1 \mu m \)) in either the silicone rubber or the epoxy resin.

Autocorrelation and height probability-density functions were obtained from Talystep measurements of the gold-coated replica, examples of which are shown in Fig. 2. Each trace consists of 8000 data points taken every 0.2 \( \mu m \) at a scan speed of 2.5 \( \mu m \) sec\(^{-1} \). Six uncorrelated traces displaced across the surface (i.e., across the grooves) were averaged to arrive at the quoted characteristics. The results in Fig. 2 show good agreement with Gaussian distributions for the height probability and autocorrelation functions. From Fig. 1 the exactness of the agreement between replica and original indicates that the initial copy in silicone rubber is also a faithful reproduction. Since the surface statistics are, to a good approximation, Gaussian, the fact that the silicone copy is a negative of the original should not affect its scattering properties.

One of the main problems involved with measuring the light scattered from the surface of a clear dielectric medium is the light reflected from the dielectric-air interface at the back of the sample. The unwanted transmitted light was absorbed with a neutral-density filter of density 4.0 optically coupled with a matching oil (refractive index 1.47) to the back face of the replica. The filter was angled at \( \sim 5^\circ \) to the vertical to prevent any light reflected from its surface from entering the detector. The diffuse scattering envelopes measured for the dielectric surface are shown in Fig. 3 and should be compared with the relevant graphs in Figs. 1 and 4 of the perfect-conductor measurements. Each measurement shows the diffuse scattering envelope for the same incident power, but the measurements have not been normalized, and the intensity

Fig. 3. Measurements of diffuse scattering envelopes of a dielectric surface illuminated at a wavelength of 0.633 \( \mu m \). \( \frac{1}{e} \) correlation length \( 2.97 \pm 0.05 \mu m \), rms height \( 1.18 \pm 0.13 \mu m \). Backscatter occurs to the right-hand sides of the graphs.
scale is therefore somewhat arbitrary. The first thing to note about the results is the lack of any significant backscatter enhancement for the dielectric surface, in contrast to observations for the gold-coated surface. Both ss and pp data have similar backscattered intensities, but in all the measurements the ss data show a greater reflectance for all angles than the pp data. A simple explanation may be found by considering Fresnel's reflection formulas: reflection of p-incident radiation from a plane dielectric surface momentarily falls to zero at the Brewster angle, whereas reflection of s-incident radiation rises at an increasing rate with angle of incidence and is always greater than for p-incident radiation. For the gold-coated surface (perfect-conductor case) away from normal incidence the ss and pp data of Fig. 4 show only slight differences, whereas the corresponding measurements for the dielectric case are quite different from each other. On comparing pp data for the two cases (metal and dielectric), one can see certain similarities, but for the ss data away from normal incidence one measurement is almost a reflection of the other about 0°.

Figure 5 shows the result of a Monte Carlo numerical calculation for a perfect dielectric of refractive index 1.43, rms surface height 1.18 μm, and correlation length 2.97 μm; 200 realizations, each with 300 sampling points along a length of 25.31 μm (40 wavelengths), were used in the calculation. Comparison of Fig. 5 with the upper graph in Fig. 3 shows broad agreement.

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References