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Alexei A. Maradudin

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California, Irvine, CA 92717
Surface Optics Corp., P. O. Box 261602, San Diego, CA 9212

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13. ABSTRACT *(Maximum 200 words)* A combined theoretical and experimental investigation of the scattering of light from randomly rough metallic, dielectric, and perfectly conducting surfaces has been carried out. A major goal of this research program has been an increased understanding of the phenomenon of the enhanced backscattering of light from such surfaces, viz. the narrow peak in the angular distribution of the intensity of the incoherent component of the scattered light in the retroreflection (backscattering) direction. At the same time, a new effect has been predicted and observed in the transmission of light through a thin metal film with random surfaces. This is enhanced transmission, viz. a narrow peak in the angular distribution of the intensity of the incoherent component of the transmitted light in the antispecular direction. Both enhanced backscattering and enhanced transmission are examples of the weak localization of classical (electromagnetic) waves due to their interaction with a random medium.

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Diffraction of Light From Randomly Rough Surfaces

Final Report

Alexei A. Maradudin

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A. Statement of Problem Studied

The problem studied during the period August 1, 1988 through December 31, 1991 with support from Army Research Grant No. DAAL 03-88-K-0067 was that of optical interactions at random surfaces. Specifically, we investigated the scattering of light from one- and two-dimensional random metallic, dielectric, and perfectly conducting surfaces, and the transmission of light through thin metallic films with one-dimensional random surfaces. The goal of these studies was an understanding of the physical mechanisms underlying the phenomena of enhanced backscattering and enhanced transmission respectively, that had been predicted and observed earlier in studies of these interactions of light with random surfaces. These phenomena are the peaks in the angular distributions of the intensity of the light scattered incoherently into the retroreflection direction or transmitted incoherently into the antispecular direction.

B. Summary of the Most Important Results

During the period from August 1, 1988 to December 31, 1991 the following results have been obtained on the enhanced backscattering of light from and the enhanced transmission of light through one- and two-dimensional random surfaces.

Computer codes were written for solving the problem of the scattering of a beam of p- and s-polarized light from one-dimensional random surfaces on metallic, dielectric, and perfectly conducting surfaces, when the plane of incidence is normal to the grooves and ridges of the surface and to the mean surface.[1.8][1] The codes for the penetrable surfaces were the first of their kind. The use of these codes in numerical calculations of the contribution to the mean differential reflection coefficient (drc) from the incoherent component of the scattered light showed that the scattering of both p- and s-polarized light from large rms height, large rms slope random metallic and perfectly conducting surfaces, and of s-polarized light from dielectric surfaces displays enhanced backscattering,[1,8] viz. a peak in the mean drc when

[1]The references are to the articles listed in Section C of this report.

the scattering angle corresponds to the retroreflection direction.

We next used these codes to show that enhanced backscattering is a multiple-scattering effect that is already present in a double-scattering approximation, and that the double scattering approximation reproduces qualitatively and quantitatively most of the features of the exact solution[8,9]. This was done by writing the integral equation for the surface field or its normal derivative (in the case of p- or s-polarization, respectively) on a perfectly conducting, one-dimensional random surface (random grating) in the form of an inhomogeneous Fredholm equation of the second kind, in which the inhomogeneous term corresponds to the Kirchhoff, or single-scattering, approximation to the corresponding surface field or its normal derivative. When this equation is solved iteratively, the n^{th} term in the resulting expansion describes an n-fold scattering process. The first few terms in such a solution have been calculated by a Monte Carlo computer simulation approach. The angular dependence of the contribution to the mean differential reflection coefficient from the incoherent component of the scattered light in the single-scattering approximation displays no enhanced backscattering; the contribution from pure double-scattering processes shows a well-defined enhanced backscattering peak. The inclusion of the contribution from triple-scattering processes modifies the sum of the contributions from the single- and double-scattering processes only slightly in the vicinity of the enhanced backscattering peak, and is most significant in the region of large scattering angles, where the lower order approximations reproduce the effects of shadowing poorly.[8]

The subsidiary maxima seen in the angular dependence of the contribution to the mean differential reflection coefficient from the incoherent component of the scattered light, most clearly at normal incidence, have been explained[9] as due to the coherent interference of a given multiply-scattered optical path and its time-reversed partner when the mean phase difference $\langle \phi \rangle$ between these paths is an integer multiple of 2π. This argument leads to the prediction that the angular width of the enhanced backscattering peak is of the order of λ/a, where λ is the wavelength of the incident beam, and a is the transverse correlation length of the surface roughness.[9] This prediction has been verified in computer simulation studies of the scattering of p-polarized light of fixed λ from silver surfaces for which a was decreased in a systematic fashion[25,28]. The inverse dependence of the width of the enhanced backscattering peak on a is evidence that the effect has its origin in interferent scattering. The fact that second, third,..., order subsidiary maxima are generally not observed is explained by the fact that the variance of this phase difference, σ_ϕ, at the scattering angles at which they would appear is large enough for them to be washed out.[9]

Calculations by numerical simulation techniques have also been carried out [6] for the scattering of p- and s-polarized light from large rms slope one-dimensional, random metal surfaces for which the surface profile function is not a Gaussianly distributed random variable. It was found that the scattering of light from such surfaces displays enhanced backscattering in both polarizations. These results indicate that enhanced backscattering is not a consequence of the commonly made assumption that the surface profile function is a Gaussianly distributed random variable.

Similar calculations of the scattering of p- and s-polarized light from random silver surfaces characterized by several different surface height correlation functions showed that while the details of the mean drc as a function of the scattering angle depend on the form of this correlation function, the existence of enhanced backscattering does not. It occured for all forms of this function considered, provided that the surface scattered the incident light multiply.[25,28]

The random surface need not be a stationary stochastic process in order to display enhanced backscattering. This has been shown in computer simulations of the scattering of p- and s-polarized light from silver surfaces for which the surface profile function is an even or an odd function of the coordinate in the mean plane of the surface that is normal to its grooves and ridges[20].

In the earliest Monte Carlo computer simulations of the scattering of p-polarized light from a one-dimensional, random surface on a nearly transparent dielectric medium no enhanced backscattering was observed.[1] It was found subsequently[8] that enhanced backscattering is present in the scattering of s-polarized light from the same dielectric surface. The former result was explained[9] as due to the dielectric medium not being sufficiently reflective: when the index of refraction of the dielectric medium was increased in the computer simulations, by a factor of 1.5-2, making the medium more reflecting, enhanced backscattering was observed in p-polarization.[8,9]

It has been shown in addition that surfaces of such dielectric media, viz. those characterized by a large positive real part of the dielectric constant and a nonzero imaginary part, support surface electromagnetic waves which give rise to enhanced backscattering on small rms slope random surfaces[17].

Recently, it was predicted that enhanced backscattering occurs in the scattering of p-polarized light from a one-dimensional random surface on a dielectric medium, without any increase of its index of refraction, when it is deposited in the form of a film on a reflecting substrate.[14] This effect has now been observed experimentally.[20,28]

Once it has been realized that enhanced backscattering from a random dielectric surface can be induced by depositing the dielectric in the form of a film on the surface of a reflecting medium, it is natural to inquire whether one can dispense with the reflecting substrate and use the (much weaker) reflection from the back face of a free-standing dielectric film in vacuum to achieve a similar effect. The answer, provided by the results of Monte Carlo numerical simulation calculations, is affirmative[28].

The role played by surface electromagnetic waves (surface polaritons) in the enhanced backscattering of light from weakly corrugated random surfaces has been investigated for one-dimensional random surfaces on metals and n-type semiconductors.[16,22] In these calculations a static magnetic field is applied parallel to the grooves and ridges of the random grating. In the presence of the magnetic field the dispersion curve for the surface electromagnetic waves supported by the surface in the absence of the roughness becomes nonreciprocal. That is, the wave number of the surface electromagnetic wave whose frequency is that of the incident light propagating in one direction across the random grating is different from that of the surface electromagnetic wave propagating in the opposite direction. This nonreciprocity breaks the coherency of the interference between the contribution to backscattering from a given light/surface electromagnetic wave path and from its time-reversed partner, which is responsible for enhanced backscattering in the absence of the magnetic field. This gives rise to two effects. The position of the backscattering peak is shifted from the retroreflection direction to larger scattering angles, which may make the experimental observation of the effect easier, and the amplitude of the peak decreases while its width increases.

In a second study of the role of surface electromagnetic waves in the enhanced backscattering of light from weakly corrugated, one-dimensional random surfaces the scattering of p-polarized light from a periodic grating on a metal surface that has been perturbed by random, one-dimensional roughness has been investigated by Monte Carlo numerical simulations.[28] The idea motivating this study is that the dispersion curve for surface electromagnetic waves propagating across a periodically corrugated metal/vacuum surface displays a gap at the boundary of the one-dimensional first Brillouin zone defined by the period of the grating. Thus, p-polarized light whose plane of incidence is perpendicular to the grooves of the grating and whose frequency falls inside the gap in the dispersion curve cannot excite surface polaritons, through the grating surface, since none exist in this frequency range. If the frequency of the incident light is lower than the frequency of the lower edge of the gap, it can excite surface polaritons. When the periodic surface profile is perturbed by random surface roughness, we should expect qualitatively different forms of the angular dependence of the intensity of the incoherent component of the scattered light when the frequency of the incident light is in the gap in the surface polariton dispersion curve and when it is below it. In the latter case enhanced backscattering should be observed due to the existence of surface polaritons in this frequency range; in the former case it should be strongly suppressed due to the absence of surface polaritons. These expectations have been confirmed by the results of numerical simulations.[28]

The results of the preceding two investigations provide convincing evidence that surface polaritons play an essential role in the phenomenon of the enhanced backscattering of light from random surfaces whose rms slopes are so small that the multiple scattering of light from them is improbable.

The enhanced backscattering of light from random two-dimensional surfaces has also been studied theoretically. The approach used has been to create numerically a square region of random surface whose edge is L on the x_1x_2-plane, and then to replicate this region periodically to produce a bigrating (a doubly-periodic grating), albeit one with a very complicated profile within each period. A vector theory of the scattering of light from bigratings was then used to solve the scattering problem. The enhanced backscattering of light from both metallic[15] and dielectric[17] random two-dimensional surfaces has been studied by this approach. In cross-polarized scattering (s to p and p to s), to which single-scattering processes do not contribute when the plane of scattering coincides with the plane of incidence, the ratio of the height of the enhanced backscattering peak to the height of the background at its position is very close to the factor of two expected theoretically.

A perturbation-theoretic study of the enhanced backscattering of light from a small rms height, small rms slope, surface of a rather different nature has been carried out recently, viz. the surface of a liquid metal that is roughened by the thermally excited capillary waves supported by it.[30] The effect is weak – the mean drc for in-plane cross-polarized scattering in the most favorable experimental conditions for liquid mercury is in the range of 10^{-6} – due to the small amplitudes of the capillary waves (1-10Å). Nevertheless, the analysis shows the ubiquity of enhanced backscattering by demonstrating its existence for a new class of random surfaces.

More recently, the scattering of a scalar beam of finite width from a large rms height , large rms slope random hard wall (Dirichlet boundary condition) has been studied theoretically.[27] The integral equation for the normal derivative of the total field on the random surface was written in the form of a Fredholm equation of the second kind, in which the inhomogeneous term yielded the Kirkhhoff approximation. This integral equation was solved iteratively to produce a multiple scattering series. The results show no evidence of enhanced backscattering in the single scattering approximation, but it is present in the double-scattering and higher order approximations.

Not all of the interesting multiple-scattering effects associated with optical interactions at random surfaces occur in reflection. It has been found that when p-polarized light is transmitted through a thin metal film whose illuminated surface is a random grating and whose back surface is planar, the angular dependence of the intensity of the incoherent component of the transmitted light shows a well-defined peak in the antispecular direction.[3] The initial calculations of this effect were perturbation-theoretic in nature, but this effect, now called *enhanced transmission*, has been reproduced by Monte Carlo numerical calculations[15,20], and has now been seen experimentally [13,15,18,19,20]. It is due to the coherent interference of a multiply-scattered surface polariton, excited by the incident light, with its time-reversed partner.

Finally, we note two studies of intensity correlation functions carried out by many-body perturbation theory for a lossy metal surface.[2,11] These are the first such calculations to our knowledge. Two types of intensity correlations were studied: the correlation of scattered intensities at two different points in a plane parallel to the mean surface; and the correlation at the same spatial point of the intensities due to the scattering of two incident beams with different frequencies as a function of the frequency difference.

C. Publications Supported by Army Research Office Grant No. DAAL-03-K-0067

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D. Participating Scientific Personnel

Professor A. R. McGurn

Professor V. Celli

Professor M. Nieto-Vesperinas

Dr. E. R. Méndez

Dr. P. Tran

Dr. R. Garcia-Molina

Dr. Zu-Han Gu

Mr. T. R. Michel

Ms. Jun Q. Lu

Mr. J. A. Sanchez-Gil

Mr T. R. Michel received the Ph.D. degree in Physics from the University of California, Irvine, in July, 1990 for a dissertation titled "Enhanced Backscattering of Light From a Randomly Rough Grating." Ms. Jun Q. Lu received the Ph.D. degree in Physics from the University of California, Irvine, in September, 1991, for a dissertation titled "Enhanced Backscattering of light From Random Surfaces and Enhanced Transmission of Light Through Rough Films." Both Ph.D. students were supported by Army Research Office Grant No. DAAL 03-88-K-0067.