Enhancement backscattering of light: a direct visual-desktop experience

R. Espinosa-Luna
GIPYS, Centro de Investigaciones en Óptica, A.C.,
Loma del Bosque 115, Colonia Lomas del Campestre, 37150 León, Guanajuato, México,
e-mail: reluna@cio.mx

G. Atondo-Rubio
GIPYS, Escuela de Ciencias Físico-Matemáticas, Universidad Autónoma de Sinaloa,
Ciudad Universitaria s/n, 80010 Culiacán, Sinaloa, México,
e-mail: p027005@uas.uasnet.mx

S. Hinojosa-Ruiz
GIPYS, Facultad de Física, Universidad Autónoma de Zacatecas,
Avenida Preparatoria s/n, Colonia Agronómica, 98062 Zacatecas, Zac., México,
e-mail: sinhue@fisica.uaz.edu.mx

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Direct visual images of the angular distribution of light scattered by one-dimensional, quasi-one-dimensional and two-dimensional randomly rough surfaces, in both plane- and conical-geometries of incidence, are shown. By using a simple desktop arrangement, the images clearly show the enhancement backscattering of light effect for these samples under a 633 nm wavelength, un-polarized, He-Ne laser illumination. Of particular interest is a circularly symmetric enhanced backscattering pattern associated to the uniformly two-dimensional rough surface employed. The surface profiles of the well-characterized samples can be modeled as a Gaussian random process with Gaussian correlation functions too.

Keywords: Optical physics; scattering; enhanced backscattering.

Se muestran imágenes visuales de la distribución angular de la luz esparcida por superficies aleatoriamente rugosas unidimensionales, cuasi-unidimensionales y bidimensionales, tanto en la geometría de incidencia plana, como en la cónica. Utilizando un arreglo simple de escritorio, las imágenes muestran claramente el efecto del retroesparcimiento reforzado de la luz para esas muestras bajo una iluminación de 633 nm de luz no-polarizada, emitida por un láser de He-Ne. De interés particular es el patrón del retroesparcimiento reforzado circularmente simétrico, asociado a la superficie bidimensional uniformemente rugosa empleada. Los perfiles de las superficies caracterizadas pueden modelarse como procesos Gaussianos aleatorios con funciones de correlación también Gaussianas.

Descriptores: Óptica física; esparcimiento; retroesparcimiento reforzado.

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1. Introduction

The enhanced backscattering of light is an effect originated from the multiple scattering processes and, from all of them, it is the most widely known [1-15]. When a pair of light rays are scattered by following the same optical-path opposite directions, they add constructively in the retro-reflection direction. This generates an interference effect, just named enhanced backscattering (EB). For waves scattered that follow other directions, the resulting intensity is not constructive because the waves have different phases and contributes to the intensity by adding each single intensity component. This mechanism explains why the intensity in the retro-reflection direction is twice the intensity present in other angular directions. In practice with very rough surfaces, the EB can be easily identified as an intensity maximum peak of light present exactly in the retro-reflection direction, surrounded at least by two minima and two maximum secondary peaks. The EB effect in very rough surfaces has been observed and explained theoretically by Méndez and O'Donnell [1,2] for well-characterized Gaussian random rough surfaces [3]. In this work, direct visual images of the EB effect present in one-dimensional, quasi-one-dimensional and two-dimensional rough surfaces in both, in-plane and conical-geometries of incidence [4-7,13] are shown. The work is organized as follows. In Sec. 2 the method employed for the fabrication and characterization of the rough surfaces is described. Section 3 shows the pictures associated to the angular distribution of light scattered by rough surfaces. The conclusions are presented in Sec. 4 of this paper. A He-Ne laser, emitting un-polarized light at 633 nm has been used as the illuminating source.

2. Fabrication and characterization of rough surfaces

The procedure employed for the fabrication of the rough surface samples used here has been described previously [14] and a book which describes clearly these and other techniques for the designing of optical diffuser has been published recently [15]. The technique employed here can be

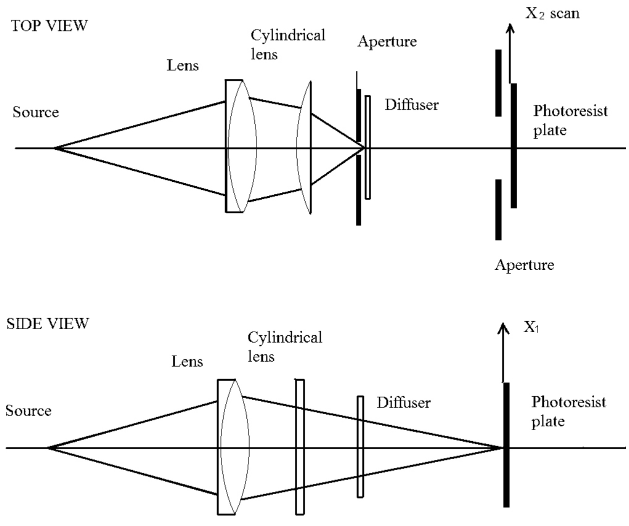

FIGURE 1. Schematic diagram of the optical system employed for the fabrication of the samples.

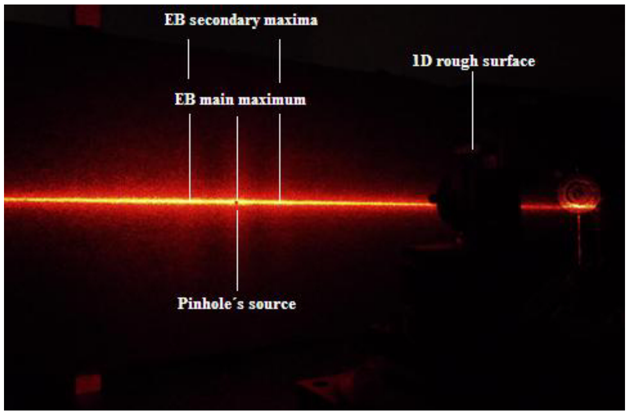

FIGURE 2. Enhanced backscattering pattern associated to a well-characterized 1D randomly rough surface. Observe the enhancement backscattering effect is present with a centered maximum, two minima and two secondary maxima located symmetrically around the principal maximum, when the incidence is perpendicular to the main plane of the surface and under an in-plane geometry of illumination.

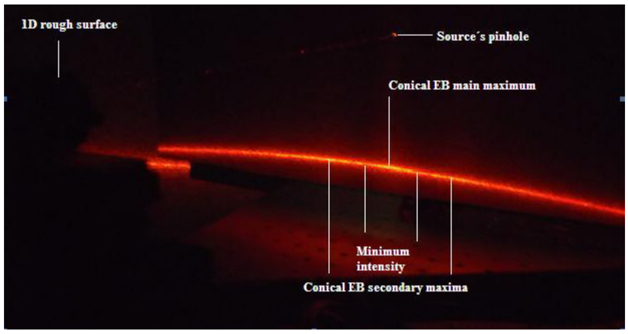

FIGURE 3. Enhanced backscattering pattern associated to a well-characterized 1D randomly rough surface in a conical geometry of incidence. Observe the conical-enhancement backscattering effect is present with a centered maximum, two minima and two secondary maxima located symmetrically around the main maximum. The conical-enhancement backscattering effect is an anti-specular effect, as has been explained previously [7-13].

described briefly in the following lines (the interested reader can consult the two previously cited references for a complete information about the full procedure). The one-dimensional randomly rough surface, 1D, (surface whose profile varies only in one direction; a diffraction grating is a periodic 1D surface) was fabricated with a variation of the technique described by Gray [3,14]. The technique consists of exposing photoresist-coated (Shipley AZ1650) plates to speckle patterns with the desired statistical properties (as substrates were employed cleaned commercial plane plates of glass, were a thick film of photoresist was deposited by using a spinning coating technique). A Gaussian beam arising from a He-Cd laser (wavelength 442 nm) is focused and cleaned by a spatial filter. Then the expanding beam is converted into a converging Gaussian beam by using a simple optical system consisting of one or more lenses, Fig. 1. Next, a cylindrical lens and a transparent diffuser are introduced in the system, where the cylindrical lens focuses the Gaussian beam onto a line on the plane where the diffuser is placed. This arrangement produces elongated speckles on the plane of the photoresist-coated plate (the correlation length of the speckle field produced is several times larger in the x_2 direction than in the x_1 direction). A rectangular aperture, approximately ten speckle correlation lengths wide in the x_2 direction, is placed in front the photoresist coated plate, which is scanned in the x_2 direction. Considering a linear response of the photoresist, the resulting samples should have a surface profile with approximately Gaussian probability density function of heights and a Gaussian correlation function.

The quasi one-dimensional surface was fabricated by reducing slightly the elongation of the speckles. The two-dimensional surface, 2D, was fabricated by changing the cylindrical lens by a circularly condensing lens, by taking-off the rectangular aperture and by exposing the photoresist coated plate to different uncorrelated-illuminated areas on the diffuser.

The samples obtained were gold-coated by using an evaporating chamber. Each of the resulting surface profile of the samples was measured with a Dektak 3030 stylus machine, with stylus radius of approximately of 0.15 μm. All of the histograms of heights and the measured correlation lengths of the samples were approximately Gaussian, with the following statistical parameters. For the 1D surface: correlation length, a = 3.2 μm, standard deviations of heights, δ=1.2 μm; for the quasi 1D surface, a = 2.87 μm, δ = 0.84 μm; and for the 2D surface, a = 2.45 μm and δ = 0.85 μm (both measured uniformly in crossed directions and providing the same values).

3. Results

To illuminate the samples, a simple office-desktop arrangement was employed. A He-Ne laser, emitting un-polarized light, was directed through a pinhole in an opaque screen to illuminate the samples. The pinhole had a small size diame-

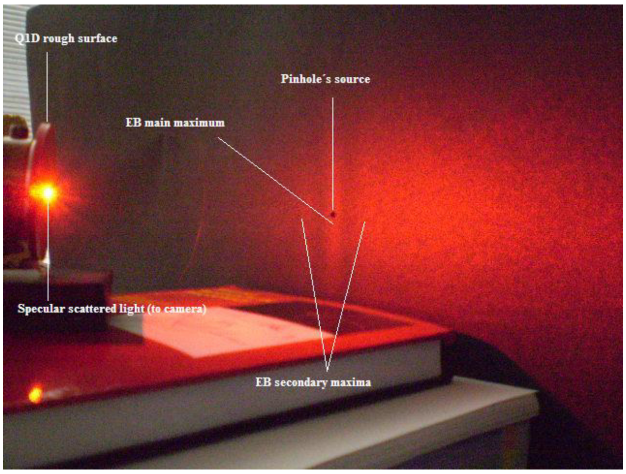

FIGURE 4. Enhanced backscattering pattern associated to a well-characterized quasi-1D randomly rough surface. Observe the scattered light pattern is broader and a high enhancement backscattering effect is present with a centered maximum, two minima and two secondary maxima located symmetrically around the main maximum. The angle of incidence is approximately 45 degrees, under an in-plane geometry of illumination.

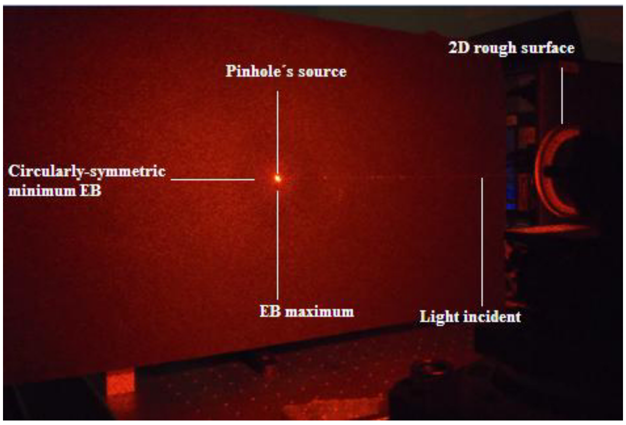

FIGURE 5. Enhanced backscattering pattern associated to a well-characterized 2D randomly rough surface. Observe the enhancement backscattering effect is present as a circularly symmetric spot around the illuminating hole, surrounded by a ring of minimum intensity.

ter, comparable to the size beam diameter of the laser. The angular scattered light by the rough surfaces was reflected in the screen and pictures of these patterns were taken by using a personal digital camera.

Figure 2 shows the angularly scattered light by the 1D randomly rough surface, when the incident wave-vector has not components along the grooves or generators of the surface. Observe the enhancement backscattered effect is present just around the hole from which the light is incident (the retro-reflection direction). Observe the scattered light is distributed just along a plane perpendicular to the grooves, with a width similar to the diameter of the illuminating hole. This behavior occurs even for non-normal incidence and the light is scattered along the plane of incidence.

Figure 3 shows the angularly scattered light by the 1D randomly rough surface when the incidence is conical [7-13]. The conical incidence geometry differs from the usual in-plane geometry of incidence, basically for the fact that the incidence wave-vector has a component along the generators or grooves of the 1D surface [10-11]. Under this geometry, the light is scattered out the plane of incidence and the plane is transformed into the surface of a semi-cone, with vertex the illuminating spot on the surface. This semi-cone of scattered light intersects the horizontal plane of the table, describing a semi-circle. Observe the enhancement backscattered effect is present and shows an anti-specular behavior; some time ago, we have named this the conical enhancement backscattering effect [10].

Figure 4 shows the angularly scattered light by the quasi-1D randomly rough surface when an in-plane configuration of illumination is employed and a beam incidence at approximately 45 degrees occurs. Observe the enhancement backscattering effect is present just around the pinhole where the light is incident (the retro-reflection direction). Observe now the plane-scattered light has a broader pattern. The camera captures the bright spot on the scattering surface; this is the specular direction. Indeed this is the intermediate situation between the 1D surface and the 2D surface cases.

Finally, Fig. 5 shows the angular scattered light by the 2D randomly rough surface. Observe the enhancement backscattering effect is present just around the hole where the light is incident (the retro-reflection direction) and it shows as a bright spot surrounded by an intensity minimum ring. To our knowledge, this is the first time such a symmetrical pattern has been reported. We hope this behavior be interesting for people who deal with numerical simulations in the scattering area.

4. Conclusions

We have presented a brief description of the fabrication process of 1D, quasi-1D and 2D randomly rough surfaces with Gaussian statistical properties. A simple office-desktop arrangement and has been employed to show direct-visual patterns of the light scattered by these surfaces. Of a particular interest has been the enhancement backscattering effect, present in all the cases, for in-plane and for the conical geometries of incidence employed for the illumination with a He-Ne laser light. We have shown a circularly symmetric enhancement backscattering pattern associated to a uniformly 2D rough surface, never seen before by the authors of this work. Even when hundredths of papers dealing with the EB effect have been reported, only a few people have seen it. We hope this manuscript be a source of visual evidence of the enhancement backscattering effect by very rough surfaces.

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