DE GRUYTER Adv. Opt. Techn. 2015; 4(1): 87–91

Letter

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Optical simulation of microstructured surfaces

Abstract: We present techniques and results of optical simulations of microstructured surfaces using BSDF measurements.

Keywords: BSDF; diffusers; microstructured surfaces; scatter; simulation.

DOI 10.1515/aot-2014-0053
Received October 27, 2014; accepted December 17, 2014; previously published online January 20, 2015

1 Introduction

Microstructured surfaces are used in many optical systems, particularly those designed for illumination, to diffuse and homogenize the light distribution. But how does one treat such a surface in an optical simulation or ray trace program? Analytic models for representing scatter from rough surfaces have been around for years. Such models include the K-correlation model, the Harvey model, the ABg model, and others [1–3]. Often, these models are used for stray light analysis in the characterization of an optical system. However, a microstructure surface designed to control and tailor the light distribution may not have a compact analytic form that works for a wide range of incidence angles.

The surface designer can use an exact physical representation of the surface features to design a surface and confirm that it generates the desired distribution. Many ray trace programs have the capability to apply textures to surfaces to scatter incident light. These may be approximations to the actual desired surface using models built into the ray trace program, or they may be true representations of a small portion of the surface with all the optical accuracy needed to generate the desired light distribution and then repeated or arrayed to fill the larger surface in the optical system. The optical system designer may not have access to the detailed surface structure needed to generate a desired light distribution. He may be using the diffuser as one of many components within a larger optical system and may not be concerned with the actual design and fabrication of the diffuser, but only that he can simulate it accurately within the optical system. The choices are to use known scatter models within the simulation program, but these are derived from statistical theories of rough surfaces and are often unsuited for microstructured surfaces designed to produce a tailored distribution. Perhaps the most appropriate choice for a microstructured surface is to use measured data in the form of bidirectional scatter distribution function (BSDF) data.

Figure 1A shows an electron micrograph of an Engineered Diffuser™ [4] used to create a uniform intensity distribution. One can quickly understand the difficulty in trying to model the exact features of such a surface with an optical simulation program. The number of unique individual elements and surfaces can quickly overwhelm a ray trace program. While the designer of the diffuser needs to be able to characterize the surface features in minute detail, the system designer needs only to know how the diffuser performs under the illumination conditions of the optical system being designed. For that, the BSDF measurements are usually sufficient.

Figure 1B shows the geometry of the diffuser and the relevant incident and scatter angles. The incident ray is defined by the polar incident angle, θ_{incident}, and the azimuth incident angle, ϕ_{incident}. The scattered ray is defined by the polar scatter angle, θ_{scatter}, and the azimuth scatter angle, ϕ_{scatter}.

2 Simulations using BSDF measurements

Microstructured surface diffusers described here can be classified as either isotropic or anisotropic. Isotropic diffusers are characterized by the circular symmetry of the scatter distribution at normal incidence. The distribution

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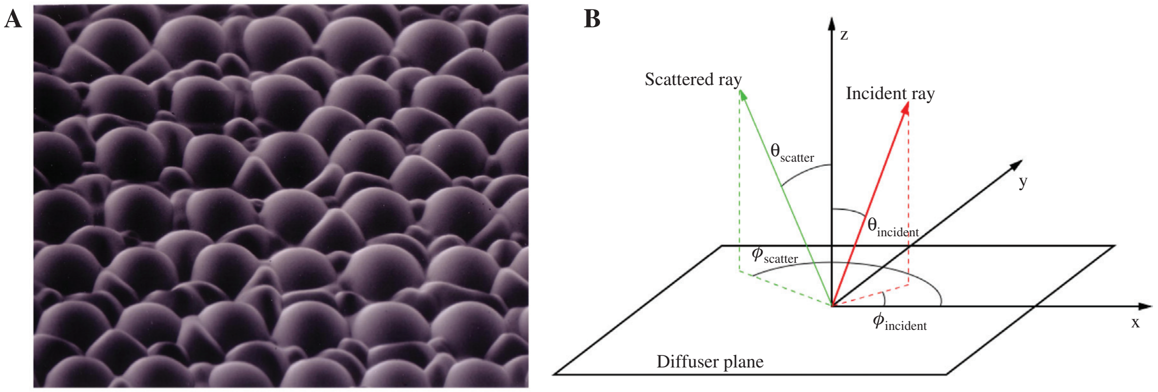

Figure 1 (A) Electron micrograph of a microstructured surface used for creating a uniform intensity distribution with collimated illumination. (B) Geometry of the diffuser and definitions of the incident and scatter angles.

is dependent on the difference between incident and scattered azimuth angles (ϕ_{incident}-ϕ_{scatter}), not on their absolute values. The distribution is symmetric about the plane of incidence and is independent of the diffuser rotation about the surface normal. Changing the polar incident angle causes the distribution to shift toward the specular direction. Changing the azimuth incident angle changes the plane of incidence, and the scatter distribution remains symmetric about this plane. Anisotropic diffusers are characterized by a noncircularly symmetric intensity distribution at normal incidence. The scatter distribution at any incidence angle is dependent on the rotational orientation of the diffuser about the surface normal relative to a known axis associated with the diffuser. Thus, the scatter distribution is a function of both polar and azimuth scatter angles, and both polar and azimuth incident angles.

An example of each diffuser is shown in Figure 2. Figure 2A is the intensity distribution from an isotropic diffuser at normal incidence. This is an Engineered Diffuser™ with a uniform circular intensity distribution and a 50° full width half maximum (designated EDC50). Figure 2B is an anisotropic diffuser, also at normal incidence. It generates a uniform square intensity distribution with a horizontal and vertical width of 40° (designated EDS40).

Simulation of these diffusers using BSDF data requires measurement data that span the range of incidence angles anticipated during the simulation. At non-normal incidence, the distributions remain approximately centered on the specular direction, but the shape will become stretched in the specular direction, and the profile will become less uniform with increasing incidence angle. The isotropic diffuser pattern will be symmetric about the plane of incidence, whereas the anisotropic diffuser pattern will not.

The implication is that we can simulate the isotropic diffuser with data sets at several polar incidence angles

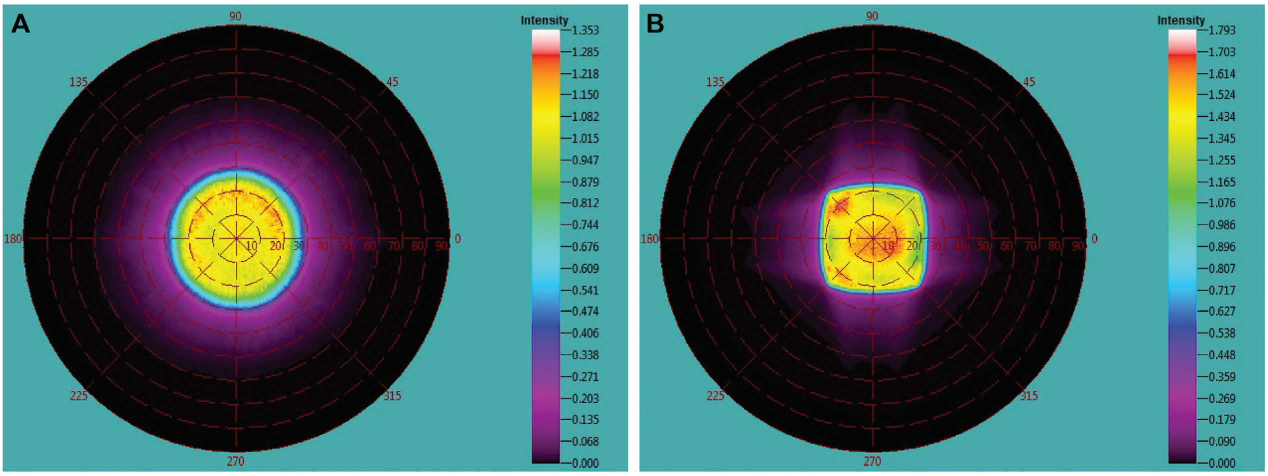

Figure 2 Measured intensity distributions for a 50° FWHM circular diffuser EDC50 (A) and a 40° FWHM square diffuser EDS40 (B) at normal incidence.

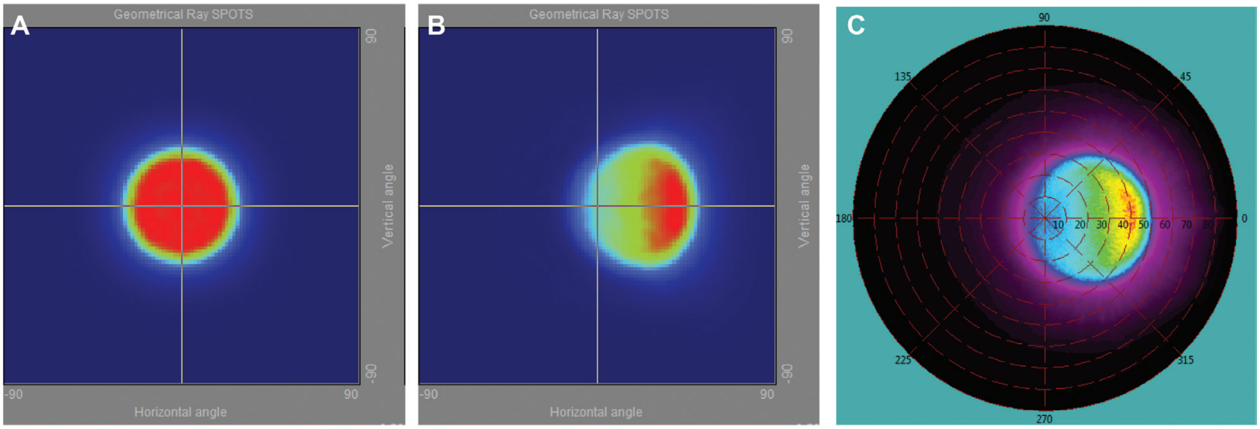

Figure 3 Simulation results for the EDC50 circular diffuser at normal incidence (A) and 20° incidence (B), and (C) the measured intensity distribution at 20° incidence.

and only one azimuth incidence angle. The ray trace program uses this symmetry to simplify the scatter of incident rays. The simulation of the anisotropic diffuser, on the other hand, requires measurement data at several polar incidence angles and multiple azimuth angles at each polar angle, resulting in a substantially larger data set.

It is the task of the simulation program to interpolate the measurement data for incident angles not specifically included in the data sets. The end user must be aware of

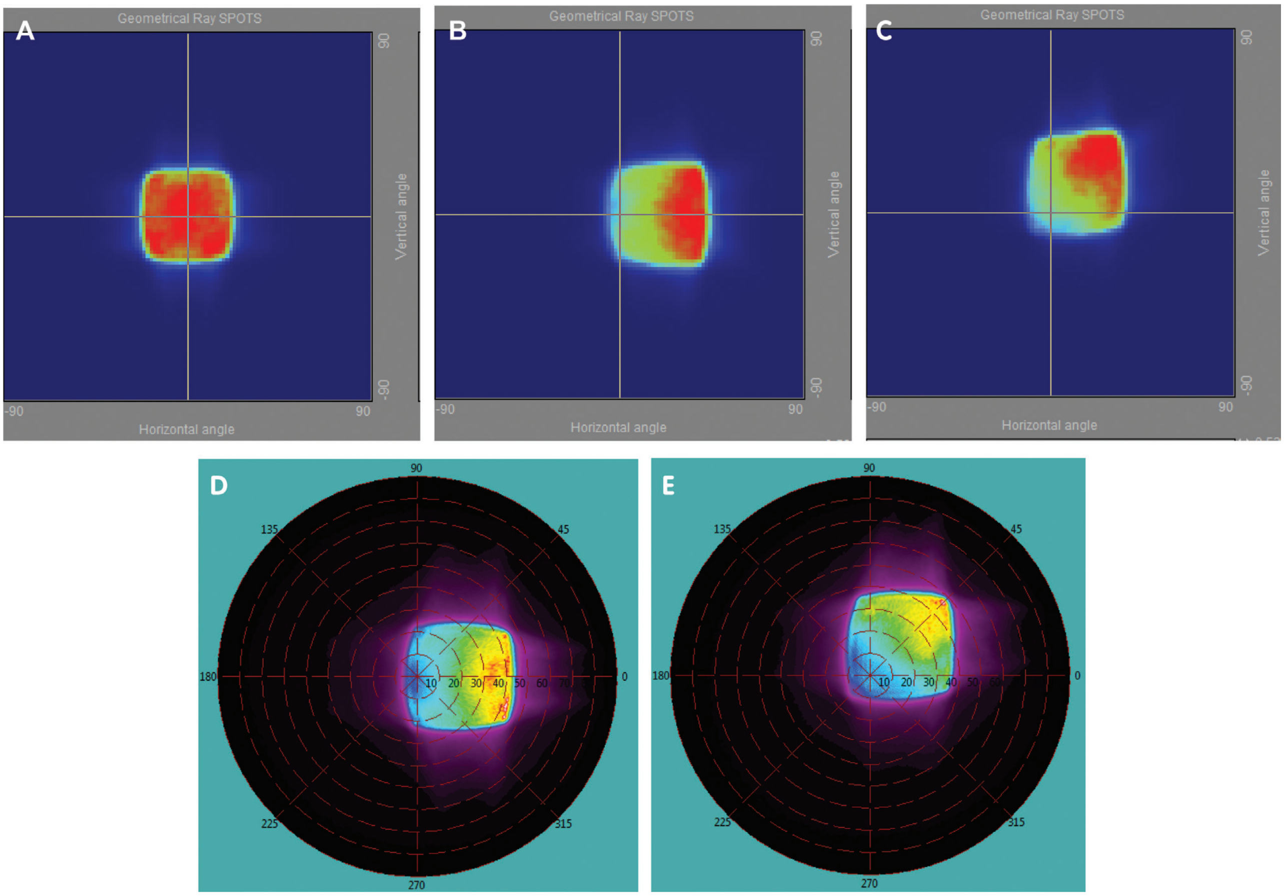

Figure 4 Simulation results for the EDS40 at normal (A), 20° polar (B), and 20° polar 45° azimuth (C) incidence, and measured intensity distributions at 20° polar (D), and 20° polar 45° azimuth (E) incidence.

the capabilities of the ray trace program and the limitations of any interpolation to ensure accurate simulation of the diffuser over the incident angular range being simulated. For example, we can simulate the above isotropic EDC50 diffuser for incidence angles up to 20° with measurements at incident polar angles of 0°, 5°, 10°, 15°, and 20°. For simulation of the anisotropic EDS40, we require data not only at each of these polar angles but also at intervals of 15° azimuth, for example, for each nonzero polar angle.

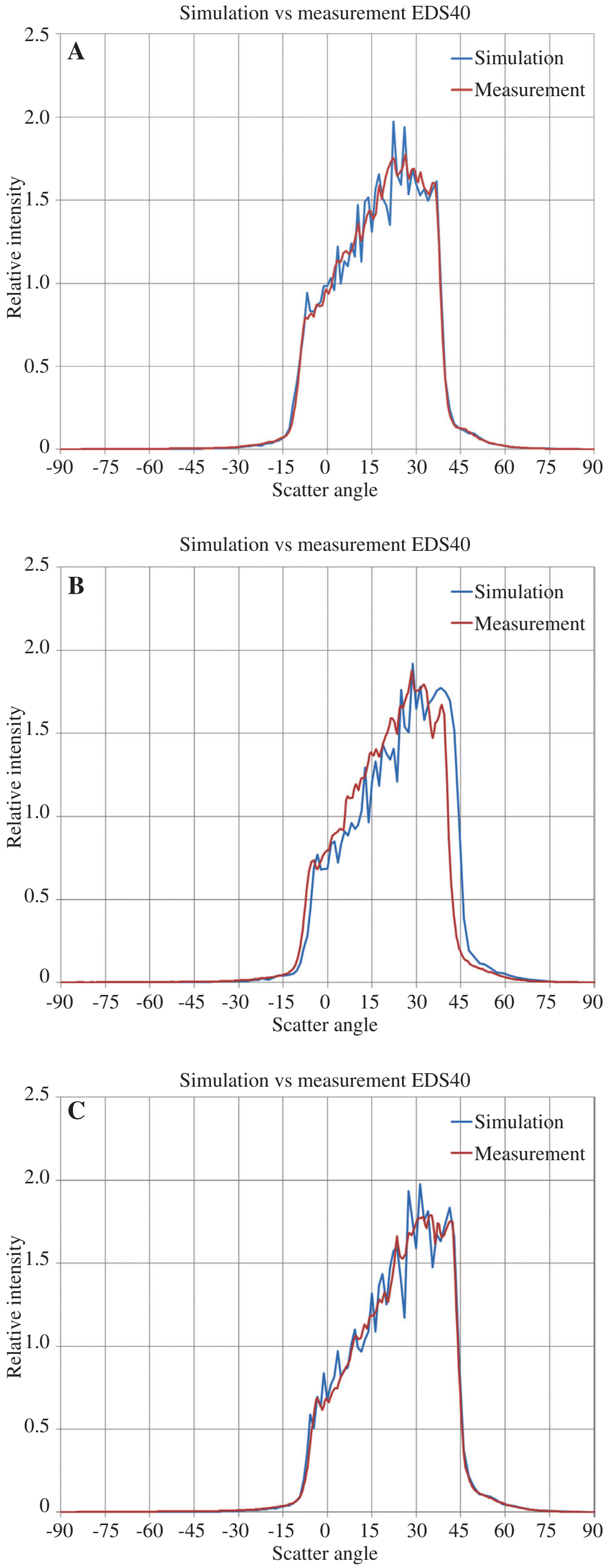

Figure 5 Comparison of simulation and measurement results for the EDS40 diffuser using BSDF data at 15° and 20° polar incidence angles, and simulation angles of 15° (A), 17.5° (B), and 20° (C), all at 0° azimuth illumination.

3 Simulation results

Simulation results for the EDC50 are shown in Figure 3 for incidence angles of 0° (A) and 20° (B) [5]. Also shown in Figure 3C is the intensity measurement at 20° incidence [6].

For this isotropic diffuser, we measured BSDF data at five polar incidence angles between 0° and 20°. Measurements were taken at 1° increments in both polar and azimuth scatter directions.

Simulation results for the anisotropic EDS40 are shown in Figure 4 at normal incidence (A), 20° polar incidence (B), and 20° polar by 45° azimuth incidence (C). The measured intensity distributions for 20° polar incidence (D), and 20° polar by 45° azimuth incidence (E) are also shown.

For this anisotropic diffuser we have measured BSDF data at normal incidence, and at the polar angles of 5°, 10°, 15°, and 20° for azimuth angles in 15° increments, for a total of 97 data sets. Measurements, again, were taken at 1° increments in both polar and azimuth scatter directions.

Naturally, we expect any simulation program to reproduce the measurement when the measured incident angles match those used in the simulation. Figure 5 shows a comparison between the horizontal cross sections of the simulated and measured intensity for the anisotropic EDS40 diffuser for three simulated incidence angles. In each of the simulations, BSDF measurement data was used for just two incidence angles of 15° and 20° polar, 0° azimuth. The simulations were conducted at incidence angles of 15° (A) and 20° (C) polar, 0° azimuth. In these cases, the scatter simulations closely reproduce the measurement results.

An intermediate angle of 17.5° polar 0° azimuth was also simulated and compared to the measured intensity. This is shown in Figure 5B. Here, there is a departure of the simulated intensity from the measurement. Some programs use interpolation between BSDF incidence angles; other simulation programs may use a nearest neighbor approach. It is up to the end user to determine and understand the algorithms used and how that will affect the accuracy of the simulation to the actual performance of the diffuser in a real system.

4 Conclusion

We have demonstrated the simulation of isotropic and anisotropic scattering surfaces using BSDF measurements of the diffuser at multiple incidence angles. System designers must be aware of the requirements and limitations of such a method in simulating the performance of the diffuser. They must weigh the tradeoffs of speed and accuracy of a simulation with the large quantity of data needed to characterize these types of surfaces.

References

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[2] P. Beckman and A. Spizzichino, ‘The Scattering of Electromagnetic Waves from Rough Surfaces’ (Pergamon Press, New York, NY, USA, 1963).
[3] J. E. Harvey, ‘Light scattering characteristics of optical surfaces,’ Ph.D. Dissertation, University of Arizona, (1976).
[4] Engineered Diffuser™ is a trademark of RPC Photonics, Inc., Rochester, NY, USA.
[5] Simulations were performed using ASAP from Breault Research Organization, Tucson, AZ, USA.
[6] Intensity distributions in angle space correspond to Type B photometry of the Illuminating Engineering Society, New York, NY, USA. Measured intensity distributions correspond to Type C photometry.