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A BIDIRECTIONAL SCATTERING FUNCTION RECONSTRUCTION METHOD BASED ON OPTIMIZATION OF THE DISTRIBUTION OF MICRORELIEF NORMALS

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ABSTRACT

The paper is devoted to the development of a method for reconstructing the scattering properties of a rough surface. The rough surface, in this case, is the dielectric-air interface. Typically, these properties are described by the bidirectional scattering distribution function. Direct measuring of such functions is either impossible, or its cost is very high. The method of reconstructing the bidirectional scattering distribution function, based on the distribution of the elevations of the microrelief, requires a complicated fitting procedure and often yields not very good results. In the proposed solution, the rough surface is modelled by a parametric function that simulates the density distribution of the normals to the faces of the surface microrelief. The result of optimizing the density distribution of the normals to the faces of the surface microrelief is in good agreement with the expected one.

Keywords: microrelief, bidirectional scattering distribution function, rough surface, diffusion, rendering, photoconductive systems, total internal reflection, wave optics, ray optics

1. INTRODUCTION

Photoconductive optical elements with rough surfaces, Fig.1, are widely used in devices with complex light distribution. As a rule, rough surfaces are used in two cases: either to form a special goniometric light scattering diagram or to create the required spatial luminance distribution in various photoconductive devices, such as liquid crystal display illumination systems, car dashboards, LED luminaires, etc. When modelling the propagation of light inside the material of a photoconductive element, it is necessary to take into account the optical properties of a rough interface between two media, whereas the optical properties of the entire element are meaningless. Moreover, these properties differ depending on whether the light falls on the interface from the side of the material of the photoconductive element or whether light falls on the surface from the air. Therefore, for physically-correct modelling of such devices, the optical properties of

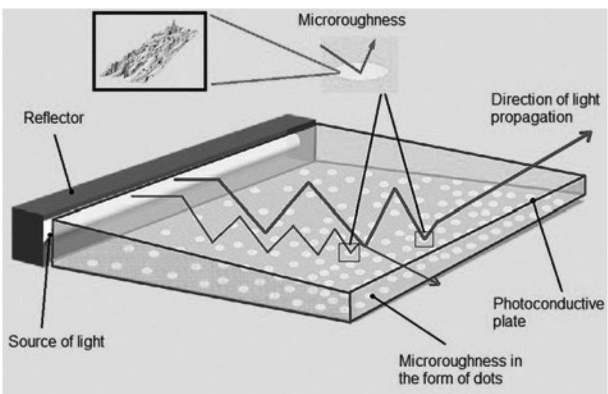

Fig. 1. An example of the use of a rough surface

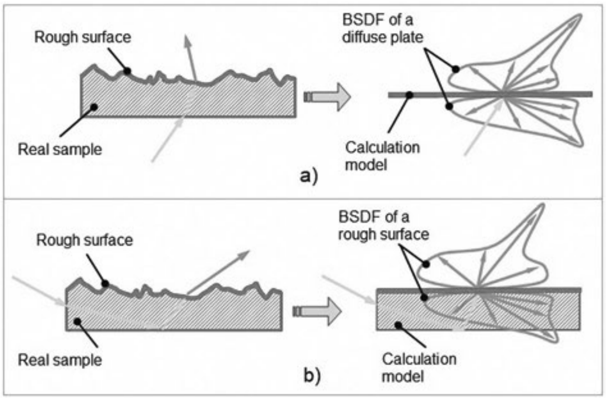

Fig. 2. "Surface" model pf a diffuse plate (a), "solid-state" model of a PCP

a rough surface must be taken into account individually for each side.

Fig. 1 shows an example of the use of a rough surface. On the lower surface of the photoconductive plate (PCP) stains with microrelief are applied. These stains are scattering surfaces. They have a relatively small size, and therefore they are sometimes called diffuse points. Inside the PCP, the light beam spreads according to the law of total internal reflection. After scattering at diffuse points, the beam deviates from the direction of specula reflection and can leave the PCP. The diffuse point's density distribution that varies along the surface of the PCP makes it possible to obtain uniform radiation over the entire area of the external surface.

The light scattering parameters of a rough surface are described by the bidirectional scattering distribution function (BSDF). The function has a complex multidimensional representation and depends on a number of parameters, such as the direction of incident light, the observation direction of light and the spectral composition (colour) of the radiation. The BSDF is a superposition of two functions: the bidirectional reflectance distribution function (BRDF) and the bidirectional transmittance distribution function (BTDF). For flat thin samples, the BSDF can be measured using a goniophotometer. In cases where the thickness of a sample with a microrelief can be neglected, its physically correct model can be represented as a single surface, on which the properties of the BSDF obtained as a result of measurements are assigned. Such a "surface" model, shown schematically in Fig. 2a, can be used to simulate various diffuse films or filters. Unfortunately, this model is not applicable if the thickness of a sample with a microrelief is important for the propagation of light inside a transparent material of the NGN. In this case, the "solid-state" model should be used, shown in Fig. 2b. This means that for correct modelling it is necessary to have two BSDFs of a rough surface, one of which describes the scattering properties when radiation passes from the air into the glass, and the other describes the scattering properties when radiation passes from the glass into the air.

The main problem is that the BSDF of a rough surface of a PCP cannot be measured directly. There are several reasons for this. First, it is the presence of multireflections between the rough surface and other surfaces of the sample being measured. Secondly, it is impossible to illuminate the sample or detect light at glancing angles to a rough surface. Solving problems is expensive and requires special equipment to eliminate multireflections between surfaces and refraction on the side opposite to the measured rough surface.

Many researchers are dealing with the complex problem of the reconstruction of the BSDF [1–8]. A number of works [1–5, 7] are devoted to accurate and physically correct reconstruction by comparison with the database of MERL BSDF measurements [9]. This database contains reflection functions for 100 kinds of materials. The authors of this database describe their method of obtaining a BSDF [10], but the question arises about the correctness of the measurements. It is difficult to say how accurate the BSDF measurements are in the MERL database due to the lack of information on certified measuring equipment. That is why the question arises about the reliability of measurements.

It should also be noted that in most papers the authors consider the problem of reconstruction only the bidirectional reflectance function (BRDF), and not in general the two-beam scattering function (BSDF). As a rule, BRDF is applied only to surfaces, but this is not enough for accurate modelling, for example, frosted glass.

One of the alternative methods of BSDF reconstruction is computer modelling of light scattering at the boundary of the microrelief of the sample medium [11]. Such an indirect method also has a number of drawbacks. In particular, the deviation of the surface profile can be comparable with the wavelength of the incident light. This means that the calculations must be carried out taking into account the aspects of wave optics, which, first, are very complex, and secondly, they may not be reliable because of insufficient accuracy in measuring the surface profile.

This article presents a combined approach. It uses the BSDF optimization, based on the approximation of the form to the Gaussian and Cauchy functions, with a limited number of parameters. This approach ensures a more correct reconstruction of the BSDF than the method proposed in [11].

The authors propose a method for reconstructing the BSDF, which allows modelling of physically correct complex scenes with frosted glass. For the experiments, GCMS-4 certified measuring equipment [12] was used, which made it possible to conduct physically accurate measurements of the BSDF. In this study, the BSDF was reconstructed and the results were compared with measurements on GCMS-4 equipment, so we can be sure that the results obtained are physically correct.

2. NUMERICAL METHODS OF BSDF RECONSTRUCTION

There are several numerical approaches to the calculation of the BSDF of rough surfaces both on the basis of wave optics and on the basis of the ray approximation. In the previous study, a solution was described, in which the surface microrelief is represented as a height distribution within the representative region of the sample [11].

The reconstruction of the BSDF of the plate with a rough surface was based on the use of two sets of measured data: the distribution of microrelief heights and the total BSDF of the sample (BTDF and-or BRDF). The reconstruction results were often not very good and required a comprehensive optimization of the microrelief (scale and profile filtering). However, filtering cannot guarantee a successful solution to the problem.

The new approach is based on using only one type of data, namely BSDR (BTDF and/or BRDF) measured for the entire sample. Despite the difference with the previous algorithm, the basic model of the new approach is the same. The initial information for the reconstruction of the BRDF is the angular distribution of the luminous intensity, calculated after the transformation of the rays at the boundary of two media, represented in the form of microgranules. The only difference is that micro boundaries are defined as the density of the distribution of the normals to the surfaces of these microgranules. The OPTOS MicroRelief tool [13], integrated into the Lumicept software package [14], provides correct calculations for the distribution of the light intensity scattered on the microrelief.

The initial distribution of the normals to the relief microfaces, necessary for simulating the propagation of light, can be reconstructed from the measured BRDF of the sample. In the absence of shadowing of neighbouring microgranules, the angular distribution of the normals is approximately 2 times greater than that of the BRDF. Of course, this is a rough approximation, but it can be used as an initial step for the whole procedure for the reconstruction of the BSDF.

To restore the BSDF, we used a real sample in the form of a plane-parallel plate, in which one surface is polished and the other is rough (matted). The plate was illuminated by a collimated light

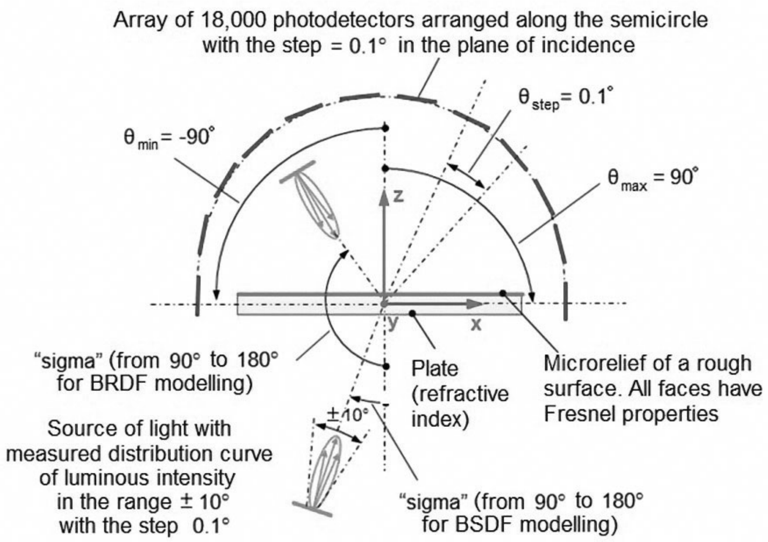

Fig. 3. Schematic model of a goniophotometer for measuring the BSDF of a diffuse plate

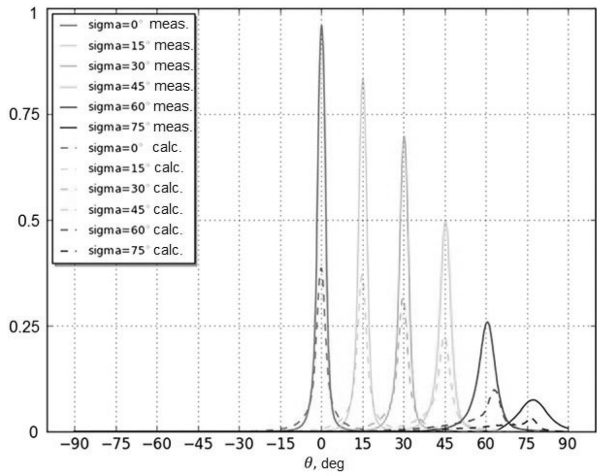

Fig. 4. Results of measurements and calculations of BTDF

beam. The intensity of reflected and transmitted light was measured for each direction of incidence. For simplicity, the measurements were carried out in the same plane – in the plane of incidence. The simulation scheme (Fig.3) is very close to the measurement circuit. A collimated beam of light with a corresponding aperture and angular divergence illuminates the plate. The rough surface of the sample was modelled by the BRDF calculated using the BSDF generation module included in the Lumicept software package [15], using the density of the angular distribution of normals. The light scattered by the plate was accumulated by round virtual detectors located along a predetermined angular grid. The distances between the detectors and the measured sample and the radius of the detectors correspond to the characteristics of the measuring device: the relative position of the measured sample and the photodetector, the angular and spatial resolution of the goniophotometer.

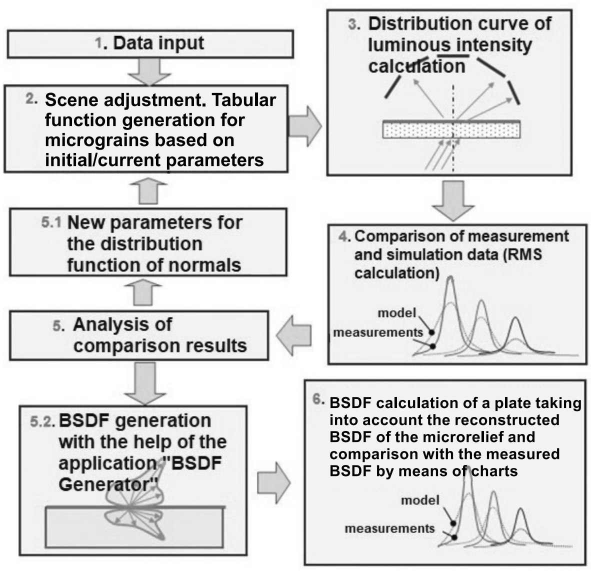

Fig. 5. Optimization procedure of the angular distribution of normal to the micrograins of a rough surface relief

Fig. 4 shows the charts of the measured and calculated BTDF in the form of the relative angular distribution of the light intensity transmitted through a sample with one rough surface. The combined graph contains the BTDF for all measured directions of the incident light: 0º, 15º, 30º, 45º, 60º, 75º (sigma is the angle between the normal to the sample surface and the direction of incident light). Note that all measurements and calculations are carried out in the plane of incidence. Solid lines indicate the results of measurements of a real sample. The dashed lines correspond to the results of modelling a sample with a reconstructed BSDF. It can be seen that there is a significant difference between simulation and measurement results. A similar trend can be observed on the chart with the results on the light reflection (not presented in the article).

3. THE OPTIMIZATION ALGORITHM OF BSDF RECONSTRUCTION, BASED ON THE DISTRIBUTION OF NORMALS

The main reason for the differences between the measurement and calculation results shown in Fig. 4 is that the initial reconstructed deviation of the normals is not suitable for the real model of light scattering on the sample. On the other hand, the angular distribution of normals is an indirect way of determining the BSDF. Thus, it is reasonable to assume that optimizing the angular distribution of the normals to the microfaces of the relief of the rough surface will yield the target BSDF of the sample.

The main idea of the proposed optimization method is that to restore the desired BSDF of a rough surface it is sufficient to use only one set of measured data, for example, the transmission characteristics of the entire sample or, in other words, its BTDF. Fig. 5 shows the optimization procedure. The rough surface is determined by the density of the angular distribution of the normals to the surface microfaces. The optimization algorithm contains the following steps:

1. In the first step, information is entered on the sample size, the refractive index, the BTDF of the sample, the initial parameters for describing the density function of the normal distribution.

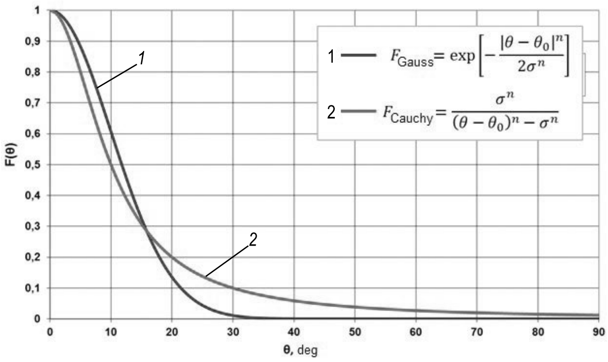

Fig. 6. General form of the Gaussian and Cauchy functions

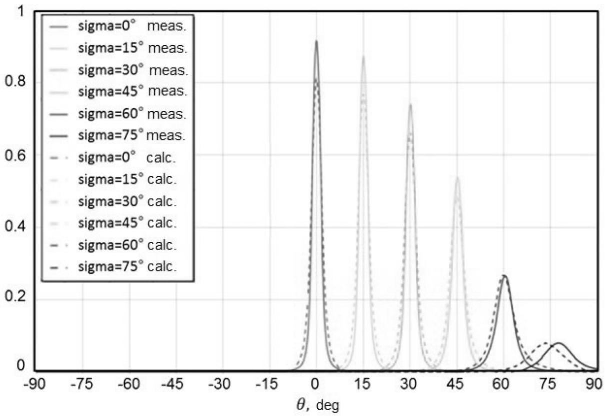

Fig. 7. Previously achieved results of BSDF reconstruction

2. The second step involves setting up the test scene, generating a table function for the microfaces based on the initial parameters. After that, the distribution of microfaces is added to the optional OPTOS MicroRelief application [13], which generates the corresponding BSDF.

3. In the third step, the angular distribution of the light intensity for the prepared sample is calculated.

4. Next, the optimizer compares the results of the calculation with the results of the measurements and calculates the root-mean-square deviation (RMS).

5. The next step is to analyze the deviation between the optimized and measured results in order to decide whether to continue or stop the optimization process.

5.1. If the desired deviation is not achieved, then the optimizer changes the density distribution parameters of the normals and returns to step 2 to continue the process.

5.2. Subsequently, if the deviation is acceptable, the final BSDF is generated using the "BSDF Generator" tool of the Lumicept software package [14].

6. Finally, the optimizer constructs the charts of the measured BSDF of the sample and the calculated BSDF of the sample, taking into account the reconstructed BSDF of the rough surface of the sample.

An important feature of this method is that when the BSDF is reconstructed, the optimization parameter is the distribution of the density of the normals to the surface microfaces. However, tabular determination of the density distribution of normals is not suitable for most optimization tools, since multi-parameter procedures require a lot of time for calculation. The most convenient representation of the distribution law is an analytic function with a minimum number of parameters. The experiments carried out by the authors made it possible to determine the two most suitable in this case types of basic functions: Gauss-shaped and Cauchy-shaped. For most cases, the Cauchy distribution gives a better result, although for some microreliefs the Gaussian approximation seems to be the best. In the authors' opinion, the Gaussian approximation gives good agreement with the BTDF measurements in zones with high transparency (at least from the point of view of the standard deviation between simulation and measurement results). Therefore, it is reasonable to use both types of functions in the optimization process. The general form of the Gaussian and Cauchy functions is shown in Fig. 6. It is clearly seen that the Cauchy distribution is wider in the zones of distant angles. The parameter θ_0, which determines the shift of the peak of the distribution along the axis of the angles, is rather formal, since in most cases the density distribution of the normals has a maximum at $\theta_0 = 0$. But this parameter is reserved for improved optimization.

Considering that the general tabular representation of the normal distribution density function is not a good optimization solution, an alternative "hybrid" solution was chosen. The base density function of the distribution of normals can be given by Gauss-form or Cauchy-form, while some regions of the function can be replaced by a locally tabular function. A brief description of the algorithm can be presented as follows:

1. Suppose that the optimization procedure with an analytic function of the density distribution of the normals can not correspond to the BSDF in a region close to the zero angle θ. This means that the density distribution of the normals in the region of

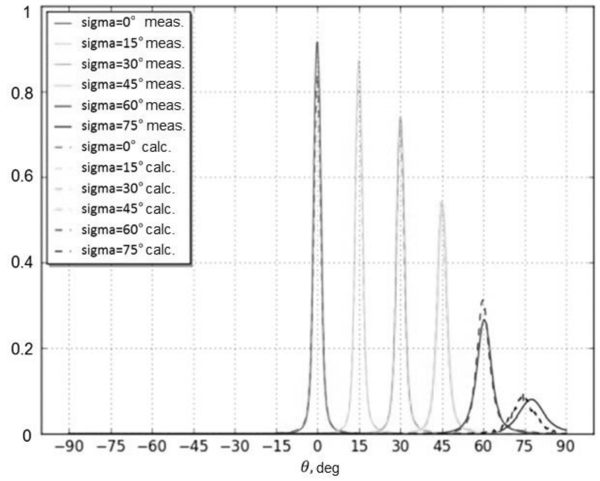

Fig. 8. The results of the BSDF reconstruction based on the Cauchy function

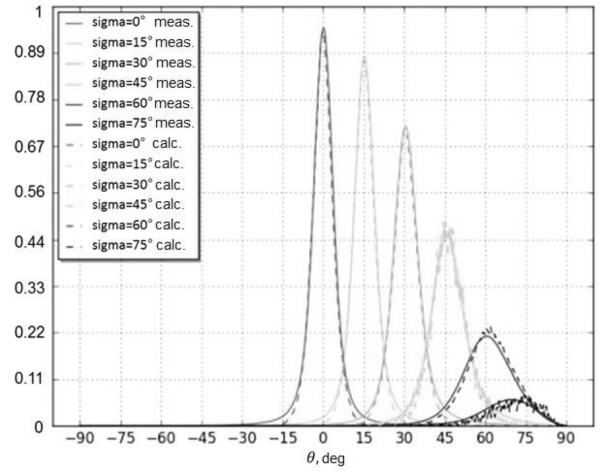

Fig. 9. The results of the BSDF reconstruction based on the Gauss function

zero angular deviation should be represented by a tabular function.

2. Then the optimizer adds several points to the tabular representation of the density of the distribution of normals in this region and continues optimizing the mixed function. If the number of points added is not high, the optimization procedure can find a solution.

4. COMPARISON OF BSDF RECONSTRUCTION METHODS BASED ON THE DISTRIBUTION OF HEIGHTS AND BASED ON THE ANGULAR DISTRIBUTION OF THE NORMALS

To test the new method, several problematic samples were selected, presented in [15]. These samples required a complicated tuning procedure based on the filtration and scaling of the measured microreliefs, for some samples an artificially created relief was used. Previously achieved results are shown in Fig. 7.

The results of the BSDF reconstruction based on the Cauchy function are shown in Fig. 8.

The results of the BSDF reconstruction based on the Gaussian function are shown in Fig. 9.

The results of optimizing the density distribution of the normals are in good agreement with the desired result (at least for the samples under study). In most cases, the Cauchy-form function gives acceptable results, at least not worse than in the case of the measured microrelief [16]. The Gaussian distribution function is also useful in some cases. All this allows us to conclude that accurate measurements of the microrelief, in general, are not required to reconstruct the BSDF of a rough surface.

Using the OPTOS MicroRelief plug-in [13] allows us to exclude the BSDF Generator Lumicept [14] from the optimization procedure. It accelerates the optimization process since it does not require the generation of a BSDF at each optimization step, which requires considerable time for calculations.

An attempt to apply the tabular density function of the angular distribution of normals as an optimization parameter failed. Optimization of the multi-parameter function is a very time-consuming task and all the advantages caused by the free form of specifying the density of the distribution of normals are nullified by the slowing down and the general divergence of the optimization procedure.

It is possible to observe a good agreement between the results of measurements and modelling for directions of incidence close to the normal ($\theta = 0$), and an acceptable agreement of the results for other directions of incidence. In this paper, the results were shown only for BTDF. However, the optimization procedure can also be applied for reflection. Usually, the optimization of the results of BTDF improves the results of the BRDF.

In addition, we simulated the construction of a photorealistic image of a plate with a rough surface. The appearance of the plate with the BSDF of a rough surface before optimization (i.e. when the measured profile was initially used) is shown in Fig. 10a. The shape of the plate with an optimized BSDF is shown in Fig. 10b.

The images shown in Fig. 10 were synthesized using a physically correct rendering based on the ray tracing method implemented in the Lumicept

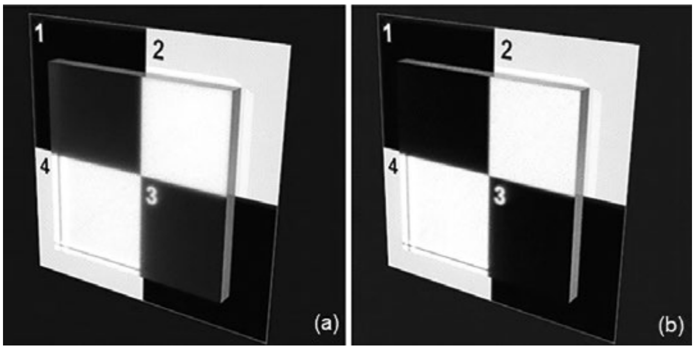

Fig. 10. The appearance of the plate with the BSDF of a rough surface before (a) and after (b) optimization

software package [14]. The scene consists of a plate, on the outer surface of which is assigned a BSDF. The plate is placed above the chess substrate and is illuminated by a set of light sources, creating a complex diffuse illumination.

5. CONCLUSION

In conclusion, it can be noted that the method for optimizing the density of the angular distribution of the normals for the reconstruction of the BSDF shows good agreement with the desired result (at least within the framework of the samples under study). In most cases, the use of the Cauchy function as the basic function for optimizing the BSDF is more preferable and in some cases shows much better results of the BSDF reconstruction than the BSDF reconstruction method from the measured microrelief. In addition, an alternative function of optimizing the BSDF can be the Gaussian-shaped function, which in some cases can provide a higher rate of convergence of the optimized BSDF to the target value. This allows us to conclude that it is possible to exclude measurements of the micro-profile in general for the exact reconstruction of the BSDF.

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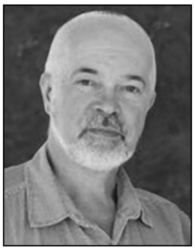

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