Reconstruction of Bi-directional Scattering Distribution Function of rough surfaces

V. Sokolov (2), D. Zhdanov (1), A. Garbul (2), I.Potemin (2), A.Voloboy (2), V.Galaktionov (2)

1 : NRU ITMO, St.Petersburg, Russia,

2 : The Keldysh Institute of Applied Mathematics RAS, Moscow, Russia

E-mail: voloboy@gin.keldysh.ru

Abstract: The reconstruction of Bi-directional Scattering Distribution Function (BSDF) for rough surfaces made of dielectrics is considered. Suggested solution provides precise and physically reasonable method for the rough surface BSDF simulation.

Keywords: BSDF, BSDF measurements, BSDF reconstruction, roughness, Gauss filtration, Optimization

1. Introduction

The surfaces with roughness are widely used in optical devices like illuminating systems of displays, car dashboards, LED luminaries etc. The rough surfaces have diffuse scattering properties typically described with Bi-directional Scattering Distribution Functions (BSDF). These functions have complex multi-dimensional representation and in many cases can be measured in special devices.

In the computer simulations BSDFs can be applied in so-called "one-sheet" mode. Fig. 1 shows it schematically. BSDF of the whole plate (both reflection and transmission) is measured. The thickness of the sample with rough surfaces is ignored and to provide physically correct simulations the thickness of sample with BSDF has to be set to zero. Unfortunately the approximation in not acceptable if the sample thickness is important to provide correct simulations. For example if the rough surface is a side of a light guiding plate (LGP) and light propagates inside of LGP then we need for simulation the BSDF of individual rough surface but not BSDF of the whole plate. The accurate extraction of BSDF of individual rough surface is very complex task because multiple internal light reflections inside plate must be taken into account. Direct measurements of individual properties of rough surface are hardly possible because it requires setting up light source and detector of measuring device inside of sample medium. Moreover an influence of the flat side of sample has to be excluded somehow.

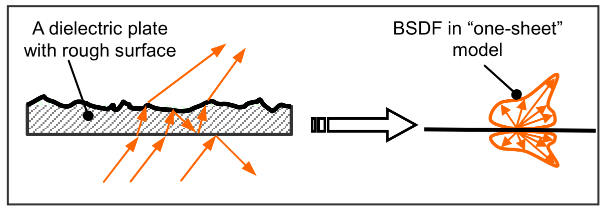

Fig. 1 "One-sheet" mode of rough surface

An alternative way of BSDF reconstruction is computer simulation of light scattering on the rough boundary of the sample media. It has a number of disadvantages too. In the current paper a combined method is proposed. It applies a computer simulation of BSDF with the following optimization of BSDF based on measurements of whole sample that provides very accurate reconstruction of BSDF of the individual rough sample surface.

2. Numerical methods of BSDF reconstruction

There are several numerical approaches of computation of the rough surface BSDF based on approximation of ray as well as wave optics. These solutions require measurement of the surface micro-roughness which is represented as height distribution of the representative sample area. An example of approach based on ray optics is micro facet model [1]. More accurate solution applies ray tracing inside of micro facet layer. The ray model is applicable for micro-roughness when height deviation is more than the light wavelength. For surfaces with smaller height deviations the wave solution based on Kirchhoff approximation [2] is used. Our investigations showed that both approaches have essential drawbacks. At first, the criterion of applicability of the method (ray or wave) is rather vague. Both methods are very "sensitive" to quality of micro roughness measurements and even small noise in measurements can result in essential inaccuracy of resultant BSDF. At second, Kirchhoff solution does not take into account light interreflections on micro facets and can be applied to smooth relief only.

Fig 2 presents measured and simulated intensity distribution of light transmitted through the plate sample with one rough surface. For simulation the BSDF of the rough surface was reconstructed using micro facet model.

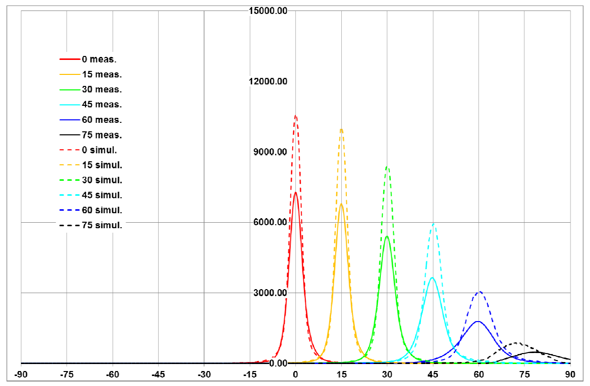

Fig. 2 Measured and simulated intensity distribution through the plate sample with one rough side

The measurements and simulations are fulfilled for several directions of the light incidence: 0, 15, 30, 45, 60, 75 degrees and marked with different colors. Solid plots present result of the sample measurements. Dash-line plots correspond to simulations of sample with reconstructed BSDF. It is seen that there is essential difference between simulation and measurement results.

3. Optimization of BSDF reconstruction procedure

Therefore measurements and numerical methods of BSDF reconstruction do not allow producing accurate result. Main idea of the proposed method is to combine both approaches. The heights of micro roughness and measured BSDF of the plate sample with this roughness are input data of the optimization process of BSDF reconstruction. Fig. 3 shows whole optimization procedure.

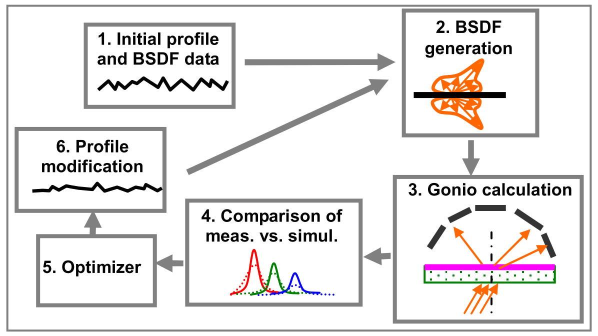

Fig.3 Scheme of BSDF optimization procedure

The optimization procedure consists of 5 steps:

1. Measurements of height distribution and BSDF of the plate sample with rough side.
2. Numerical generation of BSDF of rough micro-relief. Depending on the height deviations, the proper solution (ray or wave) is applied.
3. Numerical calculation of whole BSDF of plate sample with rough surface (in the units of the measured data).
4. Calculation of the difference Root Mean Square (RMS) between simulated and measured plate sample BSDF. If RMS is less than the defined threshold then optimization process is finished else we go to next step.
5. Optimization of parameters of micro roughness structure. Two types of surface profile modification are applied: (1) Gauss filtration to smooth profile (it allows to reduce diffuse scattering of the profile); (2) scaling of micro roughness heights (it allows to increase diffuse scattering of the profile).

Resultant BSDF can be used in accurate simulations of complex optical devices like a light guiding plate.

All numerical BSDF generations and lighting simulations were done by Lumicept [3]. All other calculations (Gauss filtration, optimization, procedures of RMS calculations, graph preparations) were written using Python script language and its open libraries (numpy, scipy etc.) integrated with Lumicept software. Taking into accounting that optimization procedure requires only two parameters (Gauss filter and scale) the whole optimization process is not expensive. Usually it requires less than ten iterations to reach acceptable RMS.

4. Design results

Fig. 4 shows measured and simulated intensity distributions of light transmitted through the plate sample with rough side. In the case of simulations, the BSDF was reconstructed using the described optimization procedure.

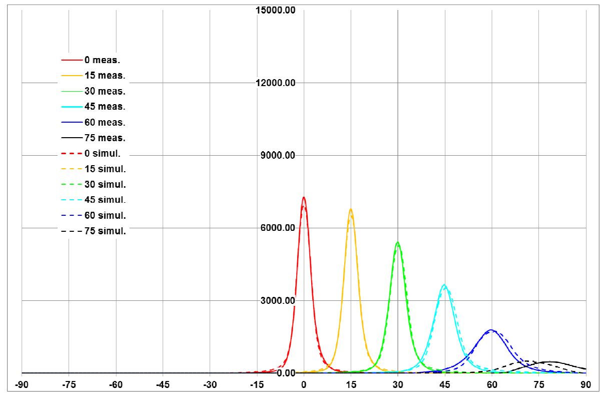

Fig. 4 Measured and simulated intensity distribution of light. BSDF was reconstructed by described solution.

We can see very close agreement between measured and simulated results. The paper demonstrates the case of light transmission only. However the similar optimization solution can be applied to the case of light reflection from the rough surface and agreement between measurements and optimally reconstructed BSDF will be within of defined threshold too.

5. Conclusion

The solution for reconstruction of BSDF of rough surface based on optimization procedure was elaborated. The comparison of measured and simulated BSDFs of real samples with rough surfaces proves correctness of our solution.

Acknowledgment: R&D was sponsored by RFBR grants #13-01-00454 and #15-01-01147.

6. References

1) B. Walter, S. Marschner, H. Li, K. Torrance, Microfacet Models for Refraction through Rough Surfaces, Eurographics Symposium on Rendering (2007)

2) Z.Wang, F. Xu, H. Ogura, A double Kirchhoff approximation for very rough surface scattering using the stochastic functional approach, Radio Science (2005) doi: 10.1029/2004RS003079

3) Lumicept – Integra Inc.
http://www.integra.jp/en/products/lumicept