Efficient application of Optical Objects in light simulation software

Sergey V. Ershov
Keldysh Institute for Applied Mathematics RAS

Dmitry D. Zhdanov
Vavilov State Optical Institute, St. Petersburg, Russia

Abstract

This article is a continuation of the previous work [1] which extends conception of OPTical ObjectS (OPTOS) and considers an application of the OPTOS in the SPECTER software [2]. The article considers three main applications of OPTOS implemented in SPECTER. They are OPTOS of scattering microstructure, OPTOS of volume scattering, and OPTOS of polarized Bi-directional Scattering Function (BSDF).

Keywords: CAD software, accurate light simulations, OPTical ObjectS, Light scattering microstructures, Volume scattering, Polarized BSDF.

1. Introduction

General purpose third party CAD software which often is used to create the initial lighting simulation scene is in most cases not capable to define or/and represent objects corresponding to complex optical elements — the key components of optical devices to be simulated or/and designed by software used for traditional light simulations. Even if a CAD software happens to be capable to define such an object, its representation is typically not sufficient or/and not suitable for efficient and accurate advanced lighting simulation. Problems of the light simulations dealing with the key components may be either wave nature of light which should be taken into account for accurate light simulations or very complex micro-geometry consisting of mega-, giga-, and tera- of deterministically or stochastically distributed complex geometrical objects (dimples, grooves, facets), or special effects of measuring devices dealing with light accumulation and future post-processing of the accumulated light.

To accommodate such optical elements into an original CAD scene, the special branch of classes of OPTical ObjectS (OPTOS) was designed. OPTOS, while securing efficiency and accuracy necessary in lighting simulation, allow retaining original properties of the scene (model) from CAD data base which is typical shared company wide. In other words OPTOS extend the original scene in non-destructive fashion, i.e. without affecting original data.

Independently of OPTOS interior the OPTOS have unified external program interface which is suitable for both Monte-Carlo and deterministic ray tracing. The unification allows using OPTOS in most of optical simulation software [1] where OPTOS work as a black box (ray emitter, ray transformer and ray accumulator). Moreover the unification of OPTOS program interface provides smooth integration of new OPTOS functionality to light simulators. The only requirements of the smooth integration are that new OPTOS functionalities have to follow OPTOS program rules and suit external OPTOS program interface. From the user viewpoint OPTOS are procedural objects controlled by external parameters like numerical parameter values, tables and functions. This type of data representation is most convenient because it does not carry any program specifics and can be adopted by any light simulation software.

Basis software of OPTOS integration is SPECTER [2-4] where OPTOS exist for years. OPTOS were integrated to Monte-Carlo ray tracing module of SPECTER and provide accurate light simulation of optical effects like volume scattering, polarized light scattering on special filters like Dual Brightness-Enhancing Films (DBEF), light scattering on deterministic or stochastic microstructures. Modifier user interface of SPECTER provides all operations to input OPTOS procedure and control all kinds of its parameters. Moreover responding to particular customer needs SPECTER has library of OPTOS.

The article regards three main aspects of OPTOS applications in SPECTER:

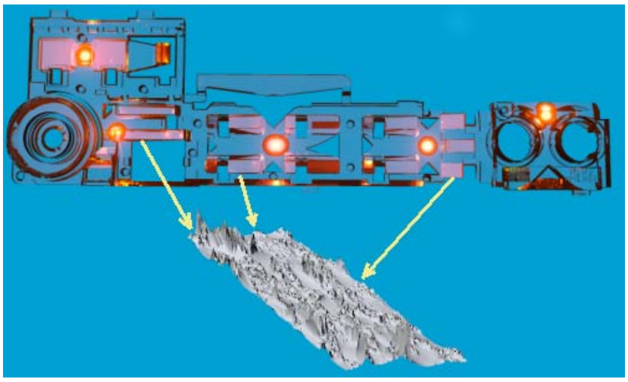
- Light scattering microstructures.
- Volume scattering.
- Polarized BSDF.

2. Light scattering microstructures

A backlight illumination system for a Liquid Crystal Display (LCD) is an example of microstructure application. Such devices can contain various prism films, surfaces with rough finished profile or containing a lot of elements with complex distributions of micro-dimples / micro-grooves placed on one or several faces of a light guiding plate.

Modeling the geometry with microelements is rather difficult due to huge number of microelements of which there can be millions and with complex spatial distribution. So a very specific approach is required to simulate such micro-geometry. Moreover inside of the micro-geometry there are a lot of partial approaches which allow optimization of concrete types of microstructures.

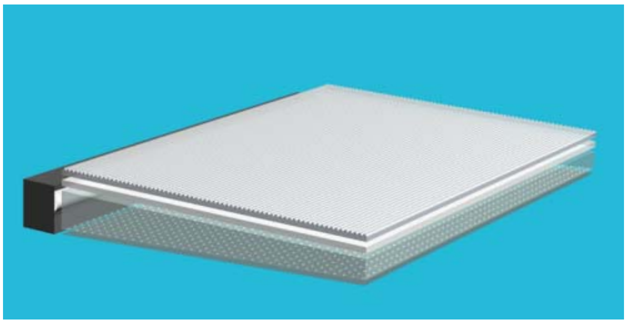
The first type is micro-roughness. Example of device with rough finished elements is shown in the picture 1.



Picture 1. Example of rough finished elements in tape car panel.

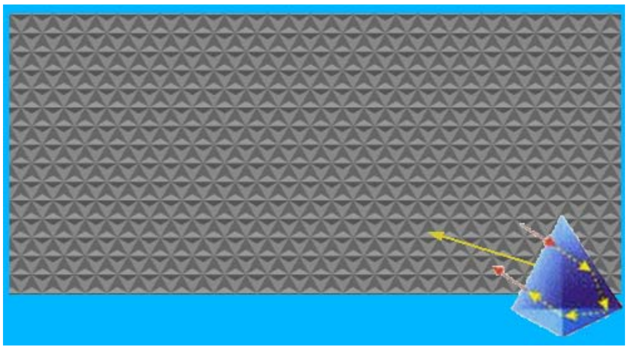
The surface roughness may be specified by one of two ways. Explicit way supposes that the micro-relief is distribution of the relief heights in the knots of a regular grid and can be directly measured by a 3D scanner. Implicit way supposes that the micro-relief is specified by means of density distribution of facet normals.

Other kinds of micro-geometry OPTOS support distribution of dimple or grooves on the plane (usually rectangular) surface. This type of OPTOS is applied in modern optical devices like LCD shown on picture 2. Usually bottom face of the Plane Light Emitter (PLE) has micro-dimpled structure and sheets structure while sheets have prism structure.



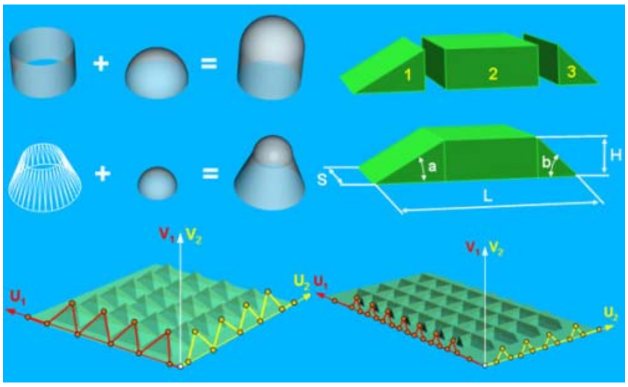
Picture 2. Example of LCD using scattering micro-elements.

Another example of micro-dimples application is reflective sheets with prism or lens structure. Example of the prism reflective sheet is shown in picture 3.



Picture 3. Example of reflective sheet.

One can see that grooves and dimples are complex objects whose shape can be either imported from CAD data (IGES and DXF formats), or built as a composition of simple shape primitives (plane, tube, cone, sphere segment, pyramid with rectangular and rhombic bases, torus, triangle mesh, etc.), or be a composition of other dimples or grooves (for example, dimples are groove intersections). Examples of possible ways of dimple construction are shown in picture 4.

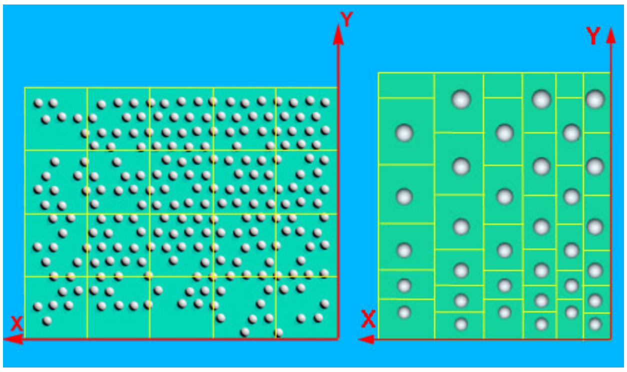


Picture 4. Possible ways of dimples construction.

The dimples may have complex distribution in space. The distribution can be either:

- Random, when position (and maybe size and orientation) of a dimple is chosen at random and only the *density* of that distribution is specified by the user, or
- Deterministic when location, sizes, orientation and other parameter of *each* dimple are explicitly determined by the user (e.g. as a periodic pattern of diffraction grating).

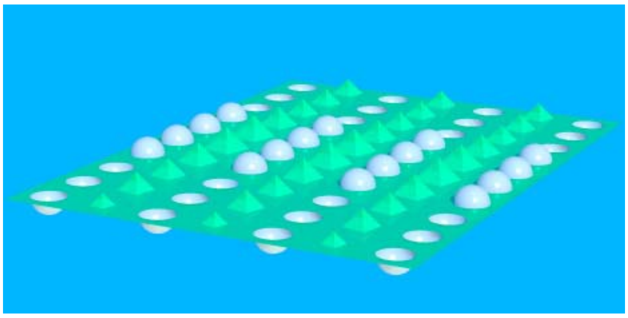
Examples of the random and deterministic distributions are shown in picture 5.



Picture 5. Random (left) and deterministic (right) dimple distributions.

Depending on complexity of dimples and their distribution, allowed number of dimples varies from ten millions up to billion of billions.

Moreover micro-geometry may include dimples of different types (or dimple series) with different orientation. Example of this microstructure is shown in picture 6.

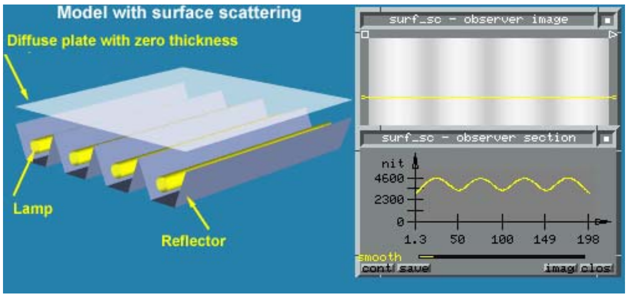


Picture 6. Combination of different dimple series on single microstructure area.

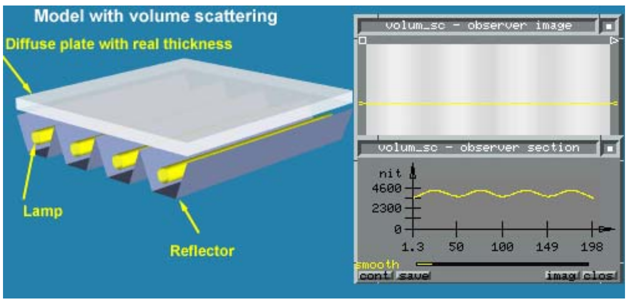
All kinds of micro-geometry OPTOS use ray tracing approach and in the frames of the approach provide high simulation accuracy and speed.

3. Volume scattering

A lot of materials used in optical design have complex volumetric properties, and precise simulation of these properties may be very important. Usually a material with Volume Scattering consists of an embedding medium with small particles dispersed in it, like milk with fat droplets. A well-known example of Volume Scattering material is a polycrystalline opal glasses, where scattering “particles” are just those “dislocations” in the same glass medium.



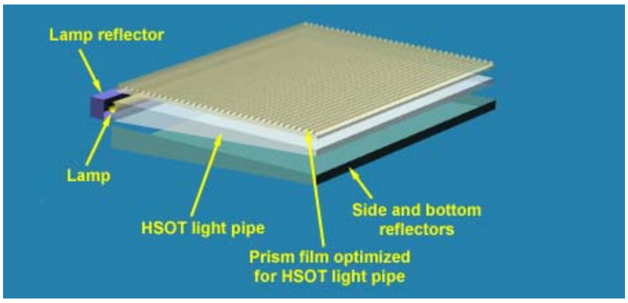
Picture 7. Approximation of volume scattering by BSDF.



Picture 8. Accurate simulation of Volume Scattering effect.

There are various applications of volume scattering materials. One example is diffuse plates of finite thickness. Substituting that diffuse plate with a Bi-directional Scattering Function (BSDF) of a *sheet* is not accurate approach because ignores subsurface light diffusion (while in a BSDF light exits it from the same point it entered it, changing only direction). Neglecting this light propagation under surface can result in a noticeable error. Luminance distribution just above the diffuse plate for a simplified surface model has some difference in respect to simulation of diffuse plate with real Volume Scattering. Examples of these simulations are shown in pictures 7 and 8 correspondingly.

Another example is application of materials with Volume Scattering in light guide plates (LGP). Simulation of such kind of a device is impossible without support of Volume Scattering at all. Backlight system can be designed by a tradition way using scattering dots or dimples on the bottom side of LGP, see picture 2. An alternative solution is LGP made of Highly Scattering Optical Transmission (HSOT) polymers; example of such device is show in picture 9. These polymers have internal microscopic heterogeneous structures (“particles”) and are characterized by volume scattering properties. Using such polymers simplifies construction of backlight devices and allows achieving better light parameters.



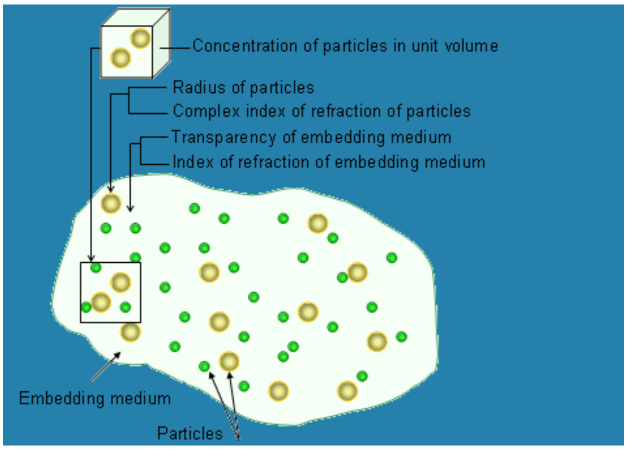
Picture 9. Example of HSOT light pipe device.

OPTOS of Volume Scattering is supported for Monte-Carlo calculations [5] and its implementation allows taking into account light polarization effects. The polarized model allows simulating transformation of polarization state of light on the particles. In this case the phase function elements will be a Mueller matrix of transformation of polarized light.

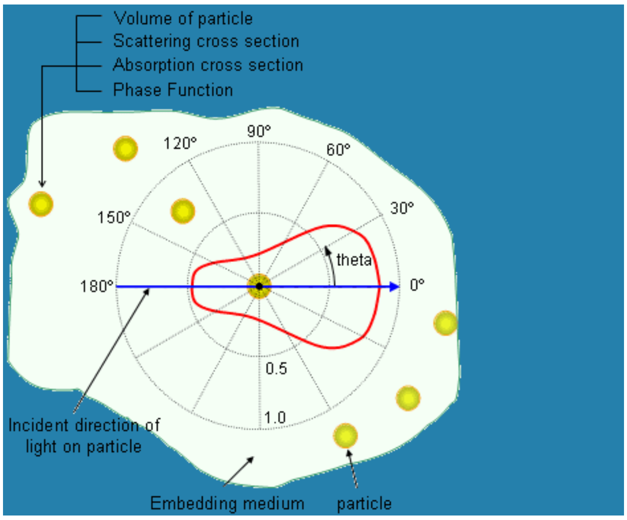
OPTOS of Volume Scattering supports two main models of scattering particles definition. The first one assumes uniform dielectric spheres (to be extended by other shapes) whose scattering properties are calculated with Mie/Rayleigh formulae, and the second one allows free-hand definition of phase function. Whether to use Rayleigh or Mie formulae is decided based on particle size. Moreover both models support combination of an unlimited number of particle species differing in concentration, refraction index, radius, volume, phase function, etc.; also different series may come in different models (spheres specified by composition *vs.* particles with explicitly given phase function).

The Volume Scattering material is defined by combination of particle parameters (concentration and either phase function given directly of composition: radius and refraction index) and parameters of the embedding medium (refraction index and transparency). Picture 10 shows how the Volume Scattering OPTOS can be specified in the frames of Rayleigh/Mie model and combination of different particle series in the single embedding medium.

Example of a user-defined model is shown in picture 11.



Picture 10. Example of the Volume Scattering material defined with help Rayleigh/Mie model.



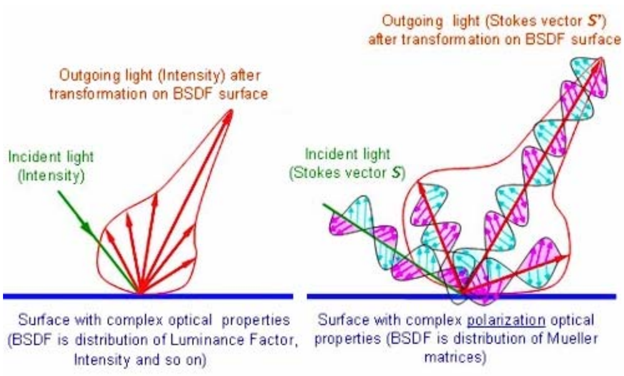
Picture 11. Example of user-defined model of Volume Scattering.

The latter (shown in Picture 11) is more general model of volume scattering. The user can specify volume scattering directly through phase function (angular distribution of scattered light) and cross-sections (scattering and absorption) of the scattering particles and embedding medium. They can be obtained by measurement or calculated elsewhere, which allows extension of the simulator.

4. Polarized Bi-directional Scattering Function

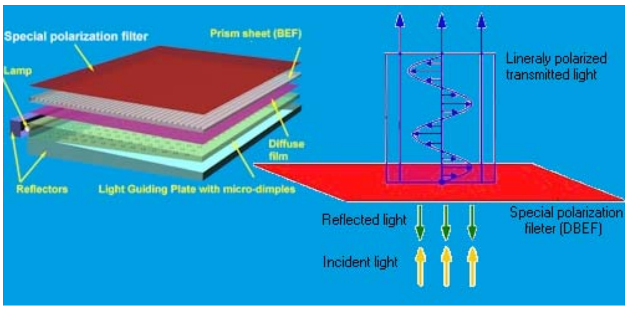
In many optical systems the polarization state of light is of critical importance and must be considered in design. Implementation of Polarized BSDF allows describing practically any complex transformation of light on surfaces. So it becomes possible to manage not only energetic light parameters but by polarization state of transformed light as well.

A usual non-polarized BSDF (diffuse reflectance) is angular intensity distribution which describes only energetic and color transformation of light by the surface. More complex BSDFs are used to support polarization transformation of light. Polarized BSDF based on the Mueller calculus can model almost any polarizing devices, including retarders, linear and circular polarizers, and custom types. It allows modeling non-polarized and partially polarized lights as well as fully polarized light. With a Mueller matrix non-polarized light can be changed to polarized light and vice versa. Picture 12 schematically shows difference between non-polarized and polarized BSDF.



Picture 12. Examples of non-polarized BSDF (left) and polarized BSDF (right).

A perspective application of polarized BSDF is simulation of complex polarization filters, like DBEF used as elements of LCD displays. Example of this device is shown in figure 13. The specific feature of such special polarization filters is very low light absorption and complex transformation of polarization state of light.



Picture 13. Example of LCD with special polarization filter.

The main feature of such a filter is its ability to linearly polarize transmitted light and jointly to reflect light. A typical linear polarization filter passes and linearly polarizes less than a half of light. The rest of light is absorbed by the filter. The simulation of such kind of filters is a complex task. Polarized BSDF tool allows doing it.

The specification of polarized BSDF OPTOS is based on the Mueller calculus — polarization state of incident/outgoing light is described with the Stokes vector. The transformation of polarization state of light on the surface is determined by the Mueller matrix. Multiplying of the Mueller matrix by the Stokes vector of input light gives the output Stokes vector of light transformed by a surface for defined outgoing direction:

$$S = \mathbf{M} * S', \text{ where}$$

S is the Stokes vector of incident ray
S' is the Stokes vector of output ray after transformation on BSDF surface.
M is the Mueller matrix describing transformation of the Stokes vector incident ray to the Stokes vector of output ray.

OPTOS of Polarized BSDF is a multi-dimensional procedural function of elements of Mueller matrices defined on a regular grid of illumination / observation angles and color as the function parameters:

Polarized BRDF = **M**(color, incident angles, observation angles)

The procedural script used in OPTOS allows describing the multi-dimensional function and opens user control to "external" parameters of the procedure.

5. Acknowledgments

This work was supported by INTEGRA Inc. (Tokyo, Japan) and Computer Graphics department of the Keldysh Institute for Applied Mathematics RAS.
The version of the paper with color illustrations can be found on http://www.keldysh.ru/pages/cgraph/publications/cgd_publ.htm

6. References

[1] Andrei B.Khodulev, E.Kopylov, Dmitry D.Zdanov. Requirements to the Scene Data Base. The 8-th International Conference on Computer Graphics and Visualization, Moscow, Russia, September 7-11, 1998.
[2] Integra Visual Computing, http://www.integra.jp/
[3] A.Khodulev, E.Kopylov Physically accurate lighting simulation in computer graphics software. Proc. GraphiCon'96 - The 6-th International Conference on Computer Graphics and Visualization, St.Petersburg, 1996.
[4] А.Г. Волобой, В.А. Галактионов, К.А. Дмитриев, Э.А. Копылов. Двунаправленная трассировка лучей для интегрирования освещенности методом квази- Монте Карло. "Программирование", № 5, 2004, с. 25-34.
[5] Akihiro Tagaya, Yasuhiro Koike. Highly scattering optical transmission polymers for bright display. Macromol. Symp. 154 (2000), 73-82.

Authors:

Sergey V. Ershov, senior researcher of the Keldysh Institute for Applied Mathematics RAS.
E-mail: measure@spp.keldysh.ru.

Dmitry D. Zhdanov, a collaborator of Department of Optical Systems Design of Vavilov State Optical Institute.
E-mail: ddzhdanov@mail.ru