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THE PHYSICS OF LIGHT DISTRIBUTION IN HOLLOW STRUCTURES

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INTRODUCTION

The purpose of this paper is to serve as an introduction, for non-physicists, to the subject of light distribution in hollow structures. The motivation for light distribution is the importance of getting the maximum value from available light. We all recognize that photons cost money (one photon costs about $\$10^{25}$ to make) so we obviously want to try to make the maximum number of photons for a given cost. What is often overlooked, however, is that these photons have the highest value only if they are delivered to the right place in the correct quantity. This means that there is often substantial economic value in the high quality distribution of light. This problem is discussed from a very general perspective, in order to show the role of general optical films for manipulating light. The underlying physics at work in such films is described, and examples of common optical light distribution films are provided.

THE DIFFICULTY OF LIGHT DISTRIBUTION

One might expect that since light travels very rapidly and efficiently in air, light distribution should be an easy matter. Surprisingly, it is this very property of light which makes it so difficult to control. Light rays spread fast in all directions, and it requires sophisticated optical engineering to "contain" light in a desired region and "channel" it so that it has the desired distribution at the final destination.

A different kind of problem results from the common opinion that light should be easy to understand, which probably arises because light is a visible part of our everyday lives. In reality, the behavior of light is often non-intuitive and generally quite different from the impression we get from our human visual perception system.

And not only is light confusing, but it is hard to measure as well! It is interesting to compare light to electricity in this regard. Although electricity is invisible, and unfamiliar to many of us, it is quite easy to measure. One can buy a voltmeter for about \$100 that will measure a voltage to an accuracy of 1 part in 10,000. In contrast one must pay \$1000 to buy an illuminance meter that can only measure to 1 part in 100. From this perspective, light is a thousand times harder to measure than electricity!

A simple example shows one way that the subject of light distribution can be confusing. Fig. 1 shows a device called an integrating sphere, which in this case is a hollow sphere with a white interior, containing at the center a light source which emits 10,000 lumens of light. The sphere interior area is 10 square meters, just to keep the numbers simple. It seems natural to estimate

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that the luminous flux density, (that is, the illuminance), at the inside surface of this sphere would be simply given by

$$I = \frac{10,000 \text{ lumens}}{10 \text{ m}^2} = 1,000 \text{ lux} \quad (1)$$

In reality, there is a correction required due to the reflectivity of the inside surface of the sphere. In Fig. 1, the sphere interior has a surface reflectivity of 0.9, and this increases the illuminance at the interior of the sphere, because the light undergoes several reflections before being absorbed. In fact the actual illuminance is not even close to the above guess. It is actually 10 times larger, since the average light ray reflects 10 times! This is just one example out of many cases in which the behavior of light rays, while basically simple, is nevertheless non-intuitive.

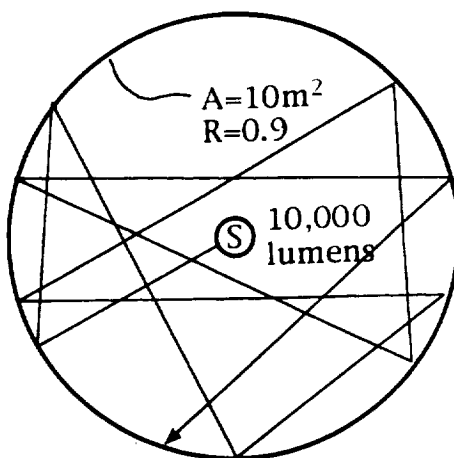


Fig. 1

A HIERARCHICAL VIEW OF LIGHT DISTRIBUTION

Fig. 2 is a general depiction of the light distribution problem. There is a structure filled predominantly with air, into which light is made available from either the sun or an artificial light source. The structure contains general surfaces which will be called "optical films" in the rest of this paper. These films interact with light rays, to guide them toward a "target" which represents the region where the light is wanted for some purpose.

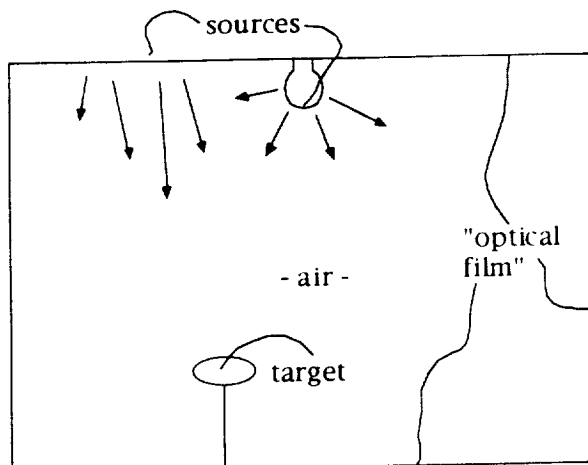


Fig. 2

It is helpful to view this situation on three hierarchical levels. The highest level is that shown in Fig. 2, and in more detail in Fig. 3, in which an example light ray undergoes numerous interactions with a variety of optical surfaces of arbitrary shape and optical characteristics. The circle in Fig. 3 shows an area of an optical surface which is small enough that the surface appears essentially flat within this circle, but which is large relative to the detailed structure of the surface itself. Typically, this circle might be a few millimeters in diameter.

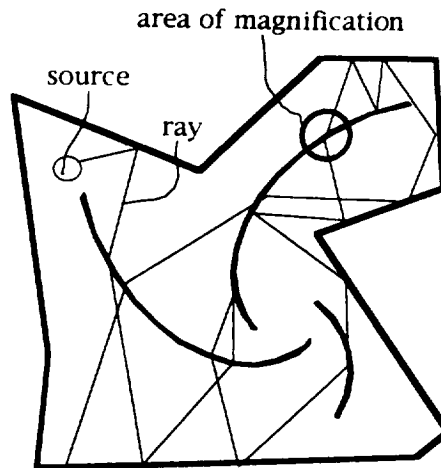


Fig. 3

Fig. 4 is a magnified view of the circle of Fig. 3, and represents the second hierarchical level of analysis. At this level, the optical surface can be seen in general to be a complex structure which interacts with light. The optical film contains interfaces between different media, and the optical behavior of the film is result of the light transmission properties of these media and the shape of the interfaces. Usually the behavior of the media are simple and the shape is complicated. At this level, the behavior of light is highly complex and non-intuitive.

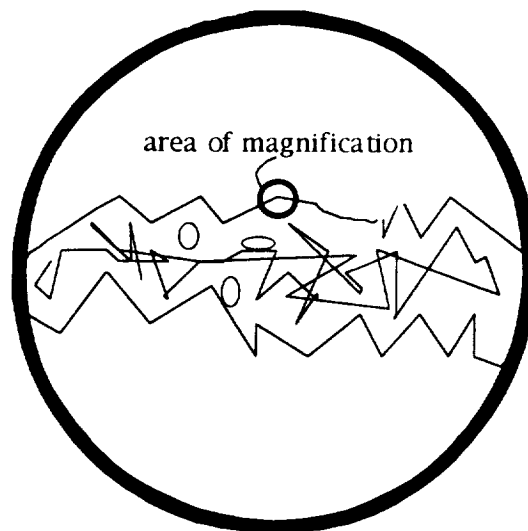


Fig. 4

Before moving on, it is important to note that this description of an optical film is very general. For example, it applies to all surfaces one might find in a room, outdoors, in a light fixture, and almost anywhere else.

The circle in Fig. 4 represents a view of a single optical interface in an optical film. The circle is small enough that the interface appears flat, but is large compared to a wavelength of light, so that it still makes sense to talk about light rays which travel in straight lines. For example, the diameter of this circle might be a bit less than a tenth of a millimeter.

Fig. 5 represents a magnified view of the circle in Fig. 4; this is the lowest level of the hierarchical analysis, and it is pleasing to find, as described below, that the behavior of light at this level is simple indeed.

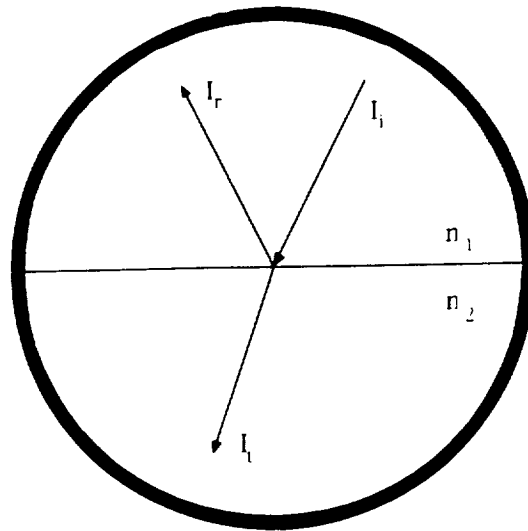


Fig. 5

THREE BASIC INTERACTIONS BETWEEN LIGHT AND MATTER

There are really just three cases one needs to understand, two involving interfaces, and one involving bulk transmission. Fig. 5 depicts one of the two interface cases, namely the interface between one dielectric material and another. The term dielectric basically means a material which is not metal and which is therefore quite clear at this size scale. Examples include glass, plastics, water, and air. For the purpose of this discussion, such non-metallic materials can be characterized by a number called the refractive index, usually denoted n . In the case of Fig. 5, the interface is between dielectric materials having different refractive index values of n_1 and n_2 . An original light ray has an intensity I_i when it hits the interface, and as shown, some of the light energy reflects with intensity I_r , and some of the light energy is transmitted with intensity I_t . There are exact formulas that describe the relative intensity of the reflected and transmitted rays, but these are not needed in this discussion. The main thing that is important here is that there is

no energy loss at this interface. Another way of saying this is that:

$$I_i = I_t + I_r \tag{2}$$

Usually, the reflected ray of Fig. 5 is much less intense than the transmitted ray. For example, this is the reason that we can see easily through a window, (although a slight reflection is also noticeable). However it is interesting to note that for some situations the reflected ray can be intense and the transmitted ray can be weak. In fact there is special case known as total internal reflection, in which there is no transmitted energy at all, and all of the light energy is reflected. This phenomenon is used in optical fibres, and also in certain hollow light guides, as will be discussed at the end of this paper.

Fig. 6 is on the same size scale as Fig. 5, and shows the second important interface case. This is the case of an interface between a dielectric material and a metal. At the size scale of Fig. 6 light travels a negligible distance in metal, and therefore only a reflected ray leaves the interface. The intensity of the reflected ray is given by the following formula:

$$I_r = RI_i \tag{3}$$

where R is the reflectivity of the metal surface. The one really important thing about this case is that R can never be 1. That is, the reflected ray is always less intense than the incident ray, with the difference representing energy which is absorbed by the metal. R typically ranges from .7 to .95, and this means that any light distribution system in which light reflects off metal many times will be intrinsically inefficient. Incidentally, such dielectric/metal interfaces are common in everyday life - they are found in mirrors, and also on the surface of shiny metal objects.

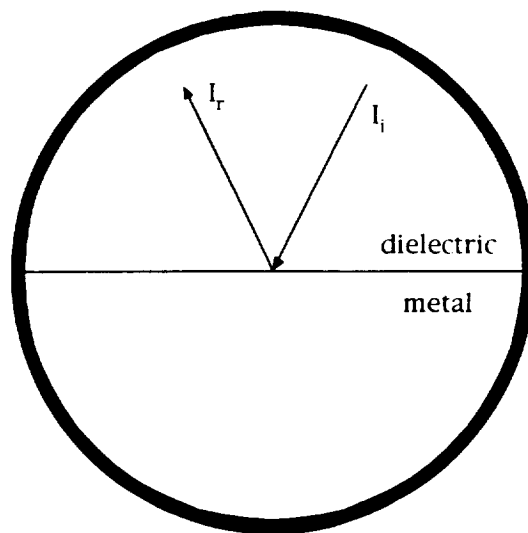


Fig. 6

Fig. 7 depicts the third important interaction between light and matter - the absorption of light as it travels through a dielectric medium. As mentioned earlier, the actual interface between two dielectric media is not absorptive. (The reason for this is that the interface itself has virtually zero thickness). However as a light ray travels through a dielectric material, some energy is absorbed. The fraction of energy lost per unit length is called the absorption coefficient, k . In solids, k can vary from as high as 10,000,000 per metre to as low as .01 per metre in certain materials, and is much lower in air. Also some materials may have dramatically different absorption coefficients for different wavelengths of light. It is this phenomenon which gives rise to color in optical surfaces.

The three phenomena described above - reflection/transmission at a dielectric/dielectric interface, incomplete reflection at a dielectric/metal interface, and absorption during transmission through a dielectric - are all that is necessary to understand the optical characteristics of the surfaces which are normally used in the controlled distribution of light. Of course applying these simple principles in order to determine the optical behavior of a given optical surface can be complicated, but is good to know that underlying the complexity is some simple physics.

Rather than theoretically predicting the behavior of an optical film, we often take a shortcut by going back to the second level of the hierarchy, and experimentally observing the optical behavior of a given film, as represented in Fig. 8. We can summarize the behavior of a film by describing the distribution of reflected and transmitted light intensity for any given direction of incident ray. This information is just a big data file for a computer to use to model the travel of light rays at the highest hierarchical level where we began.

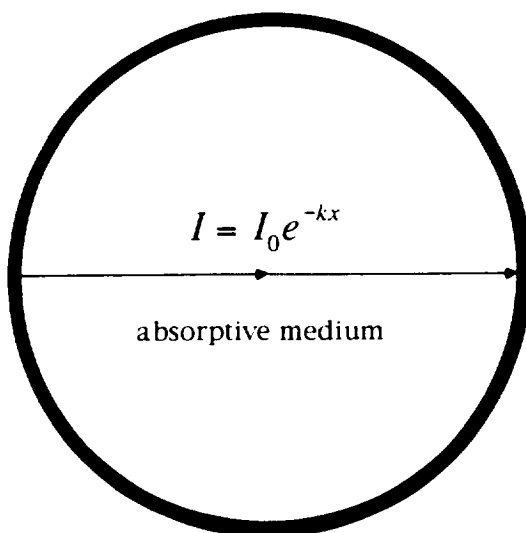


Fig. 7

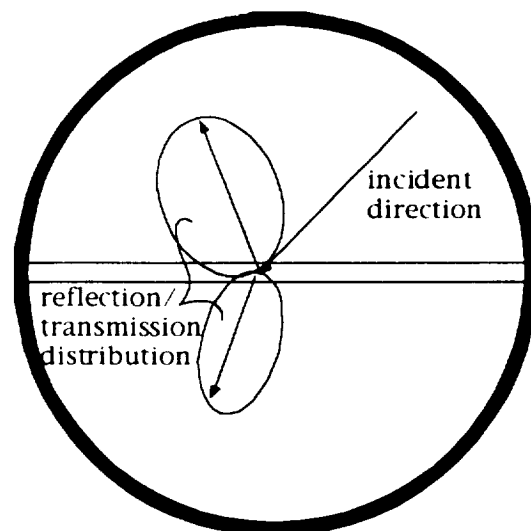


Fig. 8

EXAMPLES OF OPTICAL FILMS USED IN LIGHT DISTRIBUTION

The rest of this paper presents examples of common optical surface used in light distribution. The first, shown in Fig. 9, is a white surface such as paint, paper, cloth, snow, milk, etc. Such white materials consist entirely of dielectric/dielectric interfaces, usually formed by high refractive index particles or fibres in a matrix of low refractive index material, such as air or plastic. Each time a light ray interacts with such a particle, it is reflected or transmitted in a different direction than the incident one. The result is a "random walk" for the light ray, which results in most of the light energy re-emitting from the surface it entered originally. It is important to note that the ray is re-emitted with a random direction, independent of the incident ray direction, which can be useful, or undesirable, depending on the situation. White paints are usually not highly efficient - typical reflectivities are in the 70 to 80 percent range, but some special paints can exceed 90 percent. By the way, if the bulk absorptivity of the particles or of the matrix is wavelength dependent, the result is colored paint.

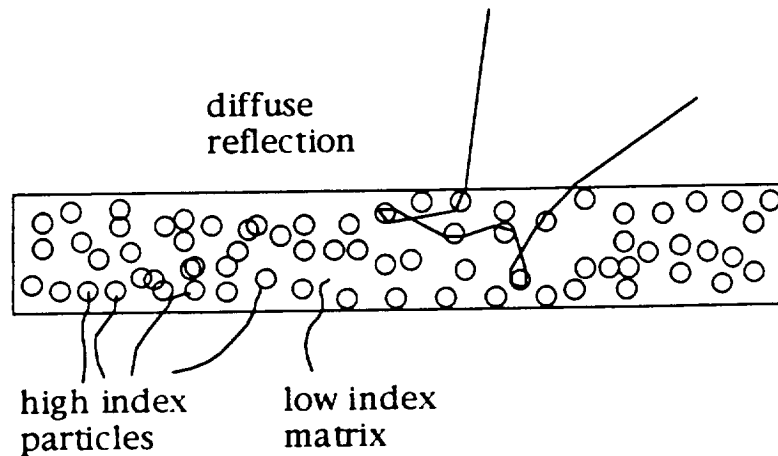


Fig. 9

Fig. 10 shows a useful film for reflecting light in a specular manner. Specular reflection means that the reflected ray travels in the same direction as the incident ray, except that the component of travel in the direction perpendicular to the surface is reversed. Such metalized films generally consist of a smooth substrate, such as polyester film, coated with a thin layer of metal, such as aluminum or silver, and further coated with a transparent cover to keep the metal smooth and to protect it from corrosion. Such films are very useful in some light guiding applications, but they suffer from the disadvantage of absorbing from 5 to 20 percent of the light with each reflection.

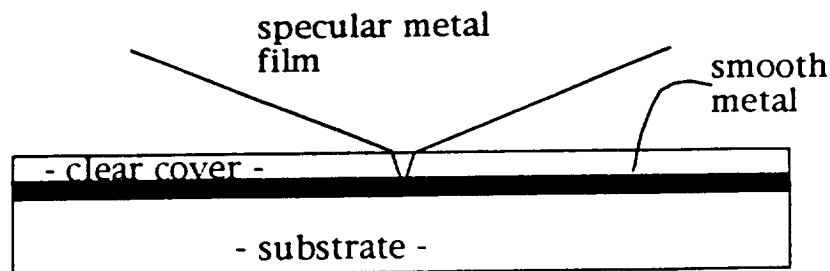


Fig. 10

Fig. 11 shows a fairly new and useful kind of general optical film, known as a textured dielectric film. The specific example shown in Fig. 11 is called Fresnel lens film. It consists of a thin dielectric sheet (often acrylic or polycarbonate resin), in which one or more of the surfaces has a prismatic structure which causes light to change direction. Such surfaces can obviously have a wide variety of shapes, and they can therefore do a variety of interesting things to the reflection and transmission characteristics of the film. Importantly, the dielectric material can be very non-absorptive. As a result such films reflect and/or transmit almost all incident energy, with virtually none lost to absorption.

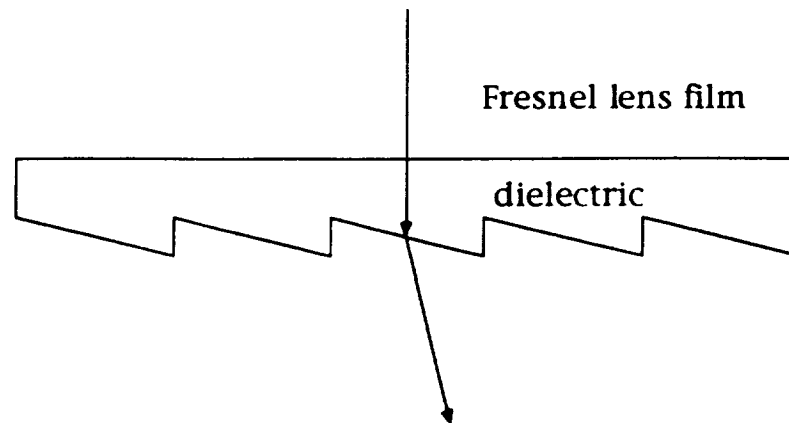


Fig. 11

Obviously there is a huge variety of such films, but in the interest of brevity, only one other example will be shown here, in Fig. 12. This film, known as prism light guide wall material, is very useful in light distribution. It has one flat surface, and one textured surface consisting of an array of linear right angle prisms inclined at 45 degrees to the flat surface. As shown, these prisms can reflect light by two total internal reflection steps, so the light is redirected back out of the surface from which it entered. Here we have a way for a film to reflect light much like a metal film, but without absorption.

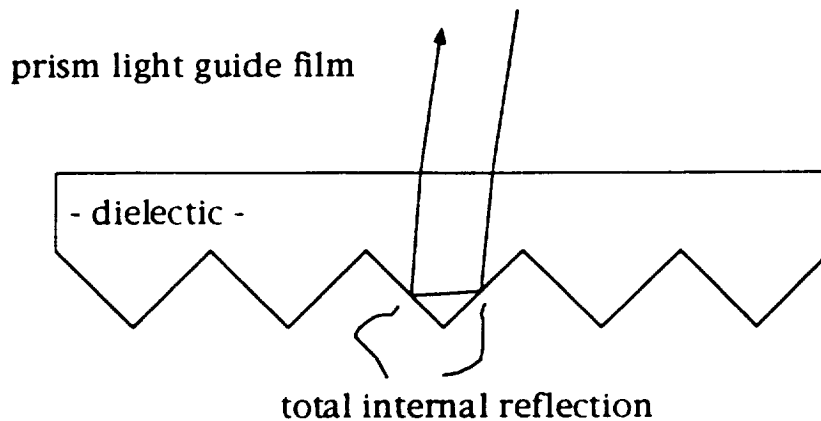


Fig. 12

This provides an important answer to the problem of channeling light in hollow structures with high efficiency. Fig. 13 shows a prism light guide - a tube whose walls are formed of prism light guide film, so that light rays entering one end can be piped down toward the other end.

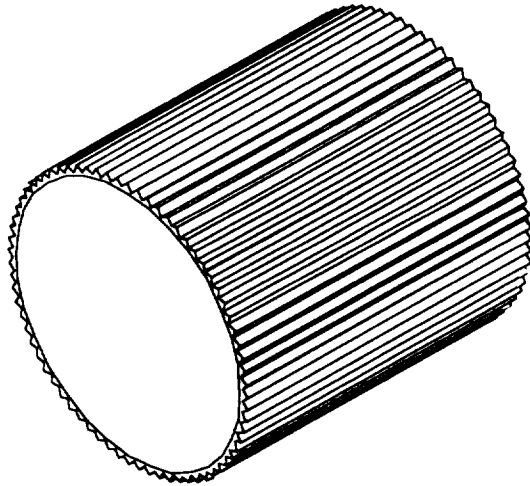


Fig. 13

CONCLUSION

By combining the prism light guide concept with the other kinds of optical films described above, it is possible to produce a wide variety of practical light distribution arrangement, on the highest level of the hierarchy where this paper began. Such arrangements are discussed elsewhere in detail; the intent of this paper has been to provide a greater familiarity with the underlying physics behind such work.

