Light losses in hollow, prismatic light guides related to prism defects: a transmittance model

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Hollow, cylindrical, prismatic light guides (CPLGs) are optical components that, using total internal reflection (TIR), are able to transmit high-diameter light beams in daylight and artificial lighting applications without relevant losses. It is necessary to study the prism defects of their surfaces to quantify the behavior of these optical components. In this Letter, we analyze a CPLG made of a transparent dielectric material. Scanning electron microscopy (SEM) and the topographic optical profilometry by absorption in fluids (TOPAF) imaging technique are conducted to determine if there are defects in the corners of the prisms. A model for light guide transmittance that is dependent on prism defects is proposed. Finally, a simulation and an experimental study are carried out to check the validity of the proposed model.

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The use of natural light inside buildings provides high-quality lighting, reduces energy consumption, and increases comfort and productivity. Light pipes can transfer light from a building's roof into the depths of the building. The overall wattage of the installed lights is reduced, and therefore, the consumption of electricity decreases, due to the decreased use of artificial lighting. Tubular light guides are a complementary product to conventional skylights and windows that can complement the artificial lighting in areas not usually covered by windows and skylights[1].

Prismatic light guides are hollow structures internally covered with prismatic sheet; they offer a technical alternative for light transport in tubular guidance systems. The prismatic light guide leads light beams using total internal reflection (TIR) and provides light transmission with high efficiency and homogeneous light distribution in buildings with minimal color shifts[2]. The film has one flat surface, and the other one consists of a textured surface with extruded prisms. The material can work as reflective or transmissive, depending upon the angle at which a light ray strikes the surface of the film. In a cylindrical, prismatic light guide (CPLG), light rays are propagated by TIR when the input light is incident under the solid angle accepted for flux transmission[3]. Light that does not fulfill this requirement is partially extracted out of the guide. Despite the fact that the manufacturing process in actual technologies makes possible the development of optimal prismatic films, it is important to analyze some geometric parameters that can affect the light output efficiency. Prism defects include corners that are not strictly 90°[4], surfaces that are not optically flat, and optical inhomogeneity in the film material.

Whitehead[3,5], along with other researchers[6], has studied the main characteristics of prismatic light guides since the beginning of their development. They have provided some methods to estimate the efficiency of prismatic guides as a function of various parameters that may affect their behavior. Those studies show the importance and complexity in the search of a model to estimate the efficiency of prism light guides. The specific geometry of the prismatic guide makes it necessary to quantify the influence of different factors that affect losses. Nowadays, new lighting requirements for buildings, new simulation capabilities, and current manufacturing processes suggest the need to define models to predict the performance of prismatic light guides that avoid the previous technological limitations.

In this Letter, we study the effects of prism corner geometries and imperfections on the efficiency of light guides. For this purpose, scanning electron microscopy (SEM) and the topographic optical profilometry by absorption in fluids (TOPAF) imaging technique[7,8] were used to obtain the measurements of the prism's microgeometry. We propose an advanced semiempirical model for light guide transmittance that takes into account corner defects, absorption, and the aspect ratio of prismatic light guides. The proposed transmittance model has been checked with experimental measurements in real light guides and with ray tracing simulations.

Surface roughness and irregularities are important factors in determining the satisfactory performance of the prismatic film structure. In order to quantify the area of the irregularities, the surface measurement that takes the nanometric scale into account has been quantified by two systems: SEM and the TOPAF imaging technique.

SEM (Jeol, JSM-6400) was used in order to determine the surface topography measurements and the quality of the corners. Prior to imaging, samples were mounted onto the sample holder and sputter coated with a thin gold layer (8 nm). They were then studied with SEM using an acceleration potential of 25 kV.

Figure 1(a) represents the top view of a prismatic surface with extruded prisms at a 90° angle. The outer edge of the prism is represented as a horizontal line of brightness through the center of the image, and the valleys correspond to the parallel, marginal black lines. The prism width value was 340 μm (cross section valley to valley). The SEM analysis revealed that the prism slope was quite homogeneous. In contrast, the white areas show small irregularities near the area of the vertex. Under SEM image analysis, we can estimate by image processing (Otsu's method)[9] the percentage of area occupied by irregularities, which represents 1.5% of the total area. The area that has the higher concentration of defects corresponds to the corners; it has the medium width of 4.29 μm, with a standard deviation of 2.40 μm. Figure 1(b) shows the prism vertex in closer detail.

The results obtained with this technique provide only an approximation of measures because SEM is basically a two-dimensional technique. Three-dimensional (3D) information could only be obtained by tilting the sample. Thus, to determine this change in the corners of the prisms, the defects are investigated by topography detection.

The TOPAF imaging technique is an appropriate technique for measuring the 3D profile of transparent complex optical surfaces and was used to perform some quantitative profilometric measurements of the prismatic film at several locations[8,10]. In Fig. 2(a), we show the topographic image of a particular location of the prismatic film. From these data, we can extract the local slope, which is shown in Fig. 2(b).

A detailed analysis of the absolute slope map provides an estimation of the area ratio that is geometrically out of design, i.e., with slope values that are significantly different from ±45°. In fact, we may appreciate the tendency of the external corners of the prism to have burrs [see Fig. 2(b) (scale bar, 1.1–1.25)], and to flatten at

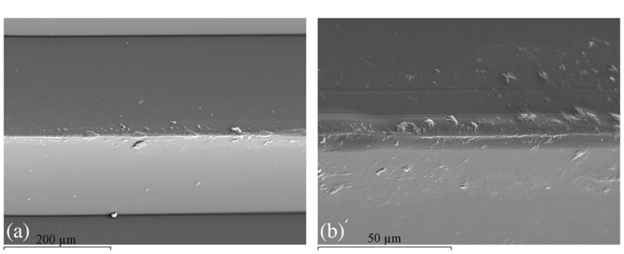

Fig. 1. Top view of prismatic film. (a) SEM surface image of polycarbonate thin prismatic film surface sputter coated with a thin gold layer. (b) A detail of the vertex.

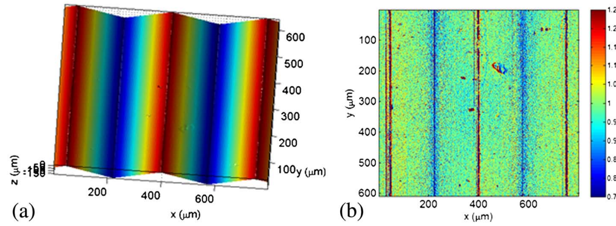

Fig. 2. (a) Topographic image of the prismatic film obtained by the TOPAF technique. (b) Slope analysis of the previous image in absolute values. The slope is ±45° ($\tan(45°) = 1$) overall except in the defect and at the ridges.

the internal corners (scale bar, 0.75–0.95). Some zoomed-in images of this previous slope map are shown in Figs. 3(a) and 3(b) for the external corners and Figs. 3(c) and 3(d) for the internal corners.

From a collection of several images, we characterize the prismatic film at several locations and estimate the effective area where the profile clearly departs from the design values. In terms of comparison with the model implemented for the simulation of propagation and losses, we can translate it to an effective width of losses. For the external corners, we have effective loss-widths of about 3–7 μm and for the internal corners (valleys) we have effective loss-widths of about 2–4 μm. An average of around ∼4 μm can be expected as a representative value of the inspected film.

In order to generate a suitable 3D model for a ray tracing, an evaluation is necessary to make some approximations in the geometry profile. In this case, we consider the corners that include the higher width of defects in the cross section as a radius of curvature r. This approach is used taking into account the relation of the circles with radii that are linearly proportional to the trigonometric function $x = 2rsen(\pi/2)$, where x is considered the chord length, α is the angle subtended at the center by the chord (90°), and r is the radius set by the enrolled circle. This

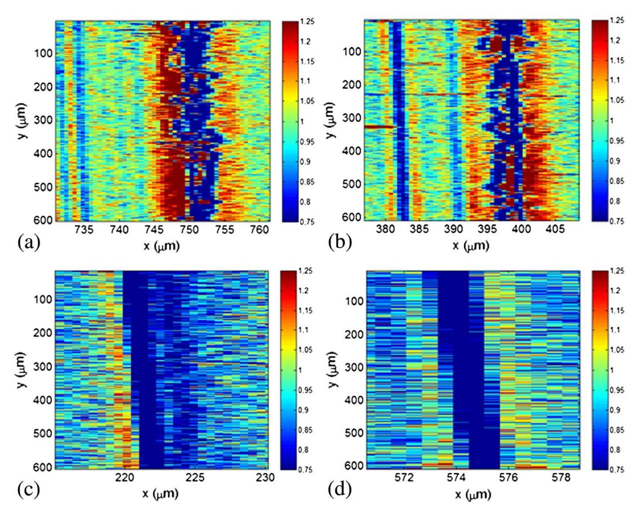

Fig. 3. Different close-up images for (a, b) the top corners and (c, d) the bottom corners.

statement is only truly accurate for a perfectly regular corner radius, but for our purpose, this is an adequate way to check CPLG losses.

From SEM analysis and this trigonometric function, we obtain a radius of 3.03 μm. Using the TOPAF imaging technique, we can obtain a suitable approximation of the radius in the corner by the mean value, resulting in a value of 2.83 μm. This TOPAF measurement is consistent with the SEM microscope observations.

In this section, we introduce a new model for estimating transmittance in prismatic light guides that depends on the aspect ratio and corner radius as complementary terms to the material absorptance coefficient. Thus, using the irradiance analysis, we can estimate the influence of the corner defects on efficiency. For this, we assume the model of light propagation in CPLG using exponential decay. To take into account all sources of efficiency loss, it is necessary that the expression for transmission efficiency contains several independent exponential terms. A higher concentration of defects in the prism corners makes us consider corner defects as the main factor evaluated that induces changes in light transmission, so it is the first term. We consider the absorptance as the second term of the model, as its contribution is necessary to achieve a high accuracy. In the third term, several parameters, inducing residual losses, are included. A detailed analysis of residual losses is a current research goal that is not included in this Letter. The first and the second exponential terms can be empirically calibrated with the previous experimental measurements and software simulations; those are related to the radius and absorptance. The inclusion of the additional third term incorporates the residual losses obtained by the experimental data. These residual losses are related to defects such as scratches, cracks, material inhomogeneities, and others not measured independently. In our method, the guide transmittance T_g can be expressed by a mathematical function as

$$T_g(r,\mu,\rho) = e^{-(k_1 r\rho + k_2\mu\rho + k_3\rho)}, \tag{1}$$

where r is the corner radius (m) of the prismatic structure, μ is the absorption coefficient of the prismatic film (m^{-1}), and ρ is the aspect ratio of the light guide. k_1, k_2, and k_3 are the fitted parameters.

Equation (1) is checked for a CPLG illuminated by an accepted semi-angle (~30°) and that is within the prisms radius range of 0–9 μm. In the case of absorptance, the analysis is over the range of 0–0.1 mm^{-1}. Absorptance has been taken into account to give the best fit value. The chosen ranges are wide enough to include revealing cases where the overlap of one contribution could overshadow another.

In this section, we report on the transmission efficiency results of the simulations and experimental work on CPLGs.

3D simulations were carried out using a nonsequential optical ray tracing software, TracePro 7.4[11]. The cylindrical light guides were modeled as hollow, cylindrical pieces of polycarbonate prism film material. The cylindrical guide diameter is 96 mm.

In this model, a sheet with the constructed parameters adapted to the prismatic material commercially called optical lighting film[12] has been simulated in 3D computer-aided design (CAD) software. The prism base is 356 μm wide and its height is 178 μm, according to the company datasheet. In order to study the efficiency along the guide, we have situated software detectors in intermediate planes at equidistant locations that record the light flux in the simulation. To check the influence of defects on prism corners, we have designed different 3D guides with several corner radii. In addition, as an ideal reference, the perfect prism ($r = 0$) was evaluated. The radius has been set to be 0, 3, 6, and 9 μm. The wavelength was set at 590 nm in the calculations. The refractive index material of the guide, which is considered to be 1.59, is determined by using a polycarbonate polymer with a linear absorption coefficient of 1×10^{-3} mm^{-1} in accordance with the data sheet[12]. In addition, the coefficient of absorptance in the prismatic material has been analyzed over the range of 0–0.1 mm^{-1}. For the simulation, the diffraction loss has not been considered because optical imperfections generate considerably more loss per wall interaction[13].

The angular distribution of the input light is a critical parameter that modifies the flux transmission with regard to distance down the prismatic guide. For the analysis, the entrance aperture is considered to be uniformly illuminated with a clipped Lambertian emission source, with which the prismatic film provides higher efficiency[3].

For the simulation, the modeled 3D system is illuminated with a Lambertian emission pattern of 8 mm-diameter spot sizes. The light source is an emitter with a random distribution that emits a semi-angle of 30°, which approximately maintains the maximum accepted angle determined by the refractive index of the prismatic film. The CPLGs were measured with aspect ratios from 0 to 49. The dimensions used to characterize the hollow guides are given as aspect ratio (ρ), which is defined as length to diameter ($\rho = L/d$).

Figure 4 shows that the decrease in efficiency obtained for the CPLGs is significantly related to the corner defects (which in this case, are defined by the radii). Their influence is a critical parameter mainly when the aspect ratio of the light pipe is high, for example, when the aspect ratio is 49 and the curvature in radius is 3 μm, the losses are close to 33.4%.

In a perfect prism, the corner radius could be mathematically treated as being equal to zero. Theoretically, it should have a transmittance equal to 100%. This configuration is not met mainly because there are losses due to the bulk absorption coefficient of the material. The percentage of absorption obtained in the perfect prism with an aspect ratio of 49 is 3.5%. In addition, a very small fraction of light falling on the angular limit of acceptance is directed out of the guide along the path. As specified earlier, CPLG light losses are also related to the angle of incidence of the light. When the collimation diminishes,

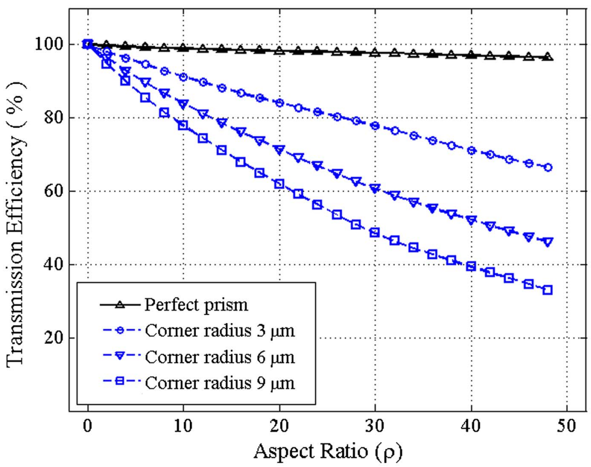

Fig. 4. Dependence of transmission for the different radii values in the corners: 0, 3, 6, and 9 μm for different aspect ratios.

the losses are increased due to the influence of the optical path length.

In this section, we present an experimental evaluation of the transmission efficiency in a CPLG. The prismatic guide is a cylindrical guide internally covered with prismatic film whose outer face is composed of a 90° microprismatic structure that is longitudinal to the axis of the guide. The light guide has a diameter of 96 mm, and the total length is 3 m. The transmission efficiency of the light guide prototype for several aspect ratios was experimentally measured using a calibrated USB complementary metal oxide semiconductor Monochrome Camera (DMK 72BUC02, Imaging Source). The light source used is displaced through the guide and is inserted into a cylindrical device to take measurements with different aspects ratios. To ensure Lambertian emission, one LED is positioned on the inner surface of an integrating sphere characterized by Lambertian reflectance. The cylindrical device that ensures the position of the sphere has three circular diaphragms located coaxially with different diameters to determine the angle cone of the emitting source. An aperture of 8 mm was used, which restricts the output emission from the integrating sphere to accomplish the photometric Lambertian distribution with the 30° semi-angle cone. The source emitter is a LED Luxeon LXHL-PL01 with a peak emission wavelength of 590 nm. This value is in agreement with the wavelength used in the ray tracing simulations. The radiant flux was measured by means of a camera through which the irradiance maps are obtained by a Lambertian screen fixed at one end of the guide.

The guide transmittance (T_g) used to characterize the flux of light transmitted within the interior of the guide is defined as $T_g = \Phi_d/\Phi_i$, where Φ_d is the flux intercepted by the screen detected at different positions of the source, and Φ_i is the flux at a given input location. The transmission efficiency was measured at intervals of 50 mm to obtain a good sample.

The measurement system was used to analyze the transmission efficiency of the CPLG. Figure 5 shows the transmission efficiency as a function of the aspect ratio down the guide. These results show a decrease in the flux of the light transmitted through the guide. For example, the experimental measurements have revealed a transmission efficiency of 73.79% with an aspect ratio of 30. This distribution curve is comparable to the results obtained from the simulations.

The ray tracing simulation actually takes into account the radii of the corners and the bulk absorptivity of the material; it cannot take into account some imperfections due to the amount of time required and the difficulty to approximate parameters like scratches, cracks, powder, material inhomogeneity, film junctions, cylinder covering, global guide bending, etc. So there is a difference in data between the simulated model and the experimental system. From the simulation, we have used the simplex optimization algorithm[14] to obtain the parameters k_1 and k_2. To adjust this, the third term of the proposed model is needed. From the experimental data, k_3 is obtained for the fitting procedure of the model of transmittance, which is obtained using Equation (2). In Fig. 5, we show the data obtained on the efficiency of the prismatic guide simulation with a 3 μm radius in the corners versus the experimental setup for several aspect ratios. This radius was estimated using microscale measurements (SEM and TOPAF techniques). Equation (1) can be expressed as a product of independent exponential terms used to analyze the effect in transmittance separately:

$$T_g(r,\mu,\rho) = e^{-k_1 r\rho} e^{-k_2\mu\rho} e^{-k_3\rho}. \tag{2}$$

The final adjusted parameters are identified after the optimization procedure as $k_1 = 2.6 \times 10^3\ \mathrm{m}^{-1}$, $k_2 = 5.8 \times 10^3$ m, and $k_3 = 1.3 \times 10^{-3}$. A comparison of the modeled results of transmission efficiency with the contributions of each parameter obtained independently are shown in Fig. 6: the radius is the solid line, the absorptance is the dotted line, and the residual losses obtained by the experimental data are the dashed–dotted line. From the resulting data, we find that the light losses due to the corner defects are approximately five times higher than the other loss factors. We therefore conclude that the decrease in the efficiency of a CPLG is

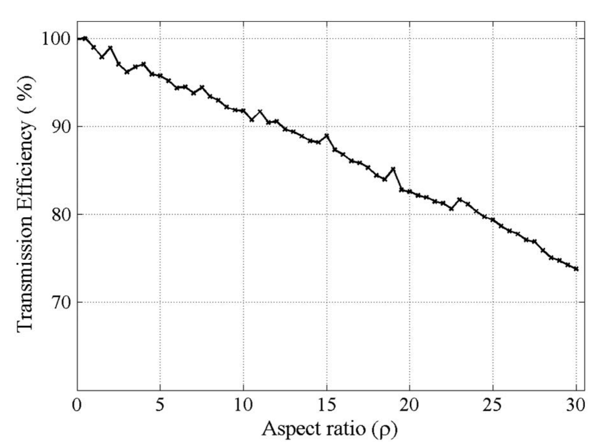

Fig. 5. Transmission efficiency in the experimental assembly.

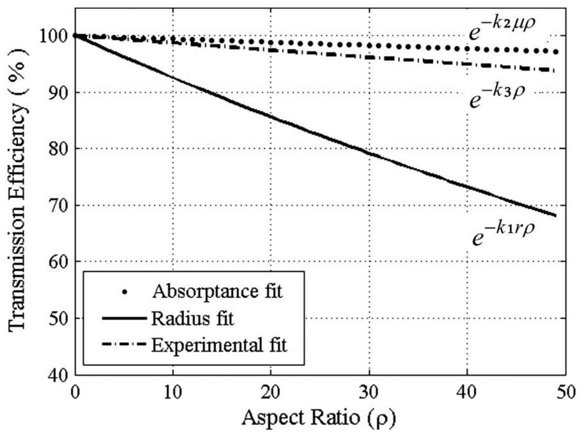

Fig. 6. Proposed model contributions with the transmission efficiency of each parameter obtained independently: the radius is the first term (solid line), the absorptance is the second term (dotted line), and the residual losses are third term obtained by the experimental fit (dashed–dotted line).

significantly related to the radii in the corners. The other parameters studied have a minimal influence.

We checked the results of the semiempirical model with the ray trace simulations and the experimental measurements. In Fig. 7, we show the good agreement between the results obtained from the proposed model, which takes into account the complete solution of Eq. (2) (solid line) and avoids the residual experimental term (dashed line). These are compared with the experimental measurements (marked solid line) and the simulation data (marked dashed line) for radii of 3 μm. The difference between the light losses associated with the two conditions checked (experimental and simulations) were from about 5% of the total decrease of transmission efficiency for hollow prismatic light guides with an aspect ratio of 30. This difference is represented in the third term of Eq. (2) and

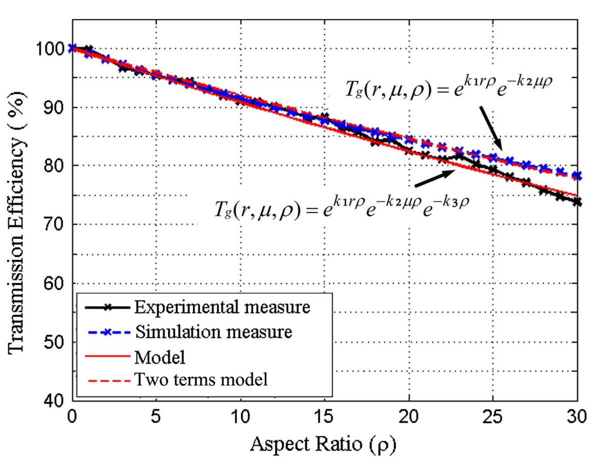

Fig. 7. Transmission efficiencies obtained in the experimental measure (marked solid line) and the simulation model (marked dashed line) with radii of 3 μm are shown for several aspect ratios. The fitted curve [Eq. (2)] is given by the red solid line, which takes all of the terms into account. The red dashed line represents the first two terms.

corresponds to the residual losses originating from the guide imperfections. It does not take into account the simulations or measurement errors.

In conclusion, the proposed semiempirical transmittance model for hollow, prismatic light guides accurately predicts the influence of the fabrication defects in prism corners, taking into account material absorptance and also residual defects. The microscopic fabrication defects are measured experimentally with two high-precision techniques and agreement is shown between both techniques. The results of these measurements are introduced in the transmittance model and in 3D prismatic light guide CAD models to perform nonsequential ray tracing simulations. Agreement is shown between the semiempirical model and the simulations.

The system is tested experimentally with a hollow, prismatic light guide prototype. The obtained transmittance measurement allows us to calibrate the residual defects in the semiempirical model. The proposed transmittance model and experimental results show that the corner defects are the main source of losses in hollow, prismatic light guides. Using the proposed transmittance model, it is possible to estimate that light losses due to corner defects are give times higher than other sources of losses. To improve transmittance in these kinds of light guides, fabrication process improvements for precise radii could be studied.

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