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Research Article

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Backlight illumination design using constant extinction

Abstract: Light guiding backlights are a good solution to attain ambient or display illuminations. Generally, they are attained using intended macroscopic defects (dots). Their size, shape and density are designed using ray tracing software. Smaller defects have the fascinating feature that they may not be perceived by the eye. Such a light guide will therefore look transparent and undisturbed. However, such microscopic or even nanoscaled defects are well beyond the limitations of geometrical optics and therefore need other approaches for their design. An interesting alternative to surface defects are particles inside the material or a well-defined surface roughness. In contrast to a defect structure, particle densities or surface roughness cannot be changed without difficulty. These may, however, be much more easily manufactured. In this paper, a simple analytical method for the design of such light guides will be presented. This method is compared to the results of commercial software and will be used to design a homogeneous illumination adopting constant particle density inside the material.

Keywords: backlight; design; lighting; scattering.

OCIS codes: 230.3670; 220.2945.

1 Introduction

One commercially significant application within illumination techniques is the attainment of backlight illumination. It is applied, for example, in displays and television devices. It can also be used in general illumination situations, whereas overall requirements might be much less challenging. However, the aim of such a design is always the attainment of a constant luminance over a distinct area. The classical solution for backlighting is the so-called light box. However, this will need a certain depth. A significant decrease in size can be achieved using light guides. Those light guides will then be planar. They guide the light that is coupled into the front side to the back side using total internal reflection (Figure 1).

Any disturbance in the total internal reflection as well as scattering within the material will lead to a damping of the luminous flux according to Lambert Beers law (for a one-dimensional geometry).

$$d\phi=-\phi\varepsilon\, dr \tag{1}$$

or

$$\phi(r)=\phi_0 e^{-\varepsilon r} \tag{2}$$

respectively (after integration). $\phi(r)$ denotes the luminous flux on a place r, ϕ_0 is the luminous flux in the beginning and ε is the so-called extinction coefficient. As long as material absorption can be neglected, such an extinction (damping) will only be caused by scattering (which can be either surface or material scattering). The flux leaving the light guide is thus directly proportional to the guided flux ϕ in the same place. The latter will decrease exponentially; therefore, the function of out-coupling illumination $d\phi(r)$ will also be a decaying exponential function. This out-coupling function can be perceived by an observer as a glow. Such an inhomogeneous/out-coupling function will be unacceptable for most applications. Therefore, it is the aim of the optical designer to reach a state where there is constant illumination: $d\phi(r)=const.$ According to Eq. (1), this leads to the requirement that the product of luminous flux and extinction coefficient is also constant.

$$\phi\varepsilon=const. \tag{3}$$

or

$$\varepsilon=C\, e^{(-r)} \tag{4}$$

Such a spatially varying extinction coefficient may be attained by impinging purposed defects – either within

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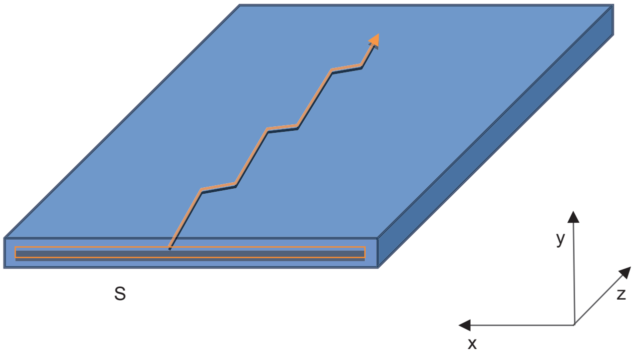


Figure 1 Total internal reflection in a light guide.
Light that is coupled into the front side is guided to the back side. *S* denotes an extended source.

the material or on its surface. The variation of the extinction coefficient can be obtained by a variation of defect density, its effective size or both (Figure 2).

This variation ends as soon as the extinction coefficient reaches unity. In this case, the whole remaining luminous flux will be coupled out. Technically, this corresponds to a complete suppression of total internal reflection.

The constant C can therefore be determined as:

$$C=e^{-r_{\max}} \tag{5}$$

with $r_{\max}$ as the maximum length of the light guide.

Indeed, the above-mentioned relationships neglect several effects (e.g., multiple scattering, Fresnel losses and reflections, as well as multiple reflections). Therefore, such backlight illuminations are usually designed based on optical simulations with ray tracing software. An example for such an approach can be found in [1].

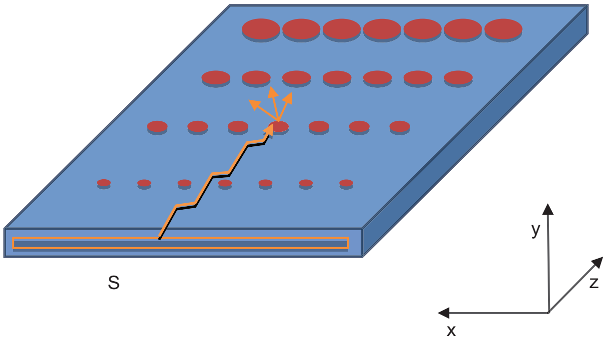


Figure 2 Variation of the extinction coefficient.
This can be attained by a variation of defect density or defect size (as illustrated by red dots).

2 Constant extinction coefficient

A spatially varying extinction coefficient is difficult in its technical attainment. Structuring a surface in such a manner, as shown in Figure 2, requires a microstructuring process. Reasonably, such microstructures can only be attained by an embossing process in plastic materials. This excludes a multitude of optical materials (e.g., glasses) and it requires an effort that increases exponentially with size. Additionally, this method is only suitable for large quantities.

It is much easier to attain a light guide with a spatially constant extinction coefficient [2]. Such a device could be achieved, for example, by slightly roughening one or both surfaces of the light guide or by impinging scattering particles into the material. The latter is already commercially available [3].

The attainment of an (at least almost) constant outcoupling function $d\phi(z)$ with such a constant extinction coefficient requires a well-defined variation of the local luminous flux. In the following section, techniques will be discussed how such variation can be achieved.

3 Luminous flux in a planar light guide

A planar light guide is characterized by the fact that its extensions are much larger in two dimensions (length z and width x) than in the third dimension (thickness y) (Figure 3). Therefore, the variation in luminous flux in this third dimension can be neglected.

When we place a point source S on one side, the luminous flux on a point P within the material can be obtained by the following equation:

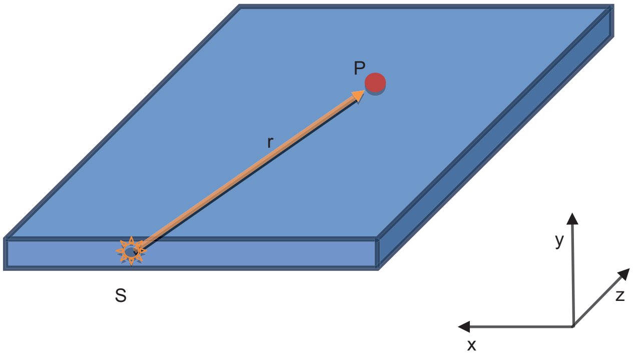


Figure 3 Geometry for the determination of flux in a point *P*.
Light from a point source *S* travels along path *r*.

$$d\phi_p = I_s(\theta) r^{-1}\, dA \tag{6}$$

The term r^{-1} is a variation of the inverse square law. It reduces to r^{-1} because the light is guided in one dimension. The distance r can be obtained from the relative positions of the point P and the source S.

$$r^2 = (x_p - x_s)^2 + z_p^2 \tag{7}$$

If we assume a Lambertian emission, the characteristics of $I_s(\theta)$ can also be expressed in terms of r and z:

$$I_s(\theta) = I_0 \cos(\theta) = I_0 \frac{z_p}{r} \tag{8}$$

When the material has a (constant) extinction, this will also affect the amount of flux that reaches P:

$$\phi(r) = \phi_0\, e^{-\varepsilon r} \tag{9}$$

Putting it all together, Eqs. (6) to (9), we obtain an expression for the luminous flux distribution within the light guide:

$$d\phi_p = I_0 e^{-\varepsilon r} \frac{z_p}{r^2} dA \tag{10}$$

This distribution is directly proportional to the out-coupled luminous flux and consequently to the luminance of P:

$$L_p = c\, \varepsilon \frac{d^2\phi_p}{d\Omega} \frac{y}{dA\, dr} \tag{11}$$

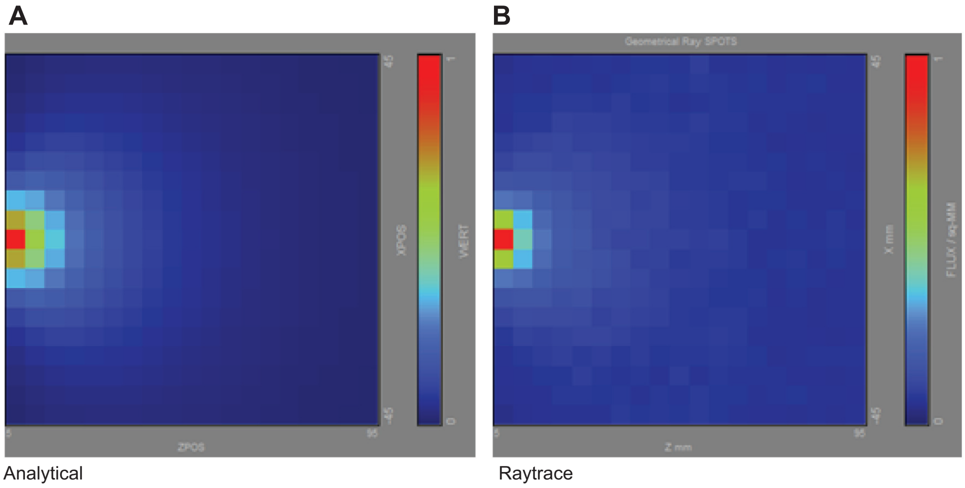
It should be noted that there is an additional factor c. This factor is a function of the observing direction. It denotes the scattering properties of the light guide material or its surfaces, respectively. For example, some of the light will be scattered under such an angle that it is still guided. However, such rays will most probably be scattered multiple times and finally leaving the light guide in a slightly different place.

A rigorous assessment of such scattering properties is challenging. It requires, for example, the measurement and the correct application of bidirectional reflectance distribution function (BRDF) data as demonstrated in [4].

This analytical model was compared to a ray trace simulation with the software package ASAP® (Breault Research Org., Tucson, AZ, USA). This program uses a simple but effective method to model volume scattering by Monte Carlo techniques [5]. The extinction coefficient of a commercially available polymethylmethacrylate (PMMA) material was measured and used for both calculations. Factor c was omitted by normalizing both distributions to unity.

This comparison shows one weakness of the analytical model. It assumes that all the energy that is scattered also leaves the light guide. In reality, some of the light is scattered under such an angle that it is still guided (as previously mentioned). It may also be scattered sidewards or even backwards. The latter is taken into account within the ray trace model as long as multiple scattering is considered. Therefore, it might be necessary to determine an effective extinction coefficient from measurements.

Another weakness is its inability to model any coupling effects. That is, any change in the luminous intensity distribution due to the interface between the light-emitting diode (LED) and the light guide. Currently, LEDs are treated as if they were immersed (glued) into the light guide. Coupling problems are discussed elsewhere [6].



Analytical

Raytrace

Figure 4 Luminance distribution by one-sided point source illumination.
The out-coupled distribution of the proposed analytical model (A) and the results from a commercial ray trace program (B) are shown.

In any case, the analytical model is much faster. For comparison, in Figure 4, Eq. (11) was programmed using the scripting language of the ray trace program. Even though this scripting language is of limited suitability for such a task, execution times were approximately a factor of 20 shorter and numerical noise is much less.

4 Multiple sources

When we attempted to use this approach for an extended source, the term I_0 in Eq. (10) has to be replaced by a function $I_0(x)$ describing the properties of the source. Additionally, distance r has to be expressed in terms of x and y.

$$d\phi_p = I_0(x)\,e^{-\varepsilon\sqrt{x^2+y^2}}\,\frac{z_p}{x^2+y^2}\,dA \qquad (12)$$

To calculate the resulting flux ϕ_p, Eq. (12) has to be integrated over dx. In most cases, this will lead to expressions which require numerical solutions.

Such an extended source might also be treated as a combination of point sources. The same applies for treatment of illumination by an LED array. Owing to their small dimensions, distinct LEDs may be treated as several point sources. The previously assumed Lambertian luminous intensity distribution function is also a good approximation to the typical distribution functions of LEDs.

An LED array with a spatial separation of 10 mm was applied to the same specimen, as already shown in Figure 4. Figure 5 shows the resulting luminance distributions for one-sided, two-sided and four-sided illumination. Again, they display only relative luminances because they are all normalized to unity for better comparability.

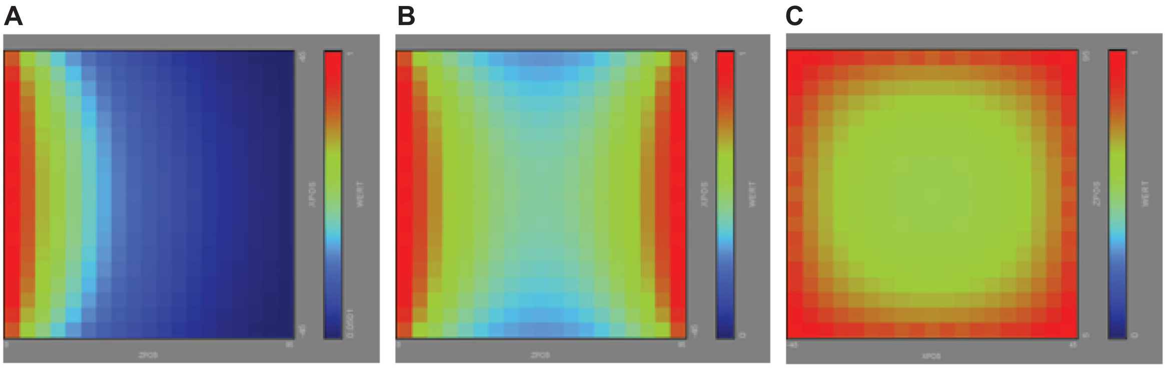
4.1 Realizing a homogeneous luminance

The four-sided illumination is of special interest. The luminance distribution has the shape of a spinning parabola, as can be seen in Figure 6.

The difference between its minimum and its maximum value is already less than a factor of 2. Depending on the application, such a distribution may already be perceived as homogeneous. However, it can still be improved: the function of Eq. (10) rapidly decays with distance r. Therefore, the luminous flux in any point is mainly governed by the flux of the nearest LED. When those LEDs that are close to the edges of the sample are dimmed with respect to the ones in the center, a significant improvement can be achieved.

In Figure 7 such dimming was applied. The total luminous flux of each LED was changed in such a manner that at least the border illumination is homogeneous. This also causes a significant improvement in overall homogeneity. Technologically, such dimming could either be realized by reducing the current or by a frequency modulation of the distinct LEDs. Alternatively, the packaging density of the LEDs could be modulated. That is, they will have to be mounted in a close distance in the center and an increasing distance close to the edges. The most appropriate solution may depend on the application.

Further improvements can be achieved when the size of the sample is adjusted with respect to the extinction coefficient.



One sided Two sided Four sided

Figure 5 Luminance distributions for several types of illumination.
The same light guide was illuminated by an LED array from one side (A), from two sides (B) and from all four sides (C). Each of the distributions is normalized to unity. Deep blue regions denote a luminance of zero.

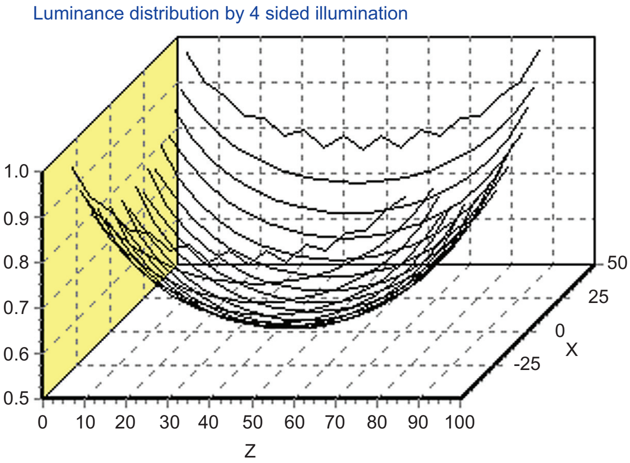


Figure 6 Luminance distribution generated by four-sided illumination.
The distribution has the shape of a spinning parabola.

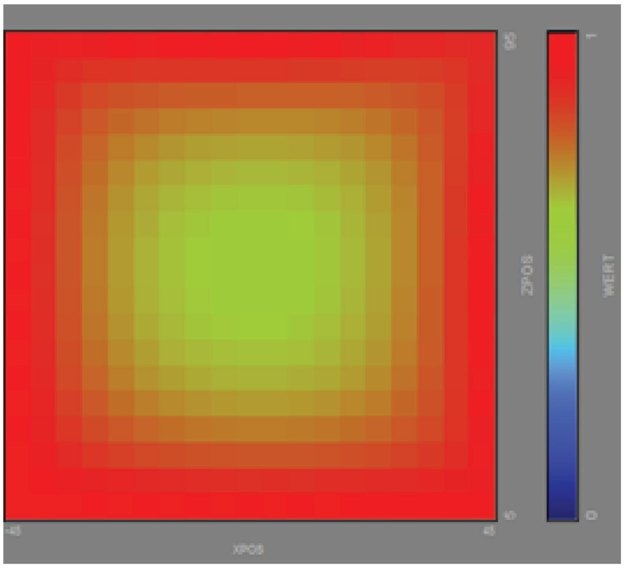
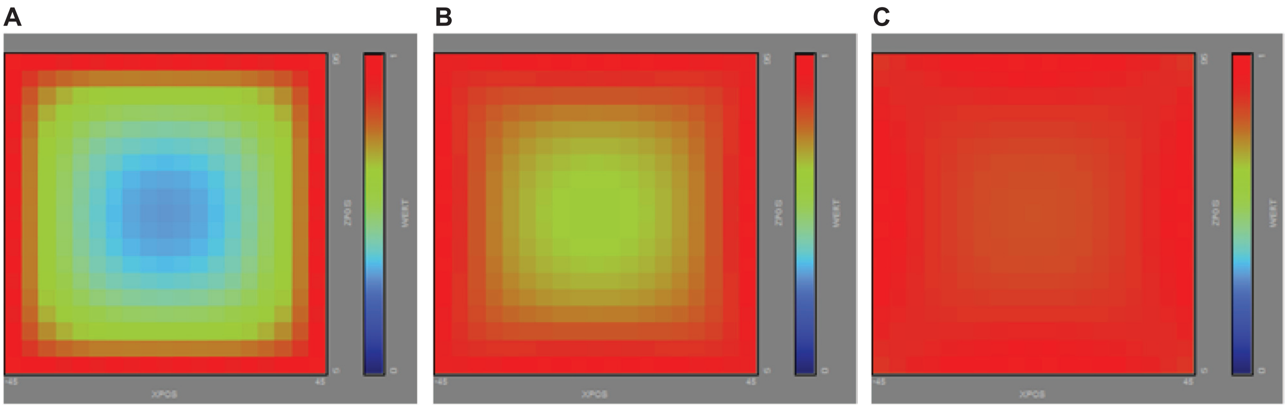


Figure 7 Luminance distribution with corrected edges.
The illumination close to the edges of the light guide was reduced in order to attain a more homogeneous illumination.

4.2 Efficiency

There is always a tradeoff between the quality of an illumination and its efficiency. This also applies to this example. The amount of flux that reaches the opposite end of the light guide (without being scattered) is lost. In the case of one-sided illumination this light can be partially recovered by the application of reflective paint. However, such reflective painting will be difficult to attain together with four-sided illumination. Figure 8 shows an identical illumination of the same sample but with different relative extinction coefficients. A small damping will lead to a homogeneous illumination but in higher losses. A larger extinction, by contrast, may reduce these losses but only for the price of inferior illumination.

There is one additional effect that has to be taken into account: scattering will always be omnidirectional. Therefore, the flux is not only leaving through the upper side but also to the underside of the specimen. For an application such as backlight illumination, this light has to be recycled by an appropriate reflector. When a homogeneous angular distribution of the luminance $L(\theta)$ is required,



Relative Extinction 2
Losses: 1%

Relative Extinction 1
Losses: 6%

Relative Extinction 0.5
Losses:13%

Figure 8 Efficiency versus homogeneity for four-sided illumination of the light guide.
The extinction factor was increased by a factor of 2 (A) and reduced by the same factor (C). Any light that reached the opposite side is assumed to be lost.

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additional diffusors or prism sheets may be necessary. Those items will further reduce the overall efficiency.

5 Conclusions

As an alternative to intended defects (dots and microdots), particles or surface roughness can also be used to attain a light guiding backlight. Homogeneous luminance can be achieved by a spatial modulation of the sources instead of a spatial modulation of the defects. A simple but effective model was developed and applied for the design of such structures. An example for a lighting solution that is based on this principle will be presented at the Light and Building Fair in Frankfurt (2014).

Acknowledgments: This work has been conducted within the Collaborative Center for Applied Research on LEDs (ZAFH LED-OASYS). The author gratefully acknowledges the research grants of the state Baden-Württemberg and the European Union, European Regional Development Fund.

Received June 7, 2013; accepted July 11, 2013

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