Performance improvements in back panel display lighting using near-Lambertian diffuse high-reflectance materials

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ABSTRACT

LCD backlighting applications require diffuse illumination over an extended area of a display unit while maintaining high luminance levels. Since such applications involve multiple reflections within a reflective cavity, the efficiency of the cavity can be affected significantly by relatively small changes in the reflectance of the cavity material. Materials with diffuse rather than specular (or mirror-like) reflectance scatter light, averaging out hot spots and providing a uniform field of illumination. Reflectors with specular components tend to propagate non-uniformities in the illuminator system. The result is a spatial variation in brightness visible to the viewer of the display. While the undesirability of specular materials for such applications has been widely recognized, some diffuse materials in common use exhibit a significant specular component. This paper describes a method for measuring the specular component of such materials, and presents a simple approach to evaluating the effect of such secondary specular behavior on the performance of a backlight cavity. It is demonstrated that significant differences exist among available diffuse reflectance materials, and that these differences can lead to significant differences in the performance of the displays in which these materials are used.

KEYWORDS: LCD backlight, reflectance cavity, diffuse reflector, Spectralon®, diffuse high reflectance

1. INTRODUCTION

Liquid Crystal Display, or LCD, monitors have widely replaced Cathode Ray Tube monitors due to attractive characteristics such as their small foot print and increased color gamut. As consumers demand higher performance from their displays, such as broader viewing angles, higher pixel densities, and greater contrast, manufacturers are compelled to place a greater number of optical devices between the backlight, which illuminates the display, and the surface of the display visible to the viewer. As a result, transmittance of the light from the backlight is adversely affected. To overcome this loss, backlights are being designed with an array of LED's or cold cathode fluorescent lamps coupled with a reflective backlight cavity. High reflectance in this cavity is crucial to optimize light sources and maximize throughput and efficiency of the display as a whole.

LCD manufacturers also face issues of non-uniformity of brightness and color. The light sources used in the backlight assembly tend to illuminate the surface of the cavity unevenly. Specular reflection within the cavity results in a propagation of this non-uniform illumination through the display, resulting in a non-uniformity of display brightness or color as presented to the viewer. The use of materials and coatings that are optimized to provide both high reflectance and high diffuseness over the entire visible spectrum can overcome these obstacles and yield immediate increases in efficiency and performance.

2. THE EFFECT OF REFLECTANCE ON BACKLIGHT EFFICIENCY

The radiance (L) of a perfectly diffuse (Lambertian) surface is described by equation 1,

$$L = \frac{\Phi_i \rho}{\pi A}, \tag{1}$$

in which Φ_i is incident flux, ρ is reflectance, A is the area illuminated and π is the projected solid angle over which the reflected flux is distributed. Since multiple reflections occur within a typical cavity, with each reflection serving in part to re-illuminate the cavity surface, the incident flux on the surface is related exponentially to the surface reflectance, and exponential efficiency gains are seen with increased reflectance, as indicated in equation 2:

$$Gain \approx \left(\frac{\rho_1}{\rho_2} \right)^n, \tag{2}$$

where ρ_1 is the greater reflectance, ρ_2 is the lesser reflectance, and n is the number of reflections.

Figure 1 demonstrates the absorption of light energy by materials of different reflectance after multiple reflections within a theoretical reflector cavity. It is shown that after only five reflections, while a 99% reflective material retains over 95% of original light energy, the 95% reflective material retains less than 80%. In the 90% reflective cavity, almost half of the incident light energy is already lost. Through the multiple reflections occurring in a reflective cavity, a material with higher reflectance will offer exponential increases in efficiency. This allows the performance of light sources to be maximized so that less input power is necessary for equal luminance levels. This allows LCD designers to increase energy efficiency, or take advantage of devices to increase pixel density or contrast without changing existing cavity designs.

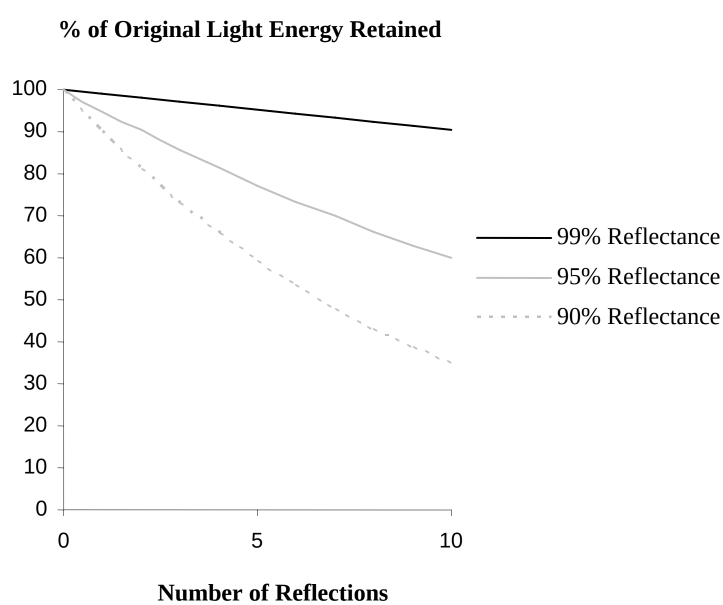

Figure 1: Percent of original light energy after multiple reflections with materials of varying reflectance

3. EVALUATING GEOMETRIC COMPONENTS OF REFLECTION

3.1 Diffuse and Specular Reflection

A surface that reflects with equal radiance or luminance in all directions, perfectly scattering light, is described as *Lambertian*. When a Lambertian reflector is subject to incident flux it acts as a virtual light source, emitting light in all directions.

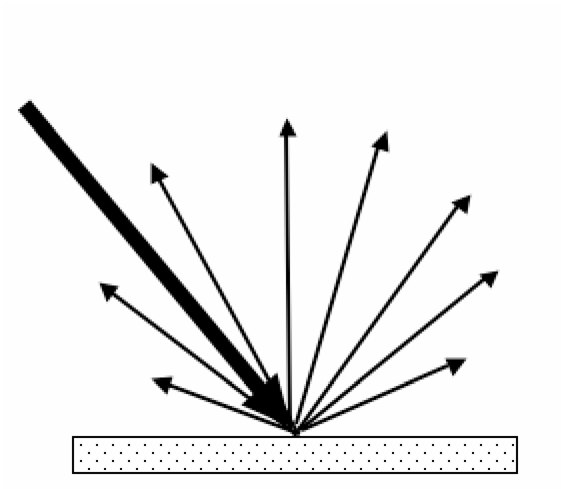

Figure 2. A Lambertian reflector scatters light uniformly regardless of the angle of incident flux

The scattering properties of any reflecting surface can be described in terms of its *Bidirectional Reflectance Distribution Function* (BRDF). BRDF is a description of the reflective properties of a material as a function of the directions of illumination and view, and is defined as the ratio of the surface radiance to the corresponding irradiance[1]. The applicable definitions of radiance (*L*) and irradiance (*E*) are given by equations 3 and 4, respectively

$$L_e = \frac{\Phi_s}{\Omega A \cos\theta_s} \tag{3}$$

$$E_e = \frac{\Phi_i}{A} \, , \tag{4}$$

where Φ_s is flux emitted in a particular direction, Φ_i is flux incident on the sample, A is the illuminated area, θ_s is scatter angle, and Ω is the solid angle into which Φ_s is directed. This leads us to a final value of BRDF as

$$BRDF = \frac{L_e}{E_e} = \frac{\Phi_s}{\Phi_i \Omega \cos\theta_s} \, . \tag{5}$$

Note that in order for the BRDF of a sample to remain constant, the intensity of light reflected must vary by $\cos\theta_s$. This is due to the fact that the viewed projection of the illuminated area varies by the same factor. Thus, the intensity of an ideal Lambertian reflector subject to unit irradiance is given as a function of θ_s, as indicated in equation 9:

$$\Phi_s = \frac{\cos\theta_s}{\pi} \tag{6}$$

When viewed at various scatter angles, the result will be a uniform luminance (brightness) across all θ_s from zero to 90 degrees. Figure 3 shows a plot of the intensity of scattered light from an ideal Lambertian material, represented by a circle in polar coordinates, compared to the intensity of light scattered from a diffuse, optical grade PTFE (Spectralon®). Note the proximity of the Spectralon® data to the ideal.

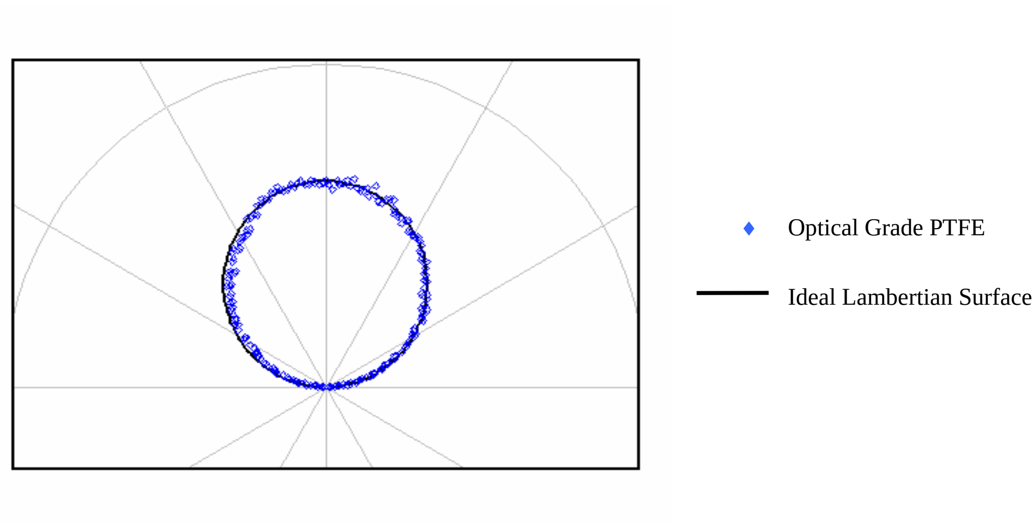

Figure 3: Radiance of optical grade PTFE diffuse reflectance material and an ideal Lambertian reflector under unit irradiance at an incident angle of 15 degrees

In contrast to the ideal diffuse reflection described above, a simpler ideal geometric behavior is that of perfect specular reflection. The term *specular* here describes perfect mirror-like reflection, in which an incident ray of light is reflected at a zenith angle (measured from the normal, or perpendicular direction to the sample surface) equal to the angle of incidence, at the opposite azimuthal angle (measured about the surface normal)[2]. Most materials exhibit some degree of specular reflection, or *near-specular* reflection, in which scattering is confined to a small range of angles about the ideal specular direction. Examples include ceramic tiles, gloss-coated papers, and enamel paints, in which the 'body-color' of the material (due to diffuse reflection) is combined with a mirror-like surface reflection. Such materials may be described as having both a diffuse and a specular component. These two components of reflection can be separated and analyzed using appropriate reflectance measurement techniques.

3.2 Measuring specular and diffuse components of reflection

When reflectance is measured, a sample is illuminated under specific geometric conditions, and the corresponding reflected flux is measured under specific conditions of collection (or view). The flux collected is compared to that which would be obtained for the *perfect reflecting diffuser* (a 100% reflective, Lambertian surface) under identical conditions of illumination and view. The ratio of the sample flux to that for the perfect reflecting diffuser is defined as the sample's *reflectance factor* for those specific geometric conditions.[2]

One common measurement geometry involves illuminating the sample from a direction near the surface normal (e.g. at 8 degrees from the normal), and using an integrating sphere to collect virtually all of the reflected flux. Since this reflected flux may be distributed over a range of angles corresponding to a complete hemisphere, such a geometry is described as *directional-hemispherical*. In the case of 8-degree incidence, the geometry is described as *8-degree/hemispherical* (8/h). In any case, such a geometry of measurement would capture both the specular and the diffuse component of reflection, and is classified as a *specular-included* geometry.[2]

An alternative type of measurement geometry is specifically designed to exclude the specular component, in order to measure only the diffuse component. This type of geometry is naturally described as *specular-excluded*. For every directional-hemispherical geometry, there is a corresponding *directional-diffuse* geometry, in which a light trap is positioned in the integrating sphere so as to absorb and eliminate the specular (or near-specular) component of reflection from the collected flux. In the case of 8-degree incidence, this geometry is described as *8-degree/diffuse* (8/d).[2]

We measured a sample of non-optical grade, extruded PTFE and compared it to an optical-grade PTFE material, using both specular included and specular excluded geometries. For each material, the difference in reflectance factor due to the exclusion of the specular component is shown in Figure 4. This difference is approximately equal to the magnitude of the specular component, expressed as a percentage of the total reflected flux. The non-optical-grade PTFE's specular component is approximately 1.5%, while the specular component of the optical grade material is negligible. Figure 5 shows the value of diffuse reflectance factor for each material, measured using the specular-excluded geometry.

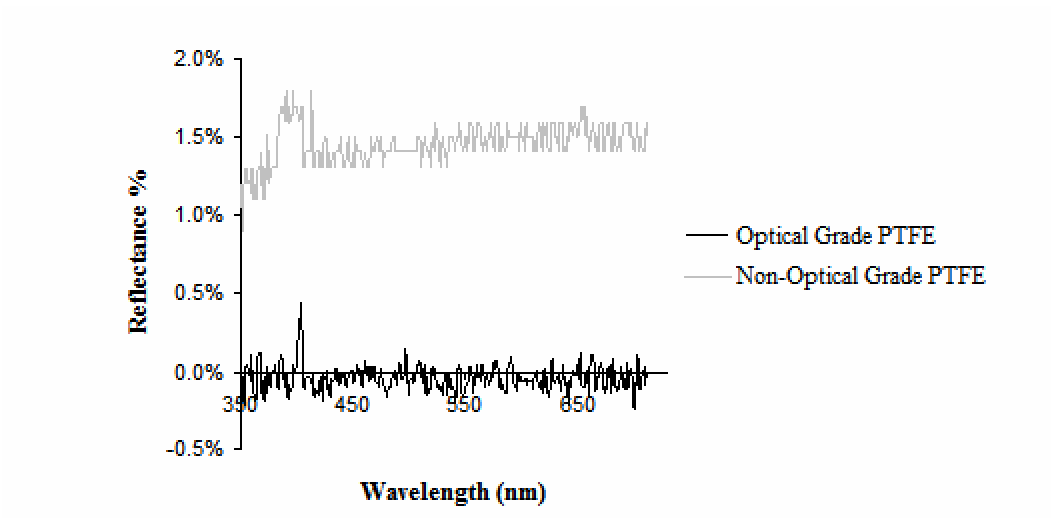

Figure 4: Estimated specular component of reflection for optical-grade PTFE and a commonly-applied alternative PTFE material. The specular component is estimated as the difference between the measured total hemispherical reflectance factor (specular-included) and the diffuse reflectance factor (specular-excluded), both at 8-degree incidence.

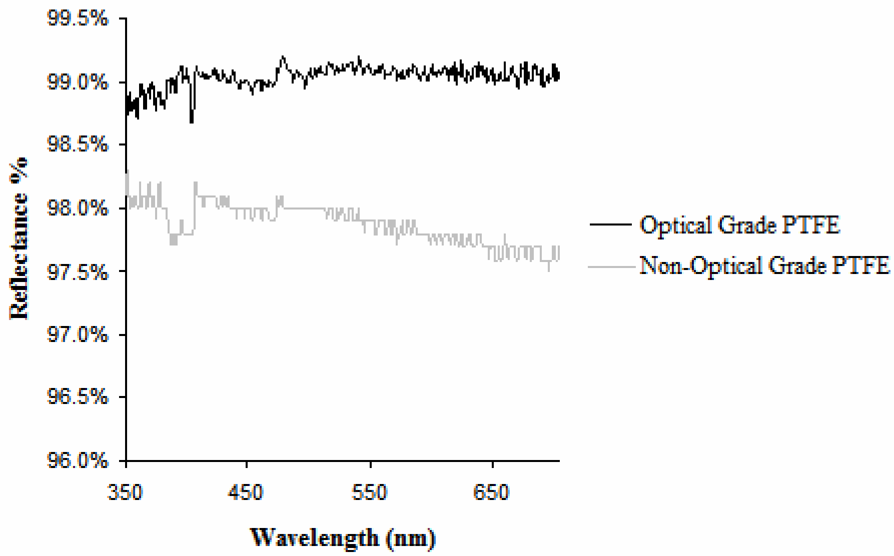

Figure 5: Diffuse reflectance of optical-grade PTFE and the alternative material as measured using 8/d geometry (specular excluded).

4. ESTIMATING THE EFFECT OF A SMALL SPECULAR COMPONENT ON SPATIAL VARIATIONS IN DISPLAY BRIGHTNESS AND COLOR

The problems associated with using specular reflectors for backlighting applications has been widely recognized. But some diffuse reflectance materials in common use exhibit a significant specular component of reflection. A typical specular component for a dielectric material would be approximately 4%. As we have seen, even some non-optical grade, extruded PTFE materials exhibit a specular component of approximately 1.5%. In order to evaluate the effect of such secondary specular behavior on backlight cavity performance, ray-tracing software (TracePro®) was first used to model the illumination non-uniformity that would be obtained in a typical backlight cavity design if a purely specular reflectance material were used. The results were then used to estimate the non-uniformities contributed by a small specular component of an otherwise diffuse cavity material.

The results of the ray-tracing analysis for a purely specular cavity are presented in Figure 6. It can be seen that the uniformity with a specular reflector suffers significantly across the display. Pronounced 'hot spots' are observed around the edges of the sample cavity near the light sources. The non-uniformity of such a display can be described by calculating the full-range variation from maximum to minimum irradiance, and expressing this as a percentage of the mean illumination, as indicated in equation 7. In this case, a specular reflector would yield a full-range variation value (*V*) of 364%.

$$V = (E_{MAX} - E_{MIN})/\overline{E}\,, \tag{7}$$

Assuming that a perfectly diffuse reflector will yield perfect backlight uniformity (V = 1), a reflector exhibiting a specular component S will exhibit an irradiance map ($\hat{L}$) with levels

$$\hat{L} = (1 - S)\hat{P}_L + (S)\hat{P}_s\,, \tag{8}$$

where $\hat{P}_L$ is the irradiance pattern of a perfectly Lambertian reflector and $\hat{P}_s$ is the irradiance map of a purely specular reflector.

Scaling max and min values according to equation 8 yields an estimate of the non-uniformity introduced to a backlight system by the specular component of a non-ideal diffuse reflector. The full-range variation (*V*) for a cavity with a typical reflective material exhibiting a 4% component of specular reflection would be over 15%. Such variation in backlight illuminance would correspond directly to a 15% variation in display luminance. Even for the material characterized above, with only a 1.5% specular component of reflection, the full-range variation of display luminance would be over 5%.

Non-uniformities in backlight illuminance also corresponds to color variations. In the case where red, green, and blue LEDs are mixed to create a white backlight, precise mixing of the colors is needed in order to create a backlight with consistent and accurate color temperature. As a result, with an RGB backlight, illuminance variation due to specular reflection could be manifested as a region of non-uniform color display. A more diffuse reflector would act to reduce such effects, smoothing out non-uniformities in brightness and color, resulting in a more homogenous, accurate display.

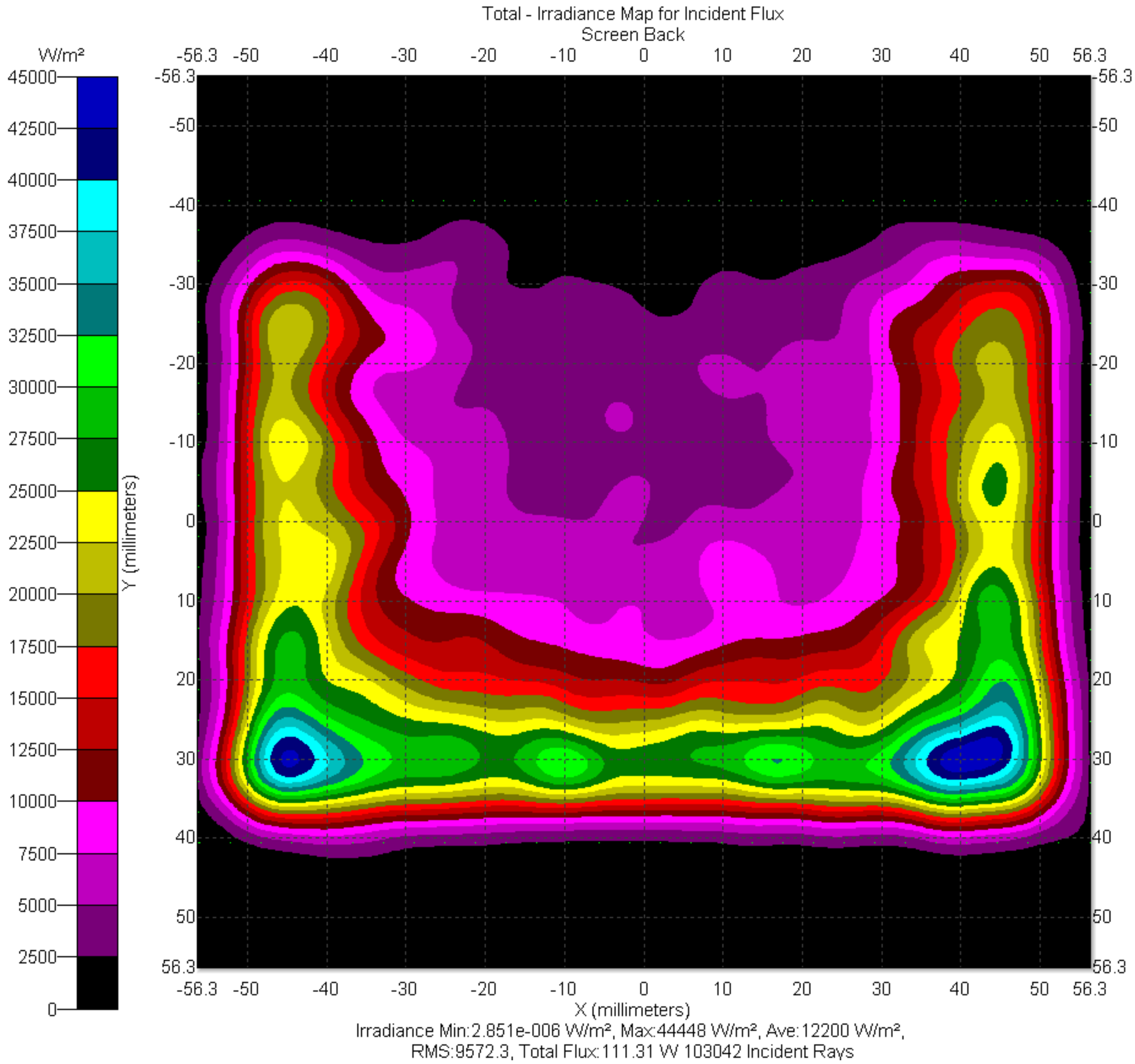

Figure 6. Irradiance map of a typical backlight cavity using a specular reflective material rather than a diffuse reflector. (Modeled with TracePro®.)

5. CONCLUSION

As consumers continue to demand higher performance displays at a lower prices, manufacturers face the ever increasing need to create more efficient backlight designs. Issues such as loss of light and non-uniformity of brightness and color can be resolved with highly diffuse, highly reflective backlight diffusers. The use of true optical-grade diffuse reflectance materials and coatings for LCD backlight units can offer immediate increases in efficiency and performance. The near-perfect Lambertian behavior of such materials improves uniformity of brightness and color, while the high reflectance yields greater efficiency. Since improvements stem from the use of better materials rather than a design modification, the advances are highly scalable, easily employed in a backlight of any size where a reflector has already been conceived. Thus, implementation in existing designs can be an economical means to gain significant improvement in performance without significant re-engineering.

REFERENCES

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