Increased efficiency and performance in laser pump chambers through use of diffuse highly reflective materials

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ABSTRACT

The use of diffuse reflectance materials in laser pump reflector design can lead to significant improvements in laser performance over reflectors employing more traditional, specular (or mirror-like) reflectors. Diffuse reflectors provide a more predictable and uniform beam profile, and reduced susceptibility to parasitic oscillations. Since laser pumping involves multiple reflections within the pump chamber, the efficiency of a laser pump chamber can be significantly affected by relatively small changes in reflectance. For example, a chamber with a reflectance factor of approximately 99% over the 400 to 1000 nm range, can provide a 15% gain in performance over a comparable 98% reflective chamber, even though the reflectance factor is only 1-2% lower. Much larger gains are possible over typical ceramic reflectors. This paper will examine high performance PTFE as a reflector in laser pump chambers compared to other materials. Gains in performance through reflectance and diffuseness are shown through mathematical models, experimental results and real world case studies.

KEYWORDS: Laser pump chamber, diffuse reflection, slope efficiency, laser pump reflector, Spectralon

1. INTRODUCTION

In lamp pumped lasers or high powered diode pumped solid state lasers where an array is used to supply energy to the lasing material, a reflective chamber is necessary to couple light energy from the pump source to the gain medium. A common laser chamber design is an ellipse of specularly reflecting material where the pump source and gain medium are located on the two foci. In theory, energy emitted in any direction from one focus which undergoes specular reflection should be reflected directly to the other focus. However, since both objects are not points in a real laser and thus have an appreciable volume, this specular reflection leads to an uneven pumping of the gain medium, where some portions receive more energy from the pump source than others. One can attenuate this non uniformity by adjusting the distance between the source and gain medium, but as gains in uniformity are made, efficiency is adversely affected. Often, to counteract the uniformity problems associated with elliptical pump chambers, circular chambers can also be used.

Since multiple reflections take place inside a laser pumping chamber before light reaches the gain medium, high reflectance can yield significant improvements in light coupling efficiency. This paper examines a diffuse highly reflective laser grade PTFE material that could greatly improve the performance of laser pump cavities. As well as being extremely reflective across the wavelengths used to pump lasers, this materials offer behavior that is closest to a Lambertian (perfectly diffuse) reflection of any known material. Use of such materials in a laser pump chamber would allow for uniform pumping of the gain medium while making gains in light coupling efficiency, resulting in better overall performance of the laser.

2. THE EFFECT OF CHANGES TO REFLECTANCE ON EFFICIENCY

2.1 An overview of radiance

When a Lambertian reflector is subject to incident flux, it acts as a virtual light source, emitting light uniformly in all directions. The radiance (L) is described by

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

where Φ_i is incident flux, ρ is reflectance, A is the area illuminated and π is the projected solid angle into which the reflected flux is divided.

In a laser reflector with all other geometries being equal, the irradiance of a point on a surface with incident flux is simply proportional to the reflectance of that surface. In a typical laser chamber multiple reflections of light will occur, thus the gain in efficiency with increased reflectance will be exponential and given by

$$\%gain = \left(\frac{L_1}{L_2}\right)^n = \left(\frac{\rho_1}{\rho_2}\right)^n, \tag{2}$$

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

2.2 Effects on efficiency from diffuse highly reflective materials

Figure 1 demonstrates the theoretical potential for efficiency increase with the use of high performance PTFE in a laser pump chamber. The remaining energy of incident light after a number of reflections is compared for materials of 99%, 95%, and 85% reflectance. The 95% reflectance is the upper bound of diffuse reflectance available with most high performance ceramics, and 85% represents a typical ceramic or aluminum coating commonly used in laser pump chambers. After only five reflections, while the 99% reflective material has maintained over 95% of incident light energy, more than 20% of light energy has been absorbed by the 95% reflective material. Meanwhile, the 85% reflective material will have absorbed more than half of incident light energy.

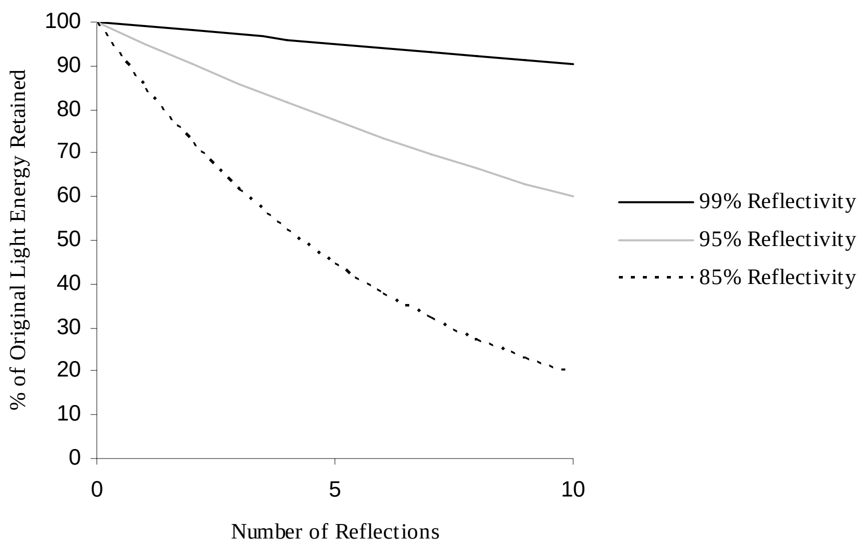

Figure 1: Percent of original light energy after multiple reflections with materials of varying reflectance

Sophisticated ray-tracing software is necessary to precisely and quantitatively describe the nature of reflections inside a typical laser pump reflector, and such analysis is beyond the scope of this paper. However, fundamental geometric analysis of a diffuse reflector chamber shows that multiple reflections will occur between the pump source and gain medium. Additionally, the gain medium will often not absorb all light energy that passes through it. This small level of transmittance allows low levels of light to pass through the gain medium unabsorbed and back into the reflector chamber. A highly reflective chamber can recycle this light, reflecting it back towards the gain medium and allowing more energy to be absorbed, further increasing efficiency. The use of high performance PTFE as the reflector in a laser pump chamber can have an immediate and significant impact on the slope efficiency of the laser unit as a whole. As the chamber becomes more efficient, waste heat becomes less of a concern. Thus, cooling systems can be more compact, resulting in a smaller unit that uses less electricity than one without high performance PTFE in the reflectance chamber.

In addition to being highly reflective, high performance PTFE also produces a reflection that is highly diffuse, bearing the closest resemblance to the ideal of a Lambertian (perfectly diffuse) reflector of any known highly reflective material. Such behavior is due to its porous molecular structure, which causes multiple random reflections at the molecular level, diffusing incident light.

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.

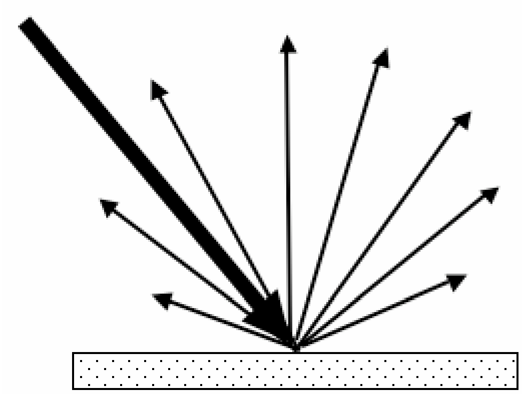

Figure 2. A Lambertian reflector scatters light uniformly regardless of the angle of incident flux

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, laser grade PTFE (Spectralon®). Note the proximity of the Spectralon® data to the ideal.

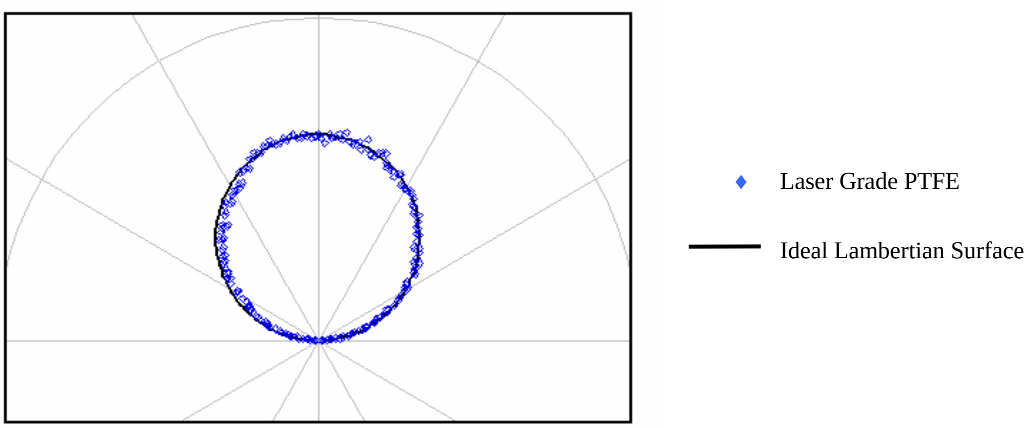

Figure 3: Radiance of laser grade PTFE diffuse reflectance material and an ideal Lambertian reflector under unit irradiance at an incident angle of 15 degrees

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 a glazed ceramic used in laser pump chambers and compared it to an laser 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 ceramic's specular component is approximately 4%, while the specular component of the laser grade material is negligible. Figure 5 shows the value of diffuse reflectance factor for each material, measured using the specular-excluded geometry.

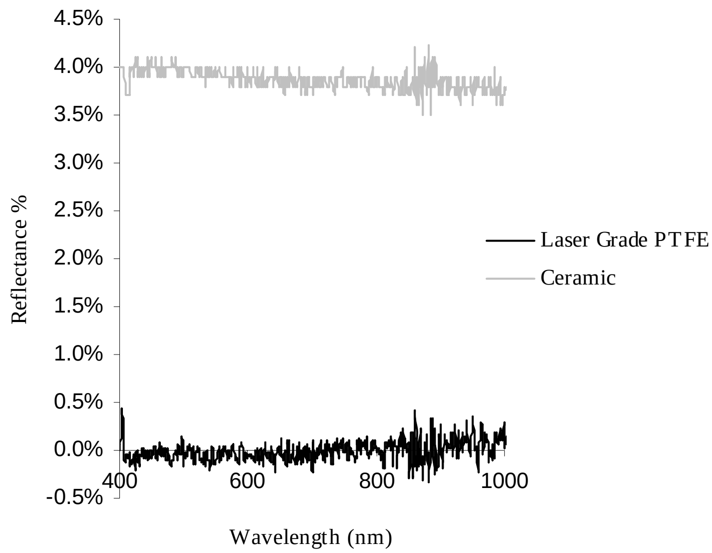

Figure 4: Estimated specular component of reflection for laser grade PTFE and a commonly-applied alternative PTFE material. The specular component is estimated as the difference between the measured total hemispherical reflectance factor (specular-included) and the diffuse reflectance factor (specular-excluded),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

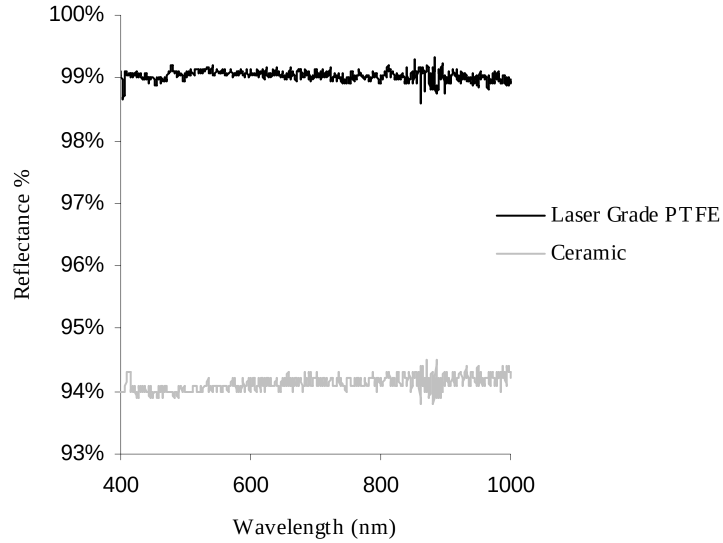

Figure 5: Diffuse reflectance of laser grade PTFE and the alternative material as measured using 8/d geometry (specular excluded).

For a mathematical equivalent to this concept, one can consider the integration of radiance across the scatter angle θ_s from zero to π. The result of this integration can then be divided by the incident flux upon the sample to yield reflectance value. With inclusion of the spike in radiance associated with a specular reflection, one can see how a specular spike would give artificially high readings of reflectance. However, if one were to integrate radiance of a specularly reflecting sample and a diffusely reflecting sample excluding the area where scatter angle is equal to angle of incidence, it is easily seen that reflectance will drop more in case of the specular sample than that of the diffuse sample. This will result in lower diffuse reflectance in the specular sample, even though the reflectance value reported was originally higher

4. CONSIDERATIONS FOR SELECTION OF REFLECTIVE MATERIALS

In precise applications such as medical applications, the need for a consistent beam intensity profile is often more important than the need for efficiency. Here, there is demand for a uniform shape in order to attain accurate and precise results. Such consistency is accomplished by maintaining uniform pumping of the gain medium, which is done more easily with a diffuse reflector rather than one which is specular in the laser pump chamber. Because of its highly Lambertian characteristics, laser grade PTFE allows laser designers to configure their pump chambers with a bias towards efficiency without sacrificing pumping uniformity.

With a specular reflector, pumping is often concentrated only on the radial axis of the gain medium. This prevents efficient extraction of energy from the entire volume of the medium, and can result in an inconsistent beam intensity profile, which is unacceptable for many precision-based applications.

The glaze applied to ceramic reflectors gives them a significant specular behavior, while the laser grade PTFE's specular component of reflection is negligible (Fig 4). The specular reflection associated with the ceramic can create uneven pumping of the gain medium, reducing slope efficiency, and making it less than ideal for laser pump chamber applications.

Another disadvantage of this specular reflection is parasitic oscillation, or unintended lasing activity within the chamber itself. This detracts from output potential and is potentially dangerous to the more sensitive optical equipment inside the chamber. A Lambertian reflector such as laser grade PTFE scatters light energy evenly in all directions instead of in a concentrated beam, which will retain maximum output and protect expensive optical components of the laser system.

5. CONCLUSION

The use of high performance laser grade PTFE materials as reflectors in laser pump chambers would yield immediate increases in efficiency and performance. The near Lambertian behavior of the materials will allow for more uniform pumping of the gain medium and a more consistent beam intensity profile, while the high reflectance and flat spectral response would allow for increased output power and greater efficiency of the unit as a whole.

An advantage of these improvements, stemming from the fact that they are due to the use of more efficient materials rather than a design modification, is that the advances are highly scalable and easily applied to a variety of laser designs using a reflective pump chamber. Implementation in existing chamber designs would allow for significant improvement in performance without additional engineering or excessive testing. Further testing and more involved simulation should be done to more accurately quantify the gains, but it has been shown that the use of laser grade PTFE will have a positive impact on performance when used as a diffuse reflector in laser pump chambers.

REFERENCES

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