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# Simultaneous measurement of laser reflection and transmission of poly(vinyl chloride)

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**Abstract.** Modeling laser transmission welding of thermoplastics requires knowledge of the optical properties of the two materials being joined. Previous work measuring optical properties for this purpose placed little importance on the light reflection, emphasizing the light transmitted through a material. This paper presents work creating a low-cost solution allowing simultaneous measurement of the light transmission and reflection of clear rigid poly(vinyl chloride) from a diode laser source. Total reflection is quantified by numerically integrating measurements of the light reflection at specified locations around the perimeter of a sphere surrounding the sample; simultaneously the light transmission through the samples is measured. From a designed experiment involving two factors—surface finish and material thickness—the absorption coefficient of clear rigid poly(vinyl chloride) was calculated. In addition the quantity and distribution of light reflection was found to be dependent on the surface finish. 
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Subject terms: laser; welding; absorption coefficient; reflection; transmission; plastic.

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## 1 Background

Most polymers in their natural, unpigmented state are highly transmissive of light in the near-infrared range, allowing laser transmission welding (LTW) with diode lasers. A complication arises, however, in that most engineering plastics contain a variety of fillers and pigments that change not only their physical properties, but also their optical properties. For this reason, testing the optical properties at a specific wavelength for all materials involved in LTW is required for accurate modeling.

Light transmission through a solid follows an exponential decay with increasing material thickness. This relationship is defined by Beer's law: $I(z)=I_0 e^{-\alpha z}$, where $I(z)$ is the optical intensity as a function of material depth, $I_0$ is the optical intensity at $z=0$, $\alpha$ is the absorption coefficient, and $z$ is the material depth.[1] Using this relationship, a primary goal for optical testing is measuring the absorption coefficient.

There are numerous methods to test the optical properties of polymers; the field has not adopted a universally standard method. Early work measuring the transmission of a variety of pigmented acrylonitrile batadiene styrene (ABS) samples made use of a quartz-halogen filament with a maximum output at 890 nm for the light source and a thermocouple for the measurement sensor.[2] Since that time, numerous other methods have been used to measure light transmission, most notably spectrometry and custom-designed systems using low-power laser sources and various methods of light detection.[3,4] Kagan et al. contributed a sizable compilation of optical properties of nylon-based plastics containing various pigments and fillers.[5,6]

Much of the previous work measuring optical properties for LTW of thermoplastics has neglected laser reflection from the material surface.[7] Other works have assumed a constant reflection value between 4% and 10% of the incident power.[3,5] When calculating the absorption coefficient from the laser transmission measurements for use in a LTW model, these variations in reflection are too large to disregard.

A substantial number of reflectometers are commercially available or reported in the literature. A portion of these devices are designed to measure the direct specular reflectance,[8] while others capture and measure the diffuse reflection.[9] This second group of reflectometers typically use a variety of precisely positioned, moving optics to redirect the light to a power meter. The majority of these devices are quite expensive and not capable of measuring both the total reflection and transmission simultaneously.

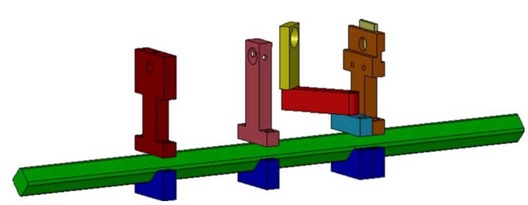

**Fig. 1** This solid model shows the major components on the interior of the black box. The items mounted to the main tube from left to right are: the stand fixturing the diode laser module, the stand fixturing an 3.2-mm-diameter aperture, the rotating reflection-measuring stand, and the stand fixturing the sample and the photodiode measuring light transmission.

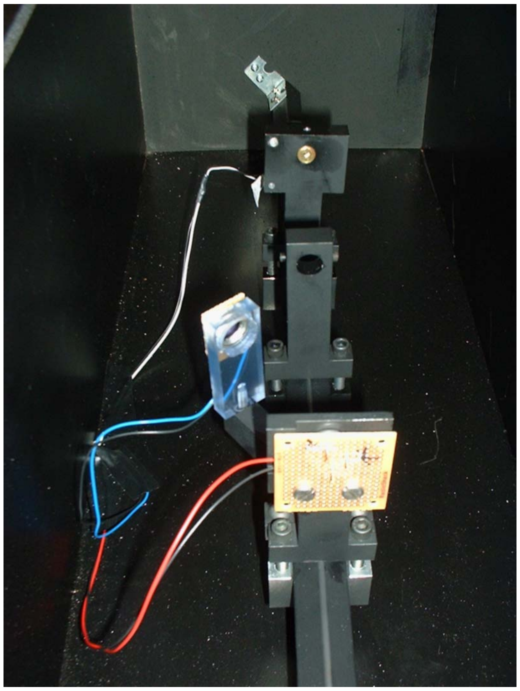

**Fig. 2** This photograph shows the interior of the black box, including the optical components. The diode laser module is supported on the farthest stand, the aperture is fixtured on the center stand, followed by the reflection-measuring photodiode, and finally the stand securing the sample and the transmission-measuring photodiode is the closest one.

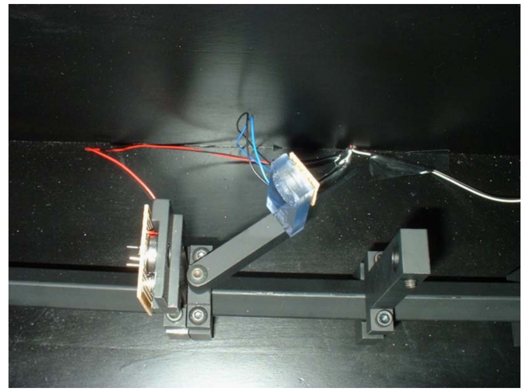

**Fig. 3** This photograph shows an overhead view of the interior of the black box, including the reflection-measuring photodiode on the rotating arm.

An experimental setup that has the potential to measure reflection and transmission simultaneously was created by Rhew et al.[10] This device used two power meters that rotated around a plastic sample. In addition to rotating the power meters, the sample was also able to rotate relative to a fixed diode laser, allowing variation of the incident angle. This device apparently was used only to measure the specular reflection, and not to calculate the total reflection.

A simple device designed specifically to integrate the total light reflection from a surface was reported by Mehmetli et al.[11] The purpose of this device was measuring the reflection of $CO_2$-laser energy while welding aluminum. This system consists of a semicircular arc that pivots on the two ends of the arc, allowing it to sweep through the surface of a hemisphere. An infrared detector is permitted to traverse the arc, allowing the detector to reach any position on the surface of the hemisphere. Measurements taken at 10-deg increments along the perimeter of the sphere allow numerical integration across the surface area, yielding a value for the total reflection.

Each of these existing methods of measuring reflection had limitations in obtaining the needed information. The reflection measurement presented in this paper measures reflection and transmission simultaneously, calculates all of the reflected light (not just the specular reflection), and has low cost.

## 2 Experimental Setup

The experimental device used to simultaneously measure near-infrared light reflection and transmission of poly(vinyl chloride) (PVC) is a custom-designed black box. The black box uses a 4-mW diode laser module from US Lasers Inc., operating at a wavelength of 808 nm as a light source. Light from the diode laser passes through a 3.2-mm-diameter aperture and is reflected from and transmitted through a thermoplastic sample mounted on a stand in front of a photodiode. A second photodiode is rotated around the sample, allowing measurement of the reflected light. Amplifying circuits convert the current passing through the photodiodes to a voltage signal that correlates to a power reading. This entire system is mounted inside a fully sealing wooden box that is painted flat black on the inside to reduce any light reflection.

The experiment involves careful measurement of the light energy reaching the photodiodes, requiring very low-noise amplification circuits. The main trade-off for a low-noise circuit, which uses an OPA228 op-amp and a $100\text{-mm}^2$-active area silicone photodiode, is slower circuit response. This, however, is not a problem for this application. The spectral response of the photovoltaic photodiodes peaks near 808 nm, minimizing the influence of other light sources. The op-amp circuit has the benefit of allowing one to vary the signal amplification through changing the value of the feedback resistor. To minimize any external noise, batteries power the photodiode amplification circuit and laser diode module. These photodiode circuits can measure light energy at values between 0.1 $\mu$W and 5 mW.

The components in the black box need to be carefully aligned. The backbone of the fixturing is a $\frac{3}{4}$-in.-square tube that is connected to the two farthest walls of the inside of the box. Mounted on the top of this tube are four stands; one holds the diode laser, a second aligns the aperture, a third supports the rotating reflection measuring photodiode, and the fourth fixtures the sample and secures the photodiode. These stands are mounted in a manner allowing them to traverse the length of the tube as well as allowing a repeatable means of clamping and alignment. Alignment is maintained with V-block clamps, which secure each stand to the square tube. The purpose of the aperture is to ensure the light strikes the sample in a small and well-defined beam. A small uniform beam forces the incident light to be collinear, which leads to more uniform reflection.

A custom solution was created to determine the total

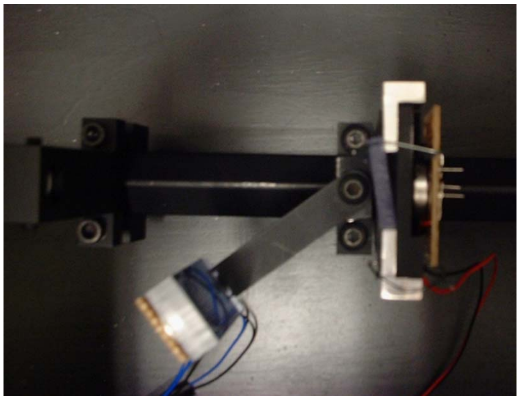

**Fig. 4** The sample angled at 9 deg from perpendicular to the incident ray. When the measurement photodiode is placed at 18 deg from the central axis, a specularly reflected ray will directly strike the reflection photodiode. Two aluminum blocks precisely position the sample on the photodiode stand at the desired 9-deg angle.

reflection within the black box. This is accomplished by moving the photodiode in a semicircular path around the front of a sample while taking measurements at specified increments. By moving the pivoting link in increments of 9 deg, the photodiode is exposed to reflected light along the entire perimeter surrounding the sample. These measurements around the perimeter can then be integrated across the surface of the hemisphere, to calculate the entire reflection. A solid model of the pivoting device and the optical stands can be seen in Fig. 1, while photographs of the machined parts in the black box can be found in Figs. 2 and 3.

The measurement locations around the perimeter of the sphere were carefully selected to ensure the photodiode sampled all angles of reflected light, as necessary for integrating the total light reflection. The first step in preparation for the numerical integration was to define the increment step size as well as the shape of the integration blocks. The active area of the reflection-measuring photodiode is 11.3 mm in diameter and is mounted at a distance of 69.9 mm away from the sample. To achieve full coverage, the pivoting link can be moved in 9-deg increments around the perimeter of the sphere. Because the reflection should be roughly symmetric about the central axis of the sphere, only one-fourth of the circumference of the sphere needs to be sampled. Thus, to acquire all the necessary information for the integration, 11 reflection measurements are necessary for each sample.

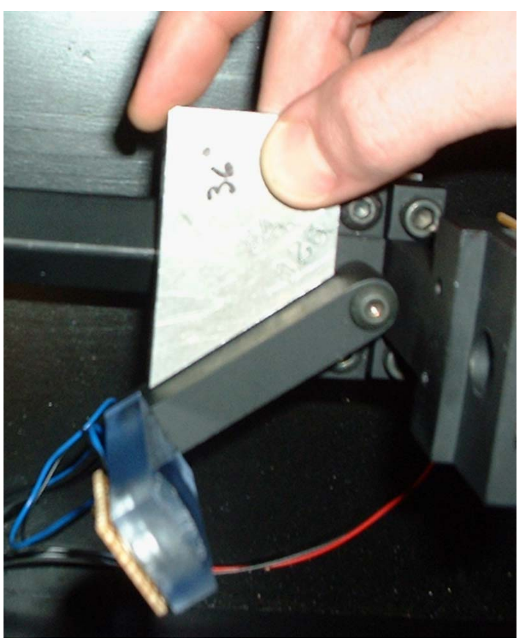


**Fig. 5** This photograph shows the aligning of the rotating photodiode at 36 deg. The machined block fully contacts the stand and the rotating arm when correctly aligned.

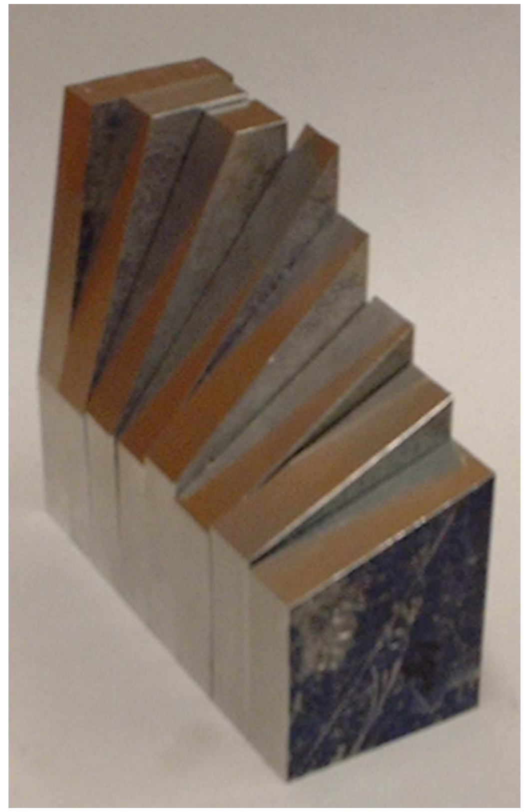

**Fig. 6** The alignment blocks, which are machined from aluminum in 9-deg increments.

With the sample orientated perpendicular to the laser beam, a complication is created when trying to measure the direct specular reflection. The centerline of the reflected light cannot be measured with this arrangement, because the measurement photodiode would interrupt the laser beam. To solve this problem, the reflection measurements were taken at angles from 18 through 90 deg in two phases. In the first phase, the sample was mounted perpendicular to the incident ray; in the second phase, the sample was set at a 9-deg angle to the incident ray. In this second situation, a specularly reflected ray would strike the reflection photodiode when it was placed at the 18-deg angle, as can be seen in Fig. 4.

To obtain accurate and repeatable measurements of the light reflection around the circumference of the sphere, the rotating photodiode needs to be precisely positioned at each of the rotational increments. This positioning is accom-

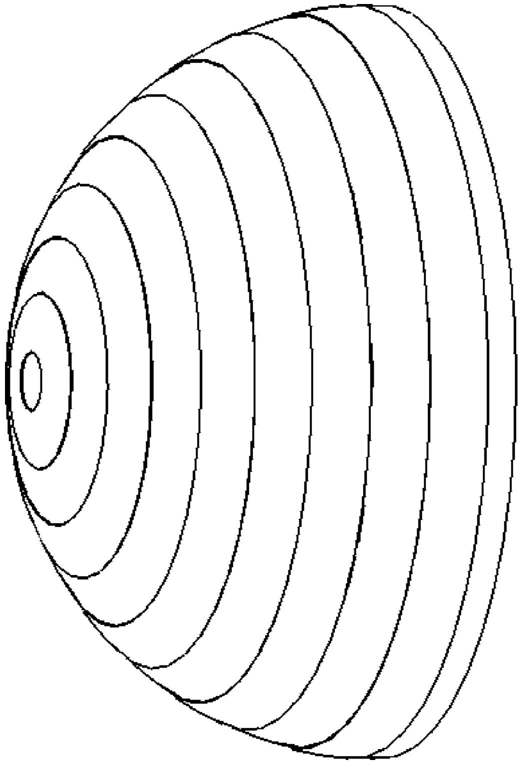

**Fig. 7** The integration steps on the surface of the sphere. The step size for this process is 9 deg. Note that the diameter of the photodiode is equal to the chord length between adjacent bands.

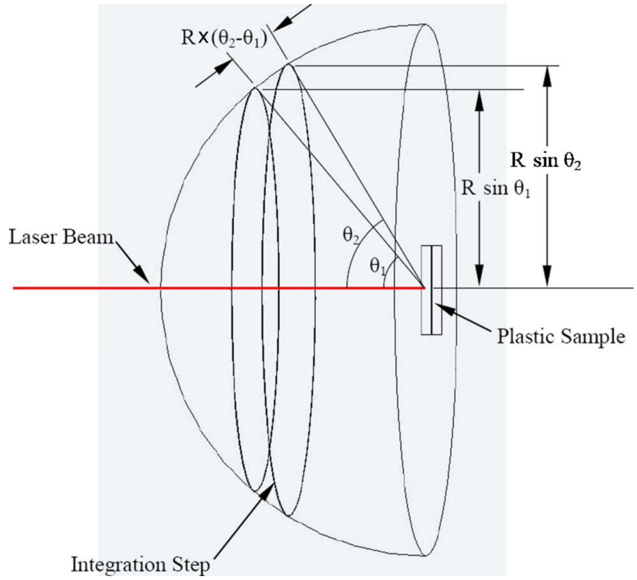


**Fig. 8** This diagram shows the one of the integration step bands and the variables used in calculating its area.

plished using machined blocks that contact the stand fixtured to the main tube and the rotating arm. Each block is machined for one specific angle of alignment. The alignment procedure and the alignment blocks can be seen in Figs. 5 and 6.

The calculation of the total light reflection requires integrating across the surface of the hemisphere surrounding the sample. The integration steps are characterized by concentric bands, defined by the angle at the center of the hemisphere, as shown in Fig. 7. These surface area elements are approximated by isosceles trapezoids, averaging the circumference of the small and large circles for the width and defining the height as the chord length. In mathematical form, relating to the variables in Fig. 8, we have the following:

- Circumference of small inner circle:

$$d_1 = 2\pi R \sin \theta_1 . \quad (1)$$

- Circumference of large outer circle:

$$d_2 = 2\pi R \sin \theta_2 . \quad (2)$$

- Chord length:

$$h = R(\theta_2 - \theta_1) . \quad (3)$$

- Integration-step area:

$$A_i = \frac{d_1 + d_2}{2} h = (2\pi R \sin \theta_1 + 2\pi R \sin \theta_2) R \frac{\theta_2 - \theta_1}{2}$$
$$= \pi R^2 (\theta_2 - \theta_1)(\sin \theta_1 + \sin \theta_2) . \quad (4)$$

This method provides a reasonable surface area approximation. Comparing the integrated surface area using this method with the actual surface area leads to a difference of $<0.1\%$.

## 3 Reflection and Transmission Experiment

An experiment was designed to measure the light transmission and reflection simultaneously from rigid clear PVC with the goal of calculating the absorption coefficient. Two crossed factors, sample thickness and surface finish, were used as the dependent variables. This experiment consisted of 18 factor-level combinations with a replication of 2. The sample thicknesses are 1.57, 3.18, 4.78, 6.35, 9.53, and 12.70 mm. Modification of the surface finish was achieved by wet-sanding certain samples with 1500-grit sandpaper for 1 min. One-third of the samples, randomly selected from each thickness level, were sanded on both surfaces that the laser light passes through, one-third were sanded on the front surface only, and the remaining samples were not sanded. The surface roughness was measured using a surface roughness tester, the Surtronic 10, manufactured by Taylor-Hobson. The unsanded surfaces had an average measured roughness of 0.0 $\mu$m, while the sanded surfaces had an average roughness of 0.2 $\mu$m.

The experiment was completed during a 16-h period to minimize any day-to-day variations. All of the prepared samples were arranged in random order and tested individually. The measurements made included: the light striking the photodiode with no sample in place, the light transmitted through the sample, the light reflected from the sample at angles between 18 and 90 deg with the sample perpendicular to the laser beam, and the light reflected from the sample at angles between 18 and 90 deg with the sample at 9 deg from perpendicular to the laser beam.

**Table 1** Average total reflected power for the three different surface finishes. Note that the samples with sanded surfaces reflected significantly more power than the unsanded samples.

| Finish | Total reflected power (mW) | Standard error (mW) |
|---|---|---|
| No sanding | 0.3413 | 0.0105 |
| Front sanded | 0.4936 | 0.0202 |
| Both sides sanded | 0.4937 | 0.0102 |

## 4 Results

The light reflection was found to be highly dependent on the surface finish of the sample. This dependence is exhibited in two regards. First, the samples with the rougher surface finish (those that have been sanded) reflect more light than the smoother samples. Table 1 displays the average total reflection and standard error for the three surface finish conditions. Second, the distribution of light reflection is quite different; the smooth samples have primarily specular reflection, while the reflection from the sanded samples is much more diffuse. This distribution can be seen in the plot of the reflection at each measurement increment averaged for each surface finish, as found in Fig. 9. Note that this is a plot of the reflected power across each angular band, which is calculated as follows:

$$\text{power reflected by band } i = \frac{\text{power measured by photodiode}}{\text{area of photodiode}} \cdot A_i, \quad (5)$$

where $A_i$ is the integration step area of band $i$, calculated with Eq. (4).

By numerically integrating the measured reflection across the surface of the hemisphere, the total reflection is calculated. The calculated reflection values varied from 8% for the unsanded samples to 16% for the samples sanded on both surfaces. In addition, the calculated light transmission, after the integrated reflection had been subtracted, became primarily a function of thickness. The variance also became quite uniform once the reflection had been subtracted. Comparing the natural log of the light transmission fraction with the sample thickness, an approximately linear relationship is found as shown in Fig. 10, which is predicted by Beer's law. Constructing a best-fit line through these data that intersects the origin allows the absorption constant, as represented by the negative of the slope of the line, to be calculated. This procedure yields an absorption coefficient of 5.58 $m^{-1}$ for rigid clear PVC, which entered into Beer's law yields the equation

$$\text{trasmission fraction} = \exp(-5.58 \times \text{thickness})$$

in metric units.

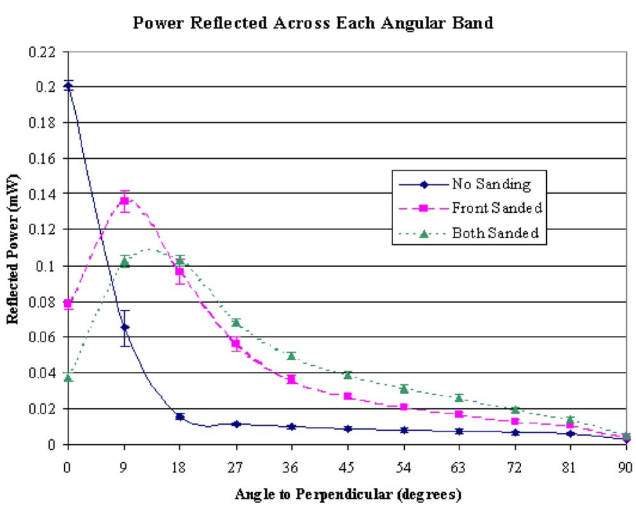


**Fig. 9** This plot shows the average of the measured power for each band of the hemisphere the reflection is integrated across. Note the large differences in the distribution of the power among the three different surface finishes. The error bars represent the standard deviation of the mean.

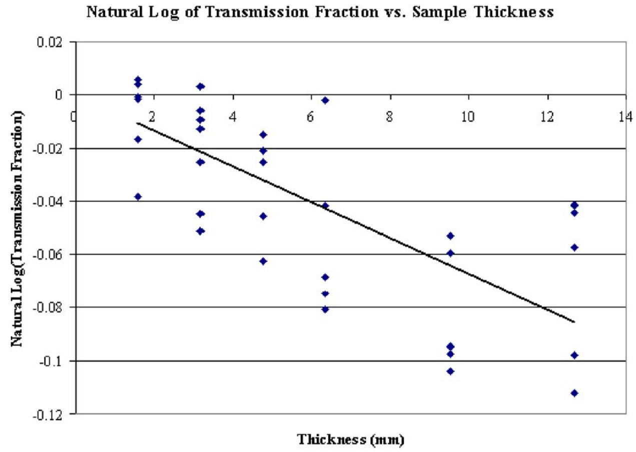


**Fig. 10** A plot of the natural log of the light transmission fraction (after subtracting the reflection) versus the sample thickness. Notice that it forms approximately a straight line that intersects the *y* axis at 0, as predicted by the Beer's law.

## 5 Limitations of the Reflection and Transmission Experiment

A systematic error, which was difficult to detect, was identified during this experiment. The source of this error was a fluctuation in the output power of the laser diode. The laser diode has a self-contained module that regulates the electrical power. Samples that have not been sanded have a very smooth surface finish and thus reflect the light specularly, as would a mirror. When these smooth samples are in the test device with the sample surface perpendicular to the laser beam, this reflection directly strikes the laser diode. It is thought that this reflected light entering the laser diode must cause additional heating, lowering the efficiency of the electrical-to-light energy conversion. This effect causes the power output to drop over a period of about 2 min. This power drop has been observed to be up to approximately 8%.

A method was designed to combat this problem. After placing a sample in the black box, it was left undisturbed for 2 min before any measurements were taken, allowing an equilibrium to be reached. After the transmission and reflection measurements were taken, the sample was removed and the laser power reaching the photodiode without a sample present was measured immediately to establish the reference power for that sample. Identifying this source of error led to a need to rerun the reflection experiment to assure the validity of the results. The preceding reported results were all based on the revised experimental method.

The idea that the reflected light could be influencing the performance of the laser was suggested by a review of the literature. A similar effect is routinely found in laser processing materials with high reflection fractions, such as aluminum. In these cases the reflected light striking the laser causes excessive heating of the laser, leading to a shorter life. One solution has been to add a filter to allow the laser light to pass through in one direction, while blocking the reflected rays.[12]

## 6 Conclusion

This investigation successfully designed and constructed a method of measuring laser light reflection and transmission simultaneously. Existing reflection measurement devices were explored, and concepts from these devices were used to create a new system for measuring reflection. A repeatable, low-cost alternative was constructed to meet the needs of the experiment.

The design solution relies on numerically integrating the reflected light across the surface of a hemisphere surrounding a sample. This integration uses measurements taken by a photodiode that rotates around a sample and collects reflection readings at specified intervals around the perimeter of the hemisphere. These reflection measurements were conducted simultaneously to measuring the light transmission.

A completely randomized experiment was designed and conducted using clear rigid PVC with two fully crossed factors: six levels of sample thickness and three levels of surface finish. The results of this experiment showed that the reflection is dependent on the surface finish in two regards. First, samples with a smoother surface finish reflect less light. Second, samples with a smoother surface finish reflect light more specularly than rougher finishes. From these data the absorption coefficient was calculated.

### *Acknowledgments*

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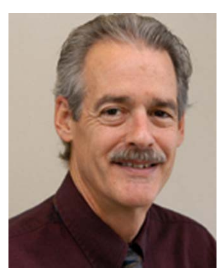

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