SLAC-PUB-9390
August 2002

Characterization of Ti:Sapphire Laser Rods for Installation in the Polarized Light Source

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August **13,2002**

Prepared in **partial** fulfillment of the requirements of the Office of Science, DOE Energy Research Undergraduate Laboratory Fellowship under the direction of Dr. Axel Brachmann in the Accelerator Department of the Stanford Linear Accelerator Center.

Work supported in part by the Department of Energy contract DE-AC03-76SF005 15.

Abstract

Characterization of Ti:Sapphire Laser Rods for Installation in the Polarized Light Source. **SEAN CORUM** (Augustana College, Sioux Falls, **SD,** 57197) AXEL BRACHMANN (Stanford Linear Accelerator Center, Menlo Park, CA, 94025).

The Flash:Ti laser in the Polarized Light Source at the Stanford Linear Accelerator Center **(SLAC)** is used to obtain spin polarized electrons for high-energy particle physics experiments. The Flash:Ti laser utilizes titanium-doped sapphire (Ti:Sapphire) crystals to produce laser light. The properties of these crystals, or laser rods, greatly affect the quality of the laser beam produced (e.g. power and jitter), which in **turn** affects the overall quality and reliability of the particle physics experiments at **SLAC.** In this interest, seven Ti:Sapphire laser rods were tested for absorption and transmission properties as a function of angular position (i.e. the rod was rotated along its geometrical axis). 833 nm light from a diode laser was linearly polarized and passed through the **rods** to test for transmission properties. The time-averaged power output of the emitted light was measured with a photodiode/powermeter apparatus. Similarly, the absorption properties of the rods were tested by passing linearly polarized light from a 543 nm green He:Ne laser through the rods. The rod with the best combination of absorption and transmission properties was selected for installation **in** the Polarized Light Source at the Stanford Linear Accelerator Center.

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Introduction

Many particle physics experiments require the use of spin-polarized electrons. At the Stanford Linear Accelerator Center (SLAC), polarized electrons are produced in the Polarized Light Source (PLS) by bombarding a gallium arsenide photocathode with coherent 805 nm light produced from a flashlamp-pumped Ti:Sapphire laser. Laser light incident on the gallium arsenide causes spin-polarized electrons to be emitted (photoelectric effect). These polarized electrons are then accelerated for use in high-energy particle physics experiments (Maruyama et all., 4-5).

Laser power levels and laser jitter are significant for the quality of experiments that utilize the PLS at SLAC. Adjustment of laser cavity parameters can increase power and reduce jitter, improving the statistics of parameters measured by high-energy physics experiments. In this interest, seven cylindrical titanium-doped sapphire laser crystals (Ti:Sapphire laser rods) will be tested for transmission and absorption properties as a function of angular position (rotation of the rod around its geometrical axis). The rod with the best combination of transmission and absorption characteristics will be selected for installation in the PLS.

Ti:Sapphire laser rods are negative uniaxial crystals. The rods are cut so that an ordinary optical axis is parallel to the geometrical axis of the rod. The two other optical axes (one ordinary and one extraordinary) are perpendicular to the geometrical axis (figure 1). The speed of light in the crystal is faster along the ordinary optical axis and slower along extraordinary optical axis. Thus, there are two different indices of refraction for the crystal, n_o and n_e, corresponding to the ordinary and extraordinary optical axes (Born and Wolf, 678-680). Absorption and transmission of linearly polarized light passing through the laser rod vary as the rod is rotated about its geometrical axis due to the interaction of the light with combination of the two indices of refraction (A. Brachmann, personal communication, August 1, 2002). When the rod is rotated so an optical axis is at an angular position θ degrees away from the polarization vector of the light, birefringence occurs and the effective index of refraction experienced by the light, n_θ, is given by:

$$\frac{1}{n_\theta^{\;2}} = \frac{\cos^2(\theta)}{n_o^{\;2}} + \frac{\sin^2(\theta)}{n_e^{\;2}} \qquad (1)$$

Absorption and transmission properties will be tested by passing green laser light (absorption) and infrared laser light (transmission) through the Ti:Sapphire laser rods. Green linearly polarized light passed into a rod will be maximally absorbed when the rod's ordinary optical axis is aligned parallel to the polarization of the light (figure 1). At this point, the rod will maximally fluoresce in the red and infrared spectrum. The same light will be minimally absorbed and the rod will minimally fluoresce when its extraordinary optical axis is parallel to the polarization of the light (figure 2).

Transmission of linearly polarized infrared laser light through the laser rods also occurs at maxima and minima when the ordinary and extraordinary optical axes are aligned with the polarization of the light. However, if an analyzer 90 degrees out of phase from the first polarizer is placed at the end of the rod where the light is emitted, four maxima will occur at rotational positions 45 degrees from the polarization of the light (figure 3). Due to the minimization of birefringence when a rod's optical axis is aligned with the polarization of the light, the analyzer will cause the extinction of the infrared laser beam. Thus, the maxima occur away from these angular positions.

Once the absorption and transmission tests are complete, the Ti:Sapphire laser rod with the best characteristics (i.e. most absorption of green light, most transmission of infrared light, correct configuration of optical axes) will be selected for installation in the Polarized Light Source at SLAC. In the future, the selected rod will be installed with its ordinary optical axis in the vertical position, which will induce maximum power output and minimum jitter during lasing. Also, this configuration of the optical axis will allow for the removal of the half-wave plate from the laser cavity. The half-wave plate rotates the plane of polarization of light emitted from the laser rod to match the orientation of the Brewster plate in the laser cavity. This process becomes unnecessary when the ordinary optical axis is matched to the Brewster plate. Since the half-wave plate is easily damaged, its removal will further improve the performance of the laser. The final purpose of these modifications will be to improve the overall quality and reliability of high-energy physics experiments at SLAC.

Methods and Materials

The laser rods tested for transmission and absorption properties were titanium-doped (0.1 +/- 0.03 wt. %) sapphire cylindrical laser crystals (Saint-Gobain Ceramics and Plastics, formerly Union Carbide). The rods have an absorption band of 400 nm to 600 nm and a fluorescence band of 650 nm to 1100 nm tunable (Koechner, 77). The seventh rod in the experiment had been previously installed in the PLS for six months prior to being tested for absorption and transmission properties.

The two-fold experimental setup utilized two similar designs to gather transmission and absorption measurements. In the first part of the setup, the laser rods were tested for transmission characteristics by passing light from an 833 nm diode laser (Melles Girot, Boulder, CO, USA) through the rods. First, the infrared laser beam's diameter was reduced from six millimeters to approximately one and a half millimeters via a 4:1 optical telescope. Second, the laser light was transmitted through a cube polarizer, allowing only linearly polarized light to pass. Third, the beam was passed through the geometrically aligned laser rod. Fourth, the laser beam was passed through a cube analyzer oriented 90-degrees from the first polarizer. Finally, the beam was filtered with a red-pass filter before striking a photodiode connected to an optical powermeter (Model 835, Newport, Irvine, CA, USA) set to measure 830 nm light (figure 4).

The rods' indices of refraction and absorption coefficient are temperature dependent. In order to account for room temperature fluctuations, a measurement was taken once a minute for a half hour duration at the four angular positions where maxima of transmitted light occurred. The mean and standard deviation of the measurements were electronically recorded using the powermeter's GPIB interface and a modified LabView device driver.

The second experimental setup tested the laser rods for absorption properties. The experimental setup and procedures were identical to that of the transmission experiment described above except for three modifications. First, light from a 543 nm He:Ne laser (Melles Girot, Carlsbad, CA, USA) was passed through the laser rod. The green light was absorbed by the laser rod, exciting fluorescence in the red and infrared spectrum. Second, the analyzer was eliminated from the setup, and the measurements were taken at the angular positions of maximum power (two) and minimum power (two). Third, the powermeter was set to measure 730 nm light from a photodiode with a red pass filter (figure 5). The fluorescence measurements were also taken at one minute intervals for a total duration of thirty minutes. The mean (time-averaged power) and its standard deviation were recorded as experimental results.

Results

All rods (except rod 4) were observed to have four power maxima and four power minima for the transmission experiments and two power maxima and two power minima for the absorption/fluorescence experiments. These readings occurred at roughly 90° intervals (+/- 15°). Rod 4 exhibited anomalous activity as only one maximum and one minimum power reading were observed during the absorption/fluorescence experiment.

The results of the laser rod transmission and absorption experiments are depicted in tables 1-14 and figures 7-8. Rod 4 transmitted the most light from the 833 nm diode laser with a time-averaged power of 308.2 +/- 119.5 μW (figure 15, table 7). Rod 3 converted the most green light from the 543 nm He:Ne laser into red and infrared wavelengths with a maximum power of 136.2 +/- 0.5 μW (figure 16, table 6). Rod 2 had nearly the same maximum power output at 136.0 +/- 0.5 μW (figure 16, table 4).

The standard deviations for the power measurements were noticeably greater for the transmission experiment than for the absorption experiment (due to birefringence). Excluding rod 7, normalized standard deviations, or jitter (standard deviation/mean *100 %), for the transmission experiment ranged from 6.5 % to 48.9 % (table 9, 11), whereas the jitter ranged from 0.2 % to 0.5 % (table 6, 10) for the absorption experiment. The jitter for the transmission experiment on rod 7 was one to two orders of magnitude lower (table 13). This difference could be attributed to the rod's previous installation in the PLS for six months as three small burn spots were observed on one face of the rod.

The transmission experiment power minima were not recorded because the 90-degree phase difference between the polarizer and the analyzer caused the extinction of the light at these positions. As such, these minima were within the background level and were thus not significant to the experiment.

Discussion and Conclusions

Analysis of the data shows that rod 4 transmitted the most infrared light and is thus a good candidate for installation in the PLS. However, only one maximum and one minimum were observed during the absorption test. Due to this anomalous behavior, rod 4 was not selected for installation in the PLS. The inconsistencies observed in rod 4 may be due to internal problems with the crystalline structure, external damage to the rod, or dirt and residue on the rod's surface. Further investigation is required to determine the cause of these irregularities.

The laser rod with the next highest power output for the infrared transmission experiment is rod 2 at 208.6 +/- 16.46 μW (table 3, figure 7). Rod 2 also has the second highest time-averaged power output at 136.0 +/- 0.4790 μW for the fluorescence experiment, just 0.2 μW below rod 3 (table 4, figure 8). This difference is less than one standard deviation of the measurement and is therefore statistically insignificant. Hence, rod 2 has the best combination of results for both the transmission and absorption/fluorescence experiments and is selected for installation in the Flash:Ti laser in the PLS.

Future work for this project includes installation of rod 2 in the correct angular position for maximum power output in the flash-lamp pumped Ti:Sapphire laser at the PLS. This will also allow for the removal of the half-wave plate (explained above) from the laser cavity. Measurements of the laser power and jitter must be taken over a period of weeks and compared to previous measurements of the same parameters before the laser cavity was modified in order to determine if and how much the performance of the laser has improved. Finally, improvements in the quality and reliability of spin-polarized electrons at SLAC should be observed.

Acknowledgements

The highest acknowledgements and thanks go to my mentor, Dr. Axel Brachmann, who contributed endless amounts of time and knowledge to this project. Thanks also go to Dr. Helen Quinn and Dr. Sekazi Mtingwa for managing the program and to the entire staff at the Stanford Linear Accelerator Center.

I thank the United States Department of Energy – Office of Science for the opportunity to participate in the Energy Research Undergraduate Laboratory Fellowship program.

The research in this paper was conducted at the Stanford Linear Accelerator Center, a national laboratory for basic research operated by Stanford University for the U.S. Department of Energy.

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Tables

Max/Min	Angle (deg)	Average Power (μW)	Standard Deviation	Jitter (%)
Max	61	104.9	36.8	35.0%
Max	151	42.0	18.7	44.5%
Max	244	88.2	25.7	29.1%
Max	327	89.4	28.3	31.7%

Table 1. Rod 1 transmission data. 833 nm light from diode laser passed through Ti:Sapphire laser rod.

Max/Min	Angle (deg)	Average Power (μW)	Standard Deviation	Jitter (%)
Min	29	95.8	0.3	0.3%
Max	103	101.3	0.4	0.4%
Min	194	95.6	0.3	0.3%
Max	290	117.2	0.3	0.3%

Table 2. Rod 1 absorption/fluorescence data. 543 nm light from He:Ne laser passed through Ti:Sapphire laser rod.

Max/Min	Angle (deg)	Average Power (μW)	Standard Deviation	Jitter (%)
Max	63	208.6	16.5	7.9%
Max	159	142.8	34.8	24.4%
Max	243	152.8	23.9	15.7%
Max	333	166.4	12.1	7.3%

Table 3. Rod 2 transmission data. 833 nm light from diode laser passed through Ti:Sapphire laser rod.

Max/Min	Angle (deg)	Average Power (μW)	Standard Deviation	Jitter (%)
Min	28	116.3	0.4	0.4%
Max	116	123.8	0.4	0.3%
Min	191	119.9	0.4	0.4%
Max	286	136.0	0.5	0.4%

Table 4. Rod 2 absorption/fluorescence data. 543 nm light from He:Ne laser passed through Ti:Sapphire laser rod.

Max/Min	Angle (deg)	Average Power (μW)	Standard Deviation	Jitter (%)
Max	87	133.3	34.6	25.9%
Max	177	166.7	36.5	21.9%
Max	267	137.0	38.9	28.4%
Max	357	114.8	47.2	41.1%

Table 5. Rod 3 transmission data. 833 nm light from diode laser passed through Ti:Sapphire laser rod.

Max/Min	Angle (deg)	Average Power (μW)	Standard Deviation	Jitter (%)
Min	42	118.7	0.5	0.4%
Max	127	135.3	0.3	0.2%
Min	222	117.7	0.4	0.3%
Max	310	136.2	0.5	0.3%

Table 6. Rod 3 absorption/fluorescence data. 543 nm light from He:Ne laser passed through Ti:Sapphire laser rod.

Max/Min	Angle (deg)	Average Power (μW)	Standard Deviation	Jitter (%)
Max	38	256.0	119.6	46.7%
Max	128	234.1	96.6	41.2%
Max	218	299.2	123.1	41.1%
Max	308	302.8	119.5	39.5%

Table 7. Rod 4 transmission data. 833 nm light from diode laser passed through Ti:Sapphire laser rod.

Max/Min	Angle (deg)	Average Power (µW)	Standard Deviation	Jitter (%)
Min	45	71.4	0.2	0.3%
Max	120	108.0	0.3	0.3%

Table 8. Rod 4 absorption/fluorescence data. 543 nm light from He:Ne laser passed through Ti:Sapphire laser rod.

Max/Min	Angle (deg)	Average Power (µW)	Standard Deviation	Jitter (%)
Max	57	132.2	64.0	48.4%
Max	146	158.8	27.9	17.6%
Max	237	110.5	29.4	26.6%
Max	327	114.2	37.5	32.8%

Table 9. Rod 5 transmission data. 833 nm light from diode laser passed through Ti:Sapphire laser rod.

Max/Min	Angle (deg)	Average Power (µW)	Standard Deviation	Jitter (%)
Min	5	117.5	0.5	0.4%
Max	101	133.6	0.5	0.3%
Min	211	122.0	0.5	0.4%
Max	289	122.7	0.6	0.5%

Table 10. Rod 5 absorption/fluorescence data. 543 nm light from He:Ne laser passed through Ti:Sapphire laser rod.

Max/Min	Angle (deg)	Average Power (µW)	Standard Deviation	Jitter (%)
Max	10	141.1	9.2	6.5%
Max	100	93.7	23.2	24.8%
Max	190	143.6	20.5	14.3%
Max	279	171.6	14.8	8.6%

Table 11. Rod 6 transmission data. 833 nm light from diode laser passed through Ti:Sapphire laser rod.

Max/Min	Angle (deg)	Average Power (μW)	Standard Deviation	Jitter (%)
Max	50	121.3	0.3	0.3%
Min	150	82.3	0.3	0.4%
Max	240	98.6	0.3	0.3%
Min	311	86.6	0.3	0.4%

Table 12. Rod 6 absorption/fluorescence data. 543 nm light from He:Ne laser passed through Ti:Sapphire laser rod.

Max/Min	Angle (deg)	Average (μW)	Standard Deviation	Jitter(%)
Max	40	32.44	0.36	1.1%
Max	130	32.72	0.11	0.3%
Max	220	24.67	0.05	0.2%
Max	310	25.45	0.03	0.1%

Table 13. Rod 7 transmission data. 833 nm light from diode laser passed through Ti:Sapphire laser rod.

Max/Min	ϕ (deg)	Average (μW)	Standard Deviation	Jitter(%)
Min	0	92.5	0.4	0.4%
Max	107	109.9	0.4	0.3%
Min	186	100.5	0.5	0.5%
Max	274	115.8	0.4	0.4%

Table 14. Rod 7 absorption/fluorescence data. 543 nm light from He:Ne laser passed through Ti:Sapphire laser rod.

Figures

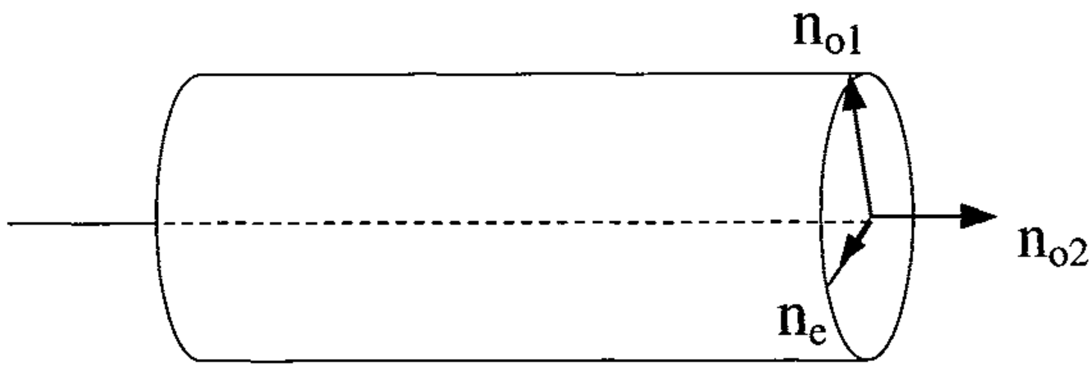

Figure 1. Depicts the indices of refraction of a Ti:Sapphire laser rod. n_e is smaller than n_{o1} and n_{o2}, and n_{o2} is parallel with the geometrical axis of the laser rod.

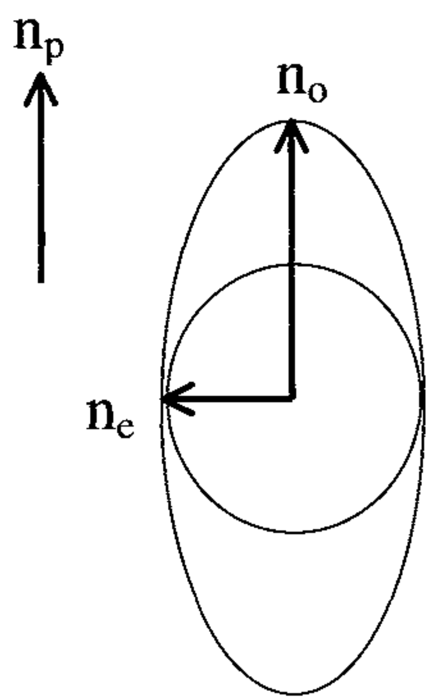

Figure 2. Depicts the orientation of the Ti:Sapphire crystal's optical axes during maximum power output during transmission experiment. The linearly (plane) polarized 543 nm light's electric field vector (n_p) is parallel to the extraordinary optical axis.

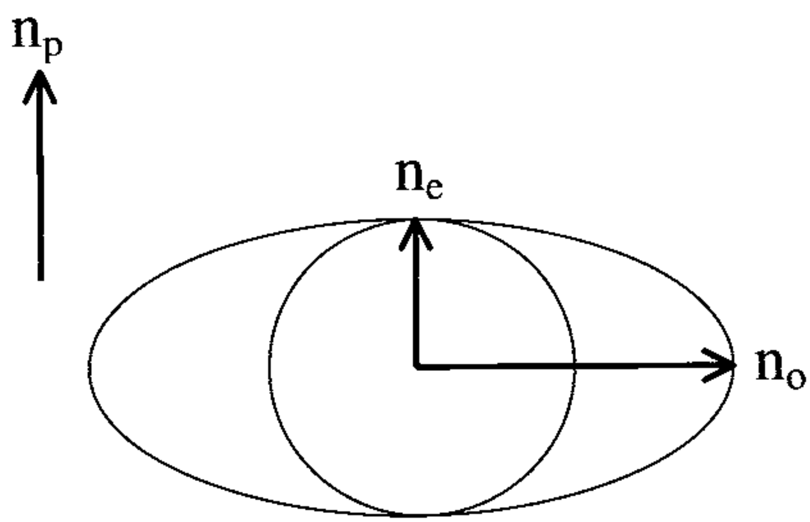

Figure 3. Depicts the orientation of the Ti:Sapphire crystal's optical axes during minimum power output during transmission experiment. The linearly (plane) polarized 543 nm light's electric field vector (n_p) is parallel to the ordinary optical axis.

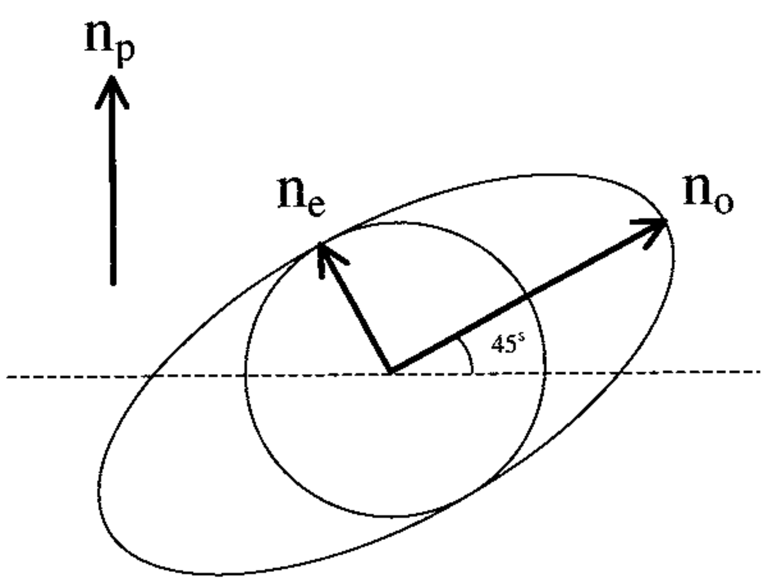

Figure 4. Depicts the angular orientation of the Ti:Sapphire crystal during the absorption experiments. n_p is the direction of the linearly (plane) polarized 833 nm light.

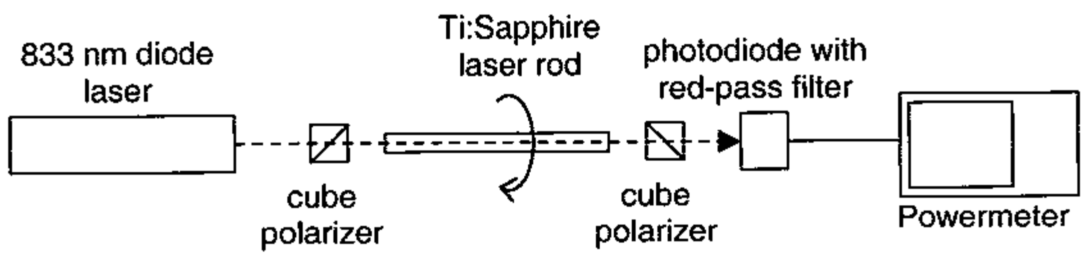

Figure 5. Diagram of the transmission experimental setup.

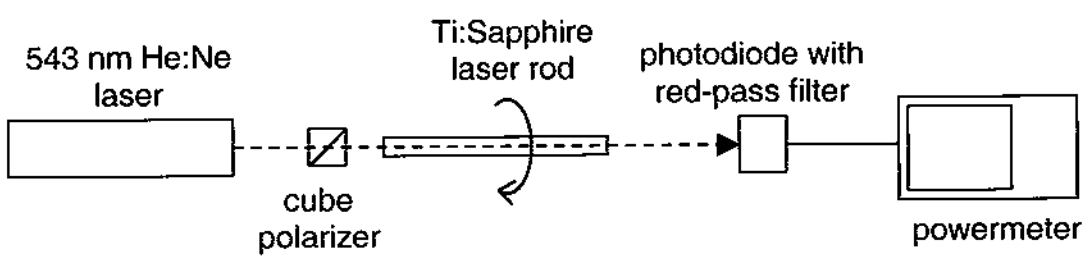

Figure 6. Diagram of the absorption/fluorescence experimental setup.

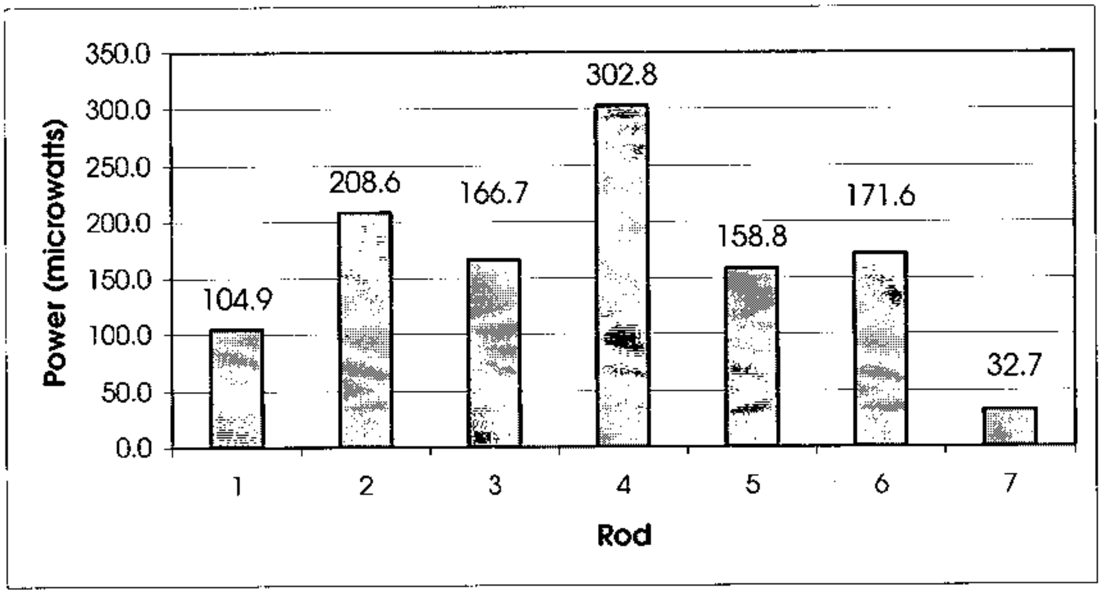

Figure 7. Depicts the maximum power output for each laser rod during the transmission experiment.

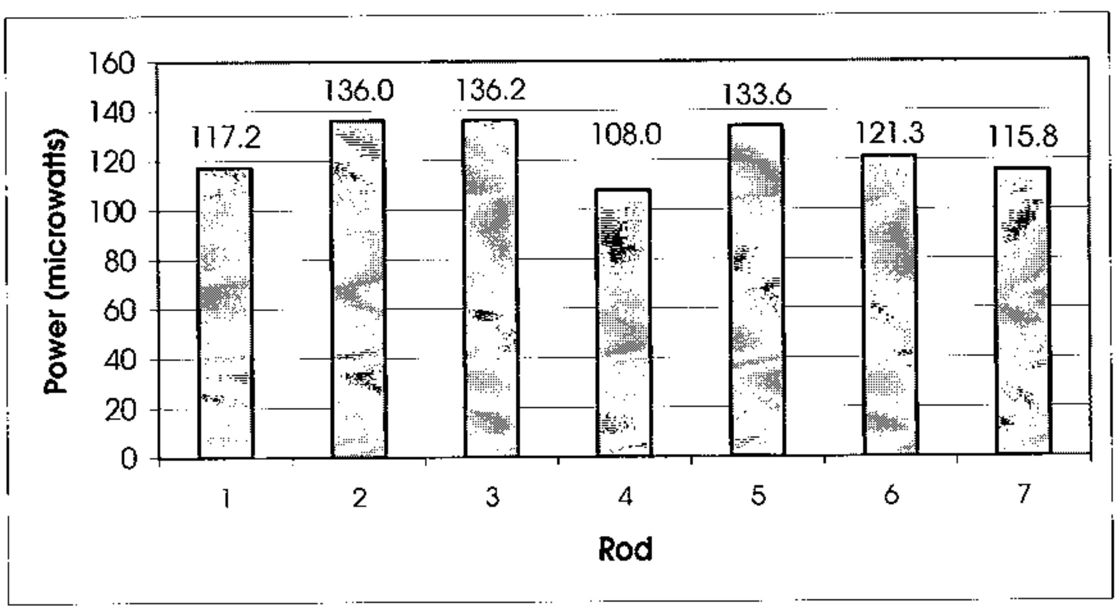

Figure 8. Depicts the maximum power output for each laser rod during the absorption experiment.