

Investigation of a method for the determination of the focussed spot size of industrial laser beams based on the drilling of holes in Mylar film

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ABSTRACT

The focussed spot size of industrial laser beams is a critical processing parameter in most laser machining applications as it determines the machined feature size and the irradiance produced by the laser at the material interface. There are a number of standard methods available for accurately measuring and analysing the focussed spot. These methods often require expensive equipment that can be time consuming and difficult to set up in a production environment.

This paper presents an investigation into a cost effective and straightforward method for the measurement of focussed laser spot sizes based on drilling of holes in mylar film. It can be shown that the slope of a plot of the square of the hole diameter versus the natural log of the laser pulse energy is equal to twice the square of the spot radius. A measure of the laser spot size can be calculated by generating laser-drilled holes at number of laser pulse energies. The practicality and accuracy of this method is investigated in this paper for a number of laser types including a diode pumped solid state laser (UV DPSS) operating at the third harmonic (355nm), a femtosecond laser and a flash lamp pumped Nd:YAG laser. A comparison between the measured results and the results generated with other available techniques is also presented.

Keywords: laser processing, beam measurement, spot size measurement, beam diagnostics

1. INTRODUCTION

The focussed spot size of industrial laser beams is a critical processing parameter in most laser machining applications as it determines the machined feature size and the irradiance produced by the laser at the material interface. There are a number of standard methods available for accurately measuring and analysing the focussed spot. These involve direct measurement of the laser beam intensity distribution using an energy meter or detector along with a knife-edge, ribbon, aperture or rotating wire. These methods often require expensive equipment that can be bulky and difficult to install. Often these methods cannot be used to directly measure the spot size at the focus of the laser without using substantial attenuation to prevent degradation of the sensor. This attenuation can tend to alter the characteristics of the beam entering the sensor and does not give a true reflection of the spot size. Other methods involve indirect measurement using the burn contour in various films such as kapton, metals films, plexiglass blocks. These methods are easier to perform and are less expensive but can be inaccurate. The method outlined here is a variant of this type of technique.

This paper presents an investigation into a cost effective and straightforward method for measurement of focussed laser beam spot sizes based on the drilling of holes in mylar film at the focus of the laser. Studies performed in [1] involved analyses of holes and surface char damage produced by pulsed laser beams in film materials like kapton. It was shown that the measured diameter of damaged material depended on pulse energy. For multimode beams, which can be modelled as truncated cones, the hole or char diameter was predicted to increase linearly with decreasing values of reciprocal pulse energy, $(1/E_p)$. For Gaussian beams, the square of the diameter of the char or hole was predicted to depend on the natural logarithm of the pulse energy [1]. This corresponds to the equation below.

$$D_h^2 = -2w^2 \cdot \ln \left(\frac{\pi w^2}{2\alpha_e} \Delta H_v \delta \right) + 2w^2 \cdot \ln (E_p) \quad \text{Equation (1)}$$

where D_h is the vaporised hole diameter, w is the $1/e^2$ distribution coefficient, α_e is the effective optical absorptivity, ΔH_v is the total heat required to heat and vaporise a unit of material, δ is the film thickness and E_p is the pulse energy.

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When w is constant, the first term on the right hand side is constant and therefore, the square of the diameter of the hole in the kapton should be linearly proportional to $\ln(E_p)$ [1]. The slope of this straight line is equal to $2w^2$ and thus the spot size can be calculated using the following equation:

$$\text{Spot size} = 2\sqrt{\frac{\text{slope}}{2}} \quad \text{Equation (2)}$$

It is stated in [1] that these relations are general and valid for any film material which ideally should have a uniform and reproducible film thickness, a low thermal diffusivity and should not form a liquid phase when heated by the laser pulse. Initial trials were performed on the 355nm DPSS laser with 25 μm thick kapton film, however the laser could not produce a hole with a single pulse with the range of energies that were available. For this reason, mylar (or biaxially oriented thermally stabilised PET) film was chosen as an alternative because sufficiently thin films of kapton were not available. Per the technical specification from the material supplier Goodfellow Inc., the thermal conductivity @ 23°C of kapton film is 0.10-0.35 $\text{W m}^{-1} \text{K}^{-1}$. For mylar, the thermal conductivity is 0.15-0.4 $\text{W m}^{-1} \text{K}^{-1}$, which is of the same order as that for the kapton film. PET is self-extinguishing and is a dimensionally and thermally stable material.

The practicality and accuracy of this method was investigated for a number of laser types including a UV DPSS, a femtosecond laser and a Q-switched Nd:YAG laser. In the case of the Q-switched Nd:YAG laser, metallised mylar film was used, as the un-metallised mylar film was transparent to the laser beam at 1.064 μm . In all cases, holes were made in the film at a range of pulse energies. The three lasers used for the experiments all produce Gaussian beams and hence the square of the hole diameters was plotted against the natural log of the pulse energies in Joules (J). The slope of this plot equalled twice the square of the beam radius. Thus an estimation of the focussed spot size of the laser beam was determined using mylar film placed at the focus of the laser beam. The conclusions regarding the practicality and accuracy of this method are discussed later.

2. EXPERIMENTAL METHODS

2.1 Mylar film details

The details of the mylar material used in the experiments is as follows:

Mylar film, Polyethylene terephthalate Polyester, PET, PETP

Thickness: 0.0015 μm ; Thermal Conductivity @ 23°C is 0.15-0.4 $\text{W m}^{-1} \text{K}^{-1}$

Part number ES301015/1, Supplier Goodfellow Inc.

Metallised mylar film, Polyethylene terephthalate (Polyester, PET, PETP) Metallised Film

Thickness 0.002 μm ; Thermal Conductivity @ 23°C is 0.15-0.4 $\text{W m}^{-1} \text{K}^{-1}$

Metallised with Aluminium

Part number ES301820/1, Supplier Goodfellow Inc.

2.2 Preparation of mylar samples

A method was devised to maintain the flatness of the mylar film for experiments. The film was held in tension, and a small fixture with an aperture at its centre was glued on top of the film. This was placed film-side down at the focus of each laser.

2.3 Experimental Set-up with UV DPSS laser

The AVIA laser was used as the diode pumped solid-state Q-switched laser providing ultra violet light at 355nm with pulse repetition rates from single shot to 100kHz. The set-up of the UV DPSS laser is shown in figure 1.

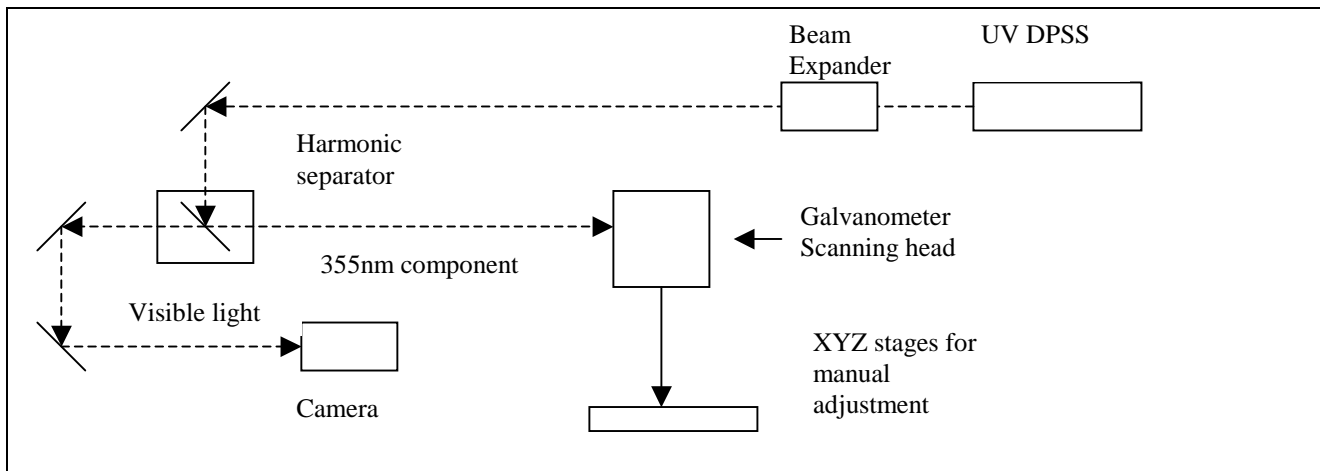


Figure 1: Optical Configuration of UV DPSS system

The beam emerging from the laser is 3.5mm in diameter and the beam expander is used to expand the beam up to a maximum of approximately 2.7X. The sample for processing is placed on a sample holder with a circular aperture, which is mounted on an XYZ stage for manual adjustment. The mylar is placed over this aperture allowing the laser beam to pass straight through the film. Holes were machined in the mylar film at seven different energy settings. These seven readings were achieved using different combinations of current and Q-switch repetition rate.

The focus of the laser beam was first determined using the mylar film. Using a constant current and repetition rate, single pulses of the laser were fired at the mylar at a range of settings on the Z height stage. The diameter of the resulting holes (X direction) was measured on a Zygo Newview Profilometer. The diameters were plotted against the height settings. A second order polynomial was fitted to the data and the position corresponding to the minimum diameter was chosen as the focus position. The seven energy settings were chosen because they produced well defined holes in the mylar film. An energy meter (Moletron model # EPM1000 with model # J8LP-4 head) was used to measure the energy at each of these settings for a single pulse of the laser. Single pulses of the AVIA laser were fired at the mylar film and the resulting hole diameters were measured using the Zygo Newview Profilometer. Two hole diameters were measured at each energy and averaged. This procedure was repeated at five different settings on the beam expander, giving the focussed spot size at the following expansions of the beam: X1, X2, X2.2, X2.7 and X3. The spot size was also measured with the beam expander removed to determine the focussed spot size obtained with the telecentric lens in the galvoscan head. The spot sizes obtained were plotted against the beam expansion settings to determine the manner in which the beam diameter responded to the different settings on the beam expander.

Results were compared with theoretical estimates, which were calculated using the following equation for spot size [2]:

$$\text{Spot Size} = \frac{4fM^2\lambda}{\pi D} \quad \text{Equation (3)}$$

where f is the focal length, M^2 the beam quality factor, λ the wavelength and D the raw beam diameter.

2.4 Experimental Set-up with Femtosecond laser

A femtosecond laser, the Clark CPS 2001, which emits pulses at $\lambda = 775\text{nm}$ with a short pulse length of $200 \times 10^{-15} \text{ s}$ was used for this study. The configuration of this laser is shown in the figure 2.

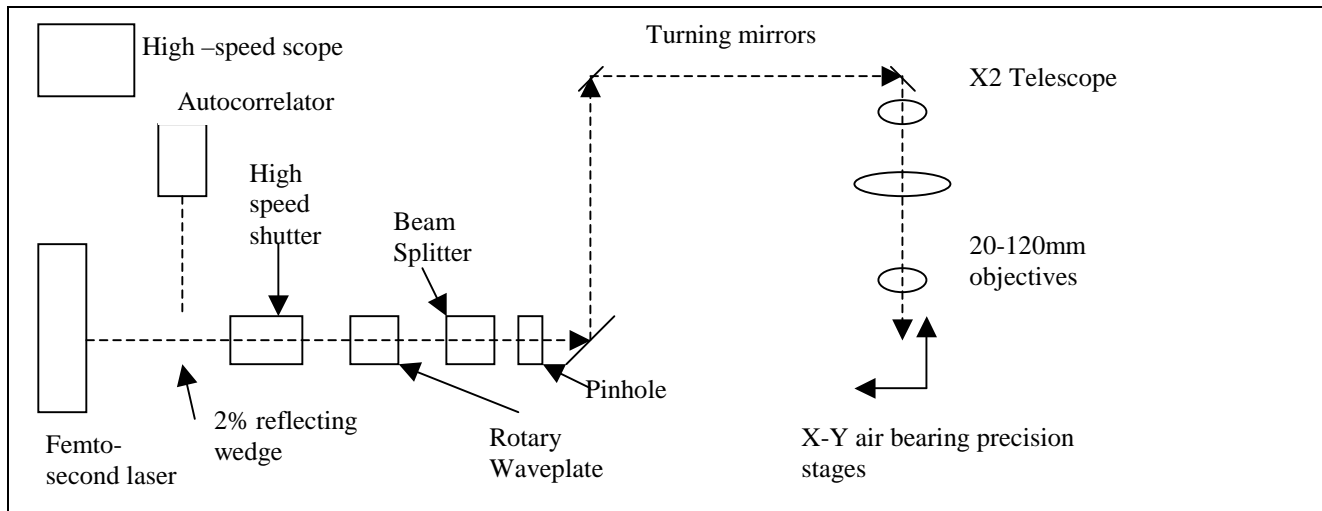


Figure 2: Optical Configuration of femtosecond system

A pinhole was inserted to give a 3.5mm beam diameter. A final focussing optic consisting of a 120mm objective lens was used. Mylar film was placed on the micrometer stage at the focus of the beam. A program was written for the motion system to machine a line of 10 holes at each energy setting. Each hole consisted of five shots of the laser beam in a total exposure time of 5ms. Single pulses of the laser are preferable for this method, however, it was not possible to configure the laser pulses with shutter opening times for single pulse energies. Ablation with a femtosecond laser results in rapid material removal and the absence of molten material and a negligible heat affected zone. This is due to the short pulse length ($200 \times 10^{-15} \text{ s}$), which effectively means that there is no time for conduction or transfer of thermal energy. The first shot ablates the mylar film and the subsequent shots have no effect on widening the diameter of the hole produced. In this experimental set-up it should be noted that the mylar film fixture is not placed over a through aperture as in the case of the other two lasers, but it is in fact placed sitting on a flat metal vacuum stage. The presence of the fixture as a heatsink is not expected to produce a bigger hole in the mylar as no thermal conduction effects occur in the metal. As an experiment, a flat sheet of stainless steel was placed below the mylar film and lines of holes were made for a number of energies. The hole diameters in the mylar were compared with the corresponding hole diameters on the stainless steel sheet and the diameters were the same. As stainless steel is a better conductor of heat, it would produce a bigger hole in the steel than in the mylar, which has a low thermal conductivity. Since the holes were the same size, indicating minimal conduction of heat occurred, the diameter of the hole in the mylar was directly related to the beam energy only. These observations are relevant to indicate that the experimental set-up is valid in this case.

The femtosecond laser used in this study does not have an internal attenuator with fixed settings and therefore the energy is varied manually using the external shutter and the rotary waveplate. Eleven different energies were chosen and the attenuation was set accordingly for each. The energy was checked with the energy meter (Molelectron EPM1000 with J8LP-4 head) prior to the machining of each line of holes to ensure that the attenuation was set to achieve the correct energy. The pulse energy measurement software averages 5000 energy readings to give the average energy at each setting. A CCD beam profiler (Dataray Wincam) was also used to check the circularity of the beam before the holes were machined to ensure the pinhole was set correctly. A line of ten holes were machined at each energy setting. The diameter (X direction) of the resulting holes in the mylar was measured on the Zygo Newview Profilometer and the hole diameters were averaged.

2.5 Experimental Set-up with Q-switched Nd:YAG laser

The Q-switched Nd:YAG laser consisted of a Spectron laser (model SL902TQ) operating at a laser wavelength of 1064nm. In Q switch mode, frequencies range from 1kHz – 20kHz with average powers ranging from 4W - 16W for single mode operation. The configuration of this laser is shown in the following schematic.

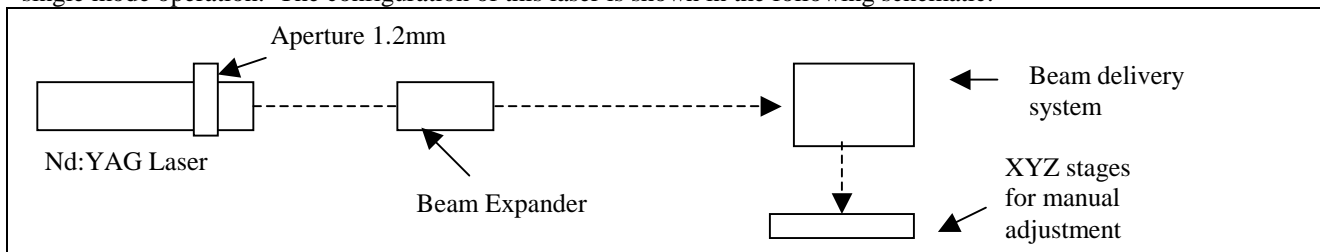


Figure 3: Optical configuration of the Nd:YAG laser

The beam expander was used to focus the beam to a spot size of approximately 100 μ m. A program was written for the scanhead to machine a line of single laser pulses. The marking speed was chosen to ensure that the pulses were resolved and not overlapping. Initial trials with mylar film showed that it was transparent to the laser beam. kapton film with a thickness of 25 μ m was also used, however, it was not possible to machine through the film in a single pulse produced by the laser in this configuration. Metallised mylar film was available in a suitable thickness of 2 μ m. Single pulses of the laser vaporised the metallised layer without penetrating the mylar layer, leaving a circular char mark on the mylar layer. Using the Zygo interferometer, it was possible to focus the interference fringes on the char mark, producing an image of a raised circular mark on the mylar film. This mark was sufficiently circular and regular that it was possible to measure its diameter accurately. It should be noted that metallised mylar is not regarded as the ideal material for this task as there is a possibility that the metal layer brings in thermal effects, which may contribute to the size of the mark created on the film.

An Optical Profiler (BeamScan, Photon Inc, Model 1180) was used initially to determine the focus and approximate spot size at that setting of the beam expander. The Beamscan can only be used when the laser is in continuous wave mode therefore the measurements of the beam in CW mode are not a completely true reflection of the beam at the conditions that are used in the experiments when the laser is Q-switched. Nonetheless, the measured spot size should be very close to the actual spot size. The Beamscan was placed on the XYZ stage and the beam diameter at a range of height settings was measured. The position of minimum diameter was defined as the approximate focus position of the laser beam. Mylar film was placed on an XYZ stage at a distance equivalent to the focal position determined on the Beamscan. The mylar is placed over a circular aperture to allow the laser to pass straight through the film. For each setting at which lines were machined, the power was measured on the Power meter (model Ophir DGX with Ophir head). The corresponding energies were calculated using the following formula

$$E_{pulse} = \frac{P_{av}(W)}{Q(Hz)} \quad \text{Equation (4)}$$

where E_{pulse} is the energy in the pulse, P_{av} is average power and Q is the pulse repetition rate.

3. RESULTS AND DISCUSSION

3.1 Results for UV DPSS laser

The spot size measurement method was used firstly with the beam expander removed and then with the beam expander set at five different expansions. Only the full results of the first experiment with the beam expander removed are presented and the results of the other experiments are summarised. Table 1 shows how the focal position was determined with the beam expander removed. The height settings are relative rather than absolute as they correspond to the micrometer setting on the Z stage. Figure 4 shows the determination of focus positions at a height setting of $Z=8$ mm on the micrometer stage. Table 2 shows the energy settings and the hole sizes obtained with the beam expander removed.

Table 1: Data for focus determination with beam expander removed

Height setting (mm)	Diameter X direction (μm)	Height setting (mm)	Diameter X direction (μm)
7.50	29.5	8.00	22.9
7.60	27.2	8.05	23.2
7.70	24.9	8.10	23.2
7.80	27.2	8.15	23.2
7.90	21.8	8.20	24.4
7.95	22.6	8.30	26.7

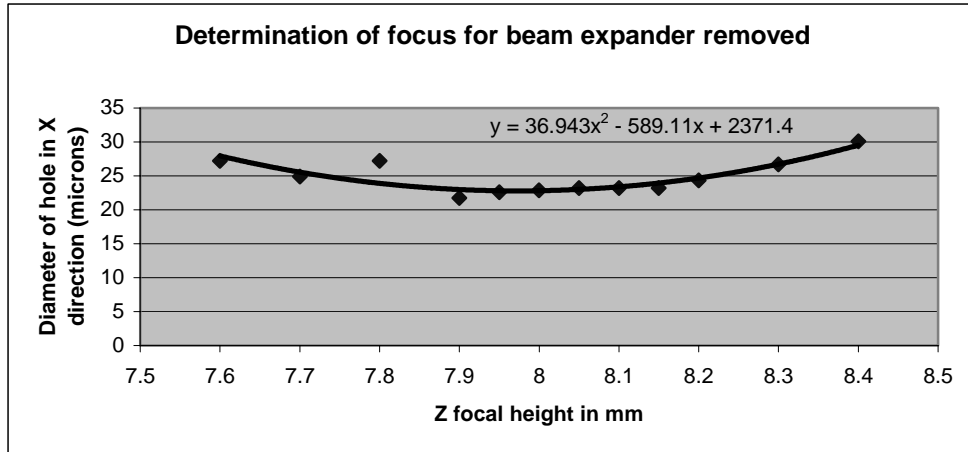


Figure 4: Focus position with beam expander removed: the dependence of the hole diameter with different positions of the mylar film under the telecentric lens

Table 2: Data for focus determination with beam expander removed

Energy (x10 ⁻⁶ J)	Average hole Diameter (μm)	Ln (Energy) (J)	D squared (x10 ⁻¹⁰ mm ²)
31	1.7	-10.38	3
71	17.4	-9.55	3
123	22.6	-9.00	5
146	22	-8.83	5
103	20.9	-9.18	4
168	25.5	-8.69	7
182	26.7	-8.61	7
186	26.1	-8.59	7
210	28.4	-8.47	8
235	28.4	-8.36	8
288	30.1	-8.15	9

The hole diameter squared was plotted versus the natural log of the energy in Joules (J). A linear trendline was fitted to the data and the slope of this line was obtained. The square root of half this slope, multiplied by 2, gave the approximation of the spot diameter. This is shown in the following graph.

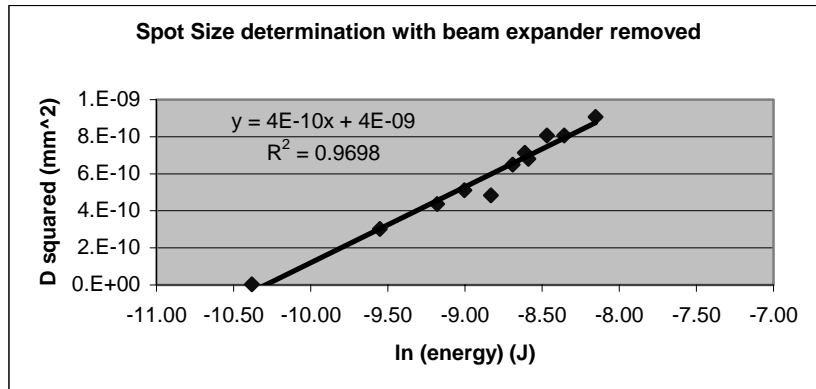


Figure 5: Spot size with the beam expander removed

A linear trendline was fitted to the data and the R^2 value (correlation coefficient) indicates that the trendline is a good fit. The slope was determined as $4 \times 10^{-9} \text{mm}^2$. Per equation (2), the spot size with the beam expander removed is determined as $29\mu\text{m}$.

Using equation 2, where $f = 100\text{mm}$ for the galvanometer lens, M^2 is taken to be 1.3 from the AVIA specification, λ is 355nm and D_z is 3.5mm (the $1/e^2$ diameter), the theoretical spot size is determined as $17\mu\text{m}$. The quoted value for M^2 of 1.3 however has not been verified by measurement and a number of factors may impact its use in the theoretical prediction of spot size.

Figure 6 shows the spot sizes graphed versus the equivalent beam expander setting. Note that X1* refers to when the beam expander is removed. A beam expander is designed to increase the diameter of a laser beam; it takes a small-diameter collimated input beam and produce a larger diameter collimated output beam, reducing the divergence of the beam and reducing the focussed spot size. The beam expander has a scale of 1-8 and so, when the beam diameter is increased, the spot size should be reduced resulting in an inverse power relationship. A power trend line was fitted to the X1, X2, X2.2 and X2.7 data points and the R^2 value showed a good fit. The calculated spot size for X3 however did not fit this relationship. It was concluded that while the beam expander is capable of expanding from 1-8 times, the expansion at X3 was limited by the 10mm aperture diameter of the beam delivery system. While the spot size for X2.7 is lower than that for X2.2, it should be used with care as it is possibly close to or at the expansion limit. The spot size of $29\mu\text{m}$ was obtained with the beam expander removed from the laser. $29\mu\text{m}$ is close to $30\mu\text{m}$ verifying that X1 corresponds to no expansion of the beam.

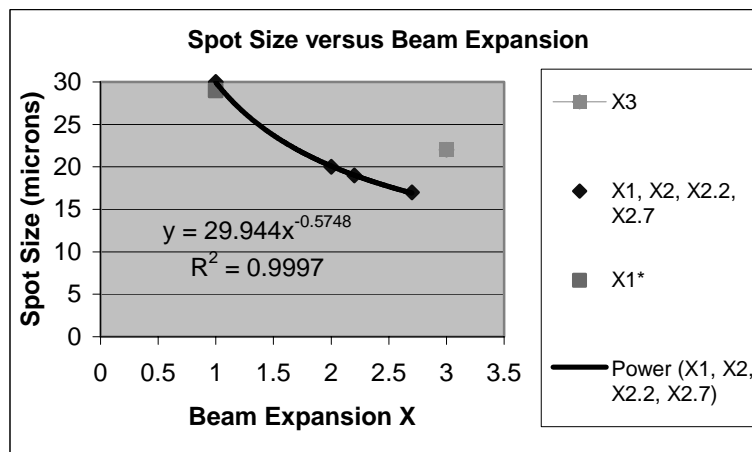


Figure 6: Spot sizes versus beam expander setting

3.2 Results for femtosecond laser

In this section results are presented for a femtosecond laser source. Figure 7 shows a profile of the beam taken on a Dataray beam profiler. It shows that the beam is circular and Gaussian in nature.

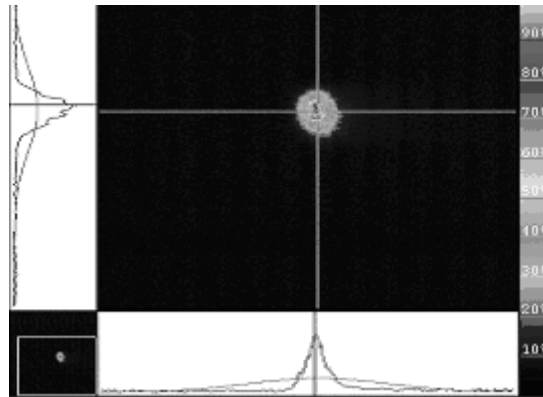


Figure 7: Beam Profile of femtosecond laser beam

Table 3 shows the energy settings and the hole sizes obtained. Figure 6 shows the hole diameter squared plotted versus the $\ln(\text{energy})$ in J. A linear trendline was fitted to the data and the R^2 value (correlation coefficient) indicates that the trendline is a good fit. Per equation (2), the slope of the line was determined to be $3 \times 10^3 \mu\text{m}^2$ and therefore the spot size is determined as $39\mu\text{m}$.

Table 3: Data for spot size of femtosecond laser

Energy ($\times 10^{-6}$ J)	Average hole diameter (μm)	Ln (Energy) (J)	D squared (μm)	Error hole diameter squared (μm)
5.25	15.67	-9.86	245.55	80.86
6.09	18.08	-9.71	326.89	95.46
7.31	21.38	-9.52	457.10	95.78
8.11	22.73	-9.42	516.65	85.01
9.12	25.22	-9.30	636.05	81.21
10.09	27.07	-9.20	732.78	103.41
11.49	28.50	-9.07	812.25	107.16
12.59	29.69	-8.98	881.50	110.45
13.56	30.69	-8.91	941.88	129.51
14.24	31.11	-8.86	967.83	142.48
15.47	32.00	-8.77	1024.00	170.88

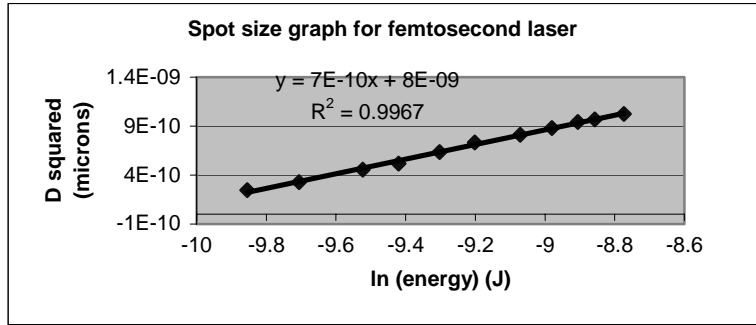


Figure 8: Spot Size graph for Femtosecond laser

Using equation 2, where $f = 120\text{mm}$ for the objective lens, M^2 is taken to be 1.3, λ is 775nm and D_z is 3.5mm (the pinhole size), the theoretical spot size is determined as $44\mu\text{m}$. M^2 was previously measured using a different focussing lens and was interpolated using a series of measurements taken either side of the focus, giving an approximate value of M^2 of 1.3. The measured value of spot size is $39\mu\text{m}$, which is smaller than $44\mu\text{m}$. The error bar on the hole diameter squared was calculated for each value and this error is shown in table 3. From this data, the error on the slope of the trendline in figure 8 was calculated as $6.2\mu\text{m}$, showing that the predicted spot size of $44\mu\text{m}$ is within this error bar. This difference in measured and predicted spot size could also be due in part to the 120mm final focussing lens giving a different divergence. Multi-phonon absorption may also be a factor in the interpolated M^2 value, which is causing the predicted spot size value to differ from the measured one.

3.3 Results for Q-switched Nd:YAG laser

Finally results are presented for a flash lamp pumped solid state laser operating in the near infrared. In this case, thermal lensing is an effect that occurs due to changes in the laser power. This causes the refractive index and focal length of the optical elements to change as a result of the change in temperature. The UV DPSS laser discussed in section 3.1 has a built in ThermaTrack function, which consists of a mirror, located in the IR cavity of the laser, which is mounted on a motor driven slide. There is an optimum position of the mirror for each current and pulse repetition rate combination. Therefore, this mirror compensates for the variable thermal lensing in the laser rod crystals at each setting. For the femtosecond laser discussed in section 3.2, the attenuation of the beam was external to the laser cavity and so no thermal lensing could occur. The Spectron Nd:YAG laser has no mirror adjustment similar to the Thermatrack, and thus thermal lensing is likely to occur when the settings are changed. For this reason, the range of energy settings was achieved by changing the Q-switch frequency while maintaining the input power from the lamp, rather than by changing both the power and Q-switch frequency together. To verify that this was the case, the energy was fixed at 0.2mJ and four Q-switch frequency settings were chosen which resulted in different power readings on a power meter (Ophir model DGX). The position of the focus of the laser was determined using the Optical Profiler and the metallised mylar was placed on the XYZ stage at this position. Lines were machined on the mylar at each of the four settings and the diameters of the resulting char marks on the film were measured on the Zygo Newview Profilometer. The results are presented in table 4.

Table 4: Diameters at different power settings based on an energy of 0.2mJ

Q-switch frequency (kHz)	Power measured on Power Meter (W)	Calculated Energy(mJ)	Average diameter (μm)
1	0.2	0.220	115
5	1	0.190	104
10	2	0.206	123
20	4	0.199	133

This data clearly illustrates that varying the power while keeping the energy constant results in different diameters on the mylar. Note that the magnitude of the diameters produced is not consistent with the corresponding power measurement either which means that the effects of thermal lensing are not linear with changes in the power. The mylar

film method relies on the changes in the produced diameters being solely related to changes in the energy of the pulse, which would not be valid in this case. Therefore, a fixed power setting of 1W was chosen and a variety of energy settings at various Q-switch frequencies producing 1W of average power were chosen.

The laser was set at a power setting that produced 1W average power and then it was switched to CW. The BeamsScan was inserted to measure the Gaussian beam diameter at focus. The beam diameter was recorded as 99µm on the BeamsScan with a Gaussian ratio of 0.897, which indicated a good Gaussian fit. The BeamsScan was removed and the mylar film was placed on the XYZ stage at the same focal position. Figure 9 shows the output of the BeamScan exported into Excel. This shows the profile of the beam with the 13.5% ($1/e^2$) clip level beam diameter.

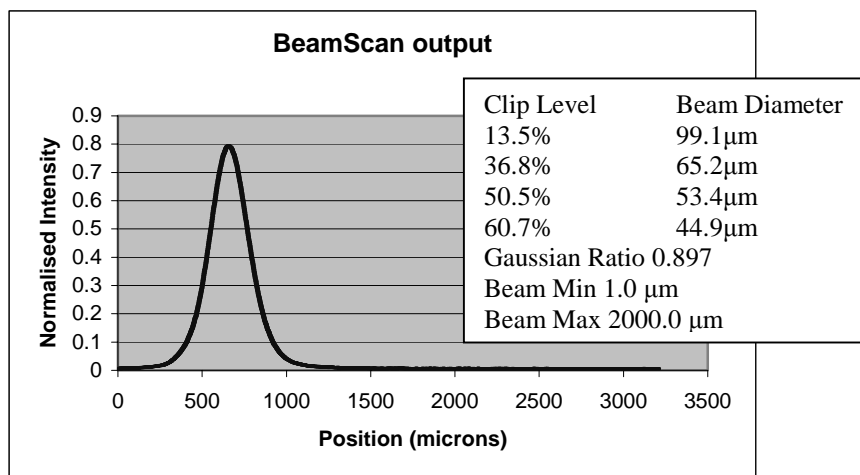


Figure 9: BeamScan output

Table 5 shows the energy settings and the char mark diameters obtained. Figure 10 shows the plot of the hole diameter squared versus the natural log of the energy in Joules. A linear trendline was fitted to the data and the slope of this line was obtained. The square root of half this slope, multiplied by 2, gave the approximation of the spot diameter.

Table 5: Data for Spot Size of YAG laser (outliers shown in bold font)

Q-switch frequency (kHz)	Energy (µJ)	Average diameter (µm)	Ln (Energy) (J)	Diameter squared (µm)
1	980	158.6	-6.93	25153.96
1.5	660	156.1	-7.32	24367.21
2	495	152.6	-7.61	23286.76
10	100	109.8	-9.21	12056.04
12	85	104.9	-9.37	11004.01
15	65	98.5	-9.64	9702.25
17	56	90.2	-9.79	8127.02
20	51	86.8	-9.88	7529.03
3	330	117.2	-8.02	13740.53
5	192	104.1	-8.56	10840.97
7	146	105.0	-8.83	11014.50
9	114	93.0	-9.08	8649.00
13	769	102.4	-7.17	10485.76

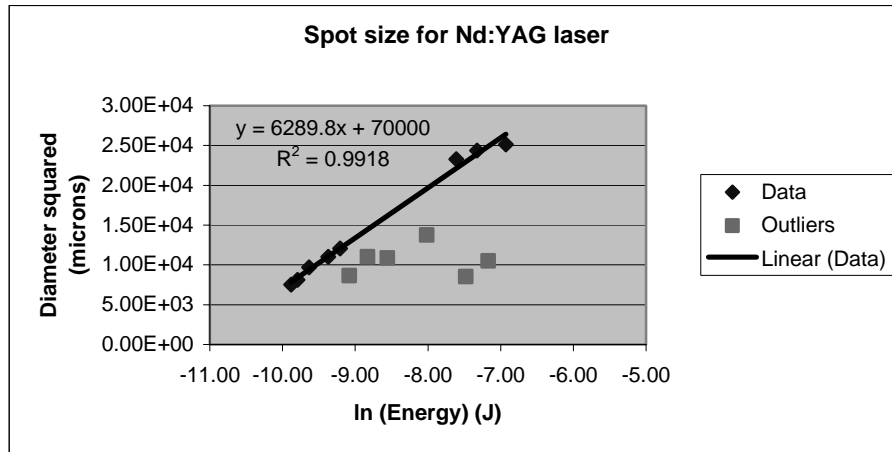


Figure 10: Spot Size for Nd:YAG laser. Note that the square points are outliers.

A linear trendline was fitted to the data (excluding the outliers) and the R^2 value (correlation coefficient) indicates that the trendline is a good fit. The Spot Size was determined as $112\mu\text{m}$.

It is not clear what is occurring to cause the outliers in the centre of the graph. Both the values at the top and bottom of the graph, which correspond to diameters of $86\text{-}98\mu\text{m}$ and $152\text{-}158\mu\text{m}$, clearly fit the trend line. These points at both ends of the line correspond to Q-switch repetition rates from 1-2kHz and from 15-20kHz. However the values in the middle, all of which correspond to diameters around the $100\text{-}117\mu\text{m}$ region or frequencies of 3-13kHz, do not fit this line. Interestingly, the measured spot size of $112\mu\text{m}$ from the mylar method is of the same order as the Beamscan measured beam diameter of $99\mu\text{m}$, implying that this method has worked to a certain degree within these limited ranges of energies.

4. SUMMARY AND CONCLUSIONS

For the UV DPSS laser, this mylar film method for determination of spot size works well. While the theoretical spot size has not been obtained with the beam expander removed, the likelihood is that the actual spot size is closer to the measured $29\mu\text{m}$ than to the theoretical $17\mu\text{m}$. The measured spot sizes at each beam expansion correlate to the expected results as described by the inverse power law described above. For a UV laser such as this, it is a particularly useful method as it is simple to set up and can be performed as a regular check. Methods such as CCD beam profiling cameras are particularly difficult to set up for these types of laser because of the high peak pulsed power output at UV wavelengths which is particularly damaging to the CCD arrays. Large amounts of beam attenuation are required to maintain the beam within the damage thresholds of the profiling device and this attenuation can alter the characteristics of the beam, thus affecting the results. The mylar film method can be carried out with the beam at full power as it would be used in laser materials processing, thus making it potentially a more accurate method. The BeamScan optical profiler is designed for continuous wave beams only and thus is not suitable for this laser. Apparatus such as the BeamScan could not be placed at the focus of a pulsed beam without extensive attenuation to prevent damage to the rotating drum. Extensive attenuation could affect the mode structure of the laser beam diameter giving inaccurate results of the beam diameter.

For the femtosecond laser, the mylar film method also works well. A measured spot size of $39\mu\text{m}$ has been found which is close to the theoretical spot size of $44\mu\text{m}$, which is calculated based on an M^2 value determined in the laboratory. Both divergence and multiphonon absorption effects may account for the slight difference between measured and predicted spot size values.

The metallised mylar used to determine the spot size of a YAG laser was problematic. There may be a linear irregularity in the region between 3-13kHz on the laser, resulting in the outlier results. Perhaps there are also some thermal effects due to the metallised film. Other low thermal conductivity materials may be investigated in future trials.

Finally, the spot size measurement method has been shown to work well for two out of the three lasers. For the UV DPSS laser and for the femtosecond laser, the measured spot sizes seem to concur well with the expected results. This method was based mainly on the strategy used in [1] where kapton was used, and this study shows that Mylar is a suitable film for these two laser types also. For the Q-switched Nd:YAG laser however, this was not the case and further work will be required to determine if this method is suitable for this laser.

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