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Author post-print (accepted) deposited by Coventry University's Repository

Original citation & hyperlink:
Shukla, P & Lawrence, J 2015, 'Identification of Optical Parameters for Determination of Radiance' Journal of Optics, vol. 44, no. 1, pp. 12 -19.
https://dx.doi.org/10.1007/s12596-014-0219-4

DOI 10.1007/s12596-014-0219-4
ISSN 0972-8821
ESSN 0974-6900

Publisher: Springer

The final publication is available at Springer via http://dx.doi.org/10.1007/s12596-014-0219-4

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Identification of Optical Parameters for Determination of Radiance

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Abstract

The ‘brightness’ of coherent beams such as lasers is known as ‘radiance’ in radiometric terms. It is a concept which is rarely taken into account in laser material processing, laser system design, and for the characterization of laser beams. The typical beam parameters such as: laser power; spot size; intensity; wavelength; beam divergence and the beam propagation factor - M^2, combined together are factors which determine the ‘radiance’ of lasers or energy beams in general. The concept of ‘brightness’ (‘radiance’ in particular), and how the laser beam parameters contribute to affect ‘radiance’, has not so far been reported in previous literature. Thus, we have investigated the theoretical ‘radiance’ for each parameter in relation to one another. In addition, a rather suitable empirical equations to determine the ‘radiance’ was also introduced herein, since, the existing equation for calculating ‘brightness’ do not employ the total power intensity of the beam. Based on this, we consider ‘power density’ rather than the ‘output power’ for determining radiance of a selected 1.064µm wavelength Nd:YAG laser for a set laser processing parameter window. The analytical investigation firstly concluded that the inclusion of ‘power density’ into the equation takes in account of ‘spot size’ and ‘laser power’ to cover all laser beam parameters. Secondly, the results have shown wavelength to be the most contributory parameter to influence the radiance value followed by power density, M^2, laser power and lastly the spot size of the laser beam. This was for a set-condition applied, but is generically applicable to different conditions and parameters, whereby, the same tendency would occur. This novel concept of brightness (radiance), of light sources such as a laser beam is not just useful for process control during laser material processing, but could prove to be a very efficient concept for laser beam characterization, and in laser system design for enhancing the ‘brightness’ or ‘radiance’ of lasers. Also not just lasers but, the concept could be applicable for other energy beams in general.

Keywords: Brightness, Radiance, Luminescence, Lasers, Beam Characterization.

1. Introduction

The ‘brightness’ of light generally refers to how shiny the source of light or an object is, relative to the observer. Brightness in technical terms is defined as the power per unit area in a solid angle of divergence [1 - 5]. In many technical literatures, it is confusing as to which type of light is referred to, since brightness could be classified in either a ‘radiometric’ or a ‘photometric’ term [1 - 2]. When dealing with a visual quality of light, brightness is rather expressed in relation with the human eye. The human eye upon visualizing a bright light directed on a surface at different angles could observe variation in its glow and the level of brightness. This type of brightness is defined as ‘luminescence’ in photometric term. Nevertheless, when dealing with a laser light, the term ‘luminescence’ is not ideal. This is because lasers are a radiometric light (measure of light in power per unit area in solid angle of divergence). On the other hand, luminescence relates to the photometric light and shows only the estimation of light at a particular angle and direction observed by the human eye [3- 5]. Therefore, an accurate measure of a radiometric light source such as a laser should be classified as ‘radiance’. So in the case for the work herein and future studies, we propose that the relevant terminology of laser light should be classified as ‘radiance’ since it is rather a ‘radiometric’ light. In addition, this paper shows the effect of the total optical energy (radiance) of the laser rather than luminescence which is the estimation of the brightness from a certain angle and direction as seen by the observer. The radiance of a laser beam is generally an unchangeable property. This is because the beam delivery system of lenses and/or mirrors called passive aberration-free loss-less optical system (PAFLOS) [6], form a direct image of the input laser beam.

Measurement of radiance is somewhat challenging since individual measurement of parameters such as beam divergence and beam parameter product - M^2 is time consuming and a complex set-up [7 - 9]. Nevertheless, analytical measurement of the radiance value is useful and could give a good measure. This would also prove to be a good mean for beam diagnostics which is not only useful but also important as it results to a better beam delivery and offer superior process

control, and enhanced beam performance. In turn, this would enhance the performance of the laser beam. Having a focused, clean and high radiance beam also results to high accuracy, tolerance and avoids undesirable noise, or light affecting the material which inherently leads to better material processing. Therefore, it is important to characterize the beam with respect to the various key parameters, namely: beam diameter and beam power (power density); beam mode; beam parameter product or commonly known as beam quality factor (M^2); Gaussian beam mode; wavelength and the solid angle of divergence which are the main focus of this research.

Literatures in mentioning or using 'radiance' of laser beams as an applicable concept are scarce. Moreover, the effects which radiance has upon the range of materials during laser beam processing to-date are unknown. Having said this, our previous investigations [10 – 12] have demonstrated that laser beams with different 'brightness' (radiance) affect materials (ceramics in particular) in various different ways. A brighter beam using identical processing parameters in comparison to a less brighter beam tends to produce larger surface tracks and considerable microstructural changes to the material. Brown and Frey [13] used a high brightness beam to cut and drill aerospace materials. The results showed improved cutting and also achieved shallow angle holes. Val *et al.* [14] demonstrated the effects of laser cladding of flat stainless steel sheets and Co-based super-alloy powder (coating material) using two different laser beams. The reported results showed that the Nd:YAG produced enlarged clad track with deeper penetration as result of a high brightness laser beam [10 - 14]. Clearly, a larger pool of results showing this effect on various material types is still called for.

Upon changing the optical parameters of laser beams individually would considerably affect the end value of the radiance. We firstly present the relationship of each parameter with one another to demonstrate how the parameters influence the radiance value. The parameters are independent to one-another, however, by determining the laser beam radiance would allow the characterization of the beam practically and analytically as well as lead to better process control [15, 16]. This is why radiance is suggested to be a very useful property and a sound means to

characterize any type of laser beams, not just analytically but on a practical basis as well. No previous investigation hitherto presents a study of the contribution of laser beam parameters, namely: power, beam diameter, power density, wavelength, beam divergence and the inversely proportional M^2 value to affect the end value of laser beam radiance. Moreover, despite experienced experimentalists understanding the effect of the aforementioned parameters, this paper is still very valuable as it collectively bring the parameters together to demonstrate factors influencing the radiance of lasers. In addition, the current equations for calculating radiance only attributes to the power rather than the actual power density which also takes in account of the spot size. Therefore, we present a modification to the equation for determining the radiance by considering the power density rather than just the laser power. What is more, the calculated radiance values for various laser beams ranging from far infra-red to far ultraviolet are also presented in this investigation.

2. Analysis

2.1 Background Theory

The radiance of a laser beam is calculated by the optical power divided by the product of the focused beam mode area, as well as the solid angle of divergence (Ω) in Equation (1) [17 - 20].

$$\mathbf{Br} = \frac{\mathbf{P_{out}}}{\mathbf{A\Omega}} \tag{1}$$

Where Pout is the laser power over the surface area and AΩ is the solid angle of divergence. The solid angle of a Gaussian beam is shown by Equation (2):

$$\boldsymbol{\Omega = \pi\, \theta^2 = \lambda^2 / \pi\, w^2{}_0} \tag{2}$$

Where λ is the wavelength and w_0 is the beam radius at the beam waste. For Gaussian laser beams that are circular, the propagation ratio is shown by Equation (3).

$$\mathbf{M^4 = M^2_y \,.\, M^2_x} \tag{3}$$

Where M^2_y and M^2_x are the parameters of the beam profile. Finally Equations 1 to 3 then results to Equation 4 which is used to conventionally determine the brightness of the laser beam:

$$\mathbf{Br} = \frac{\mathbf{P_{out}}}{\mathbf{M^4 \, x \, \lambda^2}} \tag{4}$$

The spot diameter however is not taken into consideration with the conventionally used Equation (4) in the literature [1 – 7, 11 - 16]. Nonetheless, the Equations presented herein show that brightness (radiance) is a function of not just output power, wavelength, M^2 and the beam divergence, but also the spot diameter. Thus, to include the spot size, power density can be employed as an additional feature as derived in Equation (5) for a 'top hat' (flat top) beam of an Nd:YAG laser used in this work as an example:

$$\mathbf{Power\ Density} = \frac{\mathbf{127}}{\mathbf{d^2}} \mathbf{x\ Output\ Power} \left(\frac{\mathbf{W}}{\mathbf{cm^2}}\right) \tag{5}$$

Where d is the laser beam diameter; 127 is for the 'top hat' uniform beam profile with an equal energy distribution. In case the beam is a Gaussian then the value '127' is rather replaced by '250'. Upon including laser power density into the determination of 'radiance', gives rise to Equation (6). Equation (6) adopts the use of power density rather than Equation (4) (previously employed to determine brightness) which only accounts for the laser power. This in turn, would take in consideration of the full laser beam parameters mentioned previously:

$$\mathbf{Radiance} = \frac{\mathbf{Power\ Density}}{\mathbf{M^4 \quad \lambda^2}} \tag{6}$$

Where 'radiance' replaces 'brightness' (in Equation (4)), M^4 is the cross sectional laser beam profile in any x and y direction (M^2_y and M^2_x). The beam parameter product M^2 is inversely proportional to beam divergence. Hence, the beam divergence would be relative to the M^2 value. λ^2 is the wavelength and power density would account for the spot size and the input power of

the laser beam. This equation will be used for the study herein to obtain all results as further presented.

2.2 Determination of Laser Beam Radiance

Equation (6) was set-up on the new version of Excel 2012 to determine all values of radiance. To determine the values of radiance, one parameter at a time was changed whilst maintaining other parameters constant. Having done this, it was then feasible to understand the contribution which each parameter has upon the end value of radiance. This inherently indicated the parameter which is most important to modify and change during laser processing and laser design. Table 1 shows the change in one particular parameter whist other parameters at any one point were maintained constant for calculating the radiance value for a 1.064µm wavelength Nd:YAG laser source with parameters presented in Table 1. Table 2 also shows the change in wavelength whilst maintaining other beam parameters constant for a diffraction limited Gaussian beam.

Table 1 Change in power, power density, spot diameter, and beam parameter product quality whilst keeping the wavelength constant for the determination of radiance for a 1.064 µm wavelength laser beam.

Power (W)	Power density (W/ mm^2)	Wavelength (µm)	Spot Diameter (mm)	Beam Parameter Product (M^2)
0.1 – 3600	5.16 -185950	1.064	2.2	1.7
0.2 - 3900	10 - 120000	1.064	2.2	1.7
65	3357.43	1.064	0.1 - 25	1.7
65	3357.43	1.064	2.2	1 – 30

Table 2 Change in wavelength whilst keeping other parameters constant for a diffraction limited Gaussian beam with a minimal beam divergence.

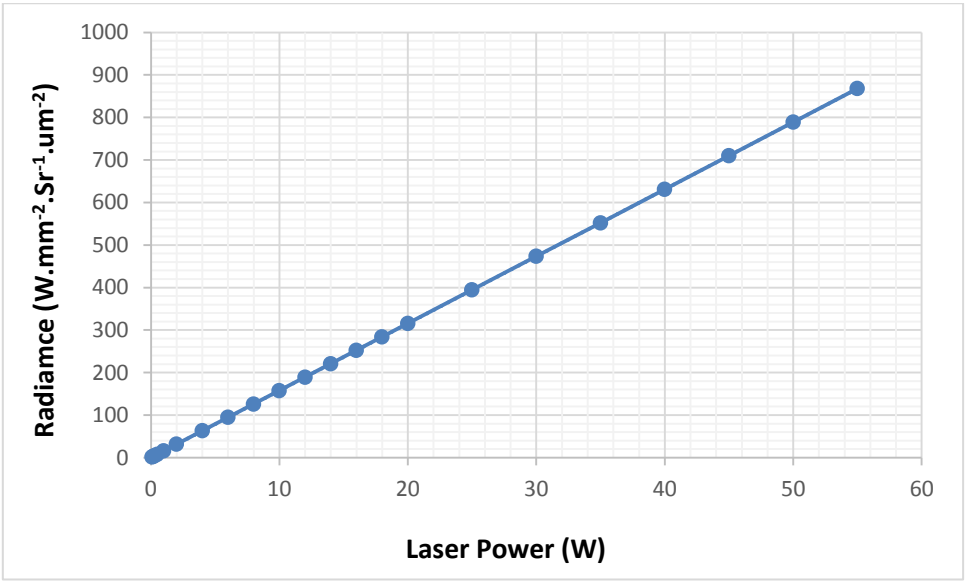
Power (W)	Power density (W/ mm^2)	Wavelength (µm)	Spot Diameter (mm)	Beam Parameter Product (M^2)
65	3357.43	0.238 - 30	2.2	1

3. Results

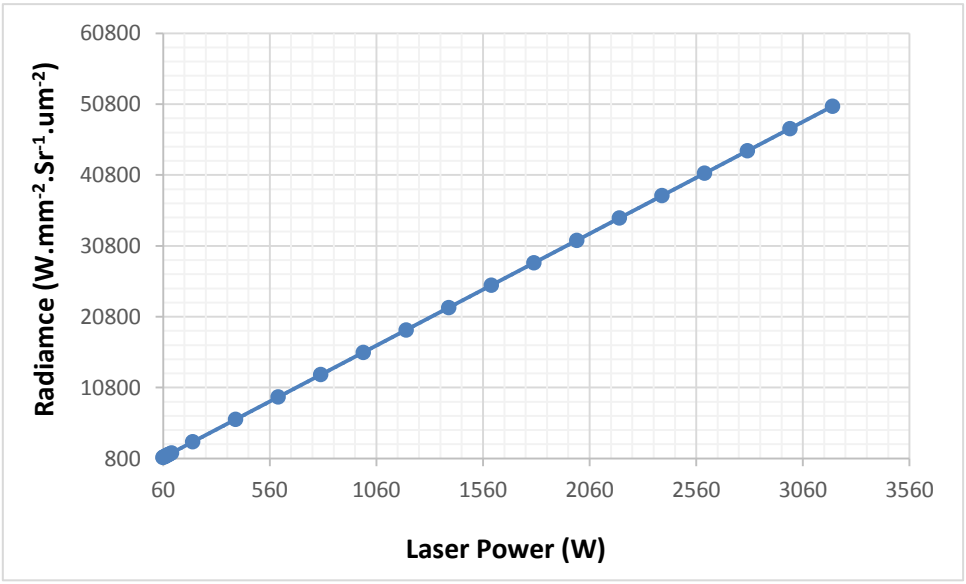
3.1 Contribution of Laser Beam Parameters to Affect Radiance

3.1.1. Laser Power

The laser power was changed from 0.5 W to 3600W whilst all other parameters were kept constant. The graphs in Figure 1 show that the radiance increases with increasing the power. At a wavelength of 1.064µm, a constant power of 65W, 2.2 mm diameter beam, 6.7 M^2 value and a beam divergence of 5.5 m/rad **µm**. At 0.1W, the minimal radiance obtained was 1.57 $W.mm^{-2}.Sr^{-1}.\mu m^{-2}$, whilst at 100W the radiance was calculated to be 1578 $W.mm^{-2}.Sr^{-1}.\mu m^{-2}$. At 3900 W the radiance value rises to 50520 $W.mm^{-2}.Sr^{-1}.\mu m^{-2}$ as shown in Figure 1(b).



(a)



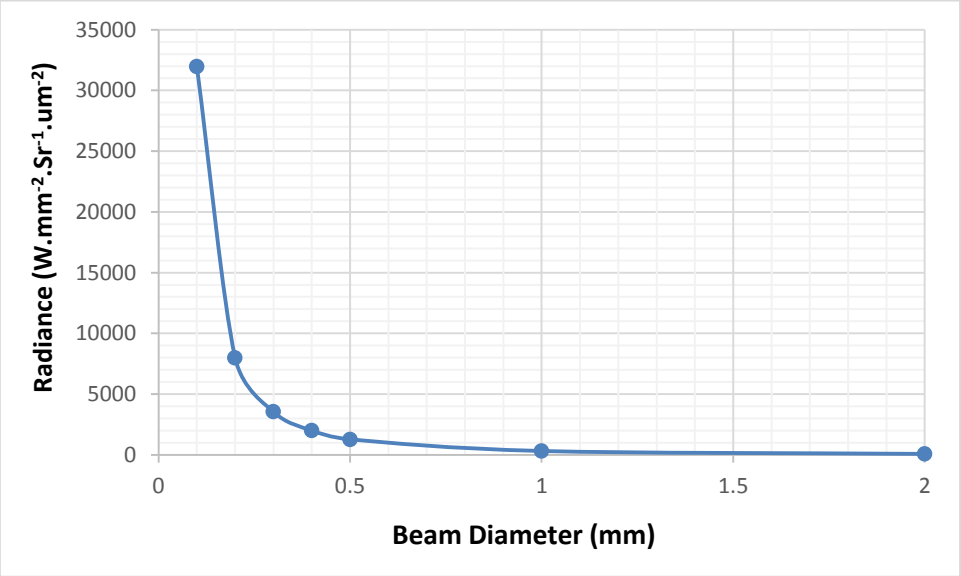
(b)

Figure 1 Radiance of 1.064 µm wavelength laser using a constant 2.2 mm diameter beam, M^2 value of 6.7 and a beam divergence of 5.5 m/rad whilst changing the laser power between ranging between 0.5 W to 3200W.

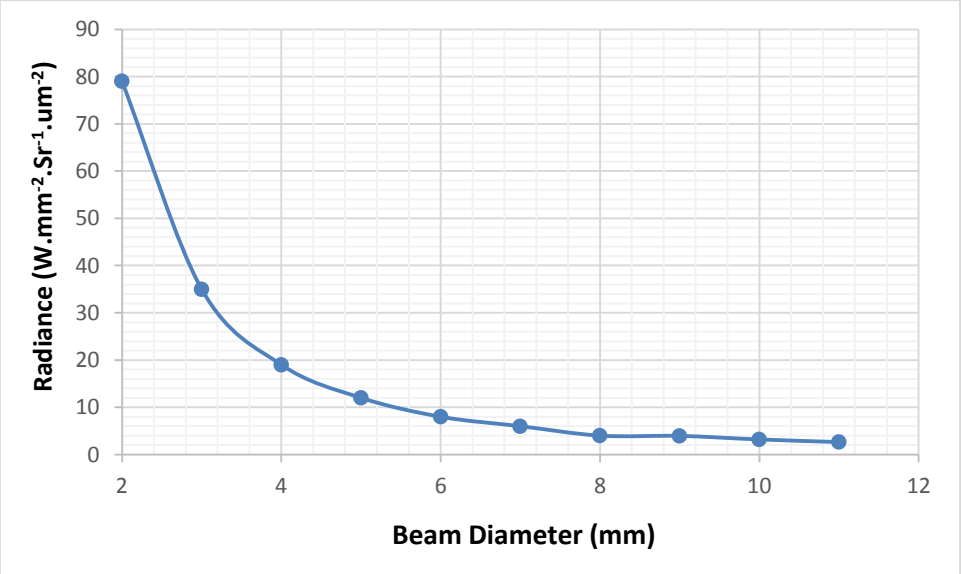
3.1.2 Beam Diameter

Figure 2 (a) to (c) shows the calculated values of radiance whilst changing the beam diameter from 0.1mm to 25mm. For this calculation, the constant beam parameters were: power of 65W, wavelength of 1.064 µm, an M^2 value of 6.7, and beam divergence of 5.5 m/rad. The radiance of the laser beam at the lowest spot diameter (0.1mm) was the highest, being 31971 $W.mm^{-2}$. Sr^{-}

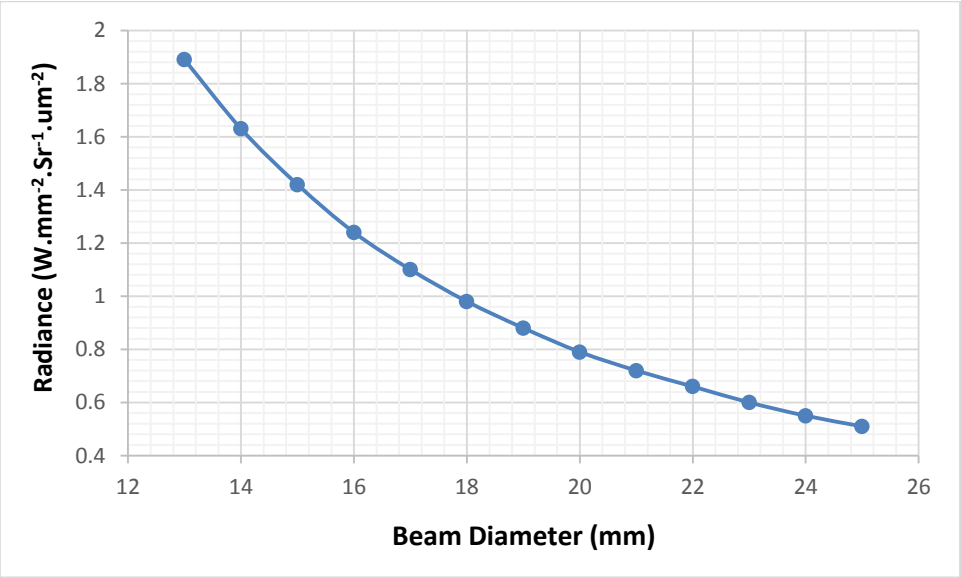
^{1}.µm^{-2} and at the highest spot diameter (25mm), the radiance was calculated to be 0.51 W.mm^{-2}.Sr^{-1}.µm^{-2} as seen on Figure 2.



(a)



(b)



(c)

Figure 2 Radiance of a 1.064 (µm) laser beam obtained by keeping constant M^2 value of 6.7 power of 65W and by changing the beam diameter between 0.5mm to 25mm in (a) to (c).

3.1.3 Power Density

Whilst changing the power density of the laser beam ranging from 0.5 W/mm^2 to 120000 W/mm^2, the constant parameters were: wavelength, M^2 and the solid angle of beam divergence. Having done this calculation, the graph in Figure 3(a) and (b) show that with an increase in the power density (a combination of the power and the spot diameter), the radiance also increased. The lower power density applied was 0.5 W/mm^2 which emitted a radiance of 15.28 W.mm^{-2}. Sr^{-1}.µm^{-2}, whereas the highest power density used was 120000 W/mm^2 which emitted a radiance value of 2361 W.mm^{-2}. Sr^{-1}.µm^{-2}.

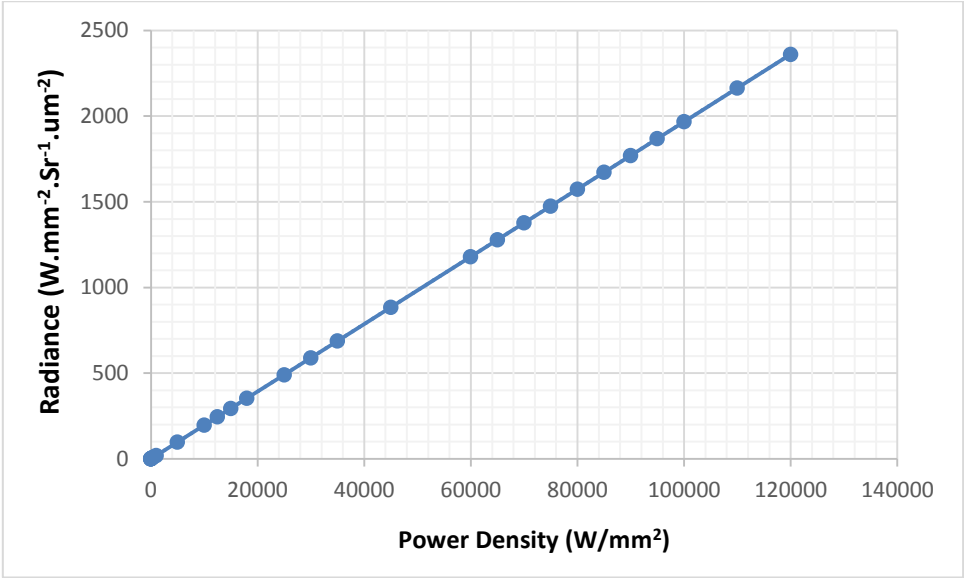


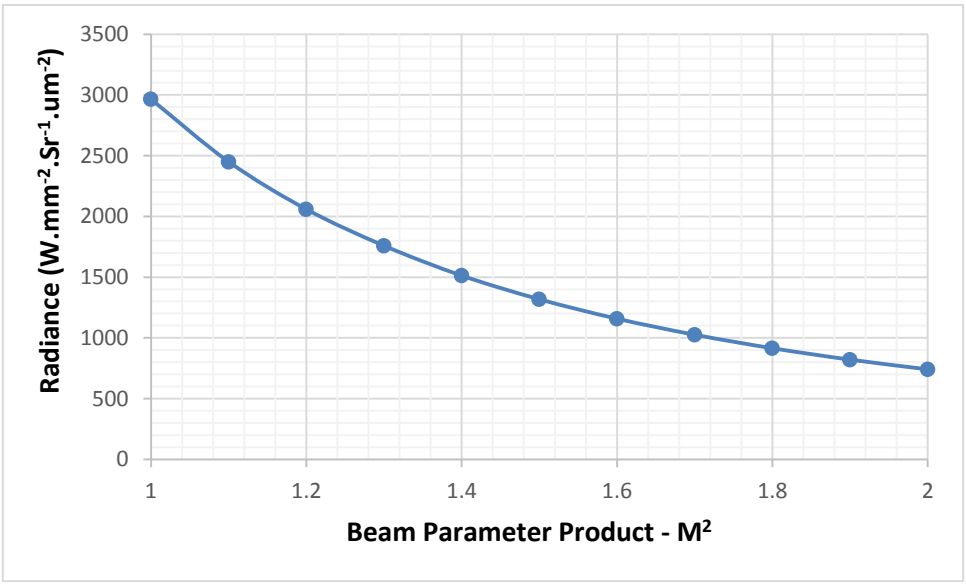
Figure 3 Radiance values for a 1.064 (µm) laser beam by keeping a constant M^2 value of 6.7, beam divergence of 5.5 m/rad, whilst changing the power density from 10 W/mm^2 to 120000 W/mm^2.

3.1.4 Effects of beam parameter product - M^2

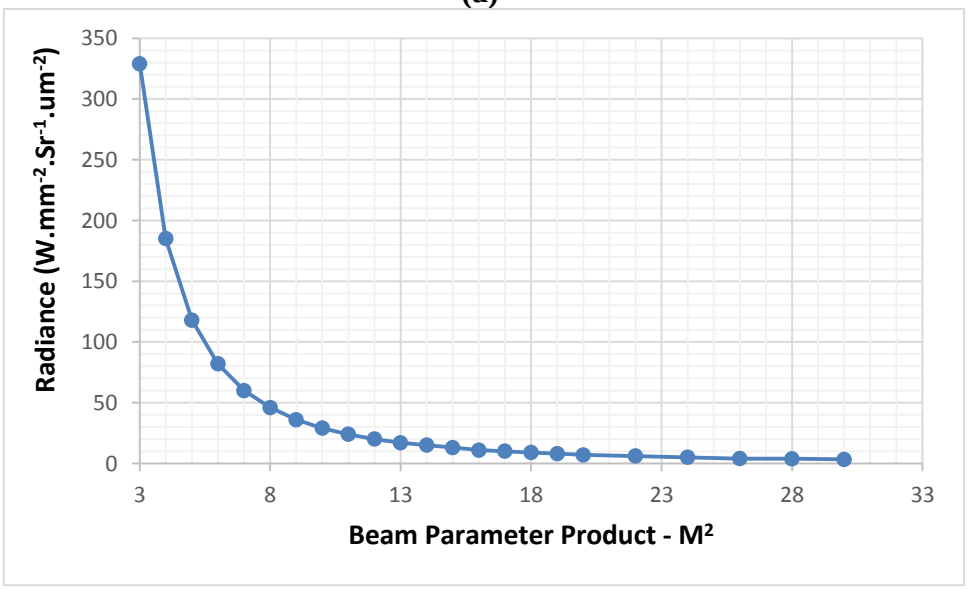
Figure 4 (a) and (b) shows the calculated radiance values by changing the beam propagation factor. The M^2 was changed from 1 to 30 whilst all the aforementioned parameters were kept constant. As one can see from what would generally be obvious, that with increase in the M^2 value shows a decrease in the beam radiance. At the highest M^2 value of 30, the radiance value determined was 3.29 W.mm^{-2}. Sr^{-1}.µm^{-2}. The decrease in the M^2 value by half (M^2:15) allows the radiance to increase to 13.18 W.mm^{-2}. Sr^{-1}.µm^{-2} and a laser beam parameter product of 1, was calculated to be 2965 W.mm^{-2}. Sr^{-1}.µm^{-2}. In other words, a diffraction limited beam closer to M^2 value of 1 obviously emits a most radiant beam, whereas, deterioration in the M^2 value reduces the radiance since the beam quality in other words has declined.

In addition, it is important to also account for the solid angle of beam divergence here, since it is inversely proportional to the beam propagation factor. So if the M^2 value is closer to 1, then the beam divergence will be very small which characteristically results to a smaller angle. However, if the M^2 value is further away from 1, then it is a good indicator that the solid angle of beam divergence is large. For the case herein, the solid angle of beam divergence is 5.5 m/rad since the

M^2 is considerably high (6.7 m/rad). This showed that the beam quality was considerably low for the laser beam investigated herein. Moreover, the contribution of the solid angle of divergence is certainly not negligible. This is because of it is inversely proportional as previously stated. Thus, if the solid angle of beam divergence is small, then the M^2 value would be closer to $M^2 = 1$, indicating a high radiance, but on the other hand, if the solid angle of beam divergence is large then the M^2 value will also be large – indicating a low radiance laser beam.



(a)



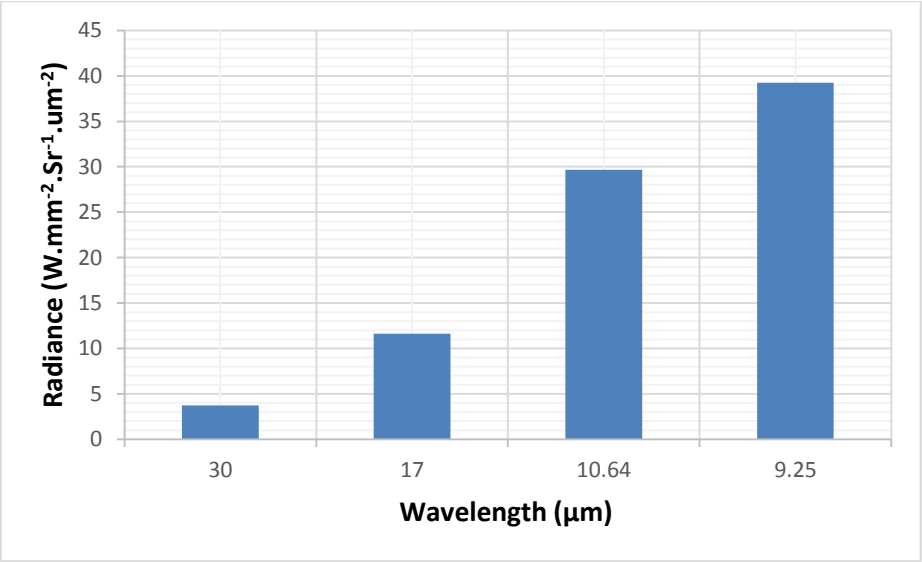
(b)

Figure 4 Radiance of 1.064 µm laser beam obtained by keeping constant parameters of 65W laser power, a beam diameter of 2.2 mm, power density of 3357.43 W/mm^2 and a beam divergence (5.5 m/rad) whilst changing the beam propagation factor from $M^2 = 1$ to 30 in (a) and (b).

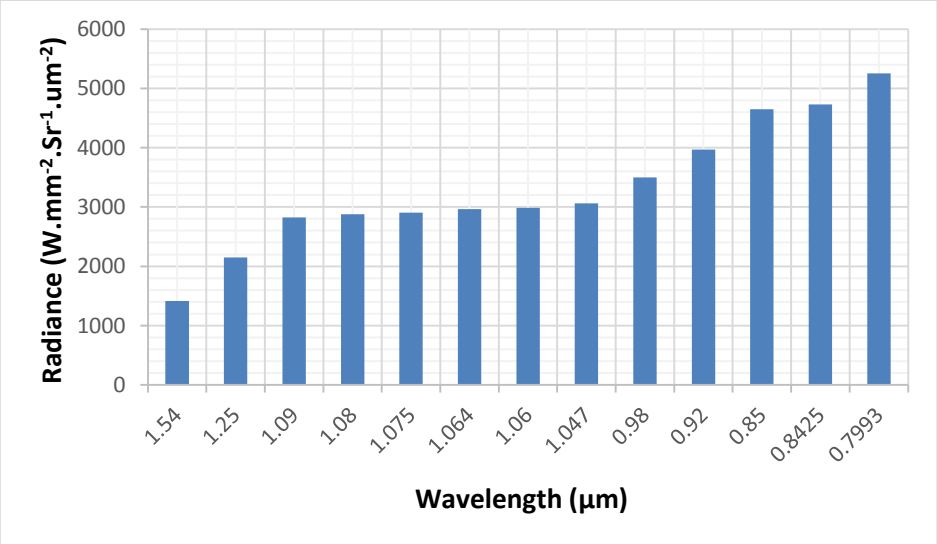
3.1.5 Effects of Wavelength

Figure 5 (a) to (c) shows the radiance values calculated whilst changing the wavelength from 0.1 µm to 30 µm to demonstrate the effect of wavelength whilst keeping 65W of power, 2.2 mm beam diameter, 3357.43 W/mm^2 of power density, M^2 - 6.7 and solid angle of beam divergence to be 5.5 m/rad as constant parameters. With increasing wavelength, the beam radiance is gradually reduced as seen in Figure 5(a) to (c). This goes to show that high radiance energy is predominantly exhibited by lower wavelength beams.

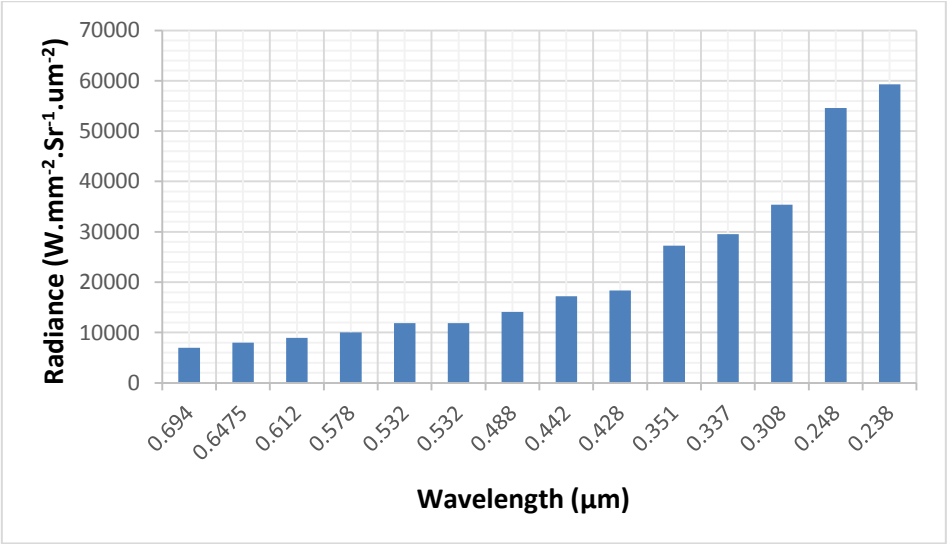
The radiance values shown in Figure 5 for laser beams ranging from far infra-red to far/near ultraviolet wavelength. The graphs show that laser beams composed of: KrF; Argon; XeCl; XeF and N_2 and comprising of the smallest wavelength has radiance values in the range of 35392 to 59272 W.mm^{-2}. Sr^{-1}.µm^{-2} for given constant beam parameters as previously mentioned. The beam at the higher end of the electromagnetic spectrum with a wavelength in the range of near/far infra-red was calculated to consist of the lowest radiance values. The terahertz, molecular and CO_2 lasers beam have the lowest radiance values in particular of 3 and 11 and 29 W.mm^{-2}. Sr^{-1}.µm^{-2}, whilst maintaining the aforementioned beam parameters constant. This affect is generally obvious since higher photon energy is generated by lower wavelength beams in the range of 10^3, whereas, the beam in the near/far infra-red region generates photon energy up to 10^0. This characteristically produces higher power per unit area in steradian, and consequently, generates high radiance of the laser beams to effect material processing.


Radiance (W.mm-2.Sr-1.um-2)
45
40
35
30
25
20
15
10
5
0
30
17
10.64
9.25
Wavelength (µm)

(a)


Radiance (W.mm-2.Sr-1.um-2)
6000
5000
4000
3000
2000
1000
0
1.54
1.25
1.09
1.08
1.075
1.064
1.06
1.047
0.98
0.92
0.85
0.8425
0.7993
Wavelength (µm)

(b)



(c)

Figure 5 Variation of different wavelengths to affect the radiance by applying constant power of 65W, a beam diameter of 2.2 mm, power density of 3357.43 W/mm^2, M^2 value of 1.

4. Discussion

Equation 4 presented in section 3 is conventionally used for the determination of laser beam 'brightness'. However, the problem lies with the fact that beam diameter is not considered in this equation, though, changing the beam diameter in practice would influence the brightness and in turn, the radiance. In addition, radiance rather than brightness is better suited for coherent beams such as a laser, because it is a radiometric form of light, whereas the brightness is a photometric form of light. By introducing Equation (6) yields this concept much true, whereby, a complete characterization of the beam could take place, analytically followed by practical means.

The results showed that changing each parameter at once allowed the evaluation of each of the parameter to affect laser beam 'radiance' for the set conditions. However, when changing parameters and comparing the change with one another would enable one to see which parameter is more influential for affecting the end value of radiance. Some may argue that the case presented in this paper is predictable. Even so, the concept of radiometric laser light 'radiance' and also the laser beam parameters and the manner in which they control radiance has not been

shown previously in published literature. Figure 7 presents the highest and the lowest value of beam radiances for each of these parameters to demonstrate which parameter affects radiance the most. From this it is obvious that the spot size of the laser beam alone, is also the least influential parameter in affecting the radiance. By changing the power alone is somewhat the least influential, nevertheless, it has better contribution in generating a higher beam radiance. Upon changing the M^2 value is considerably influential but would come third on the list of influential parameters. In any case, by combining the power and the spot diameter into power density as whole results to a significant change because it has the flexibility of accommodating two input parameters simultaneously. Having said this, the most influential parameter to affect radiance would be the wavelength of a laser beam. From the results of this study, it is obvious that the higher the wavelength, the lower the radiance, whereas the lower the wavelength results to high radiance emitted by the laser beam.

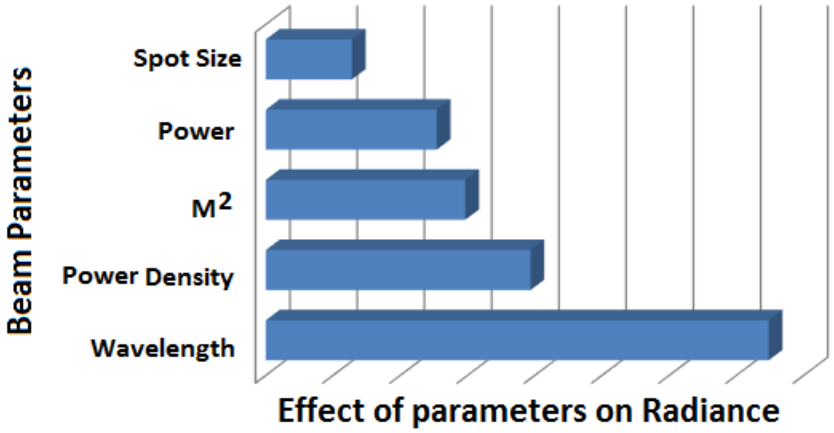


Figure 7 Most influential parameters to affect laser beam radiance for the given beam conditions in Table 2.

The beam mode of a laser is one other parameter which should be taken into consideration. However, it is not practically possible to include this as a function of the equation for the determination of laser beam radiance. But, it should be noted that with an M^2 value close to 1, the beam mode would be of a high order and have a small solid angle of divergence. As the M^2 value increases and the quality of the beam deteriorates, then it is a good indicator that a lower

order Gaussian beam is exhibited, which in turn, directly reduces the laser beam radiance. This means that the beam propagation factor M^2, dictates the beam mode and vice-versa. This characteristically will influence the end value of radiance, whereby, a higher order beam profile will have the best energy distribution, whereas a low radiance beam would comprise of a lower order beam.

Further study in radiance of lasers is currently being undertaken to further demonstrate comparison between two or more energy beam sources with different wavelength and to the extent that radiance affects material processing with respect to the track width (dimensional size), differences in processing temperature with variation in radiance; changes in the surface property and the cost per wattage between high/low radiance beams.

5. Conclusions

Literatures involving laser beam brightness and radiance are generally scarce and this concept is totally under explored in the field of beam characterization, laser process design and laser system design. Moreover, we suggest that defining 'brightness' of energy beams such as a laser is not an accurate or an appropriate practice and it is rather the 'radiance' that should be taken into account. Measuring the 'radiance' is an important and a unique parameter because it takes in account of the complete range of beam parameters, namely: laser power and beam diameter (power density); wavelength; beam divergence and the beam parameter product M^2 combined. This forms 'radiance' which is a concept in relation to equations stated in this paper and on a practical level. The study herein has demonstrated an analytical approach to not only characterize laser beams but also to differentiate the contribution of each beam parameter to affect their unique radiance values. This concept is not just applicable to laser beams but can also be applied to other energy beams.

Furthermore, previous equations used for the determination of a laser beam brightness only accounted for laser power, whereas, the work in this paper have rather attributed to the power density. Moreover, we have shown how all the laser beam parameters affect the radiance of a laser beam in this analytical study and revealed that:

- On account of increasing the laser beam power resulted to high radiance;
- By increasing the spot size has decreased the beam radiance;
- Upon increasing the power density would result to increase in the beam radiance;
- As result of increasing the M^2 reduced the radiance. Hence, it is vital that the laser beam is close to a diffraction limit to enable high radiance to exhibit. At the same time, the solid angle of beam divergence (inversely proportional to the M^2) also plays an important role. Owing to this, the solid angle of beam divergence must also be associated as a contributor in affecting the final value of laser beam radiance.

- The wavelength is a major parameter to affect the radiance of laser beams followed by the power density, M^2 factor and the solid angle of beam divergence, power and finally the spot size.

It can be argued that the above results are somewhat predictable with the use of existing equations but the work herein shows the importance of laser beam 'radiance' commonly known as 'brightness'. In addition, a contribution of each laser beam parameter to affect radiance is shown collectively by bringing all the parameters together into one equation. The concept of radiance in relation to coherent beams such as lasers has not been published in any form prior to this. Furthermore, this unique concept is applicable to not just laser beams but also to energy beams for process improvement and beam characterization in general. Further study into the radiance of energy beams are currently being under taken by the principle author of this paper.

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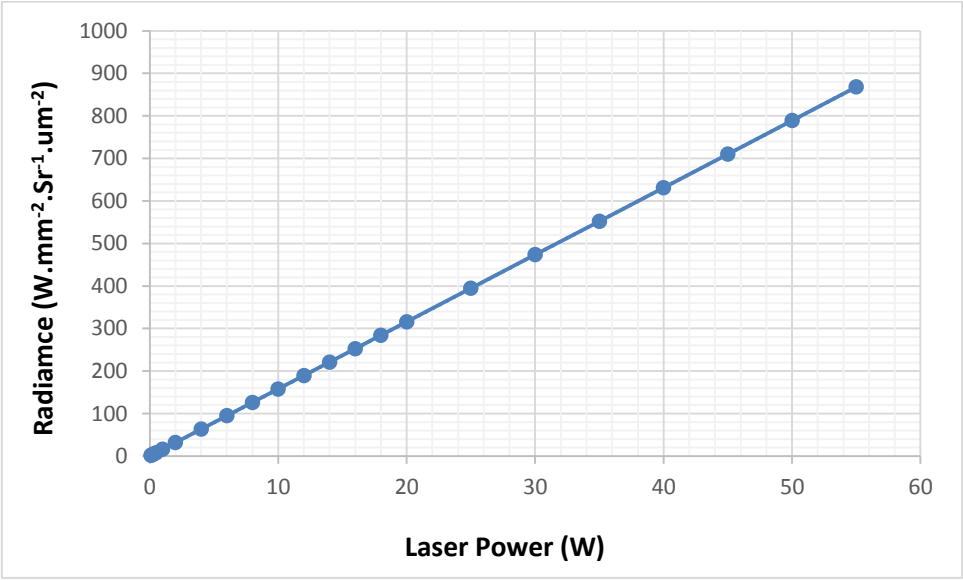
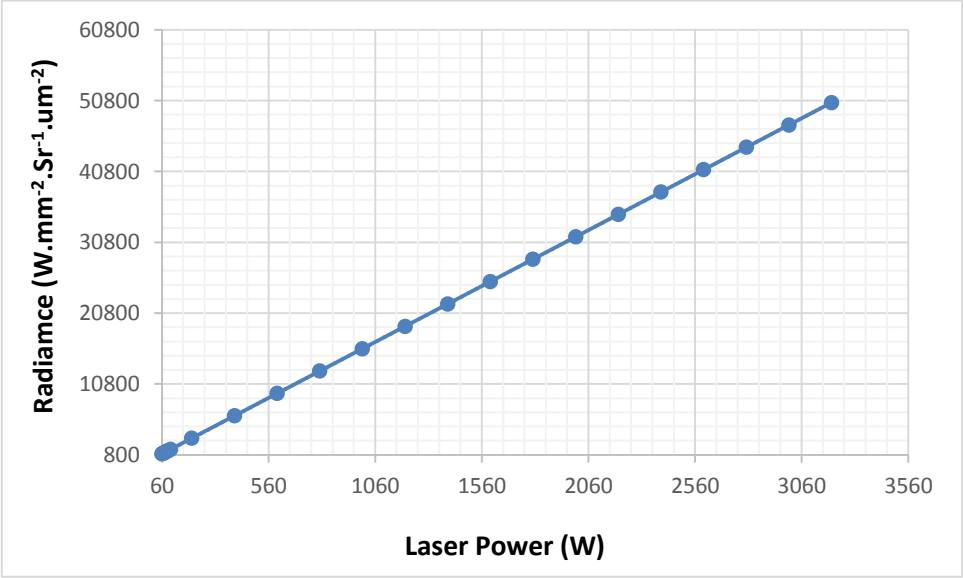
Figure

List of Figures

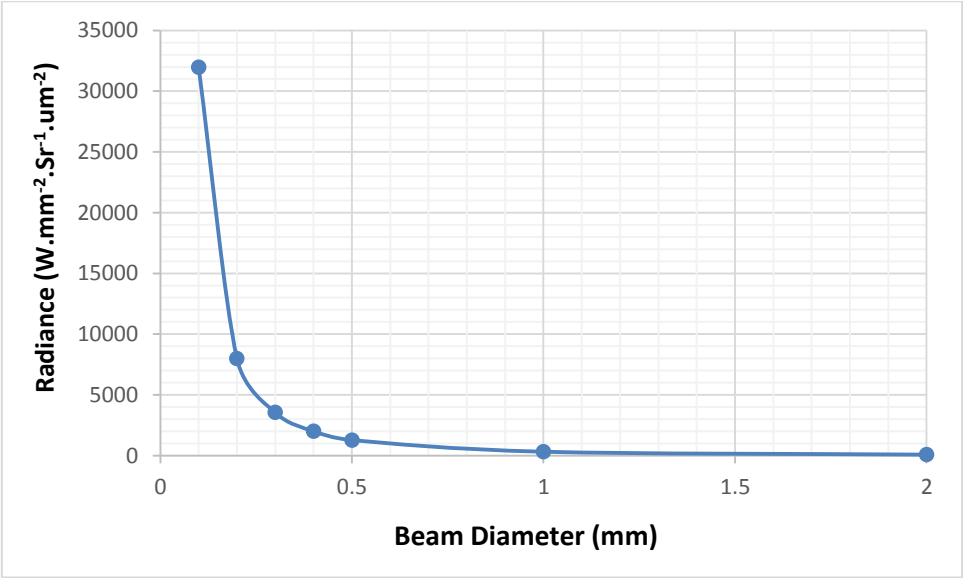


(a)

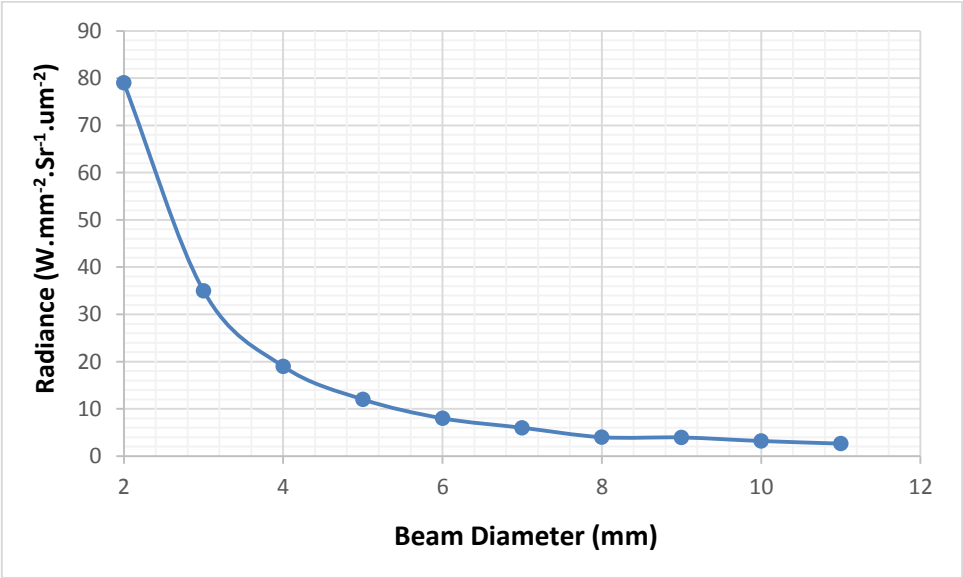


(b)

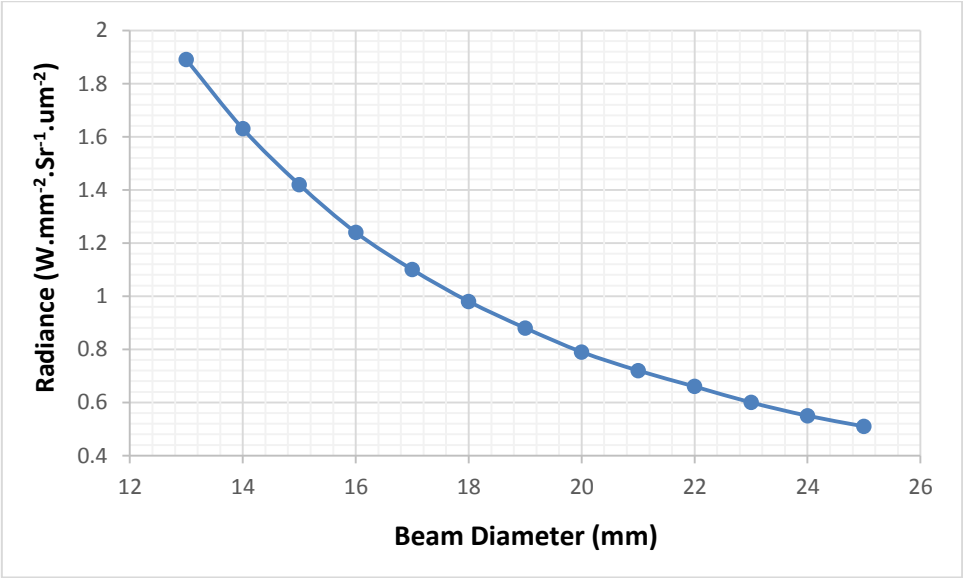
Figure 1 Radiance of 1.064 µm wavelength laser using a constant 2.2 mm diameter beam, M^2 value of 6.7 and a beam divergence of 5.5 m/rad whilst changing the laser power between ranging between 0.5 W to 3200W.


35000
30000
25000
20000
15000
10000
5000
0
0
0.5
1
1.5
2
Radiance (W.mm-2.Sr-1.um-2)
Beam Diameter (mm)

(a)


90
80
70
60
50
40
30
20
10
0
2
4
6
8
10
12
Radiance (W.mm-2.Sr-1.um-2)
Beam Diameter (mm)

(b)



(c)

Figure 2 Radiance of a 1.064 (µm) laser beam obtained by keeping constant M^2 value of 6.7, power of 65W and by changing the beam diameter between 0.5mm to 25mm in (a) to (c).

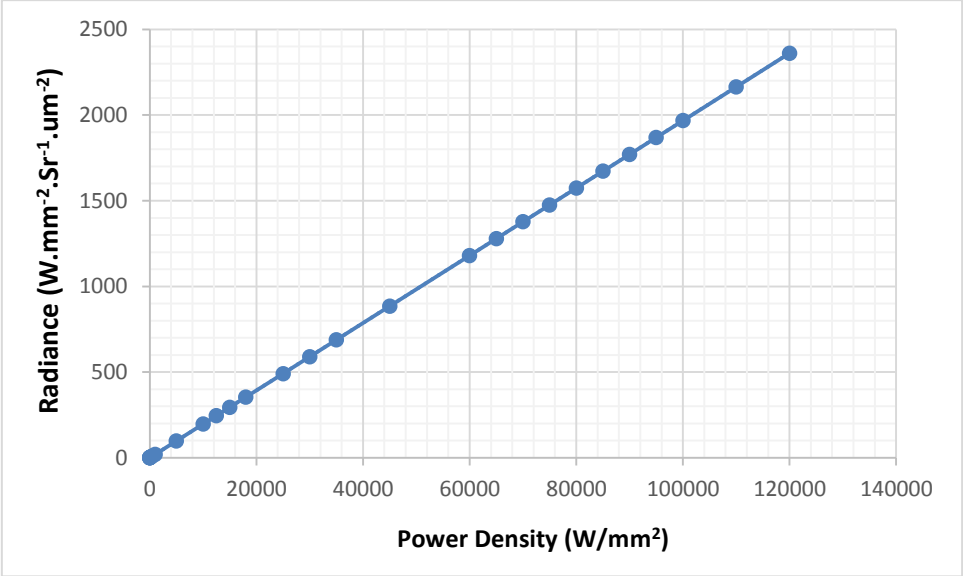
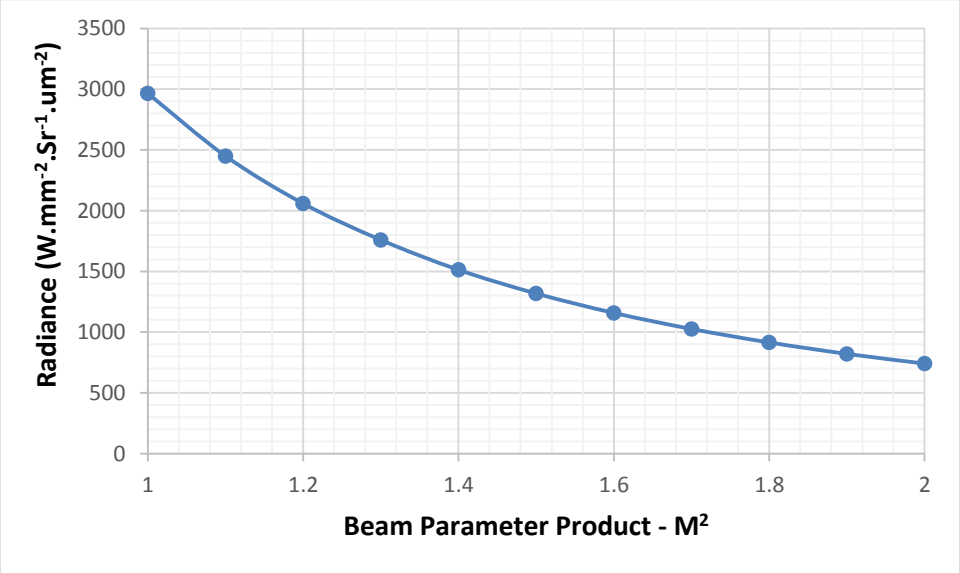
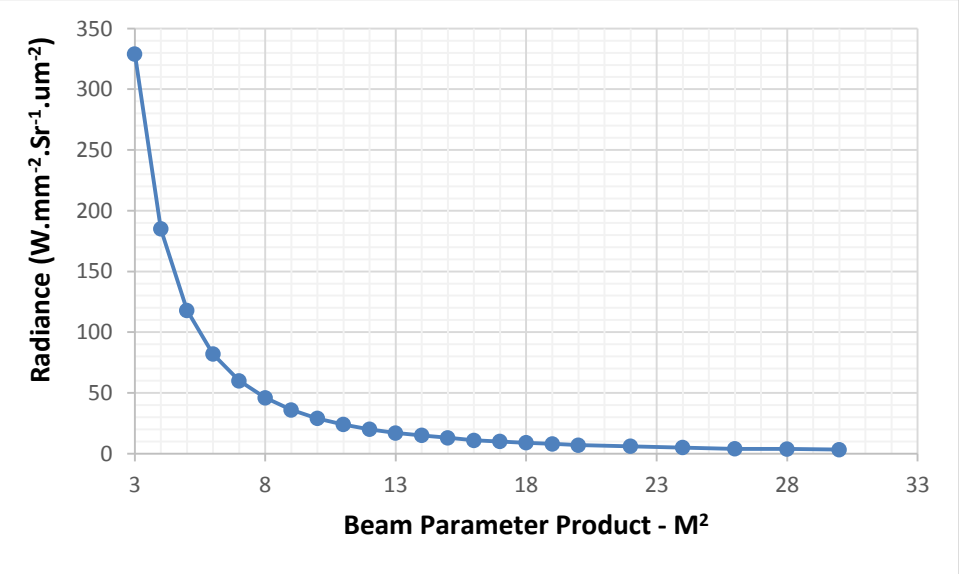


Figure 3 Radiance values for a 1.064 (µm) laser beam by keeping a constant M^2 value of 6.7, beam divergence of 5.5 m/rad, whilst changing the power density from 10 W/mm^2 to 120000 W/mm^2.

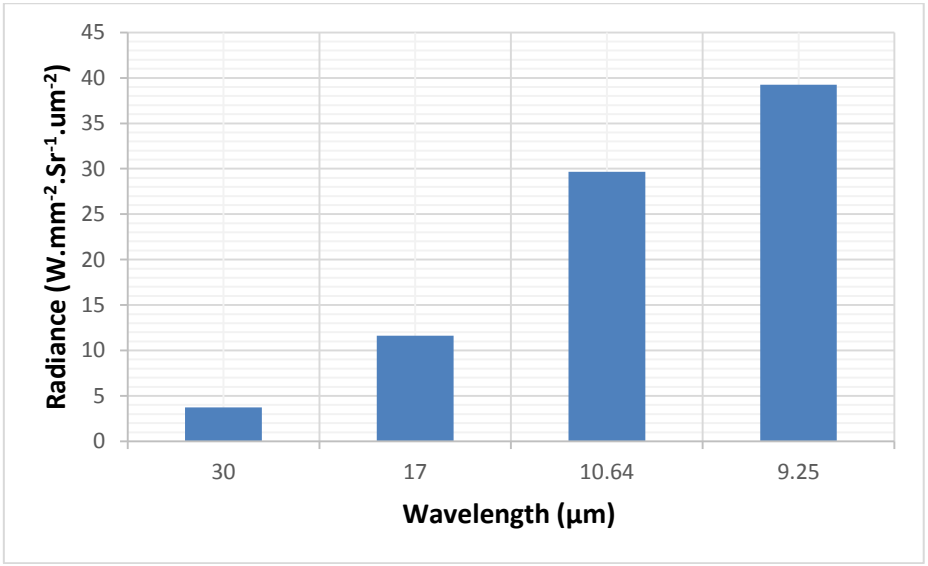


(a)

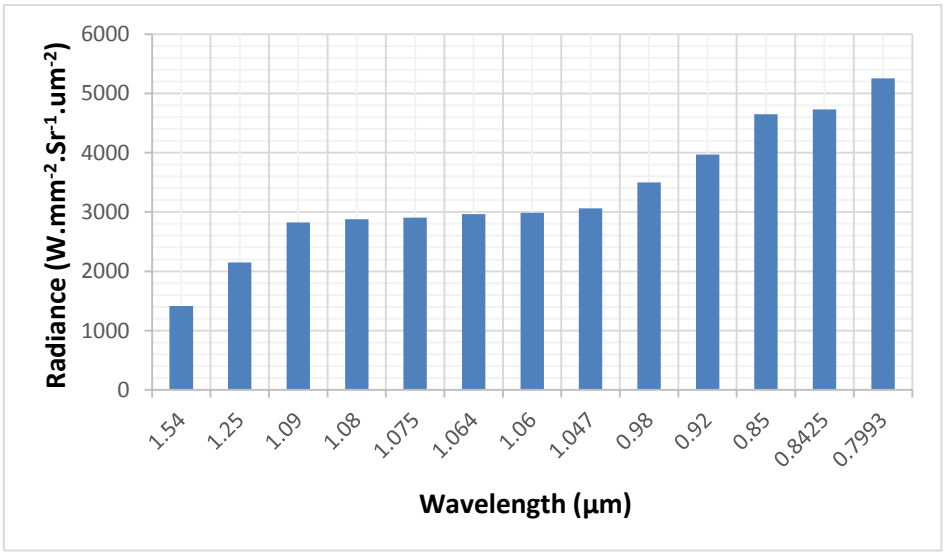


(b)

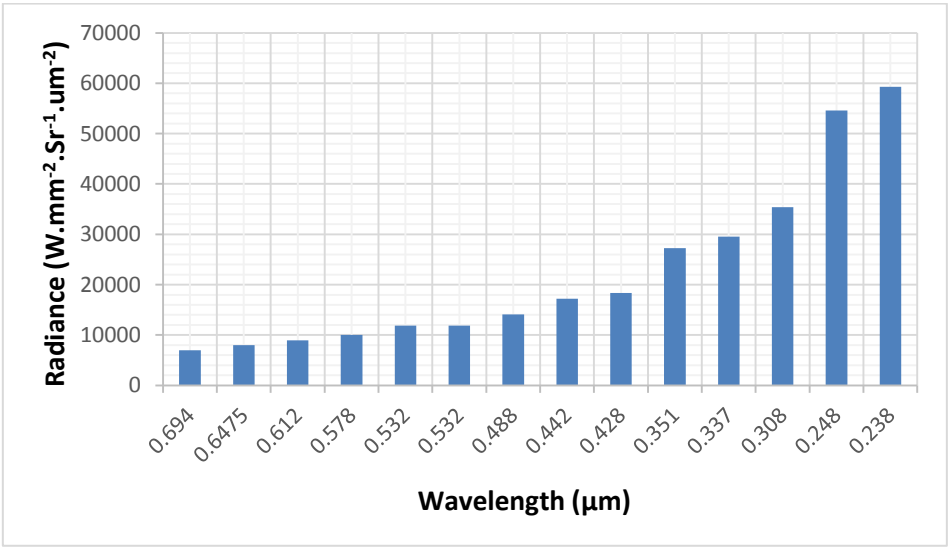
Figure 4 Radiance of 1.064 µm laser beam obtained by keeping constant parameters of 65W laser power, a beam diameter of 2.2 mm, power density of 3357.43 W/mm^2 and a beam divergence (5.5 m/rad) whilst changing the beam propagation factor from M^2 = 1 to 30 in (a) and (b).


Radiance (W.mm-2.Sr-1.um-2)
45
40
35
30
25
20
15
10
5
0
30
17
10.64
9.25
Wavelength (µm)

(a)


Radiance (W.mm-2.Sr-1.um-2)
6000
5000
4000
3000
2000
1000
0
1.54
1.25
1.09
1.08
1.075
1.064
1.06
1.047
0.98
0.92
0.85
0.8425
0.7993
Wavelength (µm)

(b)


Radiance (W.mm-2.Sr-1.um-2)
70000
60000
50000
40000
30000
20000
10000
0
0.694
0.6475
0.612
0.578
0.532
0.532
0.488
0.442
0.428
0.351
0.337
0.308
0.248
0.238
Wavelength (µm)

(c)

Figure 5 Variation of different wavelengths to affect the radiance by applying constant power of 65W, a beam diameter of 2.2 mm, power density of 3357.43 W/mm^2, M^2 value of 1.

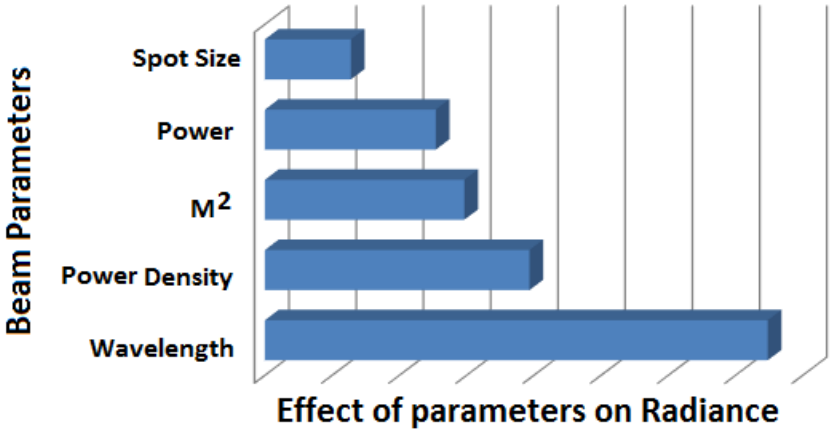


Figure 7 Most influential parameters to affect laser beam radiance for the given beam conditions in Table 2.

List of Tables

Table 1 Change in power, power density, spot diameter, and beam parameter product quality whilst keeping the wavelength constant for the determination of radiance for a 1.064 µm wavelength laser beam.

Power (W)	Power density (W/ mm^2)	Wavelength (µm)	Spot Diameter (mm)	Beam Parameter Product (M^2)
0.1 – 3600	5.16 -185950	1.064	2.2	1.7
0.2 - 3900	10 - 120000	1.064	2.2	1.7
65	3357.43	1.064	0.1 - 25	1.7
65	3357.43	1.064	2.2	1 – 30

Table 2 Change in wavelength whilst keeping other parameters constant for a diffraction limited Gaussian beam with a minimal beam divergence.

Power (W)	Power density (W/ mm^2)	Wavelength (µm)	Spot Diameter (mm)	Beam Parameter Product (M^2)
65	3357.43	0.238 - 30	2.2	1

Authors' Response to Reviewers' Comments
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Author Response

OPTI-D-00073 – Journal of Optics

Identification of Optical Parameters for Determination of Radiance

Authors: Pratik P. Shukla and Jonathan Lawrence

Dear Prof. L.N. Hazra,

I would like to thank you for considering my paper for publication and allowing me to have the opportunity to make corrections. Time and effort have now been spent to enhance the quality of the manuscript so that the suggested corrections and further changes by the reviewer could be taken on board and the paper is improved for its quality. I also thank the reviewers for providing such valuable feedback. It has and will make a tremendous difference to my research. The following text describes accurately the reviewer's comments and the author response to each points that was raised and many other changes made by the authors to improve the quality of the manuscript.

Yours Sincerely,

Dr. Pratik Shukla

Reviewer Comments

Reviewer #1: This paper has discussed about radiance of laser beams and the context is utility in laser based material processing. It has tried to cover all laser parameters which could influence radiance. Many of the conclusions are intuitively well understood by experienced experimentalists in the field. But the attempt to bring them collectively needs to be appreciated and this paper may be useful to many workers in this field and so I recommend it for publication but with some conditions.

Author response

Many thanks for providing this review.

Reviewer Comments

The quality of English is quite bad, particularly as it is from U.K. It is very important that authors improve their English, including spellings.

Author Response

We would like to apologies for this type of errors made in the initial submitted paper. The English language in general, sentence creation, spelling, and grammar have all been modified, checked for clarity and amended as required throughout the entire paper.

Other Corrections

- Please note: All the text in blue added within the manuscript are new or modified for reviewer's and editor's clarity.
- Last paragraph of the introduction, line 10 to 13: These are the new lines added. Please see as follows.

  '*Moreover, despite experienced experimentalists understanding the effect of the aforementioned parameters, this paper is still very valuable as it collectively brings the parameters of radiance together to demonstrate factors influencing the radiance of lasers*'.
- Units of radiance have been changed from W. $Sr^{-1}.mm^2$ to $W.mm^{-2}$. $Sr^{-1}.\mu m^{-2}$. This is because the wavelength of the laser beam in (µm) should be included in the units since (a) the wavelength is a large contributor to affect radiance and (b) the proposed unit would then complete all the input parameters within the equation which determine the radiance and characterizes the laser beam.
- The range of parameters used in Table 1 has been changed for laser power (0.1 – 3600 W); power density (10 - 120000 W/mm^2); spot diameter (0.1 – 25 mm); Beam Parameter Product (M^2 = 1 – 30); Wavelength (0.238 – 30 µm). This was simply because it would bring diversity in the results shown in the graphs and also to cover larger range of parameters that would make the results more informative. This is also reflected into the results section as the graphs slightly changed from the original submitted manuscript.
- Please note, we have attempted to use the correct terminology for M^2 and it is as follows: 'Beam parameter product – M^2' rather than using 'beam quality factor - M^2'.
- The X –axis in Figure 7 has now been modified for further clarity.
- Please note the addresses of both the authors have changed. Therefore, the address to be used is as follows for both the authors:

  'Laser Engineering and Manufacturing Research Group, Faculty of Science and Engineering, University of Chester, Parkgate Road, Chester, CH1 4BJ, United Kingdom'.

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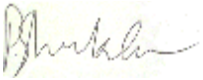
	Corresponding Author's Signature:  **Date: 19/09/2013**
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Journal of Optics
Editor-in-Chief:L.N. Hazra
ISSN: 0972-8821 (print version)
ISSN: 0974-6900 (electronic version)
Journal no. 12596