Measurement of the Diameter of a Laser Beam

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Abstract. A new and simple technique for measuring the effective diameter of a laser beam used in material processing is described. The time for the temperature of a spot heated by the laser beam to rise to 90% of equilibrium is compared with that predicted theoretically for a Gaussian TEM_{00} laser beam. A Gaussian beam diameter equivalent is thus deduced. This calculated diameter is of particular relevance to applications where the laser is used as a heat source.

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Symbols

- \( D_b \): Gaussian beam diameter equivalent of the laser beam at substrate surface [m]
- \( k \): thermal conductivity of the substrate [W/m K]
- \( P \): total incident beam power [W]
- \( r \): radial location
- \( r_b \): beam radius \((D_b/2)\)
- \( r_s \): surface reflectivity
- \( R \): dimensionless radius \(r/r_s\)
- \( t \): time [s]
- \( T \): temperature [°C]
- \( T^* \): dimensionless temperature = \( T/kD_b/\pi P(1-r_s) \)
- \( \alpha \): thermal diffusivity \([m^2/s]\)
- \( \theta^* \): dimensionless time = \( 16\pi t/(2D_b) \)

High power cw lasers are increasingly finding applications in the field of materials processing. Notably multikilowatt CO₂ systems are now in use for cutting, welding, heat treating, and surface alloying of metals. In all of these applications a knowledge of the effective laser beam diameter is crucial. The heating effect with plasma generation is thought to be dependent upon the power density \( (P/D_b^2) \), as is the onset of melting during surface hardening (a thermal conduction process). Thus a knowledge of the effective beam diameter is as important, or more so than a knowledge of the total laser power.

In fact it could be surmised that the present trade literature which lists cutting or welding speeds or penetration depth vs laser output power is only giving half the required information.

Definition of Beam Diameter

For stable cavity lasers the perfect fundamental TEM_{00} mode structure is defined thus

\[
P(r) = \frac{8P}{\pi D_b^2} e^{-8r^2/D_b^2}.
\]

That is the beam has a Gaussian power distribution. From this it can be seen that the beam diameter is defined as the diameter at which the power has fallen to \((1/e^2)\) of the central value.

Previous Methods of Measuring

Given such a distribution and perfect optics it is possible to calculate the beam diameter from a given laser cavity after passing through a lens of known focal length. One straightforward method of calculation, that of propagation circles, is described in Sinclair and Bell [1]. Such diffraction limited theory gives a relationship for the minimum beam diameter subsequent to a lens of \( D_{\text{min}} \approx 1.3F\lambda \), where \( \lambda \) is the wavelength and \( F \) is the F number of the lens, calculated as (focal length/incident beam diameter). It is a mistake to use the optic diameter as is common practice. The actual beam diameter will be larger than that calculated by diffraction theory because there is truncation at the finite sized optics used, there may not be a perfect Gaussian incident mode and there will be some...
spherical aberration at the lenses (particularly for an $F$ number $< 7$).

At the minimum spot size the difference may be a factor of 2 or more, which as far as material processing is concerned is crucial.

Many methods for measurement of beam diameter have been proposed. The techniques may be split into two groups, namely single isotherm and multiple isotherm contouring.

Single isotherm plotting includes such techniques as charring paper, drilling holes in metal foils [2, 3] and acrylic plastics or forming glow images on asbestos sheets, and fluorescent screens. All these methods suffer from the same fault, that the particular isotherm they "plot" and hence the beam diameter they give is both exposure time and laser power dependent. Furthermore the value they give need bear no relationship to the required $(1/e^2)$ value. In fact, if charring, for example, is dependent on power density and energy absorbed, then for a Gaussian beam the charred diameter, $D_c$, is given by

$$D_c = \frac{D_b}{\sqrt{2}} \sqrt{\ln \left(\frac{8P_0 t}{D_b^2 \pi A}\right)},$$

where $A$ is a constant.

It is seen that $D_c = f(P_0, t)$. This effect, which has serious implications on the accuracy of the most commonly used methods of measuring the beam diameter, is further illustrated in Fig. 1.

Multiple isotherm contouring techniques overcome this difficulty, but are tedious and sometimes impossible to analyse. The two main techniques are the use of linear response photographic paper [4] (not very useful for high powered 10·6 μm radiation) or the photon drag detector. The photographic method gives too much information making interpretation difficult. The photon drag detector gives a convoluted signal, which it is only possible to interpret if the beam is assumed to be axisymmetric.

Unfortunately, few practical laser systems give the uniform Gaussian power spread predicted by theory. Such effects as thermal distortion of optical elements tends to produce irregular nonaxisymmetric beams. This problem becomes increasingly severe as the laser power increases. For irregular beams of this sort the interpretation of the signal from a photon drag detector or of any of the other methods, to give a beam diameter becomes increasingly difficult if not impossible.

The thermal rise time technique described here approaches the problem from a different direction. It assumes that any laser beam, even an irregular one,