Laser Power Estimation by Mass Ablation for High Power Laser

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This paper reports an alternative method for estimation of laser power generated from high power carbon dioxide gas dynamic laser. An unstable resonator was employed for generation of laser. In this method an array of thin MS plates separated by an air gap is used for estimation of ablated mass from the array. High power laser beam was focused on the array by concave mirror of long focal length. A fraction of beam is absorbed by the surface which is opaque to laser wavelength @ 10.6 micrometers. The interaction of high power laser beam with array results in temperature rise of MS plates. If laser irradiation is continuous a phase change of material takes place in the array. In the array, 20 plates of mild steel got damaged by irradiation of laser beam and mass are removed by ablation. The paper also describes the development of software for estimation of laser power from ablated mass from each plate. The results are validated by measuring the laser power by a power meter. These results are in agreement with estimated power within ±10% of power measured by power meter/calorimeter.

Keywords: Mass Ablation, Mild Steel, Power Measurement, Unstable Resonator, Gas Dynamic Laser.

Introduction

The availability of lasers as a source of thermal energy has led to their use in a variety of applications in many diverse fields, such as laser material processing and defense. Typical high power lasers required for such applications involve carbon dioxide gas dynamic laser (GDL), chemical oxygen iodine laser (COIL), HF-DF laser, high power solid state laser. Except continuous wave solid state lasers and fiber lasers, the other class of laser operates for shorter durations with large beam diameters. Under these situations, the measurement of laser power is a challenging task. No commercial power meters are available to fit into the beam size of laser and the requirement of response time. The laser power estimation by mass ablation offers an alternative method for estimation of laser power generated at source under such circumstances. When a laser beam interacts with material such as metal some of its energy is lost due to spectral reflections and scattering from the surface and the rest is absorbed at the metal interface. The interaction depends markedly on both the laser beam parameters and the characteristics of the material. At the non transmitting metal interface the absorbed fraction of incident laser radiation penetrates into the bulk of material at skin depth. This skin depth is a function electrical conductivity of material. Subsequent absorption of this radiation by free carriers within the metal raises the temperature of its surface. As the temperature rises, absorption coefficient of metal for incident radiation increases resulting in stress and distortion of the surface. In the limit, catastrophic damage may occur due to mechanical failure by melting of the surface. Hence, significant mass is ablated from the surface. The estimation of ablated mass from the surface provides estimation for power being incident on metal. The method may be treated as a parallel power measurement in situations where several experiments are required to be carried out simultaneously in a single laser operation. The energy $Q$ required to ablate the mass, $\Delta m$ of a thin plate is given by:

$$Q = \Delta m \cdot s(T_m - T_0) + \Delta m \cdot s(T_v - T_m) + \Delta m \cdot L_m + \Delta m \cdot L_v.$$  \hspace{1cm} \ldots (1)

Where, $T_0$ is ambient temperature, $\Delta m$ is ablated mass from target, $s$ is specific heat, $T_m$ is the melting temperature, $T_v$ is vaporising temperature, $L_m$ is latent heat of melting and $L_v$ is latent heat of vaporisation of target material. The thermo physical properties of target material are summarized in table-I. The first part of right hand side represents the contribution due to heating of the surface which results in the temperature rise $\Delta T_m$ up to melting, second part

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represents the phase transition from liquid to vapor phase, the third part represents energy consumed for conversion of given mass during melting and similarly the fourth part represents energy consumed for given mass during phase transition from liquid to vapor.

The total energy required to ablate mass $\Delta m$ from the array is estimated by taking average of energy value required from all the individual plate. There is a focal length at which the beam will be collimated for the large distance. This focal length is known as the Rayleigh Range, $Z_r$. The beam radius at the Rayleigh Range is $\omega = D/3\sqrt{2}$, and the Rayleigh Range is given by $Z_r = \pi \omega^2/\lambda$. Therefore we have considered the experiment in the Rayleigh Range.

### Experimental Scheme and Software Development

The experimental scheme is shown in Fig 1. The annular beam of dimension about 150 mm $\times$ 88 mm from unstable resonator of gas dynamic laser is focused at an small angle of less than 20° on metal target by a concave mirror of reflection coefficient 0.98 and large radius of curvature 6 m. The target comprises of a stack of 25 sheets of thin mild steel plates each of thickness 0.8 mm separated by an air gap of 5.0 mm. The plates have surface roughness of few microns and coated dull black for absorption coefficient of 0.85 at laser wavelength. The reflection coefficient of each plate was measured at 10.6 micrometers by ratio-metric techniques using low power CO$_2$ laser. The laser produces an average output power in the range 90-100 kW for short duration of 2 to 3 sec in series of operations. The laser firing duration was for 2.3 sec. At sufficient high power at beam waist, the beam punches holes in stack of metal plates and mass is ablated from each plate in stack. The operation of the laser is controlled and the exposure time of beam on target was measured through data acquisition system. The ablated mass from each plate in a stack was measured by a high accuracy electronic weighing balance with least count $\pm0.0001$gm. A dedicated computer program is developed for calculating the power/energy consumed in ablating mass from target. This Program performs computational calculations in order to accurately predict the behavior of laser interaction phenomenon like heating, melting & vaporization. Here, MS Visual Basic 6-8 Version 6.0 as front end & MS Access 2003 as back end under windows XP environment have been employed to develop the required program. Open GL as a graphical tool and Visual Basic C++ as a prototyping language have been used to perform all operations. Open GL provides a set of commands to render a three dimensional as well as two dimensional scenes in real time. This application works on every platform and involves real time display of functions, images, sweep, logic graph, annunciations, x-y plot etc. Finally to bring whole calculations under same platform, the graphical tool “3D++ class library for MFC” supported by VC++ as well as MFC were used. The implementation of software development is concerned with translating design specification into source code, so that debugging, testing and modification are becoming easier. Clarity of source code is enhanced by structured coding style, appropriate supporting documents and appropriate comments wherever required. A variety of targets may be considered for estimation of the power/energy consumed in ablating mass from target by using this software. The implementation of inputs and outputs parameter in the software is described below:

**Inputs:** The software provides the user graphic interface for selection of input parameters of target material. The thermo physical properties of material are:

<table>
<thead>
<tr>
<th>Physical property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific heat ($s$)</td>
<td>0.465 J/gm$^0$K</td>
</tr>
<tr>
<td>Melting point ($T_m$)</td>
<td>1700$^\circ$K</td>
</tr>
<tr>
<td>Vaporizing Temperature ($T_v$)</td>
<td>3100$^\circ$K</td>
</tr>
<tr>
<td>Latent heat of melting ($L_m$)</td>
<td>275 J/gm</td>
</tr>
<tr>
<td>Latent heat of vaporization ($L_v$)</td>
<td>6362 J/gm</td>
</tr>
<tr>
<td>Density of mild steel</td>
<td>7861 kg/m$^3$</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>55 W/m$^3$K</td>
</tr>
</tbody>
</table>

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![Fig 1—Experimental scheme of ablation method for power measurement](image)
are automatically selected from the database. It requires feeding of the variable parameters viz. absorption coefficient, exposure time, ablated mass of each plate and number of target plates.

Outputs: As per the input parameters of laser and target material, software performs calculations of the energy required to damage a given target which gives an estimation of power delivered on target by laser system.

Results and Discussions
The power density achieved on the target (20 sheets of mild steel) after focusing of laser is 0.8-0.9 MW/cm². At such high power density, the surface temperature of target rises above boiling point in few ms. Mass is ablated from target plates and the subsequent plates in stack get damaged due to penetration of beam through hole on the front plate and mass is ablated from subsequent plates in stack. In our experiment 20 plates got completely damaged due to irradiation of beam on target for laser duration of 2.3 sec. Total ablated mass from all the plates was estimated by measuring the weight of each plate before and after laser irradiation. The total mass loss in stack of 20 sheets was found to be 21.82 g. The energy Q, in Joule, required for total ablated mass of 21.82 g is computed through program in PC. The results of analysis show total energy value of 192.5 kJ. By considering the absorption factor of 0.85 of plate, the total estimated energy of the source is 226.46 kJ. The corresponding source power incident on the front surface of metal was estimated to be 98 kW. The results are verified by calorimeter which is a direct method to measure the laser power of high power laser source which has the accuracy within ± 10%. Therefore, the accuracy of method is taken in this limit and it was found within ± 10%. Focused beam on target produce high temperature. At this temperature the material starts melting within several microseconds. The radiation loss and reflectivity of the beam due to the laser beam through plasma formed will not be the same but we have not taken thick one plate as a target. Target is the combination of 20 sheets of thin plate of 0.8 mm with gap of 5 mm. So there is taken negligible chance of plasma formation and no effect on the reflectivity. If inter plate spacing is reduced, then there may be chance of formation of plasma and it will affect the reflectivity of metal. Similarly inter plate spacing can be increased but in the limit of Rayleigh Range. If we increase the plate thickness, it may be the cause of plasma formation after a certain limit of thickness and will affect the reflectivity due to deposition of melted material while in case of thin sheet with sufficient inter plate gap melted metal removes naturally and does not affect to go laser on the next plate and so on. So the radiation loss due to surface temperature is therefore omitted from calculations.

Conclusions
The paper describes an alternative method of laser power estimation for high power short duration lasers where the large beam aperture and response time of commercial power meters poses problems in measurement. We report measurement accuracy of this method within ± 10%. Also a large number of experiments like laser interaction studies, power measurement, divergence measurement etc. are possible to carry out simultaneously here.

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