High Energy Laser Diagnostic Sensors

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Abstract. Recent advancements in high energy laser (HEL) sources have outpaced diagnostic tools capable of accurately quantifying system performance. Diagnostic tools are needed that allow system developers to measure the parameters that define HEL effectiveness. The two critical parameters for quantifying HEL effectiveness are the irradiance on target and resultant rise in target temperature. Off-board sensing has its limitations, including unpredictable changes in the reflectivity of the target, smoke and outgassing, and atmospheric distortion. On-board sensors overcome the limitations of off-board techniques but must survive high irradiance levels and extreme temperatures.

We have developed sensors for on-target diagnostics of high energy laser beams and for the measurement of the thermal response of the target. The conformal sensors consist of an array of quantum dot photodetectors and resistive temperature detectors. The sensor arrays are lithographically fabricated on flexible substrates and can be attached to a variety of laser targets. We have developed a nanoparticle adhesive process that provides good thermal contact with the target and that ensures the sensor remains attached to the target for as long as the target survives. We have calibrated the temperature and irradiance sensors and demonstrated them in a HEL environment.

Keywords: temperature sensor, irradiance sensor, beam profile, beam intensity, sensor array, fiber laser, CO\textsubscript{2} laser

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INTRODUCTION

Recent advancements in high energy laser (HEL) sources have outpaced diagnostic tools capable of accurately quantifying system performance. The two critical parameters for quantifying HEL effectiveness are the irradiance on target and resulting rise in target temperature. Most remote sensing techniques use the bidirectional reflectance distribution function (BRDF) to characterize reflected laser energy. The BRDF relies on reflecting properties of the material surface, which can change rapidly due to HEL heating making the technique impractical for field test measurements\cite{1}. Other issues with off-board sensing methods include interference from products of laser interaction (i.e. smoke and outgassing) and atmospheric distortion. On-board sensors overcome the limitations of off-board techniques but must survive high irradiance levels and extreme temperatures, and must have minimal impact on the optical and thermal properties of the target.

The AEgis Technologies Group and RTI International have developed sensors to directly measure HEL irradiance on targets of interest and the corresponding thermal response of the target. The conformal sensor arrays consist of an array of quantum dot...
photodetectors and resistive temperature detectors (RTD). The sensor arrays are lithographically fabricated on flexible substrates and can be attached to a variety of laser targets. Two types of sensors have been developed. The first, the temperature and irradiance sensor matrix (TISM), is designed to be attached to the front side of the laser target, and measures both the laser irradiance and the target temperature. The open mesh architecture allows up to 90% of the beam to interact with the surface. This paper will focus on the TISM sensors and materials.

The second type of sensor, the inversion-derived resistive temperature sensor (IRTS), is designed to be attached to the back side of a relatively thin target. An array of a few hundred temperature sensors measures the temperature profile on the back side of the target, and an inverse heat conduction model is used to calculate the temperature and heat flux on the front side[2].

There are many potential applications for these conformal microsensor arrays, including diagnostics for directed energy sources and evaluating the aimpoint accuracy of tracking lasers. A possible non-laser application of this type of sensor array would be to provide feedback on mirror pointing accuracy in concentrating solar power systems as part of an active control system. The TISM sensor is intended to survive irradiance levels up to 5 kW/cm². For comparison, an acetylene torch produces about 100 W/cm². Spacecraft re-entry into Earth’s atmosphere produces heat fluxes from about 150 W/cm² to 750 W/cm²[3]. The heat flux at the surface of the Sun is approximately 7 kW/cm².

**IRRADIANCE SENSOR PROTECTION**

A critical component of the program is development of a protective coating that allows the sensors to survive at high irradiance levels for operational lifetimes on the order of 10 seconds. The protective coating must also allow transmission of a portion of the incident light to a microsensor that provides a calibrated measure of the incident irradiance. The amount of light being attenuated by the protective layer must be quantified to ensure accuracy. Two different types of protection mechanisms have been tested: partially transmissive metal films and opaque layers with small apertures. A thin (20–40 nm) layer of gold deposited on top of the irradiance sensor will transmit a small fraction of the incident light (1-10 %), and has essentially no dependence on the incident angle. The second protection mechanism involves the use of small apertures in an opaque, highly reflective protective layer. In this two-layer design, the sensor layer is separated from the protective layer by a very small air gap, which is on the order of 0.25 mm. The top, protective layer has a small aperture that is offset from the location of the irradiance sensor (Figure 1). Laser light entering the aperture will reflect diffusely from the cavity, or holraum, in the second sensor layer. Some of the reflected light will propagate down the air gap between the two layers and reach the sensor. The two protection mechanisms can be combined so that the detectors can measure and withstand a wide range of intensities, up to 5 kW/cm².

The impact of incidence angle on the transmission through the offset apertures was quantified experimentally. The transmission did not depend strongly on the angle of incidence for angles of 30 degrees or less from the surface normal.
FIGURE 1. The aperture and cavity or hohlraum in the protective layer that allows light to reach the detector.

**TEST SETUP**

Several sets of HEL tests have been completed so far. In this paper we report on the two most recent tests, which were conducted at the Human Effects Directorate, Optical Radiation Branch (RHDO), Brooks City-Base in San Antonio, Texas in November 2008, and at the Naval Surface Warfare Center, Dahlgren Division, VA in February 2009.

The laser tests were conducted using one or more 1.07 μm fiber lasers. A 3 kW laser was used in the November 2008 tests at San Antonio, while the February 2009 tests at Dahlgren used six incoherently combined 5.5 kW lasers. The duration of all laser tests was 10 seconds, unless otherwise noted. We tested 2x2 and 8x8 TISM arrays, 15x15 IRTS arrays, and various materials and high temperature adhesive coupons. In the laser tests, a photodiode was positioned behind the sample to determine the exact time at which candidate materials failed.

Material test samples and 2x2 TISM sensor arrays were 40mm square. TISM 8x8 arrays were 100 mm square overall, and consisted of an open mesh of kovar foil with a photoconductive irradiance detector (PCD) for irradiance and an RTD at each node. Figure 2 shows a single node of the array, without the protective layer. The node spacing was 10 mm. The arrays of the current design have a transparency of 69 %, meaning that they cover 31 % of the target surface. Higher transparency is possible in future designs. The sensor array and protective layer were attached to 2 mm thick metal targets made of kovar, duplex stainless steel, or aluminum.

FIGURE 2. One node of the 8x8 array, without the protective layer. The irradiance detector is the rectangular area in the center. The two circles are the hohlraums. The wiring can also be seen.
**Row-Column Addressing**

The sensor arrays are configured as row-column arrays of detectors, with each detector acting as a variable resistor. Therefore the array consists of an interconnected network of resistors. To read out an individual detector located at row \( m \) and column \( n \), a voltage pulse is applied to row \( m \) and the signal at column \( n \) is read. In order to obtain the true resistance at an individual node and exclude the parallel contribution from neighboring nodes, a virtual ground circuit was used\[4,5\]. The virtual ground circuit consisted of an operational amplifier for each column, with the inverting input connected to the column and the non-inverting input grounded. The voltage on the output of the op amp on column \( n \) is inversely proportional to the resistance of detector at location \((m,n)\). The use of row-column addressing allowed us to reduce the number of electrical connections from \( 2(m \times n) \) to \( (m + n) \). For TISM this reduced the connection count from 256 to 32, and for IRTS the reduction was from 450 to 30.

**Data Acquisition System**

The data acquisition system (DAS) for laser testing consisted of a National Instruments PXI chassis with multifunction analog input modules, and a laptop computer with custom LabView software. The DAS simultaneously read the 16 columns of the sensor array, as well as signals from optical pyrometers and other sensors. Data was acquired for 1 s before laser start, and continued until 5 s after the laser was turned off.

**Calibration**

Each detector on each array was individually calibrated. The RTDs on the TISM and IRTS arrays were calibrated by heating the array uniformly and measuring the resistance of each RTD as a function of temperature. The slope of the resistance-temperature curve was the same for all RTDs (it is a function of the material properties), but the absolute value of the resistance varied as a result of manufacturing tolerances.

The PCDs on the TISM arrays were calibrated by illuminating each PCD with short laser pulses at different intensities and measuring the detector response during each laser pulse. The calibration system was automated, with software control of the laser, DAS, and a motorized x-y translator to address the sensor nodes sequentially. The laser used for calibration was a 200 W fiber-coupled diode laser with a wavelength of 975 nm. The laser pulses were 2.5 ms long, and produced negligible heating of the array. The beam was Gaussian with a diameter of 3.6 mm. The sensor array and laser beam were carefully aligned to within 0.24 mm, which resulted in an uncertainty in the actual intensity at the location of the detector of 3.4 %.

Figure 3 shows an example of calibration data for the PCDs in one row of one of the TISM sensor arrays. We are continuing to develop data analysis/visualization software to view and display the output from the TISM and IRTS sensor arrays.
FIGURE 3. Calibration data for array 8XL65, row 1. PCDs 2, 7, and 8 showed a decrease in resistance as a function of irradiance. Other PCDs in this row were considered not working.

HIGH TEMPERATURE ADHESIVES

One of the challenges for the project was identification of adhesives to attach the sensor array to the target. The adhesive must have adequate mechanical strength, high thermal conductivity to ensure accurate target temperature measurements, and it must survive to temperatures above 600°C during HEL engagement. However, because the quantum dot irradiance sensors have a maximum survival temperature of around 200°C, the adhesive curing temperature must be less than 200°C.

Many different high temperature adhesives were tested, including ceramics, metal filled ceramics, solder alloys which initially have a low melting point but change to a higher melting point composition, reactive nanofoil melted solder alloys, and nanoparticles. The ceramic adhesives failed due to their low thermal conductivity, brittleness and coefficient of thermal expansion (CTE) mismatch. The melting point changing alloys and reactive nanofoil were promising, but with the success of the nanoparticle adhesive, further development of the other materials was stopped.

We have identified a nanoparticle adhesive that sinters at temperatures as low as 130°C, and subsequently has approximately the melting point and thermal properties of the bulk material. Sensor arrays attached to targets with this adhesive remain attached to the target up to the melting point of the target (Figure 4).

An interesting feature of nanoparticles is that their melting or

FIGURE 4. 2x2 TISM array after laser testing. Array and target have been melted through, but the adhesive is intact (outside of the hole).
sintering temperature is a function of the particle size [6]:

\[ \frac{T}{T_0} \propto 1 - \frac{1}{r}, \tag{1} \]

where \( T \) is the melting point of the particle, \( T_0 \) is the melting point of the bulk material, and \( r \) is the radius of the particle. The nanoparticles in the adhesive used in this work are approximately 5 nm in diameter.

**LASER TEST RESULTS**

**Sensor Arrays With and Without Targets**

A fundamental question about the TISM sensors was whether they would accurately measure the temperature of the target, or whether the sensor itself would be strongly heated by the laser and thus give inaccurate readings. In an attempt to address this question experimentally, sensor arrays that were attached to a target were compared to sensor arrays alone, with no target. All tests were conducted with a 20 mm laser beam diameter. The bare arrays melted through much faster than arrays which were adhered to a target. At 3000 W/cm\(^2\) irradiance an array with a 1.65 mm thick aluminum target survived 3.98 s before melting through, compared to 1.2 s for the bare array. At 5000 W/cm\(^2\) irradiance, a bare array survived 0.175 s compared to 1.085 s with a 2 mm thick kovar target. This means that the temperature of the array was strongly coupled to the temperature of the target, and increased our confidence that the arrays correctly measure the target temperature. A complete answer to this question will require further study, including thermal modeling.

**Targets With and Without Sensor Arrays**

Another fundamental question about the TISM sensors was whether (or how much) they would affect the response of the target. Comparison of bare 1.65 mm thick aluminum targets to similar targets with 2x2 arrays revealed that the bare Al targets survived longer before being melted through by the laser. For example, with an 8.74 mm laser beam diameter and 5000 W/cm\(^2\), the bare aluminum target melted through in 7.191 s (average of four shots) compared to 3.34 s for an aluminum target with a 2x2 array. All of the 2x2 arrays with aluminum targets were electroplated with bright gold, which is an alloy of gold and nickel. As this impure Au plating became hot it oxidized and strongly absorbed laser light, decreasing the overall reflectivity of the target, resulting in the target melting through earlier than a bare aluminum target.

For lower reflectivity targets with more pure gold plating the results were different. Bare kovar targets melted through faster than kovar targets with 2x2 arrays attached. For example with a 20 mm beam diameter and 5000 W/cm\(^2\) irradiance, the bare target melted through in 0.665 s while the target with the array melted through in 1.085 s. In this case the presence of the sensor array increased the total reflectivity of the target surface, and the essentially pure Au plating on the array remained highly reflective as the target temperature increased. In summary, the presence of the sensor array may
increase or decrease the survivability of the target depending on the relative dynamic reflectivities of the target and array.

**TISM Array Results**

We tested a number of 2x2 TISM arrays. An example of the PCD response is shown in Figure 5. The PCDs are sensitive to both irradiance and temperature. In Figure 5 the PCD resistance decreases by approximately two orders of magnitude immediately in response to the laser irradiation, then approximately another two orders of magnitude as the temperature increased.

![FIGURE 5. PCD resistances for 2x2 TISM array, irradiated at 2000W/cm². The laser pulse begins at 4.15s. The target melted through at 7.27s. PCD resistance decreased by four orders of magnitude.](image)

**Effect of Beam Diameter**

The diameter of the Gaussian laser beam was defined as twice the radius at which the intensity had dropped to $1/e^2$ of the peak intensity. An 8.74 mm diameter (0.6 cm²) laser beam was compared to a 20 mm diameter (3.14 cm²) beam on 40 mm square targets. At the same irradiance of 3000 W/cm², 1.65mm thick Al targets with 2x2 arrays melted through in an average of 3.98 s with a 20mm diameter beam, and 7.50 s with a 8.74 mm beam. The larger diameter beam melted the target significantly faster. On bare 1.65 mm Al with 3000 W total power, the 8.74 mm beam (5 kW/cm²) melted through the target in 7.191 s compared to 8.621 s for the 20mm beam (955 W/cm²). Although the irradiance differed by a factor of five, the burnthrough times were not that different, with the smaller beam taking 16.6 % less time. These results indicate that lateral heat transfer had an effect, particularly for the small laser beams, even though the beam diameter to thickness ratio was 5.3 for the small beam and 12.1 for the large beam.

At moderate irradiance (3 kW/cm²), Al targets (with arrays) last more than twice as long as kovar or duplex stainless steel. However, at higher irradiance (5 kW/cm²), the
kovar lasts significantly longer than Al, because at higher irradiance lateral heat transfer has less of an effect.

SUMMARY AND CONCLUSIONS

Based on empirical results, we conclude that the presence of the TISM array can change the thermal response of the target, by changing the overall reflectivity. This effect is minimized by making the open area as large as possible. In some applications, such as a target board, thermal response is not measured (only irradiance), so a solid substrate could be used. Laser beam diameter has an effect on the test results, and should be as large as possible for the most relevant results. This has implications for testing of large sensor arrays, because few lasers are available with sufficiently high average power to illuminate large areas.

We have developed a nanoparticle adhesive process that ensures the sensor remains attached to the target for as long as the target survives. The nanoparticle adhesive provides good thermal contact between the array and the target, so that the sensor array will accurately measure the target temperature. We have demonstrated RTDs capable of measuring over 600°C. The irradiance sensors have a thermal and irradiance response, and additional work is needed to validate techniques for removing the temperature effects from the sensor response. We have developed a calibration system and procedure, calibrated PCDs and RTDs, and demonstrated both types of sensors in an HEL environment.

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