REVIEW OF ULTRAVIOLET AND HIGH POWER LASER MEASUREMENT STANDARDS AT NIST*

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Abstract: High accuracy laser radiometry is on the verge of growth and improvements just as new laser technologies are evolving. Our present tasks are directed toward anticipating and meeting the measurement needs in two areas: higher power and shorter wavelengths. New technologies include high-power compact laser diode sources and ultraviolet laser sources and detectors. We present an overview of laser power and energy measurement challenges, identify gaps in the state of the art, and describe research at NIST directed toward improved primary standards for laser power and energy measurements. Improvements are directed toward new coatings, materials, stable attenuators and standard detectors.

1. INTRODUCTION

The next generation of laser measurements at NIST is directed toward the development of new primary standards for measuring ultraviolet and high power laser diodes. Presently our primary standards for laser measurements rely on a cryogenic radiometer and a suite of calorimeters covering a range of power and energy levels and a range of wavelengths. Table 1 shows a matrix of standards and the range of services that are covered by our existing measurement services. The development of II-VI diodes (wide bandgap semiconductors) is making the presence of UV lasers commonplace in applications such as commercial electronic devices (for example, high definition digital video disc), water purification devices, and other technology related to chemical analysis. In addition, high efficiency diode laser sources, precursors to multi-kilowatt devices operating near 980, nm are being demonstrated with output power exceeding 5 W and 65 % efficiency (electrical to optical). These laser sources present challenges requiring technology beyond our present capability. Furthermore, we expect that customers will request calibration of laser power and energy meters to characterize these new sources as they are increasingly employed in new commercial products.

2. ULTRAVIOLET LASER MEASUREMENTS

Since its inception, our calibration services for UV excimer laser energy meters have largely served the semiconductor fabrication industry. Semiconductor process tool manufacturers rely on energy meters for process control of photolithography. Accurate and traceable calibration of laser energy meters adds value to the semiconductor industry by increasing yield and reliability in the manufacturing process.

Beginning shortly after 1990, an industry consortium known as Semiconductor Manufacturing Technology (SEMATECH) supported the development of excimer laser calibrations at 248 nm for UV photolithography. A primary standard based on an electrical substitution isoperibol calorimeter was built and measurement uncertainties were established. Before the end of the decade, the semiconductor fabrication industry required calibrations at 193 nm. A new primary standard for laser energy meter calibrations at 193 nm was established for yet another calibration service. In support of the drive to achieve even narrower photolithography linewidths and smaller features, the NIST Office of Microelectronics Programs (OMP) and SEMATECH in 2001 supported the development of energy meter calibrations at 157 nm. Because of aging and hardening of optical materials used in the

construction of these standards, a completely novel calorimeter for 157 nm was designed and built. More recently, in 2005 we began development of standards for blue/UV laser diodes and other laser sources, which is still supported by OMP.
There are many technical challenges unique to UV laser measurement. Damage, hardening and aging at UV wavelengths are known but not well understood. Mirrors for laser beam control that are commonplace at other wavelengths such as 1064 nm are typically inadequate for UV lasers, which have higher energy photons. For example, a mirror for 300 mJ/cm^2 for 1064 nm is readily available commercially. However, at the same energy density, but at 157 nm, we have found that reflective surfaces are easily damaged. In the past we have documented laser damage to polished copper, and nickel on sapphire, and that even crystalline silicon carbide may be damaged at 150 mJ/cm^2 (10 nsec pulses, 100 Hz repetition rate).[1]

3. HIGH POWER LASER MEASUREMENTS

As lasers were adopted for myriad applications during the 1960s, CW laser calibrations were pioneered at NIST with the development of isoperibol calorimeters traceable to electrical standards.[2] In recent years, most of the “business” of calibration services has grown in the area of optical fiber power meters for telecommunications. We have observed this even during the economic downturn in the optical communications industry in the late 1990’s. Since the 1960’s, the United States Department of Defense (DoD) primary standards labs have been critical to support and development of primary and secondary standards for laser power measurements for visible lasers as well as for infrared lasers operating at 1064 nm and 10.6 μm. In the late 1990s we developed and established a tunable laser ensemble for CW power calibrations from UV to IR to meet the growing need for calibration services at wavelengths other than those provided by more common gas lasers (for example, 633 nm). In the late 1990s we extended our technical capability and lowered uncertainties in our optical fiber meter calibration services by establishing a laser-optimized cryogenic radiometer (LOCR).[3] In 2005 our group was tasked by the United States Defense Advanced Research Projects Agency (DARPA) to provide electrical to optical conversion (“wall plug”) efficiency and relative spectral flux measurements of high-power high-efficiency laser diodes and arrays. Laser development in this area is poised for commercial and military applications requiring high power (exceeding 10 kW) and high wall plug efficiency (greater than 70 %). Therefore we have developed a flowing water optical power meter (FWOPM) to meet the needs of NIST-traceable high accuracy measurements of high power CW lasers.

High power lasers and in particular, diode laser arrays, present significant measurement challenges. The high power levels and the size of the arrays can cause large uncertainties with the best commercially available optical radiometers. As an alternative to the isoperibol calorimeter, a flowing water optical power meter (FWOPM) has been developed (Figure 1). The present embodiment of the FWOPM is a copper cavity with a black coating that captures nearly 2π steradians of the laser output with 99.9 % efficiency. The optical power is quantified as a rate of heating based on the temperature change of water flowing around the optical cavity. The power, P, measurement is then provided by the equation: $P=\rho_m \Delta T C_p$, where ΔT is the temperature difference between the input and the output water, ρ_m is the mass flow rate, and C_p is the heat capacity of the water. Measurements down to a few watts of precision are possible with calibrated thermistors and a high-accuracy (Coriolis type) mass-flow meter. The effective heat capacity can be measured by introducing an electrical heater into the water flow and measuring both the water flow and the temperature increase ΔT of the heater, making the optical measurements traceable to electrical standards.

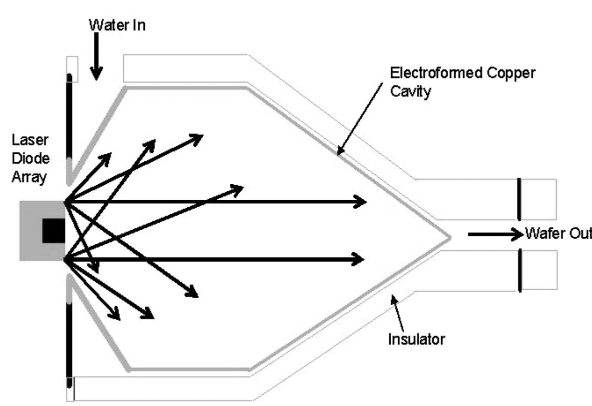

Figure 1. *The figure shows a cutaway diagram of the FWOPM, illustrating the absorbing cavity and the water-flow channel on the outer surface of the cavity. The laser diode array is placed in the entrance aperture, and the cavity absorbs nearly 2π steradians of its optical output.*

4. PROBLEMS COMMON TO ULTRAVIOLET AND HIGH POWER MEASUREMENTS

There are several areas of laser measurement where we seek improvements to our ability to provide calibration services, namely: transfer standards, coatings for thermal detectors that are resistant to damage and aging, and stable attenuators to extend the range over which the transfer standards are applicable.

Transfer standards are continually being sought that are robust, convenient, resistant to aging (that is, the responsivity is stable over many years), and spectrally and spatially uniform over a large area (1 cm^2 or more). Among the many types of optical detectors, there are tradeoffs to selecting the best one for a particular application. Experimentally determined values of detector performance, such as spectral responsivity, noise equivalent power (NEP) and spatial uniformity, and others must be known in order to select a preference. Transfer standards that meet our objective criteria of being capable of measurements having low uncertainty and long term stability, as well as more subjective criteria such as ease of use and durability, are used to provide measurement quality assurance through international intercomparisons.

We use photodiode based detectors for comparisons of optical fiber power measurement. These detectors are based on two photodiodes and a spherical mirror in a multiple reflection trap configuration and are optimized for relatively low power (~10 μW) and limited wavelength range (400 nm to 1800 nm). The development of these detectors is mature and the details of this are documented elsewhere.[4]

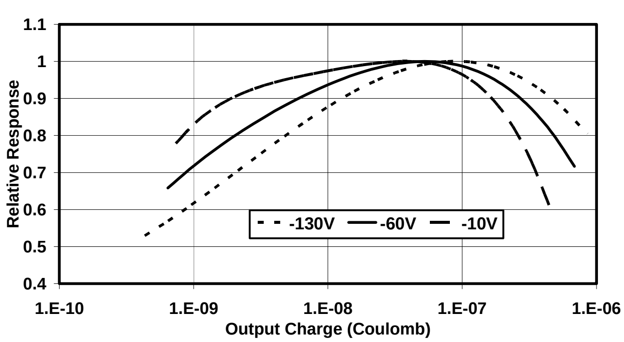

Figure 2. *UV photodiode response at three different bias voltages. at 193 nm.*

Photodiode based detectors meet many of our criteria for UV transfer standards. However, we have found that biased photodiodes used for detection of pulsed UV lasers exhibit highly nonlinear behavior as a function of input energy and bias voltage, as shown in Fig. 2. For example, the measurement results in Fig. 2 show that a UV photodiode may be nonlinear as a function of both pulse energy and bias voltage. Therefore UV photodiodes must be carefully matched to specific pulse energy, bias and pulse duration.

In principle, a transfer standard for UV and high power laser measurements (for average power) could be the same physical device if such a standard were based on a thermal detector that is resistant to damage and aging. When designing any thermal detector (bolometer, thermopile, etc.), we normally want to achieve both the highest sensitivity and the lowest NEP uniformly over a wide wavelength range. The spectral and thermal properties of the coating and detector combination must be optimized within the constraints of the composite thermal conductivity, specific heat, and mass. In principle, the spectral responsivity and spatial uniformity of a thermal detector depend on the absorption of the detector coating as a function of wavelength. For thermal detectors that are applicable to a broad range of measurements (UV through IR) we seek thermal detector coatings that have high absorption efficiency, high thermal diffusivity, and high damage resistance.[5]

During the last 50 to 100 years, thermal coatings have been developed from carbon-based paints, diffuse metals (for example, gold black), and oxidized metals.[6] Gold black coatings are capable of very low reflectance over the wavelength range from 0.2 μm to beyond 50 μm. However, such coatings may contribute substantially to the thermal mass of the detector and are vulnerable to damage from heating, aging, hardening, and physical contact.[7] We are presently evaluating optical damage and thermal properties of thermal coatings for pyroelectric detectors, thermopiles and the FWOPM.

Carbon nanotubes (CNTs) are known to be lightweight inert materials with very high thermal conductivities.[8] Experimental evidence regarding other thermal properties such as specific heat and resistance to damage indicates that carbon-nanotube coatings may be superior to present alternatives.[9] We have undertaken the evaluation of carbon nanotube (CNT) coated detector platforms in addition to making CNT-metal composites for thermal detectors.

The chief limitation of a painted copper cavity described in the context of the FWOPM is damage susceptibility and low thermal transfer to the cooling water. To meet this challenge, a CNT-metal composite is being developed that represents an alternative to the copper cavity of the present embodiment. The new cavity is expected to behave as inherently black and have both a high damage threshold and high thermal diffusivity inherent to the CNTs.

There are several strategies for building optical attenuators, including the use of absorbing glass (transmissive) or partial reflectors (reflective). Passive or active neutral density filters are also used (an example of an “active” attenuator is a tunable liquid crystal). The challenge of building attenuators for laser measurements of high power and energy (kilowatts and more) is to minimize damage and instability from heating. From a practical basis, the value of attenuation (within 10 %) is not as important as its stability. We consider that if the index of the attenuation material changes with temperature, then the attenuation is potentially variable. We also consider the attenuator to be unstable if the size and shape of the attenuator change due to thermal expansion.

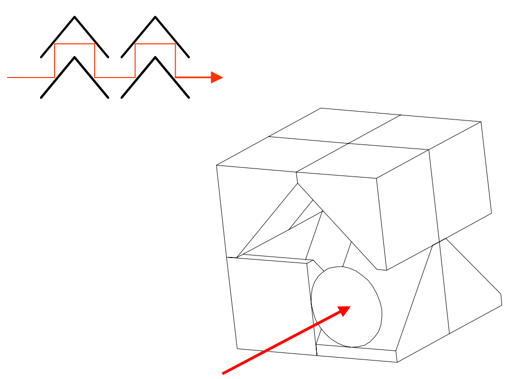

Figure 3. *Representation of a reflective attenuator with 8 mirror surfaces. Inset shows schematically the light (indicated by arrow) is reflected at 45° angle of incidence. The input beam is coaxial with the output.*

We are investigating the use of reflective attenuators with multiple reflective surfaces, each with relatively low absorption. The design goal is to distribute the total attenuation and absorption among optical elements (partial reflectors). Concurrently, the goal of our reflective attenuators is to not change the beam path. Ideally, we can achieve the convenience of a transmission attenuator and the thermal stability of a reflective attenuator. Fig. 3 is a schematic of such an attenuator. The advantages of multiple reflection attenuators are no (or small) back reflection, high energy or power capability, long-term stability, polarization insensitivity, and ease of alignment. The disadvantages are more complex construction, larger size, and higher cost.

5. CONCLUSION

We are anticipating the need for new laser measurement capability as laser technology advances with particular attention to of UV and near IR laser diodes. We require new primary standards, transfer standards, and stable means of attenuation. Thus our applied research is directed toward adapting existing technology such as “off the shelf” photodiodes, mirrors and optics having high damage resistance. In addition we are undertaking basic research in materials properties (particularly CNTs and CNT composites) and developing a novel power meter that is capable of measuring high power and wide divergence with low uncertainty. We will continue with direct and indirect support to meet the needs of industry and defense worldwide.

Table I. *Standards traceability of the NIST laser power and energy calibration ensemble. All of these primary standards employ a coating such as black paint or diffuse metal. The coating converts light to heat. Extending the capability of the coating will extend the capability of the primary standard.*

Laser power and energy range	**Primary standard or transfer standard**	**Industrial application of secondary standards – calibrated from primary standard**
1.06 μm to 10.6 μm 100 W to 200 kW 10 kJ to 6 MJ	BB-Series Calorimeter	Military applications, high-power industrial lasers
0.4 μm to 2 μm 100μW to 1 mW	Cryogenic radiometer	Optical communications Range finders, target designators, industrial processes, medical lasers
0.4 μm to 2 μm 50μW to 1 W 10 mJ to 30 J	C-Series Calorimeter	Optical communications Range finders, target designators, industrial processes, medical lasers
0.4 μm to 2 μm 1 W to 1 kW 300 mJ to 3 kJ	K-Series Calorimeter	industrial processes, medical lasers
1.06 μm 0.5 J to 15 J	Q-Series Calorimeter	Range finders, target designators, industrial processes, medical lasers
248 nm 0.5 J to 15 J	QUV- Series Calorimeter	Semiconductor lithography, medical lasers
193 nm 0.5 J to 15 J	QDUV-Series Calorimeter	Semiconductor lithography, medical lasers
157 nm 0.1 J to 15 J	QVUV-Series Calorimeter	Semiconductor lithography, medical lasers
0.4 μm to 2 μm 50μW to 1 mW	Electrically calibrated pyroelectric detector	Optical communications industrial processes, medical lasers, night vision systems
0.2 μm to 10 μm 50μW to 1 W 10 mJ to 30 J	Other pyroelectric detectors and thermopiles	Optical communications industrial processes, medical lasers, night vision systems.

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