BETTER DESIGN AND NEW TECHNOLOGIES IMPROVE LASER POWER MEASUREMENT INSTRUMENTATION

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New challenges from High Brightness Lasers

High Power Lasers have become an indispensable tool for manufacturing in a variety of applications that span from laser cutting or welding to military devices. The real work horses for the majority of high power applications have been, for decades, CO2 lasers but, since the '90, Disk Lasers and Fiber Lasers have exponentially increased their presence in the market.

Compared to traditional lasers the latters can deliver multi-KW radiation associated to an excellent quality of beams that can be focused to very small spot sizes.

It is the better beam quality of these lasers that, far beyond their capacity to generate higher optical powers, contributed to their rapid development and deployment.

In general terms, the quality of laser beams is defined by its quality factors Beam Parameter Product (BPP) and, more commonly, the M^2.

BPP, the product of a laser beam divergence angle and the radius of the beam at its waist, quantifies how well the beam can be focused to a small spot.

The ratio of the BPP of an actual beam to that of an ideal Gaussian beam at the same wavelength is denoted as M^2. This parameter is a wavelength-independent measure of beam quality.

In a simplified view, a higher beam quality (with M^2 values tending to 1 or to an ideal Gaussian beam) means that a higher density of laser power (W/cm^2) on the spot size is available for the process. This, in turn, affects operational costs, process speed and process quality. And opens to new technological challenges.

To provide a combined description of the output power and beam quality of a laser there is another term, "brightness" defined as the output power per unit area and per unit solid angle ($W/(m^2 * sr)$). High brightness can thus be seen as a high power density over a small solid angle. Fiber Lasers and Disk Lasers are commonly known as high brightness lasers.

Operation with these lasers requires then to solve challenges intrinsic to their high powers and higher power densities, both on the side of the laser source and on the process. These challenges involve:

• Optical components which need to be designed for higher damage thresholds and lower thermal lens deformation.

• Laser Safety: a shorter wavelength (typically around 1070 nm) that is more dangerous for the human eye.

• Laser systems dynamics and controls (accelerations, control of trajectories, etc.) to face the higher process speeds.

• Measurement of laser parameters; laser power, in particular, is a key parameter because it is continuously scaling up (lasers in the 10KW range are quite common nowadays) and, in all applications, its accurate measurement is also necessary for consistent process control.

Instruments for high power and high brightness laser measurements

The next generation of thermal detectors for high-power industrial and military lasers requires operation at incident power densities exceeding several KW/cm^2, which poses significant challenges in heat removal and in the capacity of materials to resist.

Calorimeters and thermopile-based power meters are arguably the most suitable instruments for high power laser measurements. Such devices measure the temperature rise due to heat generation consequent to laser radiation absorption. The rise is measured by differential thermometers in a cooling liquid or by measuring the voltage generated by thermopiles embedded in a mass of specific thermal properties.

In all cases , the instruments output signals are correlated to the absorbed laser power.

A little more in detail, instruments for measurement of optical radiation suitable for high laser powers include:

a) Continuous Flow Calorimeters: in this kind of instruments, laser radiation is absorbed and released as a continuous and stationary heat flux toward a heat sink. The heat flux is in relation to the absorbed laser radiation and is obtained by measuring the temperature difference (ΔT) of a cooling liquid (typically water) when it enters into and when it exits from the calorimeter.
Laser power is measured according to the following formula:
$P = Cp * \phi * \Delta T / k_c$
P= Laser Power (J/s);
Cp= Specific Heat Capacity of fluid (J/kg °C) ;
ϕ= Mass flow of fluid (kg/s)
ΔT= Temperature difference (°C)
$k_c < 1$ = Calibration coefficient (closely related to the absorber yield)
Continuous Flow Calorimeters are very precise instruments and are the very common tool for very high power measurements (above 10KW).

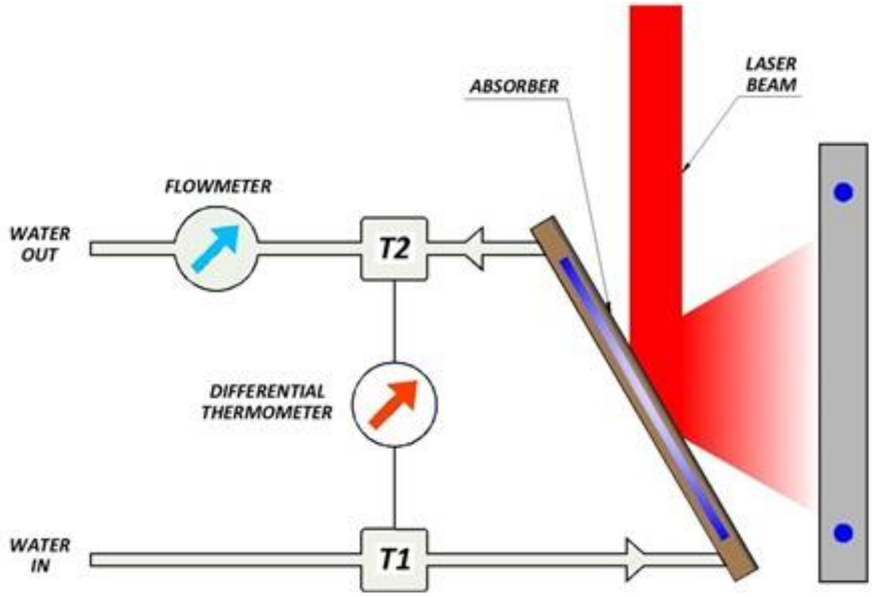


Fig1- Schematics of Continuous Flow Calorimeters

b) Thermopile based power meters: in these instruments, laser radiation is absorbed in a layer of material where it is converted into heat and furtherly turned into a voltage generated by an array of thermocouples because of Seebeck effect . The electromotive force is proportional to the temperature difference between the hot area where the laser is absorbed and a cooled heat sink.
This thermal gradient, induced by laser absorption, is thus related to the laser power.
A thermopile is simply the result of the electrical connection between all couples of hot and cold junctions and provides the total voltage.
Depending on how the heat flows, thermopiles can be divided into two categories: Axial and Radial. In Radial Thermopiles, the most diffuse for high power measurements, the laser hits and is absorbed in the central area of a sensor disk.

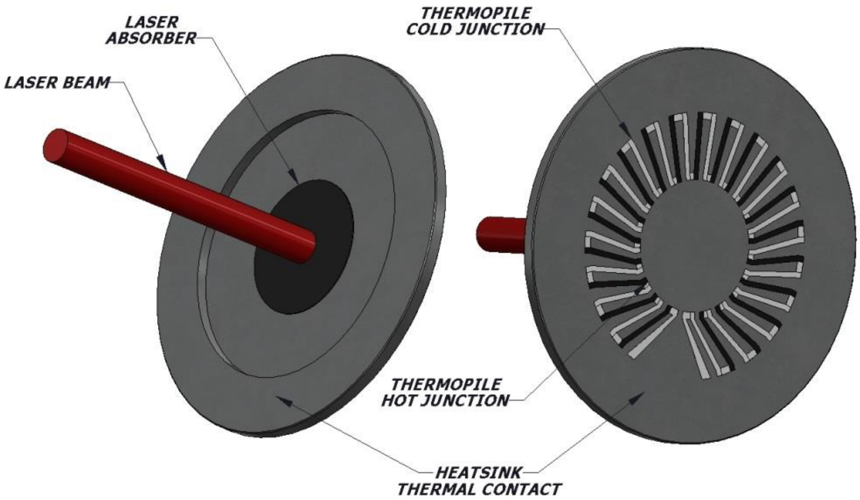


Fig2- Radial Thermopiles: they are the most commonly used for high power measurement

New challenges: very hard laser absorbers and enhanced thermal design.

Measurement reliability and instrument durability depend on the overall thermal design

The challenges posed by high brightness lasers require that the entire thermal design of measurement instruments must be dramatically improved to grant stability, measurement reliability and durability of the unit itself.

All materials used for the instruments and the transition layers between different materials are key elements to be strictly analyzed in the thermal design.

We can consider a thermopile-based laser measurement device to be substantially composed by three sub-systems: absorbing coating/ sensor disk substrate/ heat sink; in the same way, for calorimeters the sub-systems can be restricted to two: absorbing coating/ fluid or , better, the fluid's heat transfer properties .

In both types of instruments Thermal Diffusivity, which expresses the ability of a material to transfer thermal energy relative to its ability to store it, is one of the important parameters that must be optimized through a careful design of the entire system.

On those interfaces which also include the radiation absorbers, the task of a maximized thermal diffusivity can be reached by a thermal design that considers a very low thickness of coatings, such to guarantee a very low thermal capacity, associated to a high absorption coefficient .

In all thermal detectors (either they are water cooled or air cooled devices) a major technological issue arises then on the interface between substrate /heat sink: the objective of maximizing the Heat Transfer Coefficient is obtained by special geometries of water channels or dissipating fins.

The detector's thermal design must also foresee a perfect adaptation to thermo-mechanical stresses and deformations induced on all materials used as absorbing coatings, substrates and heat sinks.

For example, a reduced capacity to drain heat by the sink can have the effect of lowering the threshold of damage on the absorber, with all its consequences; in fact, a reduced heat removal capacity by a non-properly designed or optimized heat sink implies an increase of the stationary operational temperature of the heat sink itself and, as a result, also on the absorber which is in thermal equilibrium with it.

Tight needs for laser absorbers

In calorimeters and thermopile detectors, a highly resistant absorber is necessary component, being a prominent ingredient that contributes to ensure their correct operation, performance and reliability .

On thermopile detectors the absorbing coating is directly deposited on the same substrate where the thermocouples also lay, while in calorimeters the absorber coats the water cooled elements used as heat exchangers.

When designing a new device for laser power measurements, there are tight parameters for the materials that must be investigated and to which the material, then selected as laser absorber, must comply.
First, a number of chemical, physical and structural parameters that influence its damage threshold capability must be evaluated and tested. Those parameters vary from absorber to absorber and from manufacturer to manufacturer who, all , have their undisclosed " secret recipe". In all cases, however, the common aim is to provide strongly resistant absorbers and a high threshold of damage.
Damage threshold is defined as the power density (W/cm^2) beyond which it is encountered a variation >1% in the measurement of laser power, mostly as a consequence of an irreversible change in the chemical and physical properties of the materials after laser absorption.
Among those parameters, both the melting points and thermal conductivities (W/m *°K) of materials must be carefully considered and must be the highest possible.
Materials must also maintain a constant behavior on variations of temperature and, above all, resist without degrading or detaching from substrate upfront to extreme thermal stresses: those can be very high as it happens in the case of narrow Gaussian beams or in the case of localized delivery of laser radiation (hot spots). Thermal dimensioning and material selection can be said to be really optimized when the area interested by the laser is kept below 250°C, even with several KW of laser power applied.
The pulse duration, in the case of pulsed lasers, also has a sound influence on the damage threshold.
Pulse duration can affect the absorber and drive to substantially two modalities of coating damage. The damage process is ablative for very short pulses (below 100 nsec): in this temporal regime the diffusion time of generated heat within the material is much longer than the pulse length itself and this condition entails a strong localization of laser energy and the direct ablation of the absorber's atoms.
On the other extreme, with a pulse duration sufficiently long to allow a diffusion of heat within the absorber (pulses > 10msec), damages are created by thermal effect.

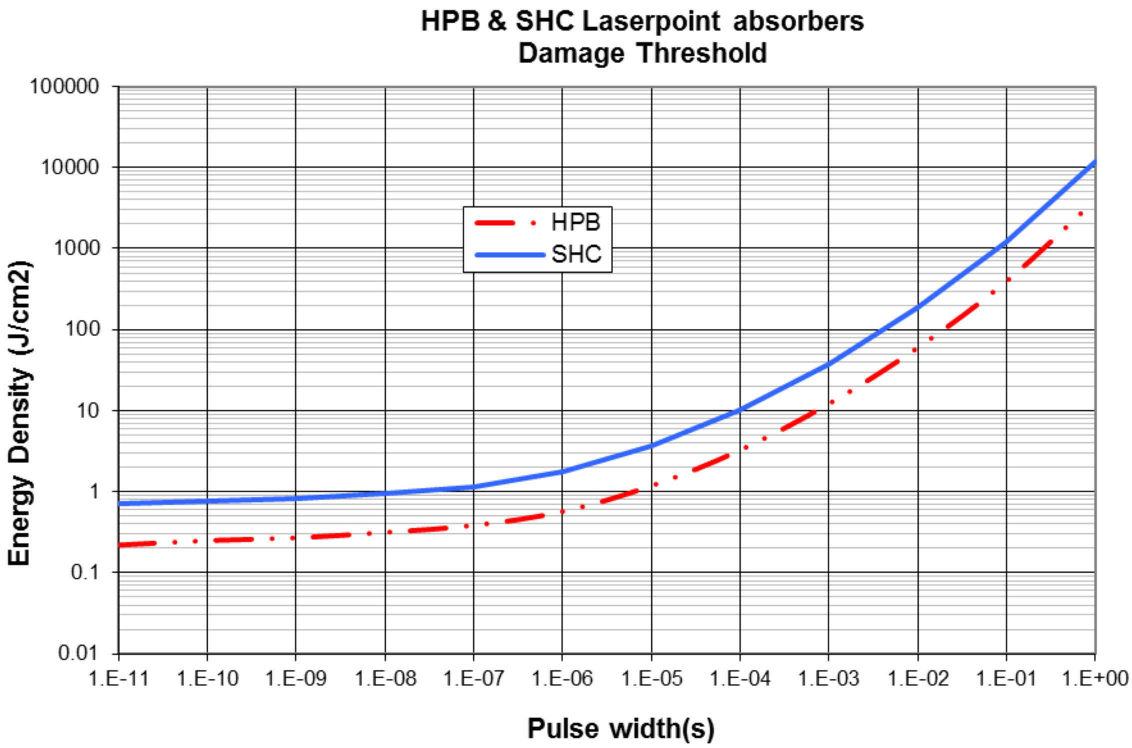


FIG. 3- Behavior of damage threshold as a function of pulse length on 2 High Power Laser Absorbers

The other important parameter to be considered for materials is their absorption coefficient in the laser wavelength ranges, which needs to have the following general characteristics:

- be as high as possible (typically >70%), to guarantee an efficient absorption of radiation even in the case of very thin thickness of deposited materials and to provide the lowest reflection at any wavelength;
- have a spectral response that covers the broadest range of laser wavelengths;
- provide the lowest possible reflection at any incidence angle;
- The above general behaviors must last over time and possibly, (misuse is not considered) for the entire lifetime of the instrument; measurements, in fact, must not be affected by ageing or any change of properties (like oxidations) which might modify the chemical and optical properties of the absorbing surface.

Given the above constraints, manufacturers of laser measurement instrumentation are compelled to make very selective technological choices because many of those materials, which could be potential candidates to be absorbers for the tough environments of high powers and high brightness lasers, have one or more characteristics that do not comply with those of a suitable coating.

A successful technological achievement, reached by combining new technologies, materials and by overcoming the constraints described in the present article is Laserpoint's Super Hard Coating (SHC).

Its property to allow an efficient and fast heat transfer gives it the capacity to resist to extremely high power densities and has been the real engine that generated two latest instruments designed for high power lasers.

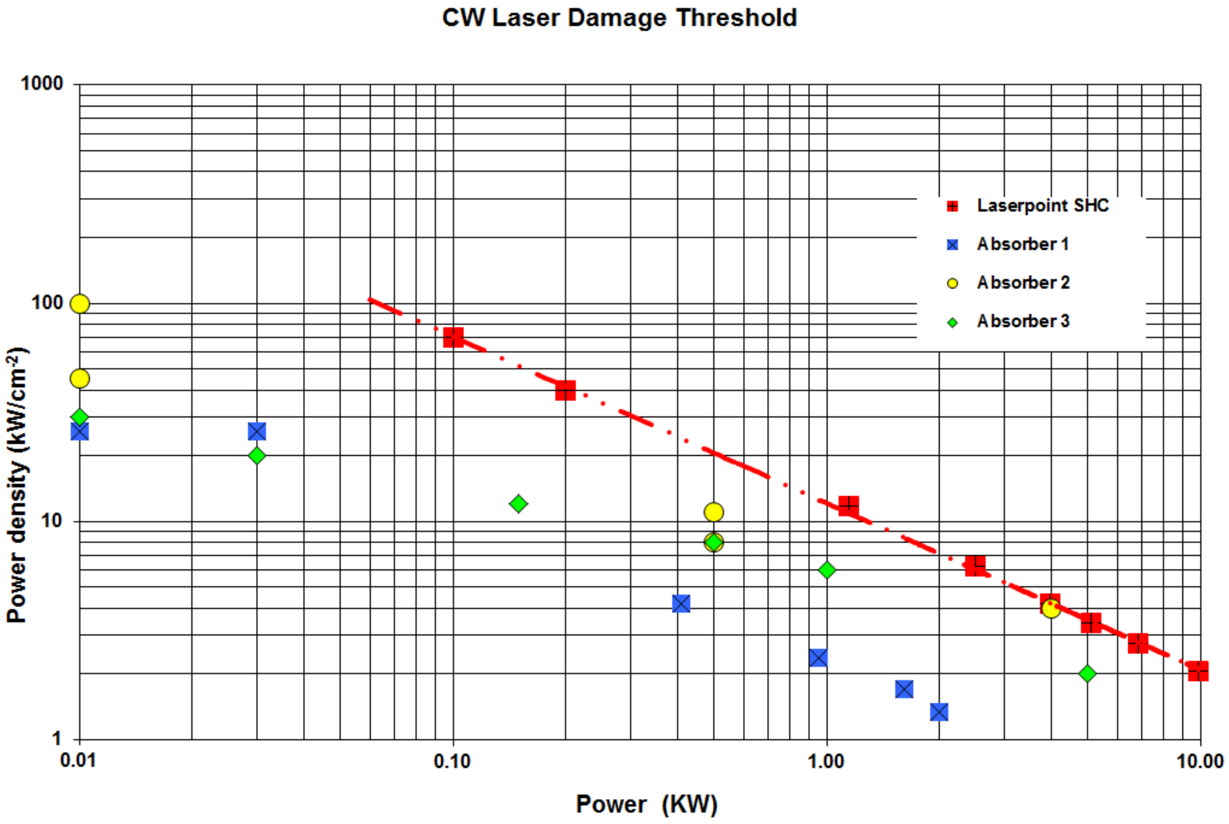


Fig.4-Damage threshold comparison between Laserpoint's SHC absorber against various types of commercial high power laser absorbers

Optimized design & new technologies: Laserpoint's Calorimeter for 12kW and Air Cooled Detector for 1200W

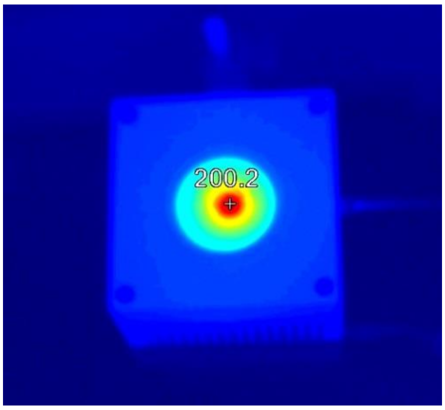
As a conclusion we would like to introduce two new instruments that can safely face the extremely high power densities of our days' lasers and which synthetize and fulfill the technological requirements described in the present article. In both instruments, the presence of SHC as radiation absorber lead to achieve a higher absolute power measurement capability with very compact footprints (in particular for the calorimeter) associated to a higher damage of threshold.

Laserpoint, after having been for several years the technological leader with an air cooled detector for 600 W (850W for short term measurements) designed for the fiber laser market, is now displaying a detector with forced air cooling for 1200 W (Mod. A-1200-D60-SHC) . It is a leap ahead in thermal management, coating improvement, optimization of design.

This detector has a Linearity of ±1.5% to its full scale and is supplied with ±3% calibration accuracy traceable to PTB/NIST standards.

The aperture is 60mm, Dimensions 140Lx140Px140H mm, Weight 4.4 Kg.

Fig. 5- Mod. A-1200-D60-SHC



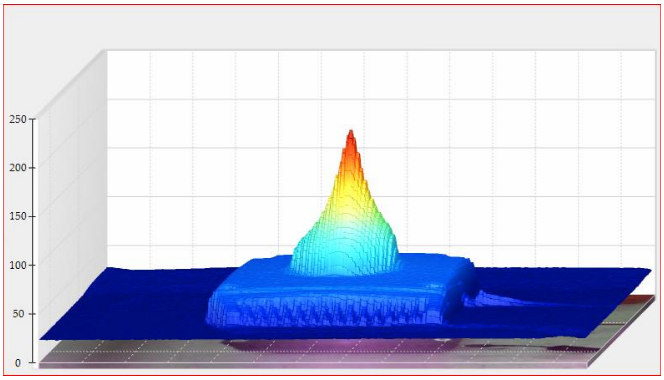


Fig.6 - Mod. A-1200-D60-SHC: Thermal images of the absorbing surface at 1200W- Max. Temperature in the coating is 200°C (IPG fiber laser YLS 2000)

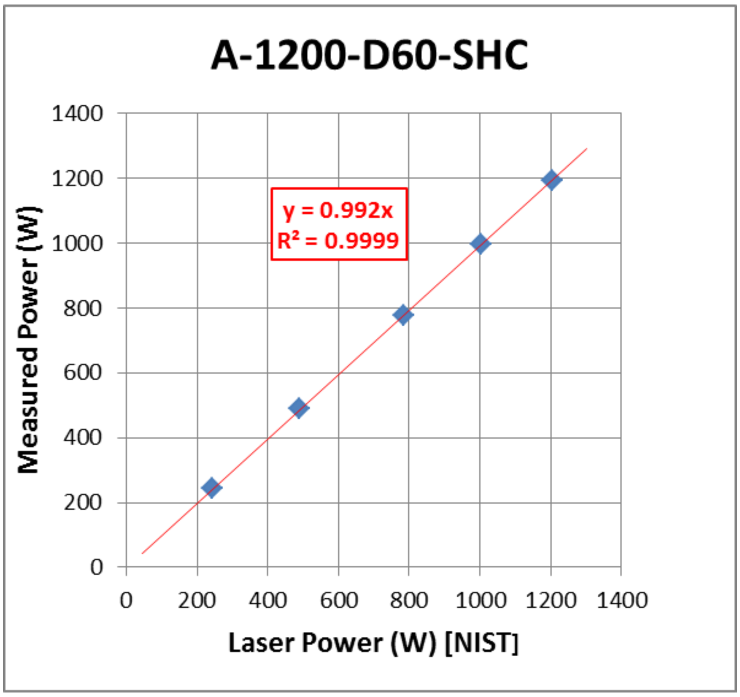


Fig. 7- Mod. A-1200-D60-SHC: Linearity

Together with the air cooled detector for 1200W , Laser Point is also introducing a calorimeter up to 12kW, result of Company's capacity to explore new materials, manage thermal design, create innovative products. The new calorimeter (Mod. W-12K-D55-SHC-USB) is extremely compact and light weight compared to alternative instruments of the same class and does not require any defocussing optics in the absorbing cavity.

This detector has a Linearity ±1.5 % to its full scale and is supplied with ±5% calibration accuracy traceable to PTB/NIST standards.

The aperture is 55mm, Dimensions L140xP200xH180 mm, Weight is 6 Kg.

Fig. 8- Mod. W-12K-D55-SHC-USB

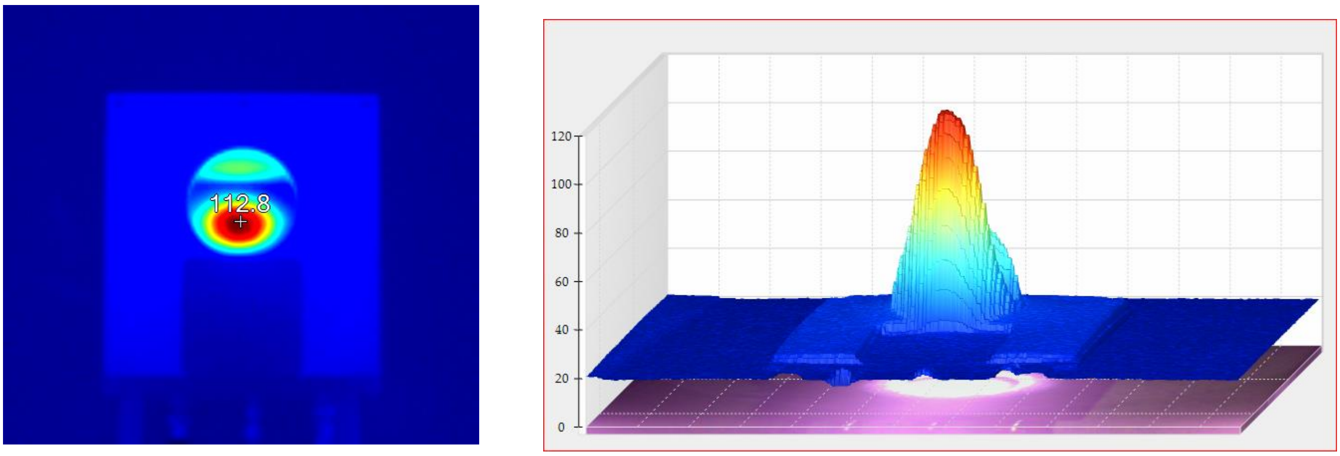


Fig.9- Mod. W-12K-D55-SHC-USB: Thermal images of the absorbing surface at 10 KW- Max. Temperature on the coating is 113 °C (IPG fiber laser YLS 10000)

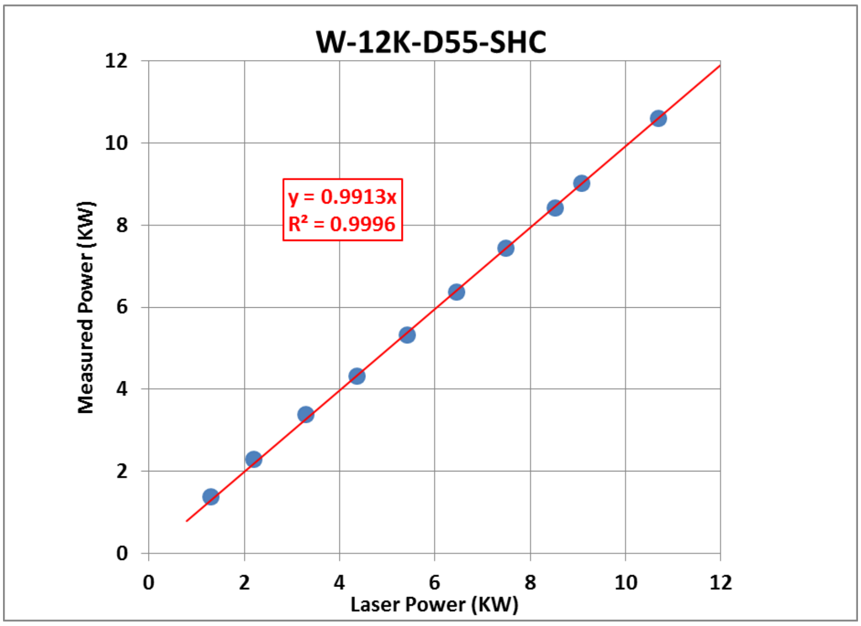


Fig. 10- W-12K-D55-SHC-USB: Linearity