New optical power sensors using pyrolytic graphite

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Abstract. A new method for measurements of laser power, using pyrolytic carbon (PyC) levitation as torsional magnetic spring, to detect the moment of force provided by radiation pressure of laser beam is currently developed at the LCM LNE-Cnam. This new power-meter could measure laser power in the range from 300 mW to 100 W with an objective to reach a relative uncertainty of about 1%. Relative to a first experimental setup, the new configuration presented in this paper has been improved taking the main disturbing sources into account. The traceability to SI units of the measurement provided by this new power-meter is presented and discussed.

1 Introduction

The French reference for radiometry at the Laboratoire Commun de Métrologie LNE-Cnam (LCM LNE-Cnam) is a cryogenic radiometer which allows accurate comparison of absorbed optical power with dissipated electrical power associated with a relative accuracy of 0.005% [1]. The calibration of customer's power-meters, such as non-thermal sensors based on photo-electron interaction (photodiodes) or thermal sensors based on thermal energy absorption (thermopiles), is provided with a relative uncertainty of 2% (see Figure 1).

As an interesting alternative to photodiodes or thermopiles in the medium power range, we have built a calibration system, called LPM in this paper, either to calibrate power-meters by comparison using stabilized laser sources or to measure and control the optical power of a laser beam at various wavelengths from visible to infrared radiation. The development of this new power-meter aims to provide power measurements with an expanded uncertainty of typically 1 % (with a coverage factor of k = 1) without needing a calibration from a cryogenic radiometer.

A first magnetic torsion-based configuration of a Laser Power Meter (LPM) was described previously [2]. Its relative expanded uncertainty for optical power measurement lied from about 20% to 5% in the range 0.3 to 1 W.

The main sources of error observed on the first experimental setup came from either environmental conditions (temperature, vibrations, movements of air) or quality of elements

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(permanent magnets, PyC, detector…) and adjustment (horizontality, lever arm lengths, rotation centre position…).

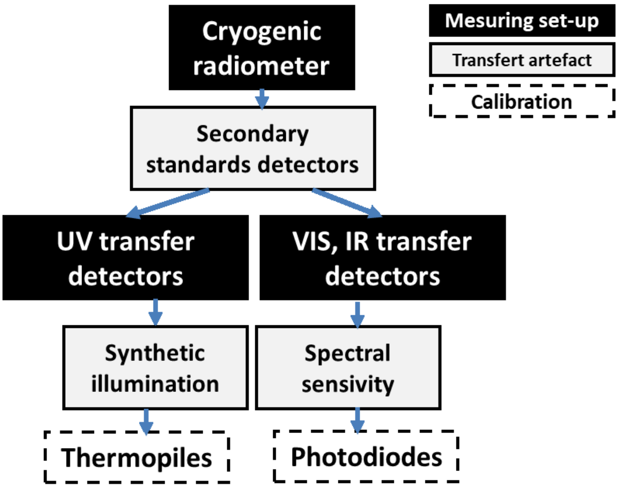

Fig. 1. Simplified traceability diagram to the cryogenic radiometer at LCM (original diagram provided by G. Obein).

All these sources of error impact the metrological characteristics of the device (resolution, sensitivity, repeatability, reproducibility, drift, bias, step response time). These metrological points relative to the first setup are summarized in section 2. In section 3, this paper describes the new experimental setup of which is based on the same principle as that of the first configuration, but which has been designed to reduce or eliminate as far as possible the main sources of error observed previously. This device provides a traceability to SI units in terms of mass, length and time. This traceability is presented and discussed in section 4.

2 Experimental setup: sources of error and uncertainties

A previous article [2] describes the first experimental setup. The power measurement is determined from the approximate expression (1). It allows to calculate the laser power P as a function of the maximum angular deflection $\theta_{\max}$ based on a force balance approach.

$$P \approx \frac{c\theta_{\max} I(4\pi^2+\delta^2)}{4T^2 l_m r \cos\varphi} \tag{1}$$

where T is the pseudo-period of the levitation oscillating system, δ the logarithmic decrement, I the moment of inertia of the levitated system, c the speed of the light in vacuum, l_m the distance between the rotation centre and the irradiation point of the laser beam on the mirror, r the coefficient of reflectivity and absorption of the mirror with respect to the wavelength of laser beam and φ the incidence angle of the laser beam on the mirror.

The displacement of the spot of the detection laser beam on the surface of a position sensitive detector (PSD) located at a distance l_d from the rotation centre of the levitated system corresponding to $\theta_{\max}$ is equal to $l_d\theta_{\max}$.

The voltage variation V delivered by the PSD is proportional to the deflection angle as follows:

$$V = S l_d \theta_{\max} \tag{2}$$

where S is the PSD sensitivity.

To estimate the parameter uncertainty contributions for the first experimental setup, we used a free software developed by the Laboratoire national de métrologie et d'essais (LNE) [3]. It is dedicated to the evaluation of measurement uncertainty using either the method described in the Guide to the expression of Uncertainty in Measurement (GUM) or in its Supplement 1 (GUM-S1) [4]. Figure 2 presents information given by this software about the variance contributions from experimental measurements for a laser power of about 1 W at the wavelength 1064 nm. The relative expanded uncertainty for optical power measurement is about 5 % for 1 W.

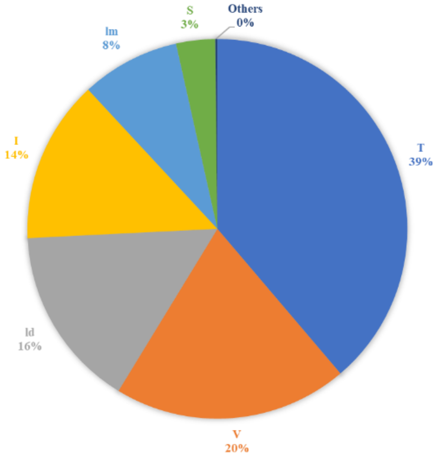

Fig. 2. Uncertainty budget according to the GUM method obtained from the LNE software.

Figure 1 shows clearly the parameters for which the variance contribution is preponderant and on which it is necessary to reduce it. Four parameters are concerned: the pseudo-period *T*, the voltage *V*, the lever arm length l_d and the moment of inertia *I*.

3 Description of the improved setup

A new improved setup has been developed with the goal to reach a relative uncertainty of 1 % in a power range from 0.3 up to 100 W. It is based on the same principle as the first one similar to a torsion balance where the restoring force is generated not by a torsion wire but by an angular magnetic spring acting on a pyrolytic carbon disk levitated on a permanent magnet array. Thus, a torsional spring-mass-damper system is obtained:

- where its angular spring constant k_θ depends on the pseudo-period *T*, the logarithmic decrement δ and the moment of inertia *I*, respectively, of the levitation oscillating system;

- where the radiation pressure of the laser beam depends on the coefficient of reflectivity and absorption r of the mirror and the incidence angle φ on the mirror assuming that the transmission and aberration errors of the lens are negligible.
- where its sensitivity depends on the sensitivity S of the PSD and the lever arm lengths l_m relative to the distance between the rotation centre and the irradiation point of the laser beam on the mirror and l_d corresponding to the distance between the rotation centre and the PSD.

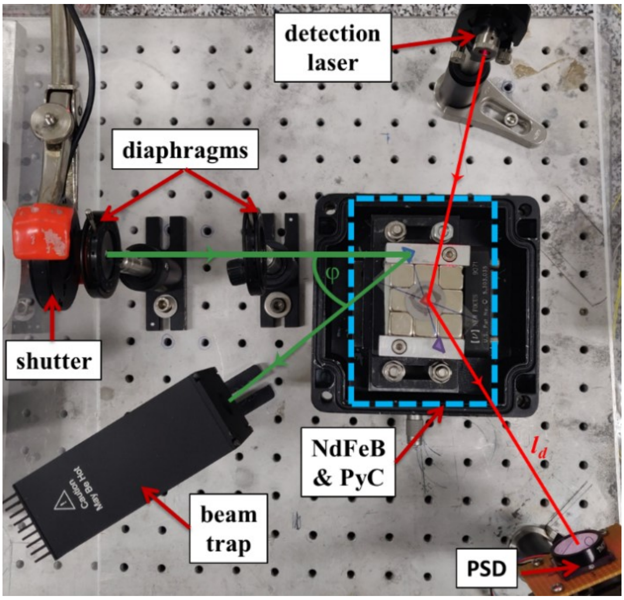

Fig. 3. Picture of the experimental set-up.

In the new setup presented in Figure 3, the measurement system is mounted on a honeycomb breadboard (600 mm × 600 mm) of which the horizontality is adjusted by means of micrometric screws with respect to a high-accuracy bubble level and a red laser source is fixed at about 30 cm above the LPM. It is also used to check the horizontality of the levitated system via the autocollimation principle. Firstly, the levitated system is replaced by a small vessel of water and the verticality of the laser beam is adjusted by autocollimation using the beam reflection on the water surface. In addition, a static camera fixed above the LPM for acquiring images of the levitated system allowing to check its position with respect to the magnet array in horizontality conditions.

The beam's incidence angle φ with respect to the plane of the mirror receiving the radiation pressure is as close to normal as possible relative to the plane of the device's entrance aperture and large enough to prevent the reflection from re-entering the optical system and to reflect the beam in a beam trap. The angle is fixed by a limiting aperture of the device. This aperture is defined by the two iris diaphragms and the beam is focussed by a lens to collimate it on the mirror. The angular deflection detection consists of a laser at 635 nm illuminating a mirror located at the centre of rotation of the LPM levitated system. This mirror reflects the beam laser on the PSD.

More precisely in Figure 4, the sensitive part of the LPM consists of a PyC disc (20 mm diameter and 1 mm thickness) supporting a rectangular cover glass (50 mm length; 24 mm width; about 100 µm thickness) on which there is a mirror at its centre used to reflect the detection laser beam. The second mirror at one of its ends is illuminated by the laser beam under test. This system is held in levitation above a nine permanent magnet array (12 mm cube edge NdFeB magnets). The temperature of the magnet array is measured with an NTC thermistor and servo-controlled by means of a Peltier module. The LPM is housing in an aluminium box with three thin glass windows (about 100 µm thickness) to protect it against movements of air. The window through which the laser radiation passes is protected by the lens.

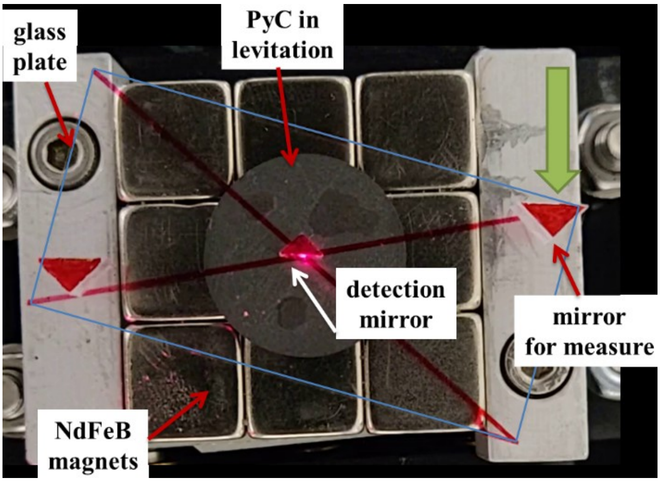

Fig. 4. Picture of the sensitive part of the LPM with NdFeB magnets, detection mirror and mirror for measure the optical power of the laser.

A computer-controlled data-acquisition and analysis system, using LabVIEW® allows to control the magnet array temperature, the input data of frequency, the duration and number of the series of opening and closing of the shutter. A Matlab® program allows filtering, smoothing, average and analysis of the output signals then the calculation of the characteristic parameters of the system and of the laser power.

This new LPM benefits from three main improvements in order to reduce the uncertainties and increase the sensitivity:

- a box with glass windows to protect it against movements of air.
- rubber absorbers against vibrations. This implies to implement a method to check that the LPM is perfectly horizontal.
- a one-dimensional PSD Sitek 1L10 (2 mm × 10 mm) with an amplifier SEEPOS to measure accurately the position of the laser spot that falls upon its active area. The signal processing system can measure positions at a resolution of 16 bits and speeds of up to 1 MHz. This PSD provides two voltage signal outputs Y_1 and Y_2 and therefore, expression (2) is no longer applicable. In this case, a ratio η is calculated from these two voltages (see expression (3)) and the sensitivity S is expressed as a factor $\frac{d\eta}{dl}$ which is the inverse of a length in terms of quantity dimension.

$$\eta = \frac{Y_1 - Y_2}{Y_1 + Y_2} \qquad (3)$$

Expression (2) remains valid replacing the voltage V by the ratio η. Finally, expression (3) becomes:

$$P \approx \frac{cI(4\pi^2+\delta^2)\eta}{4T^2 l_m l_d S r \cos\varphi} \tag{4}$$

4 Traceability and discussion

According to the International Vocabulary of Metrology [5], the metrological traceability is the "*property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty*". This definition is be supplemented by the following note: "*For measurements with more than one input quantity in the measurement model, each of the input quantity values should itself be metrologically traceable and the calibration hierarchy involved may form a branched structure or a network. The effort involved in establishing metrological traceability for each input quantity value should be commensurate with its relative contribution to the measurement result*". In the present case, it must be kept in mind that the development of the new LPM aims to provide power measurements with an expanded uncertainty of typically 1 % traceable to SI units in terms of mass, length and time.

In the new LPM, there are nine input quantities characterizing the system in defined measurement conditions (I, δ, T, l_m, l_d, S, r and φ). All the quantities can be directly measured except the inertia moment I. The measurement conditions must be controlled particularly in terms of temperature and vibration to reduce measurement drift and noise.

In addition, the laser beam conditioning is crucial to measure the power of the laser under test. Up-to-now for this study, a power-stabilized laser source (frequency doubled Nd:YAG laser), with two wavelengths at 532 nm (used for laser beam alignment by means of the two iris diaphragms) and 1064 nm (used to study the LPM response). This laser source is fixed on a translation platform and a vertical axis stage to facilitate the beam alignment and the substitution of the two wavelengths by translation while keeping the parallelism of the two beam propagation axes. A diaphragm beam shutter with controller is fixed in the front of the laser head and allows to generate a power step. The alignment must be optimized to allow that more than 99 % of the gaussian beam power passes through the two diaphragms. For this end, the alignment is adjusted to reach a maximum value detected by a commercial power-meter placed at the output of the second diaphragm.

The coefficient r of the broadband dielectric mirror receiving the laser beam under test is determined from the reflectance versus wavelength data provided by the manufacturer. The mirror is chosen to have a reflectance larger than 0.99 at the wavelength considered. Of course, the coefficient r should be measured by the calibration service of the LCM LNE-Cnam to ensure a real traceability.

The length l_m of about 25 mm between the centre of the laser spot on the mirror and the rotation centre of the levitated system is quite complicated to measure. First, a video recording of the levitated system being in oscillation allows to determine the rotation centre accurately. Secondly, the use of the 532 nm laser beam is a convenient and precise way to point the laser spot centre on the mirror. Thirdly, the distance between the two centres is measured with a digital calliper.

The quantities l_d of about 230 mm and φ which is smaller than 0.5 rad are measured with a steel rule graduated in 0.5 mm using photographic enlargements with a length reference on each photograph of the LPM element considered.

The moment of inertia I of about 3×10^{-7} kg m^2 results from the combination of several moments of inertia, each of them being calculated from measurements of mass and length of each body considered (PyC disk, cover glass, mirrors, counterweight) related to the mean axis of rotation. A mass comparator Mettler-Toledo AX206 verified by using calibrated mass standards is used for mass measurement of each body. The mass values are between 30 and 300 mg according to the body considered. The size of each body is determined by using either digital calliper or micrometre verified by means of calibrated gauge blocks. The lengths to be measured are between 0.1 and 50 mm.

The PSD sensitivity S is determined by using the motionless detection laser beam. The PSD is fixed on a horizontal translation stage with a micrometre drive. Using the translation system, the PSD is moved between ± 5 mm and the quantity η is measured at each step. From the measurements, the sensitivity $\frac{d\eta}{dl}$ is determined and its linearity is verified.

The pseudo-period T of about 4 s and the logarithmic decrement δ of about 0.2 are determined by using a program specifically developed with Matlab® from damped oscillation signal recorded via the analog output of the PSD. The figure 5 shows an example of PSD response to radiation steps in transient mode for a power of 1W from ten measurements.

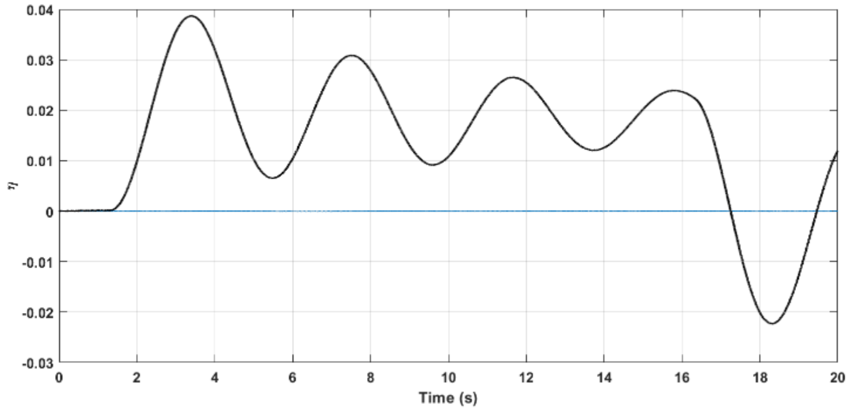

Fig. 5. Measurements of the response of the PSD at a laser power of 1 W. The curve corresponds to the average of ten signal records obtained under repeatable conditions for on-off radiation steps of 15 s. Corrections for offset has been applied.

Once all the quantities characterizing the LPM are traceably determined, associated with a measurement uncertainty and the sources of systematic errors are under control, only the input quantity (η) must be measured in repeatability conditions to determine the optical power of the laser under test.

In addition, to estimate of any systematic measurement error, we use an integrating sphere photodiode power sensor (Thorlabs S142C - 350 - 1100 nm, 5 W) calibrated with a relative expanded uncertainty of 2 % by the LCM LNE-Cnam calibration service.

5 Conclusion

We have presented an improved a new optical power meter based on the measurement of radiation pressure with a diamagnetic spring directly traceable to the new SI. This power-meter is currently able to measure laser power in the range from 300 mW to 1 W with an objective to expand the range up to 100 W with a relative uncertainty of about 1%.

With the reduction of the vibrations, the temperature changes and the increase of the lever arm, we have reduced the signal-to-noise ratio. We can estimate that the determination of the eight input quantities characterizing the system (δ, T, l_m, l_d, S, r and φ) is better than 1%. We have also reduced the repeatability value of η by a factor ten. The uncertainty determination of the inertia moment I remain the most important point affecting the global uncertainty budget**.** One possible way to reduce the uncertainty of I is to is to achieve a measurement of the length of each body using a coordinate-measuring machine with an uncertainty of about 1-5 µm.

References

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