Optical power measurements via photon momentum and its comparison with SI-traceable reference methods

Suren Vasilyan[1,2], Marco López[2], Holger Lecher[2], Marcel Pastuschek[2], Stefan Kück[2], Norbert Rogge[1],
Eberhard Manske[1] and Thomas Fröhlich[1]

[1] *Institute of Process Measurement and Sensor Technology, Ilmenau, Germany,*
[2] *Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany*
Corresponding e-mail address: suren.vasilyan@tu-ilmenau.de

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We present the comparison results of the optical power measurements performed by using a calibrated reference standard detector (Thermopile and Si-diode) against those performed by a differential electromagnetic force compensation balance via the photon-momentum generated force measurements in the optical power range between 1 W and 10 W levels. A multi-reflection principle is used to amplify the generated effective forces with an optical cavity created by two quasi-parallel ultra-high reflective mirrors. At different configurations, the measurements of the forces and the optical powers were simultaneously monitored and the relative standard deviations were obtained. Dependent from the computation principle and the absolute value of the applied laser power level the improvements of the measurement uncertainties are discussed.

INTRODUCTION

In recent years, the use of photon momentum to determine the optical power of lasers or to generate precision/calibration small forces [1, 2, 3] has made important progress, especially for the measurements of optical laser power at kilowatt levels [4]. The measuring principle is based on the measurement of the force which is exerted due to the transfer of the photon momentum upon reflection of the radiant power from high-reflective mirror. A measurement device developed by *Williams et. al.* uses this measurement technique with which a relative expanded measurement uncertainty of 1.6 % has been achieved for optical power levels between 1 kW and 50 kW [4]. In the core of the device is a force sensor, consisting of a commercial off-the-shelf electromagnetic force compensation (EMFC) weighing balance and a mirror with high reflectivity (R=0.9998) attached to it. *Vasilyan et. al.* [1, 2] carried out measurements with a device having similar components, however, here two force sensors adapted for differential measurements were used, by which the noise level have been reduced. Here, for the stability considerations a low power laser system (around 1 W) was used in multi-reflection configuration to generate a calibration forces at the currently existing lowest end of the small force standard from 10 nN up to 10 µN. Despite the statistical error observed as an oversight between the measurements and simplified theoretical calculations, under the multi-reflection configuration the total measured force was amplified at least with an order of magnitude in comparison to single reflection configuration. Furthermore, with the usage of single- and multi-reflection configuration, a possible standard for the force calibration routine, or reversed, standard for the optical (laser) power calibration routine with direct and more simplified traceable chain to the recently renewed SI base units [2, 5, 6] was already established.

EXPERIMENTAL RESULTS

In this paper we present a new, an improved set of measurements of the photon-momentum generated forces at the multi-reflection configuration with the use of differential EMFC setup ([1, 2]) at the laser power levels from 1 W to 10 W and their comparison with the optical power measurements made with the calibrated reference standard detector.

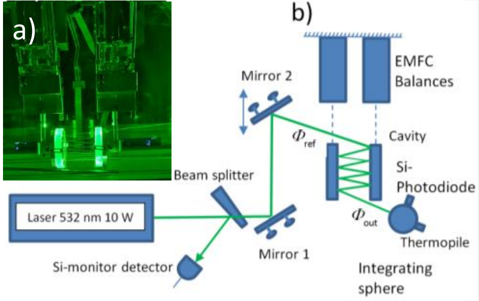

Figure 1. Setup for measuring optical power via photon momentum and vice versa; i.e. calibration of the EMFC using reference optical power.

The measurements were carried out at PTB with an optical system established in accordance to schematics presented in fig. 1(b) and with an integrated portable differential force measurement setup developed at TU Ilmenau. The input optical power Φ_{ref} is measured after mirror 2 with a calibrated reference detector (consisting of a Si-photodiode and a Thermopile attached to an integrating sphere) and simultaneously with the monitor detector. Then the monitor detector is able to determine the laser power at the input of the cavity during the measurements assuming the conversion factor including the reflectivity of the mirrors 1 and 2. The output optical power Φ_{out}, measured with the same calibrated reference detector together with the input optical power, measured with the monitor detector, allows to determine the power loss due to the cavity see fig. 1(b) and fig. 2 (bottom).

With the pre-set laser power of up 10 W and the multi-reflection (at 21, 33, and 41 cases) configuration we have substantially enlarged the limit of the upper margin of the existing experimental data in continuous force (sub-10 µN level) and laser power measurements. Additionally, to reduce the optical losses in the cavity, we replaced the conventional high reflective mirrors R=99.5 % with ultra-high reflective mirrors with R=99.997 % reflectivity (for a wavelength of 532 nm) that were used to create our optical cavity like configuration. Results showed a major improvement on reliability of the comparison of actual photon-momentum generated forces obtained from the real measurement data against the simplified theoretical computations presented in [1, 2, 3]. Thus, the force measurements are performed in combination with the optical schematics as is presented in the fig. 1. The optical power values were used to calculate theoretically the expected photon-momentum generated forces for comparison with the data from the measurements. In this configuration we are able to directly compare the reference for the force measurements and the reference for the optical power measurements, towards the SI based traceable comparison (actually to the Planck constant) of the force/mass and laser power references.

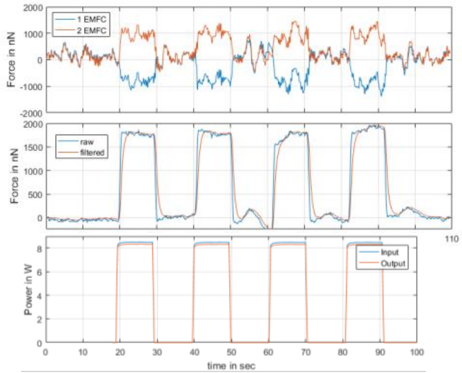

Figure 2. Example of the static force measurements with a periodically applied laser power (10 s) in the case of 33 reflections. (Top) Measured force signal from each balance, (Middle) the difference signal. A feed backward averaging filter was chosen for the last 15 bins to filter raw data. (Bottom) Input and Output power.

In fig. 2 we show one of the typical set of force and the corresponding laser power measurements. At the first glance, from the raw data of the force measurements at 33 reflection configuration (mirror reflectivity: 99.997 %, input power: 8.5 W, output power: 8.3 W), the mean value of 1873 nN is obtained with the relative combined standard deviation of 1.71 % (32 nN), if the calculations are made assuming the sample standard deviation then the value is 0.23 %. However, the relative standard error was 3.7 % due to unforeseen environmental noise (temperature and mechanical vibrations) which was detected during the measurement process. As a comparison, the standard uncertainty of the optical power measurements using the calibrated reference standard detector was 0.3 %. Furthermore, in this particular case, the mean value of the measured forces in comparison to the value calculated theoretically differs by 0.2 %, from all measurements this difference is within 3 %.

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