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Technical Note

Photon force microelectromechanical system cantilever combined with a fibre optic system as a measurement technique for optomechanical studies

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Abstract
In this paper we present a metrological measurement technique that is a combination of fibre optic interferometry and a microelectromechanical system (MEMS) sensor for photon force (PF) measurement with traceability via an electromagnetic method. The main advantage of the presented method is the reference to the current balance, which is the primary mass/force metrological standard. The MEMS cantilever transduces the PF to a deflection that can be compensated with the use of the Lorentz force. This movement is measured with the use of the interferometer and does not require any mechanical calibration. Combining the MEMS current balance system with interferometry is a unique and fully metrological solution. The resolution of the proposed measurement technique is calculated to be 4 pN $Hz^{-0.5}$ (2% uncertainty). The PF–MEMS used for the investigation is a cantilever with a resolution of 46 fN $Hz^{-0.5}$, which was calculated from the thermomechanical noise and is far below the resolution limit of the whole system. Because the whole construction is based on a fibre optic system, it does not require any complex adjustment procedure and may work as an optomechanical reference in any metrological laboratory.

Keywords: photon, force, MEMS, cantilever, current balance, optomechanical

(Some figures may appear in colour only in the online journal)

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1. Introduction

Electromagnetic radiation carries momentum that gives rise to the photon force (PF) F_{PF} [1] according to the equation

$$F_{PF} = \frac{(2R + A)P}{c}, \quad (1)$$

where P is the optical power, c is the speed of light, and R and A are the reflection and the absorption coefficients, respectively. The phenomenon was predicted independently by Maxwell in 1873 and Bartoli in 1876 [2, 3]. The first experimental verification was made by Nichols and Hull in 1901 [4, 5].

During the long history of optomechanical investigations, the application of micromechanical devices has opened up new experimental possibilities. In general, miniaturization of measurement tools improves the measurement resolution, sensitivity and repeatability. Moreover, a higher resonance frequency of microdevices makes them less sensitive to disturbances and enables faster operation at smaller excitation energies In this way, many important experiments have been done using cantilever-based microdevices integrating highly reflective mirrors [6–8].

At the microscale, radiation pressure (RP) supports many important technologies such as optical tweezers (object trapping) [9, 10], optical cooling [11, 12] and high-power laser emission measurement [13–15]. Although the obtained results have been impressive and noticeable, the measurement procedures were using time-consuming and increased the uncertainty calibration process, for example when using a cantilever as a force sensor, determination of the spring constant is needed [16]. Another approach is to calibrate the spring constant parameter with the use of a known, i.e. previously calculated, PF. Neither of these approaches is a fully metrological solution related to recognized standards.

In many experiments, the mechanical response of a micromechanical device is analysed using a bulk optics setup [17]. It is difficult to carry out precise adjustments and the size of the whole device is another weakness of such a solution. From that point of view, optical fibre technology opens up additional possibilities for reliable optomechanical investigations [6, 18].

Optical fibre technology, using flexible, low-mass fibres, offers a handy set-up, which, moreover, is significantly less sensitive to external disturbances. The only mechanical constraint of a fibre-based system occurs while coupling light to or from the fibre. A microelectromechanical system (MEMS) is a micromachine whose deflection or displacement is controlled electrically. As the MEMS and the diameter of a single telecom fibre (typically 125 µm) are of the same order of magnitude, they can be flawlessly integrated. In turn, this allows us to take advantage of, for example, silicon micromachining, which has become a mature technology that is being more often applied in various applications [19, 20]. From that point of view, further progress in optomechanical investigations should be obtained if MEMS can be more broadly applied.

In this paper we present a measurement technique that uses a PF–MEMS cantilever as a force sensor for RP investigations. The main advantage of the presented method is the reference to the current balance. The MEMS cantilever transduces the PF to a deflection, and can be compensated with the use of the Lorentz force. The displacement is measured with the use of a fibre optic Fabry–Perot (FP) interferometer. Interferometry combined with the architecture of MEMS cantilevers is a common and convenient method with applications including atomic force microscopy [21, 22]. Combining the MEMS current balance system with interferometry is a unique and fully metrological solution. A Kibble balance is the primary standard for 1 kg (10 kN) determination [23, 24]. The latest literature reports present a miniaturized version of that construction [25] that allows the measurement of hundreds of micrograms (single millinewtons). We present a solution for the measurement of tens of picograms (hundreds of piconewtons). The PF–MEMS conductive cantilever with isolated mirrors and a dedicated fibre optic head forms an ideal system for RP investigations. As the whole construction is based on a fibre optic system, it is very convenient to use in any metrological laboratory. On the one hand the current balance compensation method allows us to omit the mechanical calibration that is substantial for any cantilever mass/force sensor (i.e. determination of spring constant k and quality factor Q). On the other hand this approach allows force measurements down to the range of tens of piconewtons.

2. Measurement set-up

2.1. The microcantilever as a measurement tool

In our experiment we used a PF–MEMS cantilever [26], which was a U-shaped, 500 µm long, 130 µm wide and 1.5 µm thick structure with a stiffness of about 100 mN m^{-1} [17]. The cantilever was manufactured using silicon-on-insulator technology. High boron doping was applied to make the structure conductive, which, in turn, made its movement controllable in a magnetic field (making use of the Lorenz force actuation). The effective current line was shorter than the total width of the cantilever and was equal to 100 µm, which was evaluated by finite element method modelling [27]. The cantilever integrated two mirrors, separated by 125 µm, which made it ideal for further connection to the optical fibre measurement head. In our set-up mirror M_a was dedicated to the structure actuation and mirror M_d was applied for the deflection detection (figure 1(a)). In this case, one optical fibre OF_a provided actuation radiation while another, OF_d, was used for displacement measurement as illustrated in figure 1(b). The reflection and absorption coefficients of the mirror metallization were 90% and 10%, respectively [17]. The detection mirror M_d was placed at the very end of the structure and the actuation mirror M_a was separated from the rest of the structure so that the thermal influence on the actuation could be neglected. It has to be highlighted that the mirrors were metal layers sputtered on the cantilever's silicon body during the micromachining process, thus avoiding a costly,

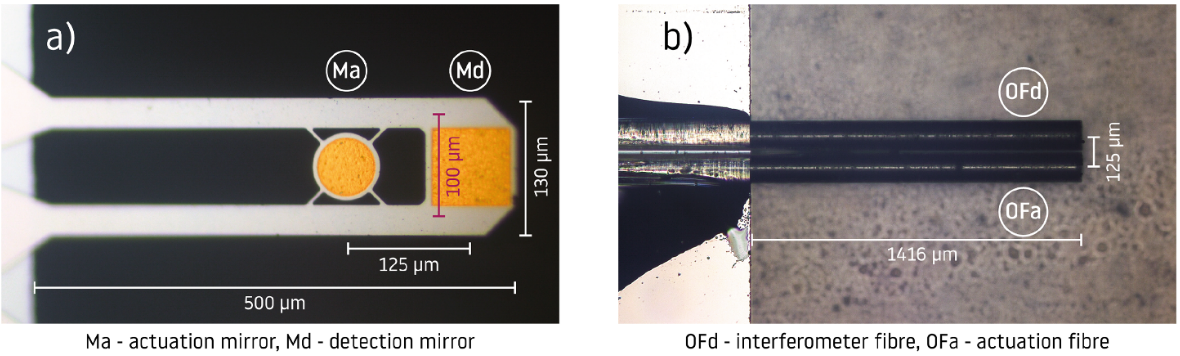

Figure 1. PF–MEMS cantilever with actuation and detection mirrors M_a and M_d, with the effective current line highlighted in red (a), and a dedicated fibre optic head with actuation and detection fibres OF_a and OF_b (b) for optomechanical studies.

Table 1. Parameters of the microcantilever.

f_{res} (Hz)	Q	k (mN m^{-1})	F_{min} (fN Hz$^{-0.5}$)
5965.9	31.8	153	46

time-consuming and manual mirror mounting process such as that described in [7, 8]. The structure's dimensions were optimized to improve its optomechanical operation [28]. Such a construction of the Lorentz loop combined with two dedicated mirrors that was insensitive to thermal actuation made the PF–MEMS cantilever ideal for the current balance experiment [23, 29].

The cantilever's parameters were measured using a SIOS SP-S 120 precise laser vibrometer. Cantilever actuation, which was needed for the beam calibration, was carried out while immersing the structure in a magnetic field excited by a Halbach array. Current biasing was carried out with the use of a bipolar Howland current source. Based on the measured resonant curves, a spring constant k, a quality factor Q and a resonant frequency f_{res} were calculated. For the structure of interest these were as presented in table 1. Additionally, the cantilever's force resolution F_{min} was calculated considering the thermomechanical structure vibration, as already shown [28]. It has to be highlighted that the structure's thermal force resolution is far below the limit of the presented measurement system. The noise floor of the designed tool was calculated to be equal to 46 fN Hz$^{-0.5}$, while the presented measurement set–up resolution was 4 pN Hz$^{-0.5}$, so the PF–MEMS itself did not limit the resolution of the measurements.

2.2. Fibre optic measurement set-up—actuation and detection

The fibre optic measurement head consisted of two single-mode fibres (telecom, SMF-28 ultra, Corning Glass) mounted in a silicon V-grooved substrate (see figure 2). Fibre OF_a was used for actuation, whereas fibre OF_d was used for detection. Actuation was done using a light from a superluminescent diode modulated at the microcantilever resonance frequency of 5965.9 Hz. The measurement head was placed at a distance of 50 µm from the PF–MEMS cantilever to avoid hydrostatic interactions between the fibre and the vibrating structure. The numerical aperture of the OF_a was 0.5 and the fibre's core diameter was 9 µm. Hence, the actuation spot did not go beyond the surface of mirror M_d. The maximum optical power acting on the vibrating structure was 36.48 mW.

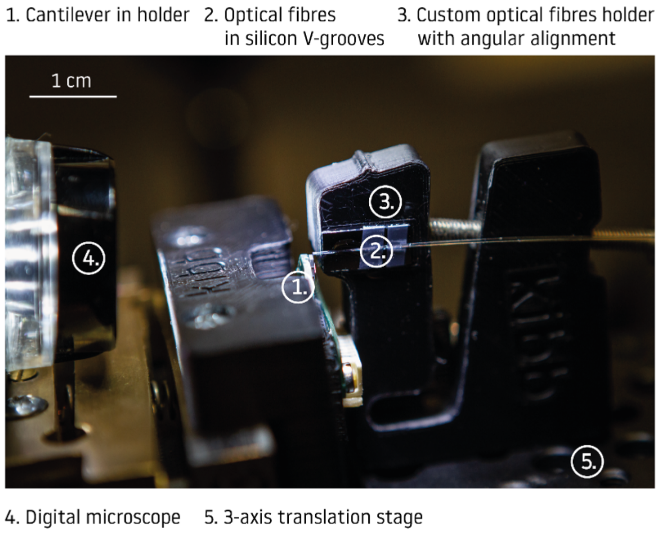

Figure 2. PF–MEMS cantilever and the fibre optic head adjustment set-up.

The deflection of the PF–MEMS cantilever, when it was actuated by RP, was measured by a FP interferometer operating with a resolution of 100 fm Hz$^{-0.5}$ as presented in a previous paper [30]. The wavelength of the investigating beam was 1306.8 nm, which in this case was the metrological reference of $\lambda/4 = 326.7$ nm for further deflection measurements (single fringe reference).

3. Experiment and results

Two steps of operation were used in carrying out the entire procedure. Thanks to the PF–MEMS design and the integrated FP interferometer, the experimental set-up was not altered in each step. In the first step, the cantilever was actuated

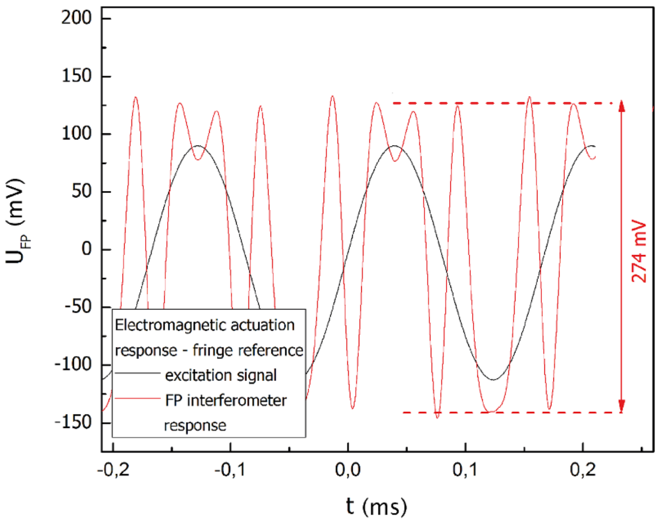

Figure 3. PF–MEMS cantilever deflection under an electromagnetic actuation force of 4.520 nN.

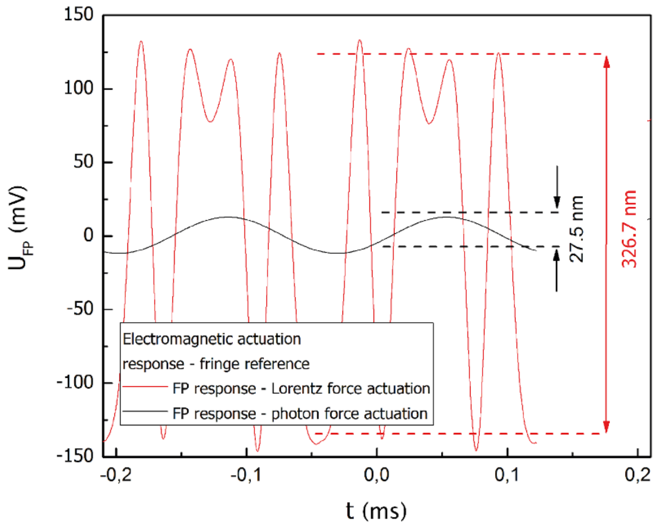

Figure 4. Comparison of data used for the amplitude measurement during RP actuation.

electromagnetically by biasing the Lorentz loop with an alternating current with amplitude equal to $I_{pp} = 400$ µA. As a result, the multifringe pattern was registered as shown in figure 3. The magnetic field in the measurement set-up was $B = 113$ mT, so the Lorentz force acting on the microcantilever was 4.520 nN (the active part of the current line length was 100 µm long) [27]. The cantilever vibrated with an amplitude of about 1000 nm. A single fringe (which corresponds to 326.7 nm of deflection) was measured as a reference and its height was equal to 274 mV (see figure 3).

RP actuation was performed in the second step. The Lorentz loop was shorted, and as the result the PF–MEMS was not electromagnetically deflected. The estimated force induced by PF on the cantilever was 0.231 nN (from equation (1) and taking into account that due to Fresnel reflection, the optical power used for actuation purposes was 96% of the incoming one). It is important to notice that while the photons were acting on mirror M_a, the deflection was measured simultaneously on mirror M_d. The value of the the measured deflection was calculated to be 28.24 nm (the deflection due to actuation on M_a is 1.7 times smaller than when acting on M_d, where the read-out was done).

The height of the fringe when the PF–MEMS cantilever was displaced by impinging photons was 23 mV. Thus, based on the height of the reference fringe, a displacement of 27.5 nm was determined as shown in figure 4. The obtained conformity between both calculated and measured data was proven by multiple measurements. Recalculation of the PF gave a value of 225 pN. All the experiments were conducted at ambient conditions so low-frequency vibrations affected our measurement results. Isolation from low frequencies had to be done and our solution was to remove them via statistical averaging.

When considering the measurement uncertainty, the most influencial factor was the resolution of the PF–MEMS deflection read-out interferometer, which was 100 fm Hz$^{-0.5}$. When referencing to the current balance, the uncertainty of the measurement is related to the values of the current flowing in the PF–MEMS structure and the magnetic field in which it is immersed (assuming the magnetic induction vector is perpendicular to the direction of the current flow). In this study, standard laboratory equipment allowed us to obtain a force resolution value of 4 pN Hz$^{-0.5}$.

In the standard approach to measurements, the uncertainty value of the spring constant determination, which was calculated with the procedure proposed in [27] for typical spring constants ($k > 10$ N m^{-1}), has to be included in the calculus. For soft cantilevers, like the one presented in this study (i.e. $k < 1$ N m^{-1}), the uncertainty is much greater and reaches 10%. Moreover, since all the experiments were carried out in resonance mode, the uncertainty in determination of quality factor Q has to be taken into account (introducing no more than 5% to the uncertainty). In the case of our system, a PF resolution of 15 pN Hz$^{-0.5}$was calculated.

Thus, comparing the two approaches, the standard one and the current balance, there seems to be a slight difference in the resulting uncertainty in favour of the latter. Moreover, the current balance mode requires a lot of improvements when using advanced metrological solutions for electromagnetic induction and current value measurement. Nevertheless, the fact that no calibration process needed is the most important advantage of the proposed measurement technique. In our opinion, achieving such high resolution (low noise floor) at ambient conditions makes the proposed construction very attractive.

4. Conclusion

The obtained results demonstrate that both the PF–MEMS cantilever (as the tool) and the fibre optic measurement set-up are reliable solutions for quantitative optomechanical studies. Thermal separation of the actuation mirror reduces thermal influence on the structure's movement, which improves the selectivity of the investigations. The dedicated fibre optic set-up is compact and convenient to use in metrological laboratories. Along with the double-fibre optical head, it allows for repeatable analyses without the need for a time-consuming and difficult adjustment processes. The specified optical path of the actuation beam improves the resolution of the PF calculations (so-called standard mode of operation), here 15 pN $Hz^{-0.5}$. The PF resolution derived from the current balance mode of operation was 4 pN $Hz^{-0.5}$. All these features and the calculated PF–MEMS cantilever force resolution of 46 fN $Hz^{-0.5}$ form a reliable system for metrological optomechanical investigations.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

[1] Aspelmeyer M, Kippenberg T J and Marquardt F 2014 Cavity optomechanics *Rev. Mod. Phys.* **86** 1391
[2] Maxwell J C 1873 *A Treatise on Electricity and Magnetism* vol 1 (Oxford: Clarendon)
[3] Bartoli A G 1876 *Sopra I Movimenti Prodotti dalla Luce e dal Calore: e Sopra Il Radiometro di Crookes* (Firenze: Coi tipi dei successori Le Monnier)
[4] Nichols E F and Hull G F 1901 A preliminary communication on the pressure of heat and light radiation *Phys. Rev.* **13** 307
[5] Nichols E F and Hull G F 1903 The pressure due to radiation (second paper) *Phys. Rev.* **17** 26
[6] Wilkinson P R, Shaw G A and Pratt J R 2013 Determination of a cantilever's mechanical impedance using photon momentum *Appl. Phys. Lett.* **102** 184103
[7] Kleckner D and Bouwmeester D 2006 Sub-kelvin optical cooling of a micromechanical resonator *Nature* **444** 75
[8] Kleckner D, Marshall W, de Dood M J, Dinyari K N, Pors B J, Irvine W T and Bouwmeester D 2006 High finesse opto-mechanical cavity with a movable thirty-micron-size mirror *Phys. Rev. Lett.* **96** 173901
[9] Ashkin A 1970 Acceleration and trapping of particles by radiation pressure *Phys. Rev. Lett.* **24** 156
[10] Neuman K C and Block S M 2004 Optical trapping *Rev. Sci. Instrum.* **75** 2787–809
[11] Cohadon P F, Heidmann A and Pinard M 1999 Cooling of a mirror by radiation pressure *Phys. Rev. Lett.* **83** 3174
[12] Metzger C H and Karrai K 2004 Cavity cooling of a microlever *Nature* **432** 1002
[13] Williams P A, Hadler J A, Lee R, Maring F C and Lehman J H 2013 Use of radiation pressure for measurement of high-power laser emission *Opt. Lett.* **38** 4248–51
[14] Ryger I, Artusio-Glimpse A B, Williams P, Tomlin N, Stephens M, Rogers K, Spidell M and Lehman J 2018 Micromachined force scale for optical power measurement by radiation pressure sensing *IEEE Sens. J.* **18** 7941–8
[15] Artusio-Glimpse A B, Ryger I, Azarova N A, Williams P A, Hadler J A and Lehman J H 2020 Miniature force sensor for absolute laser power measurements via radiation pressure at hundreds of watts *Opt. Express* **28** 13310–22
[16] Çelik U, Karcı O, Uysallı Y, Özer H O and Oral A 2017 Radiation pressure excitation of a low temperature atomic force/magnetic force microscope for imaging in 4–300 K temperature range *Rev. Sci. Instrum.* **88** 013705
[17] Orlowska K, Majstrzyk W, Kunicki P, Sierakowski A, Pruchnik B, Tomaszewski D, Prokaryn P, Grabiec P and Gotszalk T 2018 New design of the cantilevers for radiation pressure investigations *Microelectron. Eng.* **201** 10–15
[18] Rugar D, Mamin H and Guethner P 1989 Improved fiber-optic interferometer for atomic force microscopy *Appl. Phys. Lett.* **55** 2588–90
[19] Rugar D, Mamin H, Erlandsson R, Stern J and Terris B 1988 Force microscope using a fiber-optic displacement sensor *Rev. Sci. Instrum.* **59** 2337–40
[20] Chen K, Gong Z, Guo M, Yu S, Qu C, Zhou X and Yu Q 2018 Fiber-optic Fabry–Perot interferometer based high sensitive cantilever microphone *Sens. Actuators* A **279** 107–12
[21] Erlandsson R, McClelland G, Mate C and Chiang S 1988 Atomic force microscopy using optical interferometry *J. Vac. Sci. Technol.* A **6** 266–70
[22] Rasool H I, Wilkinson P R, Stieg A Z and Gimzewski J K 2010 A low noise all-fiber interferometer for high resolution frequency modulated atomic force microscopy imaging in liquids *Rev. Sci. Instrum.* **81** 023703
[23] Robinson I A and Schlamminger S 2016 The watt or Kibble balance: a technique for implementing the new SI definition of the unit of mass *Metrologia* **53** A46
[24] Robinson I A *et al* 2018 Developing the next generation of NPL Kibble balances *2018th Conf. on Precision Electromagnetic Measurements (CPEM 2018)* (IEEE) pp 1–2
[25] Yamamoto Y, Fujita K and Fujii K 2020 Development of a new apparatus for Si traceable small mass measurements using the voltage balance method at NMIJ *IEEE Trans. Instrum. Meas.* **69** 9048–55
[26] Orłowska K, Majstrzyk W, Sierakowski A, Piasecki T and Gotszalk T 2018 Mechanical impedance analysis of a novel MEMS photon force sensor *Eurosensors Multidisciplinary Digital Publishing Institute Proc. 9–12 September 2018* vol 2 p 921
[27] Majstrzyk W, Mognaschi M, Orłowska K, Di Barba P, Sierakowski A, Dobrowolski R, Grabiec P and Gotszalk T 2018 Electromagnetic cantilever reference for the calibration of optical nanodisplacement systems *Sens. Actuators* A **282** 149–56
[28] Di Barba P, Gotszalk T, Majstrzyk W, Mognaschi M E, Orłowska K, Wiak S and Sierakowski A 2018 Optimal design of electromagnetically actuated MEMS cantilevers *Sensors* **18** 2533
[29] Kibble B 1986 The SI ampere and volt—an example of electrical metrology *Int. J. Electr. Eng. Educ.* **23** 293–302
[30] Orłowska K, Światkowski M, Kunicki P and Gotszalk T 2018 Metrological 2iOF fibre-optic system for position and displacement measurement with 31 pm resolution *Rev. Sci. Instrum.* **89** 045001