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We cordially invite you to a lecture

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# The force effects of light: How to measure the electromagnetic power by radiation pressure

## The lecture will take place on 14/09/2018 at 10.00 AM in the IEE SAS meeting room (Rm.101).

**Abstract:** The property of photons to carry momentum was first described by J. C. Maxwell in 1873. This was later confirmed experimentally at the beginning of the 20th century by works of Lebedev [1], Nichols and Hull [2]. At that time, it was mostly matter of scientific curiosity, rather than of practical importance. The importance of the force effects of the microwave power [3] has become of scientific interest after introduction of high power electromagnetic sources like magnetrons or klystrons shortly after WW2. Nowadays, the force effects of light have found many practical applications from the micromanipulation of biological objects by means of optical tweezers [4][5], through on-line microwave/laser power monitoring during welding processes of medical devices or front glass for smartphones, microwave sintering of ceramics, additive manufacturing, and up to space applications like solar sails. The radiation pressure effect has also been thoroughly investigated [6] in the LIGO project (Laser Interferometry Gravitational Observatory) famous for its discovery of merging black holes. In such an experiment a high-finesse optical cavity is needed to pronounce its sensitivity to sub-nm optical path variation. This goes hand in hand with increasing the stored energy in the resonator, leading to non-negligible forces pushing onto suspended interferometer reflectors. Emerging 3D additive manufacturing processes considerably affect the global industry, since it allows “machining” parts of complicated shapes that were not

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possible before. An example is a fully 3D printed fuel injection nozzle [7] (LEAP engine) designed by General Electric that reduces the fuel consumption by 15%, going hand in hand with a 50% cut in NOx emissions and increased combustion efficiency compared to its predecessor (CFM engine). It is also 5-times more durable than its counterparts machined by standard technologies. However, to ensure consistent quality of the process, a careful control of energy delivered to the melt spot is necessary. This becomes a challenge because current power measurement techniques allow either fast or accurate measurements, but not both at the same time.

The accurate measurements of either microwave or laser power traceable to SI units have traditionally been carried out in bulky calorimeters [8] that, in the case of 50 kW measurement device, weigh about 50kg, require a water tank of 380L, and have a time response on order of minutes. Recently, Williams, et al.[9] showed the SI-traceable measurement of high optical power by means of radiation pressure traceable to SI with thorough investigation of the error budget. They demonstrated that the device can operate without breaking the optical path with a noise floor of 100W/sqrt(Hz) and response time of 5 sec – a significant improvement over the calorimeters. The main advantage of electromagnetic power measurement by means of the radiation pressure is that during the measurement process the photons are not annihilated through the process of absorption, but (specularly) reflected. This is of paramount importance in the practical world since their energy can be still used in the target process. In my talk, I will discuss the approach of electromagnetic power measurement by means of radiation pressure. I will target the main challenges we are facing while doing nano-Newton force measurements and briefly describe the micromachined force sensor[10] that overcomes these obstacles, bringing us closer to real-world industrial application. I will demonstrate the current operation of the device and conclude with future outlook.

**References:** [1] P. N. Lebedev, Ann. Der Physik, 6, 433 (1901); [2] E. E. Nichols and G. F. Hull, "The pressure due to radiation," Phys. Rev. vol. 17, no. 5, pp. 315-351, Jun. 1903; [3] Cullen, A. L. Absolute power measurement at microwave frequencies. *Proc. IEE*, **1952**, 92, 100-111; [4] A. Ashkin, "Observation of a single-beam gradient force optical trap for dielectric particles," Optics Letter 11(5), 1986. [5] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1523313/;
[6] https://gwic.ligo.org/thesisprize/2008/Corbitt_Thesis.pdf; [7] https://www.cfmaeroengines.com/engines/leap/; [8] https://dx.doi.org/10.1088/1681-7575/aaae78;
[9] https://dx.doi.org/10.1364/AO.56.009596; [10] I. Ryger, *et al.* "Micromachined force scale for optical power measurement by radiation pressure sensing*", to be published in IEEE sensors journal*