Politecnico di Torino

ELECTRICAL, ELECTRONICS AND COMMUNICATIONS ENGINEERING

INRiM - Advanced Metrology for Electrical, Electronics and Communications Engineering

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Context of the research activity	This Thematic Grant includes 7 research Topics (listed below), with a specific title and proponent Supervisor/s. The applicants have the possibility to identify the specific topic they are interested in. Topic 1: Electrostatic MEMS generator/actuator of nanoforces traceable to electrical and mechanical quantities Topic 2: Ultra-high Precision Absolute Earth Gravity Measurements Topic 3: Wideband sampling quantum digitizer for primary AC waveform metrology Topic 4: Testing and characterization of supercapacitors Topic 5: Highly sensitive electro-optical microsensors based on responsive polymers. Topic 6: Laser interferometry on telecom optical fibers: a tool for fundamental and applied physics. Topic 7: Chip-scale optical clocks for space applications.

	Topic 1: Electrostatic MEMS generator/actuator of nanoforces traceable to electrical and mechanical quantities The measurement of small masses, and thus of small forces, in the range from pN to µN, is of great interest for various fields of science and technology, such as physics, biology, and materials science. Many devices sensitive to extremely small forces are based on the deflection of an elastic structure measured by a deformation sensor (e.g. piezoresistive, optical), which however relies on non-linear effects difficult to characterize. One strategy to provide traceability in the field of small forces has been the development of

electrostatic balances, in which the weight force is equal to the electrostatic force. The realization of a MEMS generator/actuator will allow the measurements of nano-forces traceable to the SI through the conversion of electrical into mechanical quantities. More specifically, the candidate will have to design, model and fabricate an electrostatic MEMS with a comb structure, in collaboration with CNR-IMM Bologna. In addition, the candidate will have to implement a set-up for the characterization of the electrostatic behavior of the MEMS sensor, based on a piezoelectric actuator for traceable displacement measurements and electronic devices to measure/generate voltage and capacitance signals.

Topic 2: Ultra-high Precision Absolute Earth Gravity Measurements
The value of the local acceleration due to gravity and its variations with time is of interest in a wide field of physical sciences, such as metrology, geophysics and geodesy. Measurements of the acceleration due to gravity are performed by absolute gravimeters, traceable to the units of length and time. The current Italian primary standard has been developed and maintained at INRiM, which is a transportable ballistic rise-and-fall absolute gravimeter (IMGC-02) with a relative uncertainty in the order of 10e-9. It uses laser interferometry to measure the gravity from the analysis of the motion of a test mass in the gravity field (unique instrument in the world adopting symmetrical motion). Nevertheless, the system, beyond needing further improvements to perform more accurate launches, to reduce vibration transmission and to decrease the uncertainty related to the observation site, is rather overperforming for the uncertainty levels (around 10e-5) required by calibration laboratories, thus a new transportable and more suitable absolute gravimeter has to be developed. The PhD candidate will be mainly focused on such tasks and also involved in in-situ measurements and activities aimed at realizing a reference network for absolute gravity and at establishing the International Height Reference System/Frame in the Italian area, part of a PRIN project funded by MUR. The PhD course will include:
- theoretical and experimental activities to improve the IMGC-02 transportable absolute gravimeter, the inertial reference system, the new launch system, and the other influence factors
- development of a new transportable and more suitable absolute gravimeter addressed for calibration laboratories at an uncertainty level of 10e-5
- measurements on different observation sites, mainly in Italy
- scientific support in the realization of a reference network for absolute gravity and at establishing the International Height Reference System/Frame (IHRS/IHRF) in the Italian area

Topic 3: Wideband sampling quantum digitizer for primary AC waveform metrology
Overview: Digitisers play a vital role in practically all areas of metrology. High-resolution digitisers, are now used for complex signal analysis in a wide range of applications including those in the power quality (PQ) industry, automotive, aerospace, communications, medical fields and quantum computing. For ACV measurements, their accuracy decreases significantly with increasing frequency. For example, in the context of smart grids, there is a growing need for reliable and improved traceability up to 100 kHz related to PQ issues in presence of non-sinusoidal waveforms due to massive renewable energy integration.
The proposed research topic focuses on the integration of AC Josephson voltage standards into sampling setups to address the need to establish a new traceability chain for non-RMS quantities, PQ and synchrophasor measurements within the framework of the new SI.

Objectives	Need: The primary AC waveform metrology relies on thermal converters, which are insensible to harmonics and do not provide a direct link to the new SI. Existing AC programmable Josephson voltage standards (PJVS) are usable up to 1 kHz, while PQ interest bandwidth goes up to 100 kHz. Objectives: Develop a wideband sampling quantum voltmeter based on AC-PJVS using differential sampling, subsampling and superconducting quantum interference devices (SQUIDs). Methodology: • Design and build a differential sampling quantum voltmeter (DSQV) based on multi-bit binary Josephson junction arrays (JJAs) for operation in the kHz range. • Set up a WSQV using subsampling and data processing algorithms for AC measurements up to 100 kHz. • Develop and fabricate cryoprobe and cryogenic front-end circuitry suitable for direct coupling of JJAs and SQUIDs. • Testbed setup for simultaneous operation of quantum devices in the same cryogenic bath. Outcomes: • Verification and validation of the wideband AC quantum voltmeter; • Reduce cost and time for AC waveform calibrating and maintaining in the new SI. Topic 4: Testing and characterization of supercapacitors Supercapacitors (SCs) represent an environmentally friendly technology that can replace batteries or pair them in higher-power density applications. To support the increasing use of SCs, accurate characterisation is required also under operating conditions. In addition, validated circuital and software models are needed to identify the SCs behavior in dynamic applications. Along slower but highly accurate methods, novel quick, traceable, and effective measurement techniques are required to evaluate SCs' State of Charge (SoC) and State of Health (SoH) and to promote the uptake of SCs and banks in consumer, energy, transport, aerospace and in many other applications. Topic 5: Highly sensitive electro-optical microsensors based on responsive polymers. Miniaturization of intelligent devices requires functional materials able to autonomously interact with the environment by modifying their properties. In this context, the PhD project aims to employ responsive polymers, such as liquid crystalline networks to realize sensors based on MEMS (Micro-Electro-Mechanical System) and MOEMS (Micro-Opto-Electro-Mechanical System) for the detection of chemical agents (such as solvent vapors, humidity, pH). These devices promise to be a stable and cheap platform for sensing by offering remote measurements even in hostile environments. The PhD project tackles the design, the fabrication and the characterization of highly sensitive MOEMS. The candidate will engineer micrometric structures based on a three layer geometry (metal-responsive insulator-metal) where the sensing capability will be monitored by optical (Fabri-Perot spectra) and electrical measurements (variation of capacitance). The validation of both working regimes will result in a combined opto-electro mechanical response sensor. The polymer engineering will target enhanced analytical capabilities based on the anisotropic deformation of dielectric layers in response to different external stimuli, and in particular to the different concentrations of chemical species that is translated in the variation of the optical/electrical properties of the sensor. Photopolymerizable dielectrics will be considered thanks to their

compatibility with photolithographic techniques and to the expertise and strong collaboration of INRiM (National Institute of Metrological Research) and Polito.
The miniaturization and integration of the MOEMS sensors will be performed at the new fabrication facility Piquet at INRiM in the context of the Next Generation Metrology project LCE-SENSE (Liquid Crystal Elastomer capacitive SENSors for multipurpose chEmical detection). The research activities will take advantage of the new laboratories of the INRiM headquarter in Florence (Sesto Fiorentino).

Topic 6: Laser interferometry on telecom optical fibers: a tool for fundamental and applied physics.
Optical fibers are the infrastructure that most pervasively covers our planet. While primarily established for global telecommunications, they can also be used for many scientific applications. For instance, they are used to connect distant atomic clocks and fundamental physics experiments across the EU, or to exchange quantum cryptographic keys and enable secure communication, or they can be turned into a capillary sensing grid for earthquake monitoring.
At the basis of such applications is laser interferometry. The Italian Metrology Institute (INRIM) has developed low-noise methods to measure deformations of deployed optical fibers induced by changing environmental conditions (e.g., seismic noise) down to a few nm, using narrow-linewidth lasers. We have successfully exploited this technology to improve quantum key distribution (QKD) [Clivati et al., Nat Comm. 13, 157 (2022)], compare distant atomic clocks [Clivati et al., Phys. Rev. Appl. 18, 054009 (2022)] and detect earthquakes in subsea and metropolitan fibers [Donadello et al., arXiv:2307.06203 (2023)].
The proposed activity builds upon these results and may focus on different aspects also in consideration of the candidate aspirations, in collaboration with international Institutions and Companies. Among possible topics are:
1)in the context of earthquake monitoring: the development and installation of advanced laser interrogators in telecom network nodes to realize a distributed earthquake observatory; modelling the fiber response to seismic events as a function of their magnitude and location; advanced probing strategies to localize deformations and adapt to peculiar network (e.g., fiber-to-the-home) architectures; advanced techniques for pattern recognition and data science.
2)In the context of QKD, the demonstration of secure key exchange at regional scale exploiting advanced laser sources, in the framework of the European Quantum Communication Infrastructure.

Topic 7: Chip-scale optical clocks for space applications.
Today, the best atomic clocks have relative accuracy at the 1E-18 level, that enables steps forward in fundamental physics experiments on Earth and in Space, precision atom spectroscopy, satellite navigation. In atomic clocks, a local oscillator is kept on resonance with a specific atomic transition by active feedback, and a clockwork coherently down-converts the local oscillator signal into a usable radiofrequency output. While these devices are mostly based on bulky and lab-scale equipment, out-of-lab applications require miniaturized devices. Research thus focuses on the on-chip integration of the laser source, of the atom reservoir and the clockwork [Z. Newman, Optica 6, 680 (2019)], requiring hybrid research at the forefront of laser physics and nonlinear optics, atom physics, low-noise electronics and material science. The present project sets in this framework and concerns the realization of an integrated optical clock prototype, based on an infrared laser stabilized to the

	two-photon transition in Rubidium atoms and its down-conversion to the radio-frequency domain through a microresonator Kerr frequency comb. The activity includes the realization of the clock's building blocks and the optical and electronics equipment for the laser beam manipulation, the study of strategies for interrogating atoms and accessing the nonlinear optical soliton regime. The characterization of the realized clock in terms of accuracy, stability and sensitivity to external environment will finally be pursued. Based on the candidate attitude, the project also offers the possibility to perform fundamental studies on light-resonator interactions, design of novel atom-confinement schemes and microresonator geometries, that in the future could be fabricated and tested in collaboration with the INRIM Piquet facility for micro and nanofabrication [https://piquetlab.it/].

Skills and competencies for the development of the activity	Topic 1: Electrostatic MEMS generator/actuator of nanoforces traceable to electrical and mechanical quantities The candidate must have a basic knowledge on the microfabrication processes, such as photolithography, thin film deposition and etching. Furthermore, a basic knowledge of the following software is preferable (not strictly required): - COMSOL Multiphysics, for the simulation of the MEMS device; - LabVIEW software, for data acquisition and control of instruments of the MEMS characterisation set-up. Topic 2: Ultra-high Precision Absolute Earth Gravity Measurements Skills on mechanical and electrical measurements, optical-interferometric systems, measurement uncertainty assessment, CAD design. Finite Element Method (FEM) software, LabVIEW skills and C++ development or other programming languages are appreciated, but not mandatory. Topic 3: Wideband sampling quantum digitizer for primary AC waveform metrology • Design and modelling of electrical and mixed electronics, signal theory and processing; • Knowledge of the physics of superconducting devices; • Knowledge of macroscopic quantum effects, with particular emphasis to the Josephson effect. • Knowledge of cryogenic physics. • Arrangement to work in a research laboratory and conduct activities related to modelling, designing and preparing suitable devices and cryogenic experiments. • Knowledge of programming languages C, LabVIEW, Matlab, etc. Topic 4: Testing and characterization of supercapacitors Electrical measurements, good basis of mathematics (differential equations) and physics. Topic 5: Highly sensitive electro-optical microsensors based on responsive polymers. The multidisciplinary PhD project will allow to gather knowledge in different fields form materials science to electro-optical micro-device characterization exploiting cutting edge fabrication processes and exploring novel challenges for next generation sensors. Knowledge in one of the following fields: materials engineering, physics, chemistry or electrical engineering. Positive evaluation will be given to knowledge of polymer science, lithographic processes, basics of optics and electronics.

	Topic 6: Laser interferometry on telecom optical fibers: a tool for fundamental and applied physics. Depending on the candidate attitude, the activity can focus more on experimental or on data analysis. In the former, the candidate will gain experience in free-space/fiber optics, laser physics and low-noise electronics. In the latter, the candidate will develop advanced signal processing and pattern recognition, also based on Artificial Intelligence tools. Previous experience in relevant fields can be useful; however, the candidate will have the chance to fill initial gaps during the activity. Topic 7: Chip-scale optical clocks for space applications. The activity is predominantly experimental. Interest in experimental laboratory activity is thus a prerequisite. Basic background in optics, laser physics, atomic/matter physics is welcome. However, the motivated candidate will have the chance to fill initial background gaps during the activity.