Title:

New cryogenic-hydrogen-based optical technologies for quantum sensing of temperature and pressure.

Molecular hydrogen (H_2) is the simplest molecule in Nature, it consists only of two protons and two electrons and, hence, its structure can be calculated extremely accurately from the first principles of the quantum theory. This makes H_2 a very attractive system for fundamental and applied studies. For instance, H_2 is used as a quantum sensor of the standard model effects that goes beyond the Schrödinger-equation quantum mechanics allowing one to clearly see the presence of virtual photons and other subtle effects of the quantum electrodynamics. Furthermore, such accurate measurements open also a way to use H_2 to search for new physics beyond the standard model such as long-range hadron-hadron interactions. In this project we will benefit from the unique features of the H_2 molecule to address another important problem, which is the realization of some of the SI units at deep cryogenic regime (down to 5 K). The recent redefinition of the SI system of units completely changed the foundations of metrology (i.e., the foundations of the measurement methodology in physics and other natural sciences). Instead of using unit artifacts, such as the International Prototype of the Kilogram in the form of platinum-iridium cylinder, the new definition is based on cesium atomic clock time reference, fixed and exact physical constants, and fundamental laws of physics. On the one hand, this made the long-awaited dream of basing the measurement units on fundamental laws of physics come true, and now the SI system is fully open access and free of human-made artifacts. On the other hand, however, this poses a huge challenge for experimental realization of the newly defined units.

In this project, we will address this challenge for the case of temperature and pressure units in a difficult-to-access deep cryogenic regime. To achieve it, we will combine the recently developed in our laboratory cryogenic high-finesse optical cavity (the only such system in the world) with the state-of-the-art optical technologies aimed at ultra-accurate molecular spectroscopy (these methods are based on high finesse optical cavities that extends at laboratory conditions the photon-molecule interaction path to tens of kilometers). This will enable us to perform ultra-accurate spectroscopy of hydrogen molecules at temperatures from 5 to 20 K and for the first time use this huge metrological potential for SI unit realization. From the thermal broadening of the H_2 transitions we will determine the kelvin unit and combining it with the measured intensity of the transition, we will determine the pascal unit. This way, we will introduce optical metrology to the fields typically belonging to other branches of science such as solid-state physics or acoustic methods.