Novel solid-state laser structures as miniature, highly-sensitive gas detectors for laser spectroscopy

Reasons for undertaking the research topic:

The global production progress and industrial expansion observed for many decades have had a clear impact on our planet's condition, quality of life and human health, mainly due to the increasing emissions of many dangerous and toxic gases, volatile organic compounds or greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and others. According to a NASA report, only methane emissions reach more than 550 million tons annually and are increasing dramatically. Moreover, according to the study, methane is responsible for 20% of the increase in the global warming effect. Environmental monitoring and protection, detection of hazardous gas leaks, and control of industrial processes are among the many areas where the problem of simple gas detection methods at a level of a few parts per billion (ppb) is crucial and ever-present. Such a level of gas molecule detection (detection limit of the sensor) can be compared to the possibility of finding a human red blood cell on the surface of a football field at Camp Nou in Barcelona.

Currently, the most sensitive gas detectors use laser light, which can be absorbed by gas molecules when the frequency of the laser light coincides with the frequency of the gas absorption line. Gas detection methods are supported by laser spectroscopy. The gas detection capability (sensitivity of the sensor) can be increased by extending the interaction path of the laser beam with the gas to be measured or by increasing the wavelength of the radiation that excites the gas (mid-infrared or further terahertz range), where the absorption of most gases of interest becomes much stronger. Most known high-sensitivity laser spectroscopy techniques use multi-pass absorption cells to extend the laser-gas interaction path length up to tens of meters. Unfortunately, such absorption cells have several serious drawbacks, such as large size and weight, susceptibility to misalignment, and mechanical and acoustic vibrations, causing difficulties in their non-laboratory applications. Currently, experimental sensor systems use a long section of antiresonant hollow-core fiber (ARHCF) filled with the gas to be measured, replacing typical multi-pass cells. However, ARHCFs are limited to selected wavelength ranges and operate up to 5.5 µm. Thus, further attractive detection ranges in the mid-infrared and terahertz (THz) become unreachable for them, where the absorption of the gases of interest is much higher.

Project Goals: Within this Project, to eliminate the mentioned sensor drawbacks, we propose to research novel configurations of diode-pumped solid-state lasers (DPSSL) which become gas detectors themselves rather than just being laser light sources for laser spectroscopy setup applications, providing a non-complex design, versatile, cost-effective, and ultra-compact sensor configuration. In addition, we propose a pioneering, never-before-used approach to enhance the sensitivity of laser-based gas sensors using optical vortices generated in the laser beam. To the best of our knowledge, the proposed research topic has no counterpart among currently developed laser-based gas detection techniques and approaches for increasing their sensitivity.

Research description: We intend to achieve the goal of the Project by utilizing the phenomenon of photothermally induced change in the refractive index of a gas directly inside three innovative DPSSL laser structures. They will be laser resonator structures with polarization-separated laser beams, a single-input-output type resonator with an independent air gap length, and a mini-resonator in a Michelson quasi-interferometer configuration. That allows us to observe significant changes in the frequency of the generated laser beam caused by slight changes in the refractive index of the gas, proportional to its concentration, which will be measured using a heterodyne technique for detecting frequency signals. In the last task of the Project, utilizing the orbital angular momentum phenomenon, we aim to concentrate gas molecules inside the vortex beam, locally increasing the measured gas concentration. Using such a solution in any laser gas detection system will increase their measurement sensitivity.

Expected project results will be the realization of innovative gas sensors as a monolithic, miniature (<20 mm in length), lightweight (a few grams), highly sensitive (gas detection limit at the level of few/several molecules per billion (ppbv)) laser structures with concise laser-gas interaction paths (a few mm) and fast response. In addition, the proposed sensor structures are unlimited by the range of wavelengths at which we detect gases, enabling THz range exploration, which is currently unreachable by almost all experimental sensor configurations based on laser gas spectroscopy.