Grzegorz Gomółka, M. Sc.
Doctoral School of WUST

Laser gas spectroscopy using antiresonant hollow-core fibers and heterodyne detection

Abstract

Laser gas detection is currently a very important tool in many aspects of human activity, from the extraction of natural resources, through environmental protection, to scientific research. Galloping technological and economic development is rapidly creating new challenges for gas sensors, such as miniaturization, energy efficiency, reliability and increased availability with reduced production and operating costs. To meet these requirements, scientific research is needed on innovations in laser spectroscopy, which will lead to the development of new solutions supporting the operation of measurement systems, as well as those that will result in completely new configurations that will further push the limits of the capabilities of laser gas detectors.

The scientific goal of the presented doctoral dissertation is to present the results of research focused on the applications of antiresonant hollow-core fibers (AR-HCF) and optical heterodyne detection (OHD) in laser gas spectroscopy. Both technologies are currently very promising branches of research on optical gas sensors, the first – as small optomechanically stable gas cells, and the second – as a signal detection technique, allowing to overcome certain limitations that occur in conventional spectroscopic systems.

The dissertation is divided into several parts. In the first part (Chapter 2), the reader is introduced to the necessary basics of the interaction of light with gas molecules, which is the basis of infrared absorption spectroscopy. The second one describes the techniques of tunable diode laser absorption spectroscopy (TDLAS) together with wavelength modulation spectroscopy (WMS), which is commonly used in currently presented sensor systems. Chapter 3 also reviews the applications of hollow-core fibers in laser gas spectroscopy, starting from the first demonstrations with cylindrical hollow waveguides with a metallic reflecting layer, to today's advanced interferometric systems based on antiresonant fibers, which detect gases in the near- and mid-infrared with unprecedented spectral resolution and sensitivity of the order of single ppb. Chapter 4 of the dissertation is devoted to the topic of absorption spectroscopy in AR-HCF fibers. The first section of the chapter presents a mid-infrared methane detection system using an interband cascade laser emitting at 3.27 μm. Thanks to the high detection sensitivity, it was possible to use this system for long-term monitoring of methane concentration in the Wrocław's air (approx. 2 ppm), which resulted in the first demonstration of the practical use of the AR-HCF-based sensor. During research on this sensor, it was also realized that there were certain problems, of a fundamental and technical nature, related to the use of anti-resonant fibers in gas detection. These included: connecting optical fibers with the possibility of filling them with gas at the same time, effective filling of longer sections of AR-HCF with gas, measurement of absorption lines in conditions of non-uniform broadening caused by the pressure gradient in the fiber, and intermodal interference in AR-HCFs, which manifested by the presence of fringes in the absorption spectra. Solutions to these difficulties are described in the second section of Chapter 4 in new systems for methane detection in the near infrared, where the availability of fiber optic components was additionally used to develop the so-called "all-fiber" sensor systems, which exhibit simplicity and resistance to misalignment. The last part of the thesis (Chapter 5) describes gas detection systems in which heterodyne detection was used to present new measurement possibilities. The first of four experiments shows how OHD enabled the sensor using AR-HCF to work in a reflective configuration. The second one describes how differential dispersion spectroscopy in a heterodyne interferometer can be used to detect differences in oxygen concentration between two gas cells. The last two demonstrations are focused on OHD applications in photothermal interferometry in a pump-probe configuration, first with a single-frequency light source and then with a frequency comb from a quantum cascade laser (QCL-FC). In both cases, heterodyne detection enabled the observation of photothermal phase modulation in the beatnote of two probe beams with slightly different frequencies. The QCL-FC modulated Fourier spectrometer system was the first demonstration of broadband multiheterodyne photothermal spectroscopy in the mid-IR at approximately 8 μm.

In conclusion, the doctoral thesis describes how the use of antiresonant hollow-core optical fibers and heterodyne detection can be used to develop new methods and configurations in laser gas detection. The systems presented constitute a study of the possibilities and problems of these technologies, and the solutions shown allowed for the development of gas sensors with previously unavailable properties.