Techniques of generation of the optical frequency comb in the mid-infrared region for laser spectroscopy

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Thanks to their broadband spectrum, high spectral resolution, and frequency accuracy, optical frequency combs (OFCs) have opened the way for precise spectroscopy of entire molecular bands in short acquisition time, as well as simultaneous monitoring of multiple gas species with a single light source. Stable OFC sources in the mid-infrared, where the absorption lines of molecules are strong, can be obtained by nonlinear conversion, such as difference frequency generation (DFG). The dissertation presents an analysis of generating OFCs in mid-infrared and experimental examples of using them for laser spectroscopy purposes.

The first part of the dissertation is devoted to the theoretical study of OFCs and the basics of laser absorption spectroscopy. It consists of various methods of obtaining OFC, especially in the mid-infrared, as well as their characteristics, stabilization, amplification, and conversion. Particular attention was paid to the new amplification method of laser pulses, gain-managed nonlinear (GMN) regime. It can deliver high-power pulses with an optically broadband spectrum beyond the conventional gain profile of the active medium and with the possibility of compressing them to nearly transform-limited pulses. Next, OFC spectroscopy was described, pointing out its advantages. Different techniques for enhancing the absorption signal were covered, with an emphasis on using antiresonant hollow-core fibers (ARHCFs). The theoretical part of the thesis ends with a short description of detection methods and details on the Fourier transform spectrometer (FTS) used for experimental studies.

Two Chapters of the dissertation are dedicated to experimental setups, which have been demonstrated and discussed. First, an in-depth analysis of GMN amplification of ytterbium-doped fiber laser is presented. Two different amplifiers were constructed with various laser pump diodes (918 and 976 nm wavelengths). Additionally, two different laser sources with high (125 MHz) and low repetition rate (30 MHz) were used for seeding the amplifier. The obtained results showed the influence of seed laser and pump diode parameters on the characteristics of amplified pulses. The comparison was based on parameters like optical spectra, autocorrelation functions, pulse durations, spectral and temporal phases, noise properties, and output powers. It was the first presentation of the GMN amplification noise properties. Numerical simulations of the GMN amplification complemented the experimental data. Furthermore, the amplified and compressed pulse with a duration of 33 fs and peak power of 2.29 W is, up to date, the shortest laser pulse with the highest peak power achieved for this regime. The setup for amplification was also used for constructing the DFG-based OFC working in the 3-5 μm spectral range.

The next part of the dissertation concentrated on the experimental usage of OFC for laser spectroscopy in the mid-infrared. The first experiment demonstrated the ability to detect multispecies thanks to the broad spectrum of the OFC. The results of simultaneous measurement of methane and ethane were presented. The second study was the first demonstration of using ARHCF-based absorption cell with OFC in the mid-infrared. In this experiment, concentrations of the four different hydrocarbons with broad and narrow absorption lines were measured by the FTS. A comparison of the results for ARHCF and a multipass cell was conducted, demonstrating better performance of the ARHCF.

The dissertation demonstrated the capabilities of OFC spectroscopy. The achieved results were compared with the best achievements in this field, and further development perspectives were identified. The results of this work were published in three articles in JCR-listed journals and presented at fourteen national and international scientific conferences.

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