Light pulses are the shortest events that are produced by humans in a controlled manner. Manipulation of their parameters- especially their duration- pushes the boundaries of knowledge in the study of matter's structure and in disease diagnostics. A sequence of identical and equidistant ultrashort light pulses creates an optical frequency comb (OFC), which in the frequency domain is described by two parameters: the repetition rate (f_{rep}), meaning the spectral distance between successive 'teeth of the comb,' and the carrier-envelope offset frequency (f_{ceo}) - see Fig.1. Optical frequency comb is a powerful and versatile tool- recognized twice with the Nobel Prize (in 2005 and 2023)- used in, among other things, attosecond pulse generation, spectroscopy, time measurement with optical clocks, and even the discovery of exoplanets.

However, if both frequencies fluctuate, for instance due to the temperature changes, humidity or mechanical vibrations, the shape and timing of the consecutive light pulses are not stable. These instabilities can disrupt the whole system relying on the laser and prevent successful applications. Research into a new method for fast and reliable stabilization of both parameters is the main goal of this project.

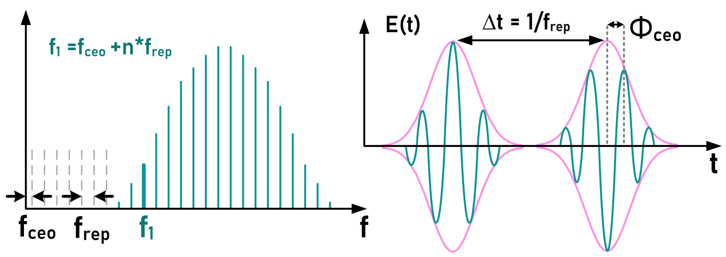

Fig. 1: Spectral (left) and temporal (right) characteristics of optical frequency comb.

Conventional OFC stabilization methods, such as pump power modulation for f_{ceo} or mechanical cavity length adjustment for f_{rep}, are limited by the properties of the cavity dynamics and the speed of moving mechanical components. In the preliminary results for this proposal [1], we introduced a new f_{ceo} stabilization technique based on direct phase modulation via an intracavity electro-optic modulator (EOM). Electro-optic modulators change the optical path length for the transmitted light beam if a voltage is applied, allowing us to shift the frequency comb and stabilize f_{ceo} to the expected value. We have shown that this novel approach proved to be a promising alternative to traditional solutions due to its potential to reach a higher modulation speed (bandwidth), leading to a reduction in laser phase noise and increasing stability. Nevertheless, we have also discovered that this new method is not without its challenges. One limitation we observed involves piezoelectric resonances, which are unwanted vibrational effects caused by the modulator material itself, restricting the modulation bandwidth.

In this project, we will focus on the complete characterization of the EOMs and optimization of their parameters for f_{ceo} and f_{rep} stabilization. Initially, we will address this by investigating alternative EOM geometries and materials. The material we identified to have a lower piezoelectric response, rubidium titanyl phosphate (RTP), is a very promising candidate. However, it is not well-researched in the mid-IR spectral region. Using a spectrally broad (1 - 4 µm), femtosecond chromium laser, we will determine the material's optical properties crucial for electro-optic modulation- refractive index and electro-optic coefficient. If it proves to be suitable, we benchmark its stabilization performance (first of f_{ceo}, then of f_{rep}) against commonly used Lithium Niobate of different geometries. After selecting the best-performing units, we will apply two modulators inside the chromium laser cavity- one for stabilizing f_{ceo}, the other for f_{rep}- to achieve full stabilization of the optical frequency comb. We expect that such a configuration will significantly reduce phase noise, matching or even surpassing the most stable optical frequency combs today.

Our proposed research has the potential to advance both fundamental knowledge and practical tools in laser physics and mid-IR photonics. Anticipated contributions include: the introduction of a new, universal method for OFC stabilization; new insights into the optical and electro-optical properties of the RTP crystal; the establishment of RTP as a viable EOM material in the mid-infrared range; the development of an OFC with exceptionally low phase noise in a solid-state laser system; and new application possibilities in molecular spectroscopy, environmental monitoring, and medical diagnostics. By addressing material, optical, and systems-level challenges, this project will contribute to next-generation frequency comb technology and elevate the capabilities of precision optical systems across disciplines.

[1] K. Suliga, J. Sotor, and M. Kowalczyk, "Direct electro-optic phase control for carrier-envelope offset frequency stabilization in solid-state lasers," Optics Express **33**, 21870–21879 (2025). Publisher: Optica Publishing Group.