Towards smart lasers: nonlinearity management in optical fibers for ultrashort laser pulse generation supported with machine learning

Popular science abstract

The scientists agree that ultrashort laser pulses are the shortest phenomena ever created in nature. What do we understand under the term "ultrashort"? The current state-of-art laser systems can generate few tens of femtosecond-short pulses routinely (a femtosecond is a billiardth part of a second, i.e., 1 fs = 10^{-15} s). The shortest laser pulse that can be physically generated corresponds to one full cycle of the electromagnetic waveform. It means that at a wavelength of 1.55 μm (typical wavelength used in telecommunications, for high-speed data transmission in optical fiber networks), the shortest pulse can be only 4.3 fs long. It is the time period that is necessary for light to travel a distance of 1.55 micrometers. Such short pulses fascinate scientists from almost all areas of technical and life sciences. They allow us to observe phenomena so fast that we cannot follow them using any other method. These pulses are used similarly to a shutter in a photographic camera while taking a photo of a moving object. If the shutter opening time is sufficiently short, the object will be sharp and not blurred. In professional-use cameras, a shutter of 1/5000 s is enough for taking photos of, e.g., a runner or a fast sports car during a race. A femtosecond laser provides a shutter almost a billion times shorter than a photo camera. Therefore, we can "photograph" various ultrafast processes like chemical reactions or electron movement in atoms. It is a significant contribution to our basic knowledge about fundamental chemical and physical phenomena. On the other hand, femtosecond laser technology enabled the development of many new techniques in industrial manufacturing, metrology, or medical diagnostics.

Unfortunately, lasers capable of emitting pulses that short are usually quite complicated and expensive setups, absolutely not designed to be used outside the scientific laboratory. Moreover, there are so many physical effects occurring in ultrashort-pulsed lasers (not yet fully understood), which are nonlinear and thus unpredictable. Manual tuning of such lasers is really bothersome and time-consuming. Scientists using such lasers very often spend long hours (and sometimes even months!) on them to squeeze out another femtosecond. In this Project, we will explore tools that will save researchers time and help them not to worry about the performance of their lasers: we intend to use artificial intelligence, in the form of so-called machine learning. By machine learning, we mean algorithms that can improve and enhance themselves through experience. We will equip our lasers with a special element, a so-called programmable optical filter, which is capable of shaping the temporal and spectral profiles of pulses. The pulse shaper will be controlled by a computer with a machine learning algorithm. Based on the data gathered from the pulse measurement device, the algorithm will learn how changing the parameters of the programmable filter affects the duration of the pulse, and will find the right conditions under which the laser will generate the shortest possible pulses.

Sounds trivial! Of course, in real life, the whole thing is not so simple and requires several years of work by a four-person research team. First, we need to design and build appropriate laser systems and understand the impact of individual nonlinear phenomena on the parameters of generated pulses. Then we will deal with artificial intelligence - we will study various methods of machine learning and choose the most appropriate. We will check if the selected algorithms can be applied to our lasers. We will explore several configurations of laser systems: from quite simple to more complex ones incorporating pulse amplifiers and compressors.

Eventually, once we have achieved few-cycle pulses, we will use them as a source to study nonlinear phenomena occurring in nonlinear optical crystals. There exist specialized crystals that can convert the pulses from one wavelength to a completely different one: for example, from the infrared to the visible, or vice-versa. The proposed project will be a response to the current demands of biologists, chemists, physicists, and electrical engineers: building a laser that emits ultrashort pulses in the visible spectrum (i.e., approximately 720 – 770 nm), and development of a source emitting radiation from the other end of the electromagnetic spectrum, namely mid-infrared (> 3000 nm). The first one is particularly desirable in such applications as microscopy: so-called multiphoton fluorescence microscopy. This technique enables in-vivo eye retina imaging to better understand the vision process or early diagnosis of diseases. The second one will be an essential building block of laser spectroscopy platforms – for precise and accurate detection of small amounts of gases and molecules (e.g., air pollutants, greenhouse gases) in the atmosphere.