Ultrafast optical sampling oscilloscope

Abstract:

Unlike traditional optical correlation techniques, ASychromous OPtical Sampling (ASOPS) offers a number of advantages in terms of resolution, speed, accuracy and precision. This whitepaper reports on how the technique of ASOPS can deliver these benefits, with particular emphasis showing the precision available.

The dimensions of functional objects governing our daily life are ever decreasing with technical progress. Therefore, it is essential for scientists to better understand the dynamics of physical processes at the microscopic and even nanoscopic scales. This includes knowledge on processes such as heat transfer and dissipation at transistor level in computer chips; energy relaxation in solar cells; organic semiconductors for flexible screens, and even dynamics in mesoscopic objects suspended in electro-magnetic fields such as the atom clouds used in novel optical atomic clocks.

Researchers have traditionally employed optical correlation techniques to facilitate ultrafast optical time-domain spectroscopy (TDS). Such techniques utilise a very short laser pulse to generate a non-equilibrium state in an object and a second time-delayed pulse to record an instant image of the sample's reaction to the excitation at a defined post-excitation moment.

Classical approaches to ultrafast optical TDS use a single pulsed laser and a beam splitter to create pump and probe pulses in spatially separated beams. One pulse travels a path with variable length for relative time of flight adjustment before both pulses reach the sample. In most cases, timing is controlled via a retroreflector on a mechanical translation stage with travel ranging from a few centimetres up to a metre. These stages can be problematic and cumbersome as they tend to cause significant time axis calibration errors and beam walk-off via residual misalignment, as well as pitch and yaw during travel. Moreover, any delay

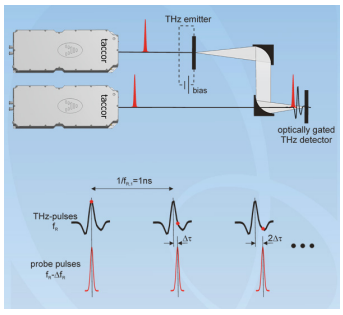

Figure 1: Optical layout of ASOPS based THz-TDS experiment. One laser pulse train pumps an emitter of THz radiation, the second probes the THz pulses in an optically gated detector (after interaction with a sample). As result of the repetition rate offset, the probe laser samples different advancing data points of the signal with each pulse pair.

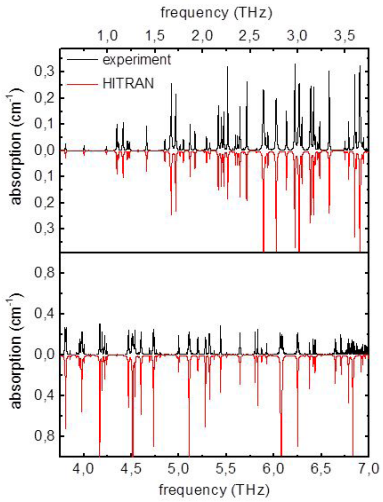

Figure 2: THz absorption of water vapor compared to data compiled from the HITRAN database. Agreement below ~2.5THz is excellent with dynamic range limitations to the peak height at higher frequencies. Total measurement time was 1 minute.

stage will add noise if data is taken on the fly (i.e. while in motion) or cause dead time if it needs to be accelerated and decelerated to allow settling between data points and avoid acoustic noise. This dead time and the fact that the significant physical mass of a stage can't be moved arbitrarily fast, fundamentally limits the measurement speed. Therefore, measurements under rapidly varying environmental or physical conditions (e.g. in pulsed magnetic fields, rapid temperature or pressure changes) or the investigations of dynamic phenomena become impossible, and imaging applications of ultrafast optical TDS require unreasonably long frame acquisition times.

Asynchronous optical sampling (ASOPS), however, is an approach to ultrafast optical TDS avoiding the above issues, pioneered by Elzinga et al. in 1987 with picosecond lasers [1]. It was transferred to the femtosecond world by the authors in 2005, employing two femtosecond lasers with repetition rates f_R at 1GHz locked together in a master-slave configuration with a slight offset Δf_R [2]. This offset, typically between 1 and 10kHz, causes the delay amongst pairs of pulses from the lasers to incrementally increase by $\Delta\tau=\Delta f_R/f_R^2$ with each shot, i.e. by 10fs at Δf_R =10kHz. Figure 1 illustrates the principle for a terahertz-TDS setup. The lasers are then used exactly as in a classical setup except that no translation stage is required. Timing precision is now determined by the ability to measure and stabilise the repetition rate offset. Uncertainties at the level of a few parts in 10^5 are reached, typically more than an order of magnitude better than mechanical delay generators.

The key feature of the ASOPS approach is speed, enabling applications that are impossible with mechanical delay generators. A typical system scans 1ns long TDS traces at sub-100fs resolution in an acquisition time as short as 100µs. By comparison, a translation stage would have to move 15cm distance at an average speed of

Figure 3: The Laser Quantum **taccor** with 1GHz repetition rate, to facilitate the ASOPS principle.

1500m/s in order to achieve the same. This leaves the user full freedom to acquire data in a single shot fashion in very rapid succession or to average an arbitrary number of scans to enhance the signal to noise ratio. A further bonus of ASOPS is that the temporal zero point does not need to be searched, a task that can be quite tedious in a classical setup. Here we discuss an application where ASOPS plays out its advantages in THz spectroscopy.

Another characteristic of the ASOPS technique is the improvement in the precision and accuracy of frequency measurements. Figure 2 shows a measured absorption spectrum of ambient air with 28% relative humidity between 0.5 and 6.5THz and with 1GHz resolution compared with data compiled from the HITRAN database, a widely accepted reference for spectroscopic data [3]. The total measurement time was 60 seconds. The qualitative agreement between the spectra, even for the smallest and weakest features, is remarkable and differences in the absorption values are at the 1% level for frequencies below ~2.5THz, increasing towards higher frequencies only due to limitations in the dynamic range of the system that could be overcome by longer averaging time. An evaluation of frequency accuracy of our data compared to the HITRAN reference shows a mean error of only 140MHz or at 9×10^{-5} in relative units which is in line with earlier mentioned expectations. These values are at least an order of magnitude lower than reports for classical systems at comparable measurement time and bandwidth. Even at 1 second acquisition time, the mean frequency error only slightly degrades to 160MHz. This level of precision has been shown to enable accurate spectroscopy of weakly concentrated constituents of a gas mixture within a highly absorbing background by fitting and subtraction of reference data [4].

The experiment summarised here has been performed using two **taccor** lasers with 1GHz repetition rate and the repetition rate offset stabilisation unit **TL-1000-ASOPS**, both from Laser Quantum, to facilitate the ASOPS principle. For this application, the step from stage to ASOPS is probably equivalent to the step from an analog data plotter to a digital sampling oscilloscope.

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References:

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