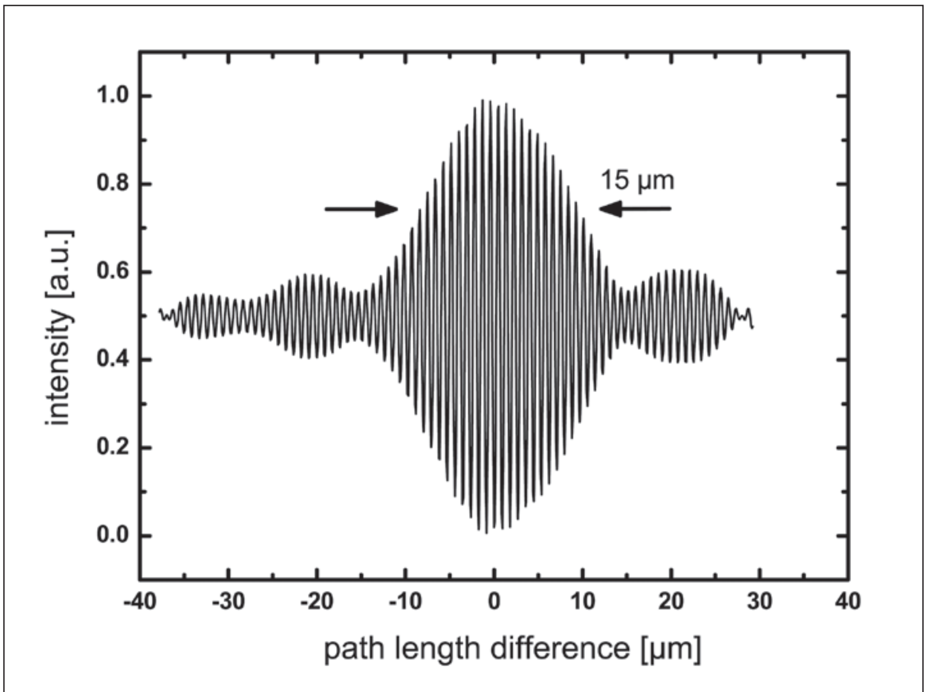
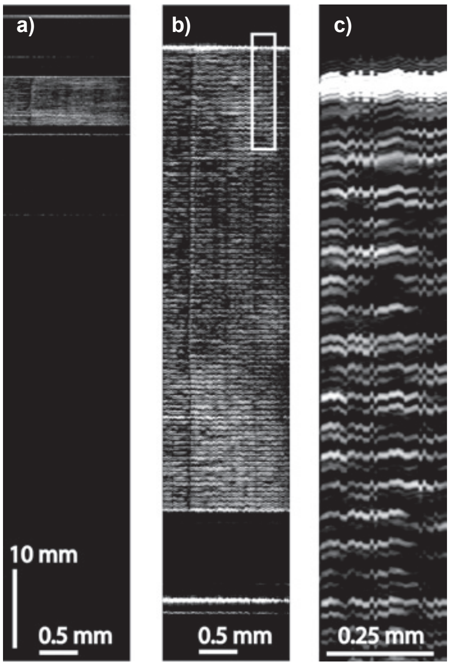
Optical Coherence Tomography with fs Fiber Lasers and ECOPS

Optical sampling techniques speed up optical coherence tomography measurements by several orders of magnitude. Novell approaches benefit from the smart use of electronical feedback loops, thus replacing all movable parts in tomography setups.

Optical coherence tomography (OCT) is becoming a popular analytical tool these days. Originally developed for ophtalmology, OCT now spreads over to a variety of applications, e. g. material inspection. The benefit of this technique is the imaging capability of sample structures which are located even a few millimeters inside the sample with micrometer accuracy.
For example, invisible defects lying underneath the surface of manufactured parts can be detected. Real-time OCT therefore enables online quality control and lowers the waste of production processes.
OCT relies on low coherence interferometry utilizing spectrally broad light sources like superluminescent diodes or pulsed ultrafast lasers. The typical setup is based on a Michelson type interferometer with a sample branch and a reference branch. The (laser) light is first split and – after passing both branches – overlayed again on a photodetector. In time-domain OCT (TD-OCT) the reference light pulses are delayed in time using a mechanical translation stage. The reference pulses interfere differently with the sample pulses at the photodetector depending on the position of the stage. The detected amplitude modulations at each position lead to the desired depth information of the sample. The axial resolution of OCT is determined by the coherence of the light source respectively its spectral bandwidth. Today, ultra-broadband ultrafast lasers push the resolution of OCT down to approx. one micrometer.
Recording speeds in TD-OCT are limited by the slow mechanical scanning of the translation stage. Therefore, spectrally detecting OCT techniques were developed. They lack however the huge imaging depth of TD-OCT. In this article, two new approaches will be discussed which replace the mechanical stage by much faster electronics. In this way the biggest drawback of TD-OCT is inverted into its biggest advantage: very fast scanning while maintaining the long imaging depth. These approaches are named »asynchronous optical sampling« (ASOPS) and »electronically controlled optical sampling« (ECOPS).
In contrast to the standard procedure, not only one but two ultrafast lasers are employed: one for each branch of the interferometer. Both lasers emit light pulse series with a fast repetition rate of typically 100 MHz. The time window between two consecutive pulses is therefore 10 ns and corresponds to the round trip time of the laser resonator. The sample and reference pulses must hit the detector at nearly the same time to generate the desired interference patterns. Due to the active control of the resonator lengths, both round trip times are kept the same and therefore both lasers are synchronized. In this case the time windows of both pulse series are equal. There's only a constant time difference left between both pulse series. This time delay is technically also referred as phase difference. The synchronization is actively controlled



▲ **Fig. 1: Typical interference patterns for TD-OCT measurement. The full width half maximum of the peak determines the axial resolution of 15 µm in this setup.**



▲ **Fig. 2: Exemplified OCT scan of a tape roll as sample. From left to right with increased resolution the single layers become better and better visualized.**

by an electronic feedback loop which therefore is called »phase locked loop« (PLL). Setting the time delay to zero, which means that pulses from both series hit the detector at exactly the same time, is accomplished mechanically or also electronically.

The depth scanning in TD-OCT is achieved with a prolongation of the reference branch. This produces a time delay of the reference pulses in regard to the set time zero: the reference pulses hit the detector later. Interference is now only possible, if the sample pulses are scattered back from a deeper structure inside the specimen under investigation in comparison to the time zero. This leads to the depth information of the sample – as mentioned earlier.

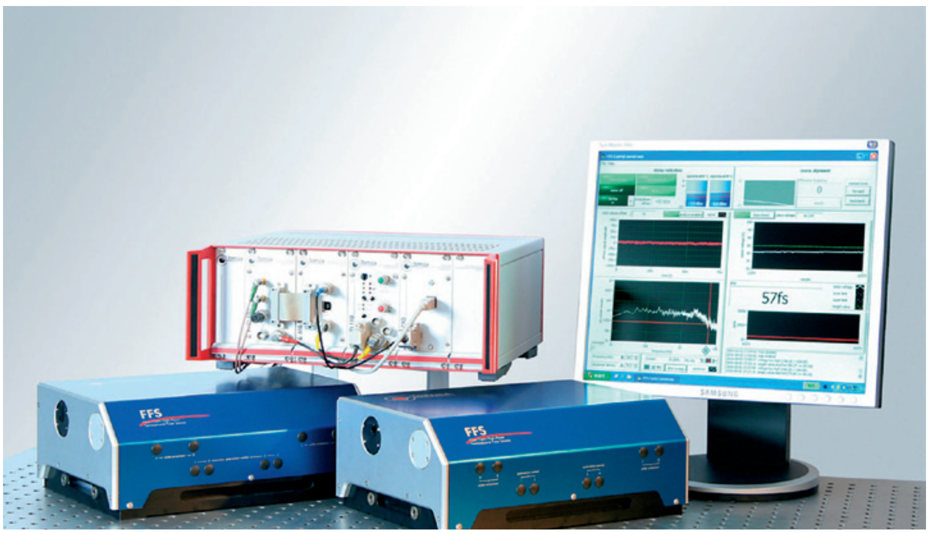
The PLL-electronic allows changing the phase difference or time delay between both pulse series and adds the needed degree of freedom. Now the mechanical translation stage of the reference branch becomes obsolet.

To achieve this, the feedback loop of an ASOPS system keeps the resonator lengths of both lasers different by a small amount. The corresponding round trip times differ accordingly and the pulse series are asynchronous (leading to the name). This means that each reference pulse hits the detector earlier than the respective sample pulse with a steadily increasing time delay. This happens until the reference pulse has overtaken the earlier emitted sample pulse and the game starts again. The round trip times typically differ only by just 100 fs and so the entire time window of 10 ns is scanned after the emission of 100.000 laser pulses. With a repetition rate of 100 MHz it is possible to scan the entire time window with a rate of 1 kHz. The time window of 10 ns corresponds to an imaging depth of 1.5 meter. The otherwise used mechanical stage would need to scan more than 1 m in less than 1 ms – which seems impossible. The optical sampling speed is therefore more than 3 orders of magnitude faster. Although ASOPS allows for an extraordinary high scanning depth, the penetration depth within the sample structure usually amounts to only a few millimetres, which is only a small fraction (1/1000) of the scanned delay. Despite the very fast scanning rate of 1 kHz, no useful signal is generated in 99.9 percent of the measurement time.

Lasers with significant shorter resonator lengths must be used to improve this unwanted waste of time. Few resonators can have round trip times of only 1 ns and shorten the scanning depth down to 15 cm. Here, at least 1 percent of the measurement time generates useful signals.

A simpler and more flexible approach is taken by ECOPS. While in ASOPS the time window is continously scanned with fixed time steps (e. g. 100 fs), ECOPS offers variable step sizes.

The degree of freedom which is intrinsic to mechanical delay lines is preserved: the time delay can be kept constant, shortened or prolonged. This additional degree of freedom makes it feasible that nearly 100 percent of the measurement time can be utilized. In contrast to the mechanical delay, the step sizes are controlled electronically (leading to the name). Therefore ECOPS shares the biggest advantage with ASOPS: the fast scanning speed. Applying a voltage to the electronic feedback loop of ECOPS determines the time delay between both pulse series. Increasing the voltage increases the delay and lowering the voltage decreases the delay. For example, applying a triangular voltage let the reference pulse advance the sample pulse until the maximum voltage is reached and then retard again until the minimum voltage is reached and



▲ **Fig. 3: ECOPS system with two FFS lasers and the PLL electronics von TOPTICA Photonics** so forth. Therefore the scanning delay can be choosen freely – with proper setting of amplitude and offset of the applied voltage. This offers also another advantage over ASOPS: The size of the time window doesn't play any role and »normal« laser resonators can be used. Nevertheless nearly during the entire measurement time useful signals are generated, because only the relevant delay range is scanned with the proper choice of the applied voltage.

Both optical sampling techniques were first successfully demonstrated by S. Kray and coworkers from the Institute of Semiconductor Electronics of the RWTH Aachen University. They employed the ECOPS system from TOPTICA Photonics. This consists of two femtosecond fiber lasers and the perfectly adapted PLL electronics which enables the synchronization of both pulse series with a timing jitter of less than 100 fs. A triangular voltage with a frequency of up to 600 Hz was applied to the phase locked looped of the ECOPS system and the interference patterns were recorded with the transient recorder »Saturn« from AMO GmbH. Fig. 1 depicts a typical interference peak which shows the axial resolution of 15 µm achieved in this setup. Fig. 2a) shows the OCT image taken from a tape roll as sample. Every single layer of the roll is clearly visible (see Fig. 2b) and 2c)). ECOPS enables the imaging of huge depths as well as of small regions of interest by the proper choice of amplitude and offset levels of the applied voltage. This allows the user to realize an electronically controlled optical zoom in OCT.

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