Research Center for Non-Destructive Testing GmbH (RECENDT)
Optical coherence tomography group

SC4500 supercontinuum source for mid-IR OCT imaging

Ivan Zorin* and Bettina Heise
*ivan.zorin@recendt.at

June 27, 2022

Optical coherence tomography (OCT) is a well-established technique for non-destructive and non-contact three-dimensional structural imaging of complex samples. OCT systems are versatile, providing high spatial performance and high sensitivity at high imaging speed. For these reasons, OCT methods operating in the visible and near-infrared (near-IR) spectral ranges are the gold standard for various biomedical research and diagnostics.

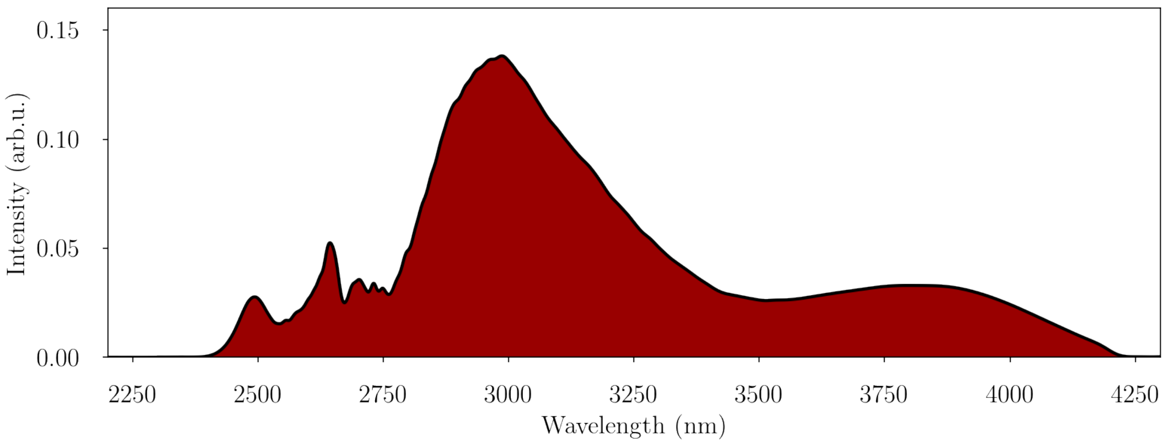
Advances and developments in mid-IR light sources and detection technologies have recently enabled OCT to move further towards longer wavelengths. Several reports on mid-IR OCT imaging have been published over the past few years, starting in 2018. OCT in the mid-IR spectral range is still in the research and development phase but is already attracting a lot of attention due to its superior immunity to scattering. Thus, mid-IR OCT systems facilitate increased probing depth for high-scattering (e.g., porous, turbid) materials. This opens up various new application possibilities and is of great interest also beyond biomedicine that is traditional for OCT.

One of the enabling technologies for mid-IR OCT was supercontinuum light generation. Supercontinuum sources are suitable for mid-IR OCT because they have appropriate emission parameters and provide high brightness in ultrabroad spectral ranges [1].

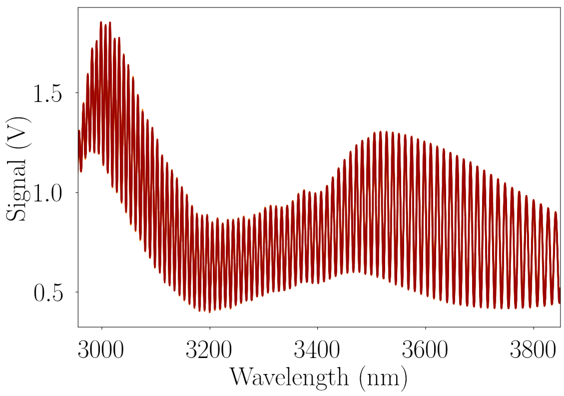
Researchers at the Research Center for Non-Destructive Testing have recently applied the novel Thorlabs SC4500 supercontinuum source for mid-IR OCT imaging, characterized its emission properties and evaluated the imaging capabilities. SC4500 is a femtosecond-laser-pumped supercontinuum source based on a dispersion-engineered indium fluoride (InF_3) fiber. The supercontinuum source provides a spectral coverage from approximately 1.3 µm to 4.5 µm with around 100 mW of average power emitted in the mid-IR range (see the emission power spectrum in Fig. 1(a)); the combination of the emission properties is well suited for mid-IR OCT applications. A particularly relevant feature of the SC4500 source is the high pulse repetition rate of 50 MHz that enables superior pulse integration capabilities and quasi continuous-wave operation for standard photonic mid-IR detectors.

The SC4500 supercontinuum source was integrated into a time-coded mid-IR spectral-domain OCT research setup [2]. The OCT system was re-configured, calibrated, and adapted for the source. Since the supercontinuum source has a free-space output, the emission was coupled into an intermediate InF_3 fiber (Thorlabs P1-32F-FC-2) to facilitate integration. A reflective collimator (Thorlabs RC04FC-P01) was employed for this purpose; due to the high beam quality, the coupling efficiency was 65.2%. For detection, a MCT detector (7 ns time constant) was used.

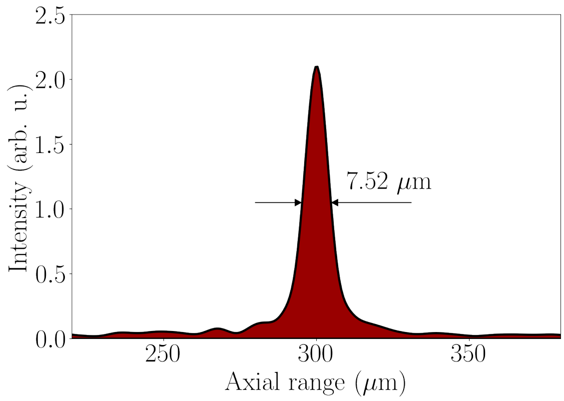
The spectral range from 2955 nm to 3850 nm was used for OCT imaging in the mid-IR range as the emission features a suitable shape in this region. Due to the enhanced averaging capabilities provided by the high repetition rate, the supercontinuum source demonstrated



(a) Emission power spectrum of SC4500 (FTIR measurements, mid-IR part, 2.4 µm edge-pass filter is used)



(b) OCT system: 50 sequentially recorded interferograms



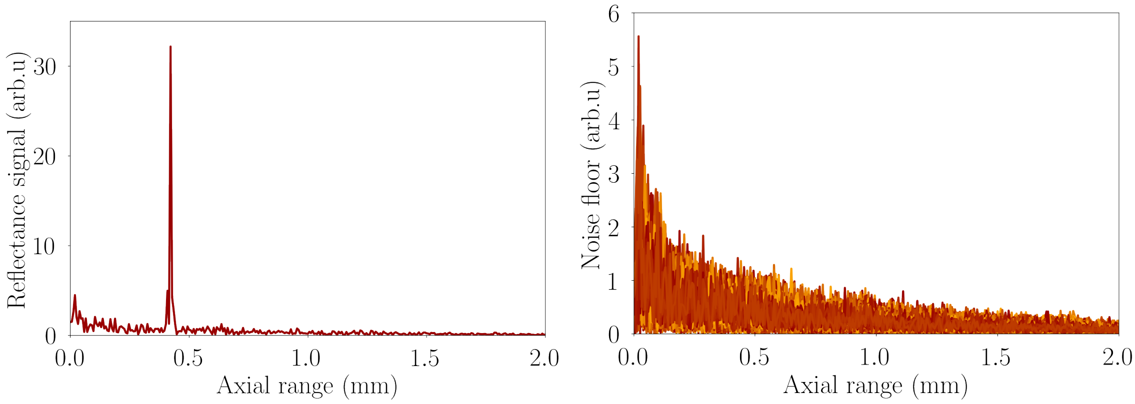
(c) OCT System: characterization of axial resolution

Figure 1: Spectral characteristics of the SC4500 supercontinuum source and corresponding mid-IR OCT imaging features.

superior short- and long-term spectral stability. Figure 1(b) shows 50 sequential spectral interferograms (for a single metal reflector) recorded with the OCT spectrometer. The acquisition time for one spectrum is about 40 ms. The interferograms exhibited high phase and amplitude stability as the fringes are stable from frame to frame. In addition, an Allan variance analysis was performed for the evolution of the spectrum shape over 7 hours; the analysis revealed the predominance of white noise during 420 sec.

The time-coded OCT spectrometer was calibrated using a tunable Fabry-Pérot filter. Prior to performing the Fourier transform, a nonlinear remapping of interferograms into k-space was applied. The axial resolution of the system for the given spectral bandwidth was characterized using an A-scan of the mirror. Figure 1(c) depicts the axial point spread function (smoothed), the full width at half maximum is around 7.5 µm. which is high enough for OCT in the mid-IR range.

The signal-to-noise ratio of the SC4500-based OCT system was characterized using a standard procedure. An A-scan of a flat gold mirror behind a neutral density filter (optical



(a) A-scan of a gold mirror behind a neutral density filter (Thorlabs NDIR20B, OD=2, 1% transmission)

(b) Background noise floor used to calculate the noise level

Figure 2: Characterization of signal-to-noise ratio for the SC4500-based mid-IR OCT system; the resulting sensitivity of the system is 79 dB; the high repetition rate of the source provides extensive pulse averaging reducing noise.

density of 2, i.e 0.01% of the sample arm intensity was detected) was obtained. The scan clearly shows the image of the mirror above the noise floor [see Figure 2(a)]. The noise level was calculated as the standard deviation of the background noise [within 2 mm axial range, see Figure 2(b)], the sample was removed for noise assessment. The sensitivity of the mid-IR OCT system based on the SC4500 supercontinuum source was calculated using the derived levels and is 79 dB.

The imaging capabilities of the mid-IR OCT system based on the SC4500 source were verified experimentally. For the evaluation, various high-scattering ceramic samples were selected. These samples cannot be examined with any commercial near-IR system due to the dominance of multiple scattering events. The sample materials are industrial—some parts were fabricated using the emerging method of lithography-based ceramic manufacturing (LCM)—and are of great applied interest. The LCM samples were fabricated and provided by Lithoz GmbH. A simple sintered polycrystalline aluminium oxide ceramic sheet (0.3 mm thickness, porosity 1%, mean air pore diameter 0.4 µm) was measured at first as a proof-of-concept. A B-scan of the plate is shown in Fig. 3(a); both interfaces are revealed and imaged, volumetric scattering within the sample can also be observed providing additional information. Figure 3(b) displays a cross-sectional scan of a 450 µm thick ceramic sheet with laser-milled microchannels (sintered polycrystalline aluminium oxide, porosity 1%, mean air pore diameter 0.4 µm). The channels as well as both interfaces are well distinguishable. In contrast to the scan shown in Fig. 3(b), this plate has a lower roughness of the top interface, thus the signal from the top surface is remarkably higher. A B-scan of a significantly more challenging aluminium oxide microstructured sample (325 µm thick) is shown in Fig. 3(c). This sample is 3D printed, produced by the LCM method and has higher porosity (around 2%) and surface roughness. Despite high surface and volumetric scattering, the complete structure of the sample was accessed and can be analyzed. A manufacturing defect occurring during thermal processing (curved shape) can be observed. Figures 3(d) and (e) depict volume and en-face scans of a green part—an intermediate LCM part that consists of ceramic particles embedded in a polymer matrix (at a production stage before the thermal treatment stage). The green part has a thickness of about 650 µm. The material is strongly scattering and cannot be probed by near-IR OCT, while mid-IR OCT can efficiently image the complete structure and reveal possible imperfections.

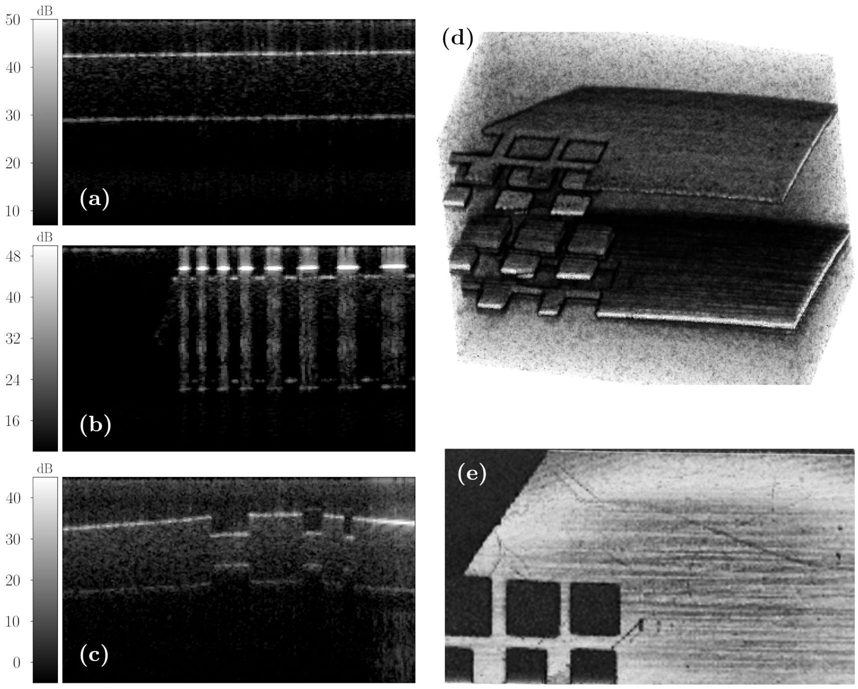


Figure 3: OCT scans recorded: (a) B-scan of 300 µm thick sintered alumina sheet (1% porosity), scan length 8 mm; (b) B-scan of 450 µm thick sintered alumina sheet with embossed microchannels (1% porosity), scan length 8 mm; (c) B-scan of high-porous (2%) and high-roughness 3D printed ceramic alumina sample (325 µm thick), scan length 8 mm; (d) volume scan (4×8 mm^2 area) of a green LCM part [650 µm thick, corresponds to the printed part shown in (c)], consists of ceramic particles embedded in a polymer matrix; (e) En-face scan of the back interface, retrieved from (d).

The experimental results presented here show that the SC4500 supercontinuum source is well suited for mid-IR OCT imaging. The broad spectral bandwidth enables high spatial resolution of the OCT system that is above the standard for OCT in the mid-IR range. In addition, the high pulse repetition rate of the supercontinuum emission offers extensive pulse averaging thus lowering spectral noise and increasing the sensitivity of OCT modality. The source can be seamlessly integrated into mid-IR OCT systems and, as shown above, can be used for material research and imaging of highly scattering samples in applications that are hindered by near-infrared OCT.

References

[1] I. Zorin, P. Gattinger, A. Ebner, and M. Brandstetter, "Advances in mid-infrared spectroscopy enabled by supercontinuum laser sources," *Opt. Express*, vol. 30, pp. 5222–5254, Feb 2022.

[2] I. Zorin, P. Gattinger, A. Prylepa, and B. Heise, "Time-encoded mid-infrared fourier-domain optical coherence tomography," *Opt. Lett.*, vol. 46, pp. 4108–4111, Sep 2021.