

Optical Coherence Tomography

SPECIAL NOTE:

OCT Microscope Now
Beta Testing at
Selected Customers.
Commercial Availability-
January 2006.



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Rapid 3-D Optical Coherence Microscope Based on Swept Source Optical Coherence Tomography

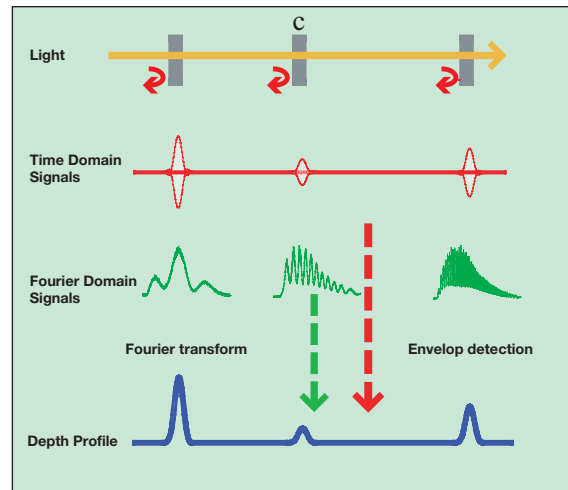
Introduction

Optical Coherence Tomography (OCT) has found widespread applications for cross sectional imaging of tissue in-situ with micron scale resolution. Recently, OCT techniques based on Fourier domain detection have become an active area of research. Analogous to frequency domain reflectometry, these detection techniques measure

magnitude and time delay of light by spectrally resolved detection of the interferometric back-scattered signal from the sample.

A high-speed three-dimensional optical coherence microscope using the swept source optical coherence tomography technique has been developed by Thorlabs, Inc. in Newton, NJ. The system incorporates a broadband

high-speed swept laser source, a fiber-based Michelson interferometer, and a multi-functional microscope to provide simultaneous en-face microscope imaging and cross-sectional tomographic imaging of the sample. Novel data acquisition and signal processing methods that support real-time video-rate two-dimensional imaging have been demonstrated. Three-dimensional imaging and optical profiling of the sample have also been demonstrated with this microscope system.



Measurement of the echo of light using time domain and Fourier domain methods

OCM1300SS Microscope System: Capable of simultaneous cross-sectional OCT imaging and conventional en-face microscope imaging as well as three-dimensional imaging of the sample.

Imaging Specifications

2D Cross-sectional OCT Imaging Capability

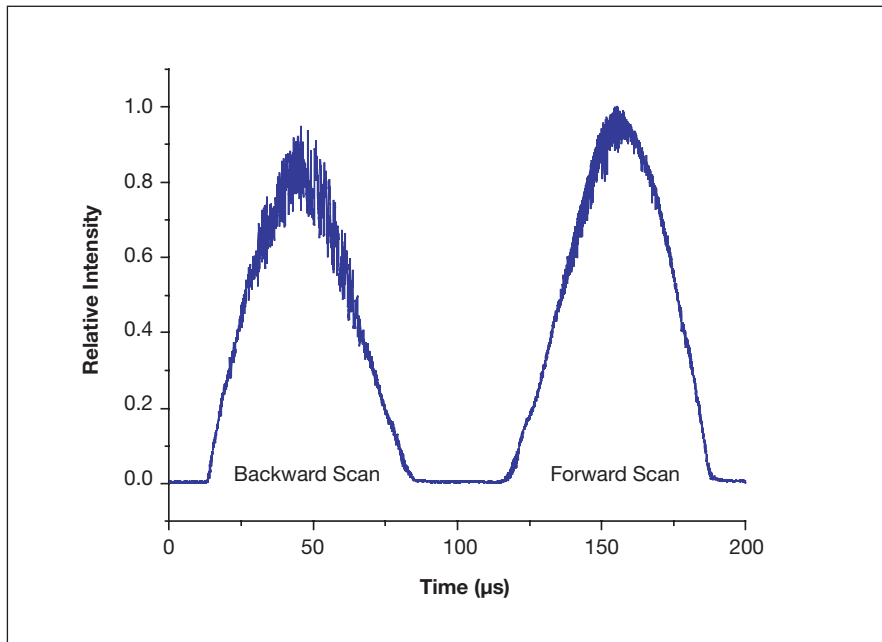
- Imaging Speed: 25 Frames Per Second (Based on 500 Axial Scans Per Frame)
- Maximum Image Size: 800 (W) x 512 (H) pixels
- Maximum Imaging Width: 6mm
- Maximum Imaging Depth: 3mm
- Axial Resolution: 12 μ m (in Air)
- Transverse Resolution: 15 μ m (in Air)
- System Sensitivity: 108dB

2D En-face Microscopy Imaging Capability

- CCD Camera: 2.0 Mega Pixels
- Maximum Resolution: 1600 x 1200
- Frame Rate: 100 @ 640 x 480, 20 @ 1600 x 1200

3D OCT Volume Imaging Capability

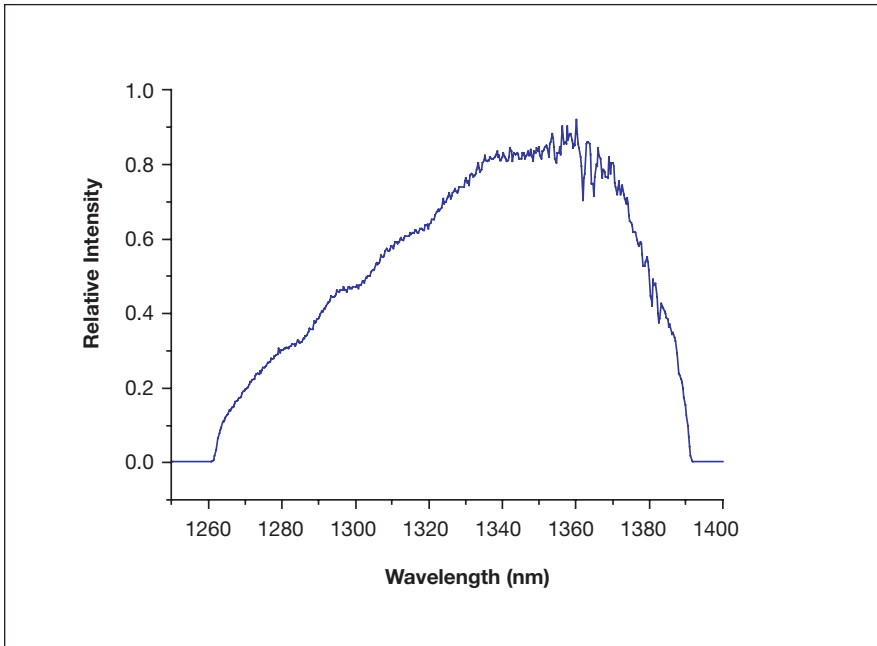
- Volume Size: 500 (W) x 500 (L) x 512 (H) Pixels
- Data Acquisition and Processing Time: 20 Seconds



Temporal intensity profile of the sweep for a backward and a forward scan.

Broadband Swept Laser Source

The swept laser engineered and manufactured in Thorlabs AB Sweden is an ideal light source for video-rate OCT microscopic imaging. The laser supports 20 kHz wavelength sweeping rate with a 3 dB spectral bandwidth up to 110 nm, centered at 1325nm.



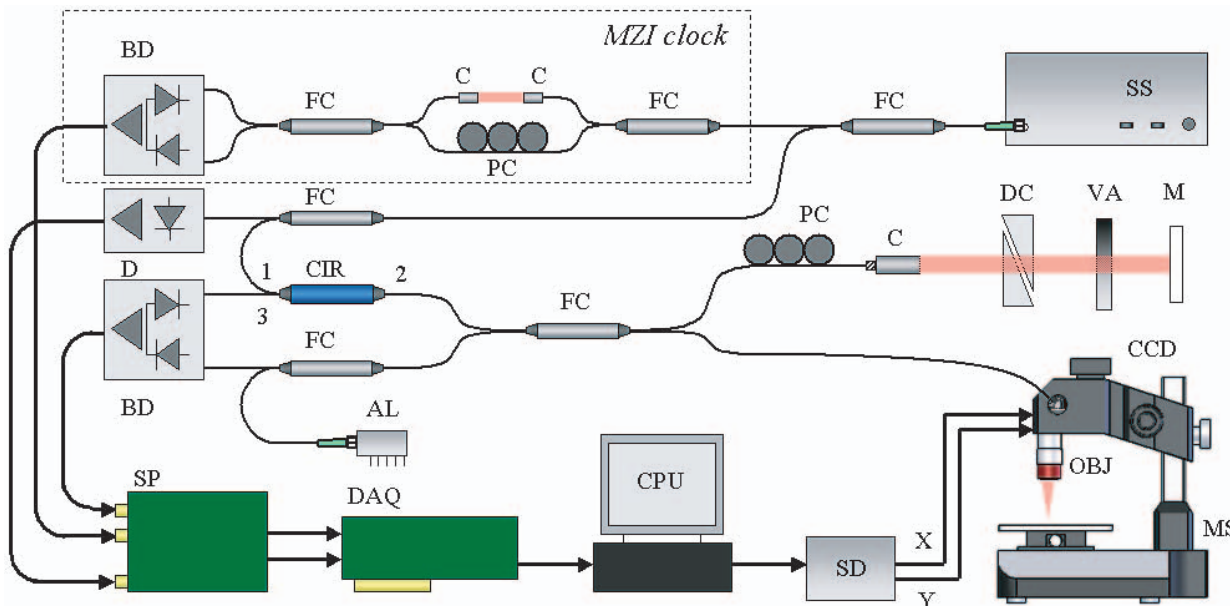
Output spectrum of the laser.

System Specifications

- Central Wavelength: 1325nm
- Spectral Bandwidth (3dB): 100nm
- Axial Scanning Rate: 16 kHz
- Analog-to-digital Resolution: 14 bits
- Maximum Analog-to-digital Conversion Rate: 100 MHz

Optional Feature

- Application Specific Probes: Upon Request

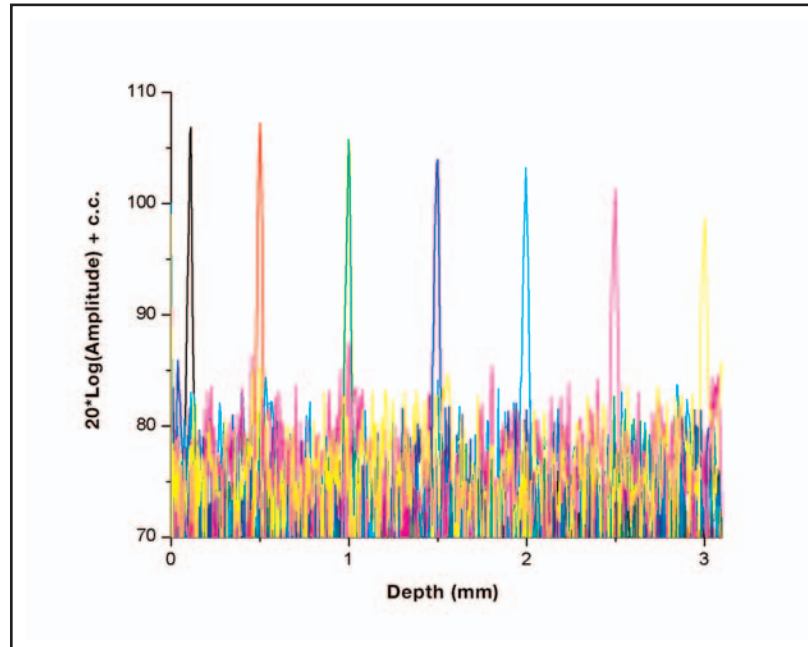


OCT Microscope Schematic

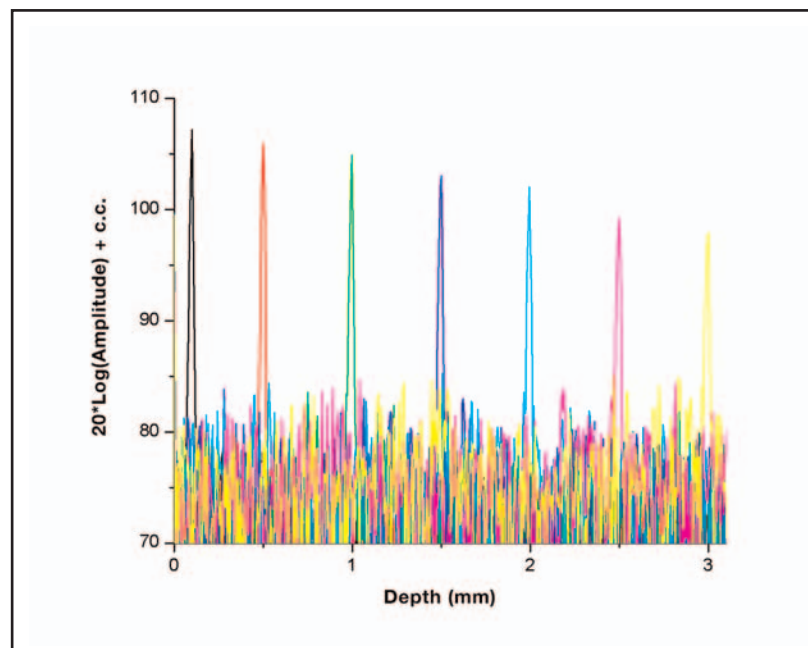
Schematic of swept source OCT microscope. SS: swept source, FC: fiber coupler, PC: polarization controller, CIR: circulator, C: collimator, DC: dispersion compensator, VA: variable attenuator, M: mirror, BD: balanced detector, D: detector, SP: signal processor, DAQ: data acquisition board, SD: XY scanners driver, CCD: CCD camera, OBJ, objective, MS: microscope. AL: Aiming Laser

System Performance

The OCT system has sensitivity of 108 dB. The coherence length of the laser is measured to be >7 mm, which supports OCT imaging depth of > 3 mm. The FWHM of the point-spread function of the interference fringes is measured to be ~12 μm for both forward and backward scan, suggest effective axial resolution of ~ 9 μm in tissue.



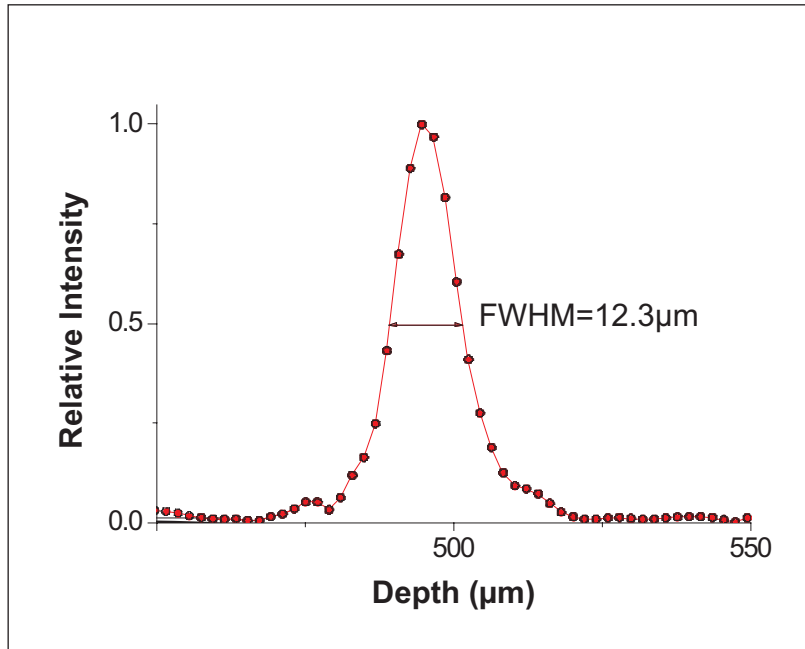
Forward scan point spread function from seven A-scans each with a different delay.



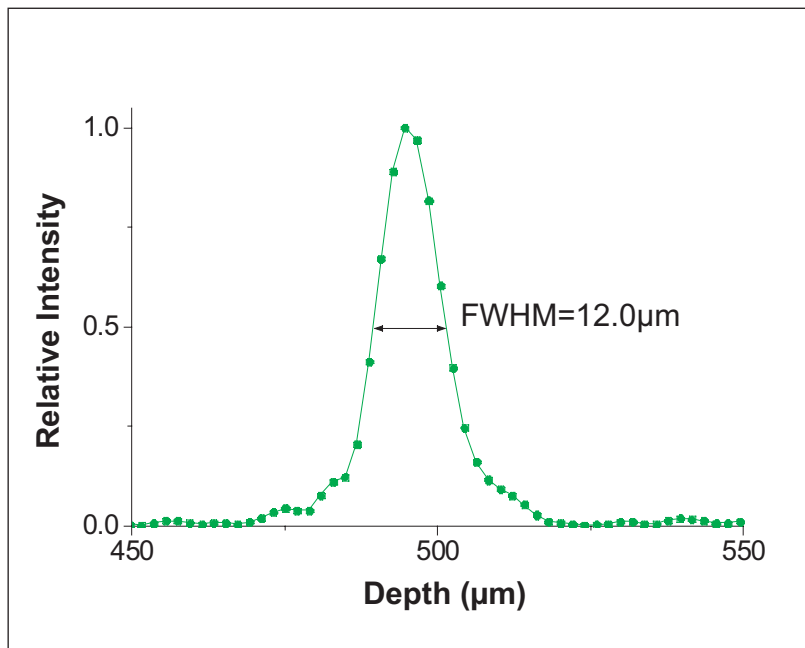
Backward scan point spread function from seven A-scans each with a different delay.

Hardware Signal Processing

An OCT signal processing board is developed to accelerate the calibration of fringe signals from time to frequency. The clock board processes the MZI clock signal to generate pulses equally spaced in frequency. The digitizer is configured in external clock mode and uses the clock pulses as time base to sample OCT fringe signals with data points linear in frequency.



Forward scan point spread function showing the resolution of the system in air.



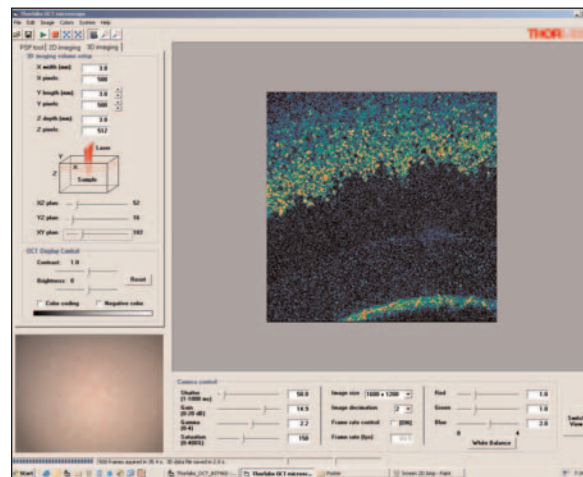
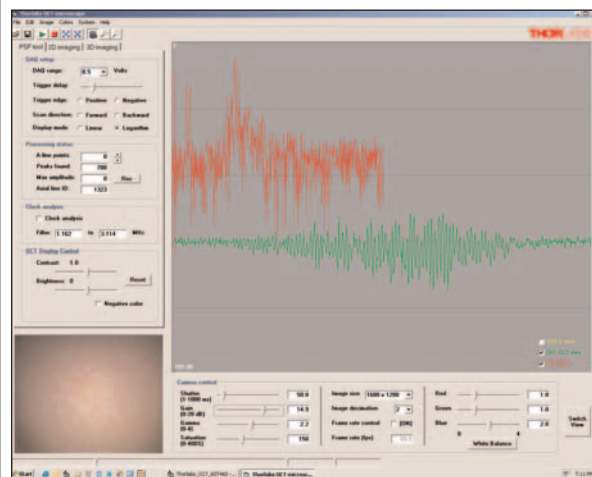
Backward scan point spread function showing the resolution of the system in air.

Microscope OCT

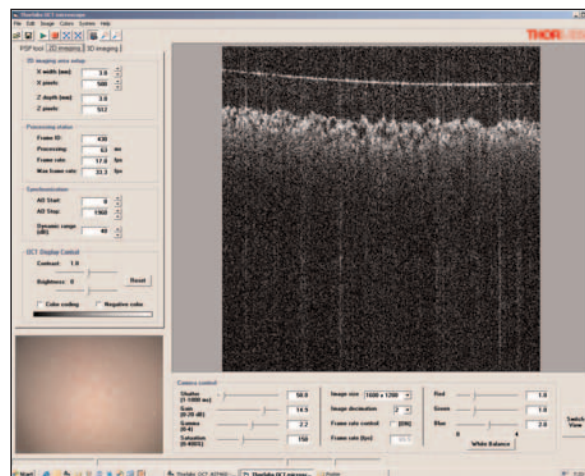
Swept Source OCT

Spectral Radar OCT

Software



OCT interference fringes point spread function diagnosis (1D mode).



CCD Channel

3D volume imaging mode (500 x 500 x 500 pixels) with en-face imaging capability.

OCT Channel

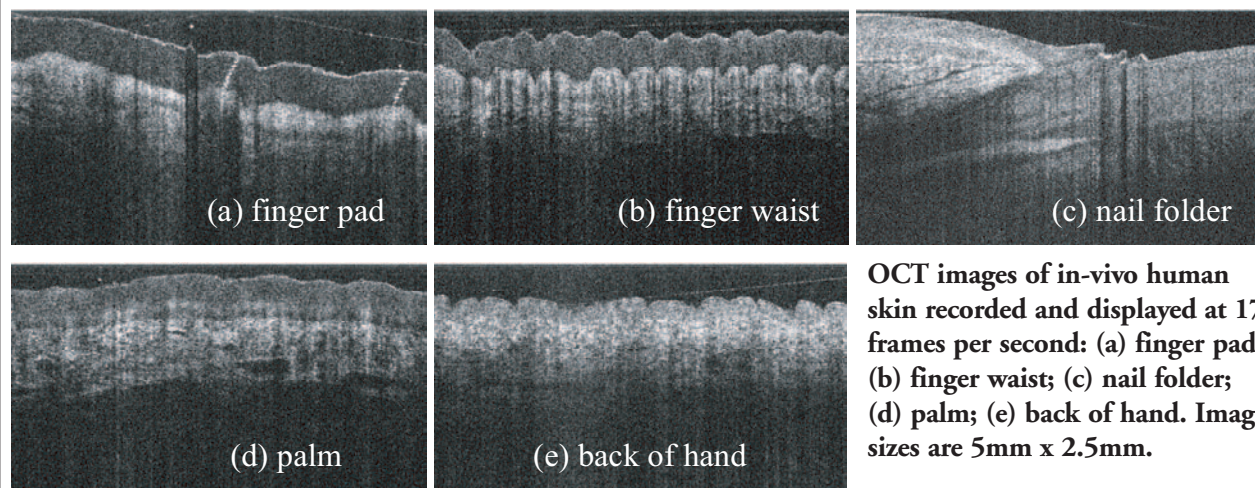
2D cross-sectional imaging mode (500 x 500 pixels)

Real time video-rate imaging

Real-time video-rate imaging speed with 17-30 frames/second based on 500 axial scans per frame and 1024 points Fast Fourier Transform (FFT) can be achieved in the swept source OCT system.

Results

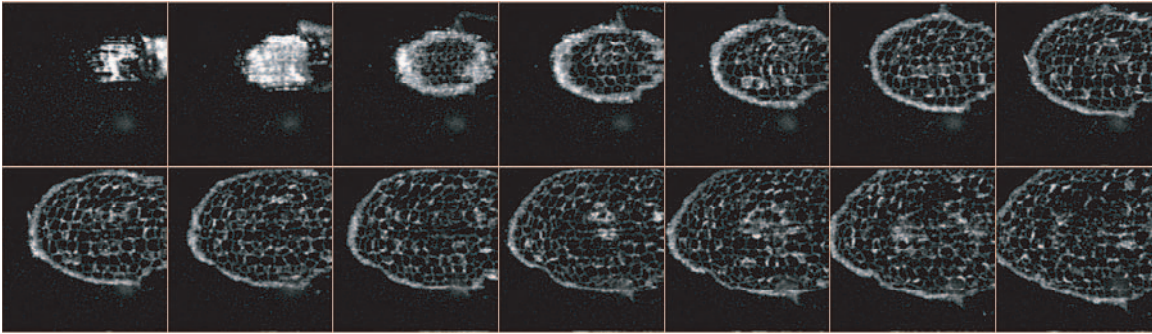
2D tomographic images of in-vivo human skin



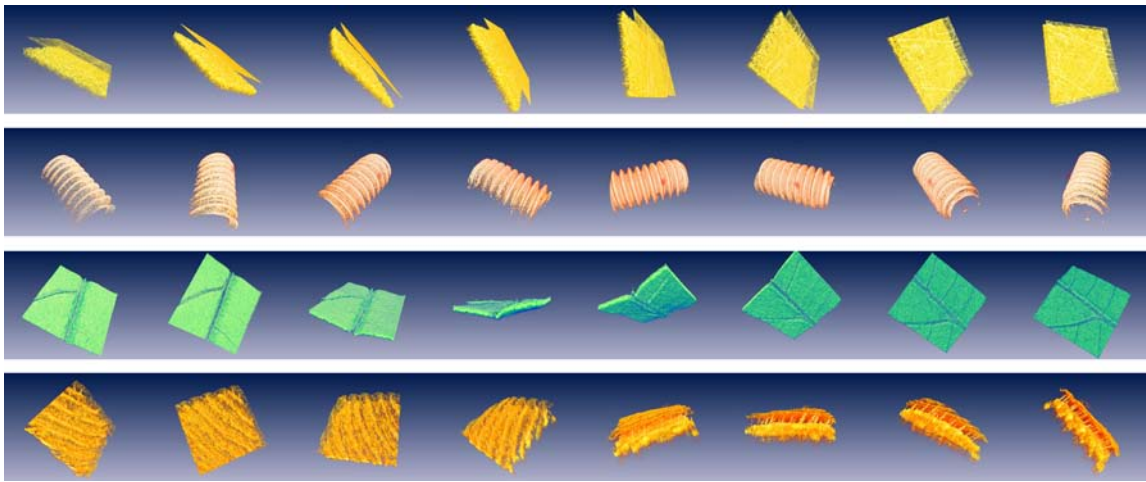
OCT images of in-vivo human skin recorded and displayed at 17 frames per second: (a) finger pad; (b) finger waist; (c) nail folder; (d) palm; (e) back of hand. Image sizes are 5mm x 2.5mm.

Serial en-face images of the onion skin

A 3 mm x 3 mm x 3mm volume containing 500 x 500 x 500 pixels



3D imaging of the sample (top to bottom: IR card, screw, leaf, skin)



Potential Applications

1. Biology and medical imaging
2. 3D optical profilometry
3. Material inspection and product quality control
4. Thin film test and measurement
5. Other non-invasive laser imaging applications

References

R. Huber, M. Wojtkowski, J. G. Fujimoto, J. Y. Jiang, and A. E. Cable, "Three-dimensional and C-mode OCT imaging with a compact, frequency swept laser source at 1300 nm", submitted to Opt. Exp. 2005.

Acknowledgements

We acknowledge scientific discussions and helpful advice from Dr. Robert Huber and Prof. James G. Fujimoto at Research Laboratory of Electronic of Massachusetts Institute of Technology.

Rapidly Swept Tunable Laser

SS-OCT Swept Source Optical Coherence Tomography



SL1325-P16

Swept Source Optical Coherence Tomography (SS-OCT) applications require a laser that can be swept over a wide wavelength interval with very high speed. The wide wavelength range is required for obtaining high image resolution, and the high tuning frequency is needed for obtaining video image rates.

Thorlabs is pleased to offer a fast sweeping, continuous wavelength, external cavity laser source specifically designed for SS-OCT applications. The standard system sweeps at least 100nm at a 16kHz repetition rate, offers a coherence length of 6mm and delivers more than 12mW of average optical power out of an SMF28 single mode fiber.

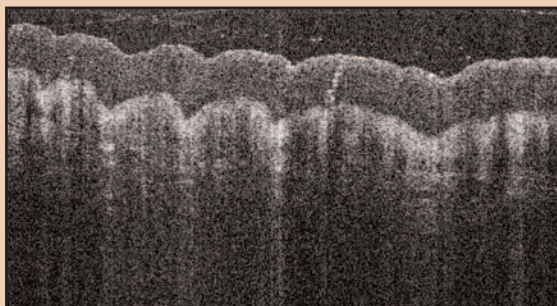
The laser is available with the following fixed scanning frequency, coherence length and tuning range:

- SL1325-P16-16KHz scanning frequency, 6mm coherence length, 120nm tuning range

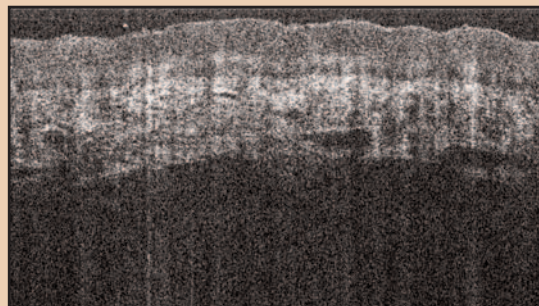
The SL1325 comes with a Mach-Zender interferometer (MZI) with an adjustable free spectral range of 50 to 100 GHz. The MZI is used to digitally resample the raw Optical Coherence Tomography (OCT) signal into equally spaced points in frequency. BNC connectors are available to monitor the wavelength sweep direction and laser intensity signals. The SL1325 comes in a 19 inch rack unit configured for 115VAC or 220/240 VAC.

OCT is a relatively recent and fundamentally new way of obtaining high-resolution images in turbid media. Various OCT techniques are employed in dermatology, surgery (surgical guidance), and in ophthalmology. One of the driving forces of the development of the various OCT techniques is to find methods for in-vivo histology. However, the OCT techniques can be used for other types of characterization and visualizing of structures in turbid media, for example, materials research. The development of OCT started in the 1990's and is a continuously growing field of research and usage.

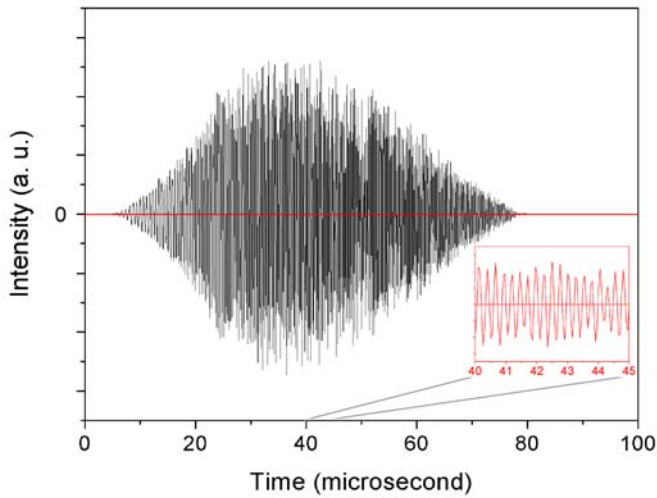
Shown below are two raw OCT images acquired from the OCT microscope without any additional image processing. The sampled tissues are from an in-vivo human finger and palm. The sample area sizes are 5.0mm (width) x 2.5mm (depth). The layered structures of human skin as well as the blood vessels can be clearly identified from these images.



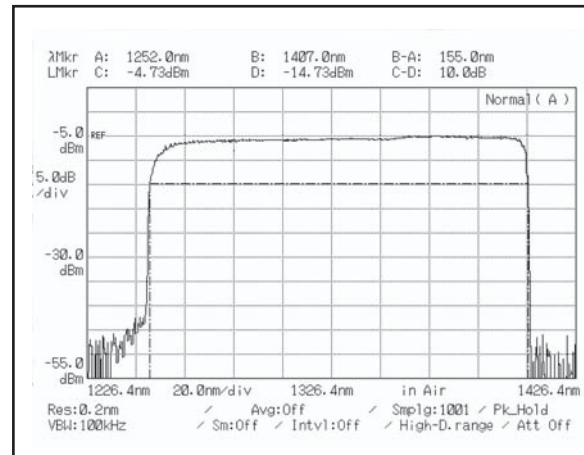
OCT image of in-vivo finger tissue



OCT image of in-vivo palm tissue



INVISIBLE LASER RADIATION
 DO NOT VIEW WITH
 OPTICAL INSTRUMENTS
 CLASS 1M LASER PRODUCT
 1200-1400nm <10mW
 IEC 60825-1 EDITION 1.2 2001-08



Spectrum of the OCT swept laser showing an active wavelength tuning range of 155nm centered around 1325nm.

MZI Clock: The frequency clock of the swept laser is from a build-in Mach-Zehnder interferometer with balanced detector output. The zero-crossings, as well as maxima and minima, of the interference fringe signals, are equally spaced in frequency and can be used as frequency clock to synchronize other measurements.

PARAMETER	MIN	TYPICAL	MAX	COMMENTS
Wavelength Range (nm)	1265	-	1385	
Center Wavelength (nm)	1315	1325	1340	
Tuning Range (nm) (-10dB cut off point)	100	-	140	See models above
Repetition Rate	15	-	17	See models above
Tuning Speed Continuous (nm/ms)	-	2000	-	Mean tuning speed around center wavelength
Average Optical Output Power (mW)	10	12	15	Averaged over 1 second
Optical Power Stability (dB)	-	-	± 0.5	Forward to forward scan or backward backward scan during 1 hour usage
Signal Source Spontaneous Emission Ratio (SSE) (dB)	-	25	-	
Optical Isolation (dB)	50	-	-	
Operating Temperature	+ 10° C	-	+ 40° C	
Storage Temperature	0° C	-	+ 70° C	
Diff. Optical Power at Forward and Back Scan(%)	-	20	-	
Coherence Length (mm)	6	-	8	See models above
Linear Polarization	-	>80 : 1	-	Measured at laser output facet
Repetition Rate (kHz)	10	16	20	Other rates on request
Return Loss (dB)	-	45	-	
Physical Size	600 x 450 x 300			Width x Depth x Height

ITEM#	\$	£	€	¥	DESCRIPTION
SL1325-P16	\$ 30,000.00	£ 18,270.00	€ 26,100.00	¥ 5,100,000	SL1325-P16, 16kHz scanning frequency



An OCT cross-section of a human fingernail

**For Details on Our Full Line
 of OCT Products
 Visit us at www.thorlabs.com**

Spectral Radar Optical Coherence Tomography



Photograph A - Spectral Radar OCT Imaging System

Imaging Specifications (Other Options Available):

- Imaging Speed: 2-5 Frames per Second
- Image Depth: 1.6 mm
- Image Width: 6.0 mm (Adjustable)
- Axial Resolution: 6.2 μ m
- Transverse Resolution: 9.2 μ m
- Measurement Dynamic Range: >96 dB

System Specifications (Other Options Available):

- Central Wavelength: 930 nm
- Spectral Bandwidth: 100 nm
- Signal Loss Max. Depth: 16 dB
- A-scan frequency: 1100 Hz
- Analog to Digital Resolution: 16 bit
- Dimensions W x L x H: 210 x 270 x 60 mm
- Weight: 6 Kg
- Power: 110/220 VAC

Optional Features:

- Dual SLD Broadband Source: 150 nm
- High Speed Imaging Upgrade: 10 Frames per Second
- Application Specific Probes: Upon Request

Introduction

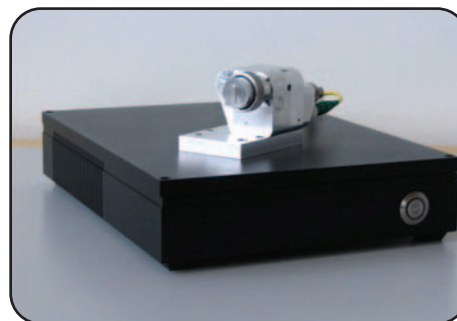
Fourier-domain optical coherence tomography (FD-OCT) is used to obtain subsurface cross-sectional images of a sample with micron level resolution by mixing light collected from a sample with reference light within an interferometer. These adjacent cross-sectional images are often synthesized into 3-D models. These systems are able to obtain a direct measure of the scattering amplitude along a vertical axis within a bulk sample; one exposure provides the complete measurement of the scattering amplitude from the surface into the bulk of the sample (this

measurement is commonly referred to as an A-scan). Typical scan depths for highly scattering biological samples range from 1.5 mm to 3 mm, and is effected by both the scattering properties of the sample as well as the design of the instrument.

FD-OCT offers significant advantages to existing time-domain optical coherence tomography (TD-OCT) imaging techniques due to its increased sensitivity (approximately 20 dB) which consequently enables a significant increase in speed without overly compromising the image quality. This resultant speed enhancement allows for cross-sectional images of 500 A-scans at 10 to 30 frames per second thus providing for the interrogation of larger sample volumes than was previously possible. Early clinical studies based on TD-OCT systems operating at just a few frames per second had indicated that this increase in imaging speed was required for OCT based imaging to realize its potential as an important micron level clinical and industrial volumetric imaging modality.

Two main FD-OCT techniques have been presented in the scientific literature, one previously presented on pages 2-7 is based on the use of a rapidly swept laser source and a balanced detector.

The other approach, presented in this section is based on the use of a broadband light source



Photograph B - Spectral-OCT Engine and Handheld Scanning Probe

combined with a high speed spectrometer, this second method is referred to by numerous names, we have chosen to use the term “spectral radar optical coherence tomography” which for brevity we have adopted the shortened term “spectral-OCT”. A brief overview of the underlying principles of spectral-OCT are presented below, this is followed by a presentation of the main operating parameters of our system. For more details please visit our website and search on OCT, or call Thorlabs to speak with a member of the OCT development team.

The Thorlabs spectral-OCT system comes complete and is operational within minutes,

simply make a few connections, and power up the pre-configured PC (included, photograph A shows the complete system), and then begin taking images of your samples with the handheld scanner probe that is included. The system has been developed through a collaboration between Thorlabs Lübeck AG, and the University of Lübeck both located in Germany, as well as Thorlabs, Inc. located in Newton NJ.

Simplified Operating Principle of Spectral OCT

A light source with a broad range of wavelengths is split between two paths. A portion is delivered to the sample via the handheld probe shown in Figure I, the same optical path used to deliver the illumination light is also used to collect the signal light that is backscattered or reflected by the sample. And a portion is delivered to a reference arm which is subsequently mixed with the light collected from the sample.

In a classic Michelson interferometer the interference pattern is produced by varying the length of one of the interferometer arms; in a Fourier Domain interferometer a variation of the wavelength of the light field is what gives rise to the interference pattern. Consider an interferometer with a fixed path length difference between the two arms. For some particular

wavelength this fixed path length difference will give rise to totally destructive interference of the mixed light field, assuming the two arms of the interferometer are balanced. Now allow this wavelength to change with the path lengths still fixed; the change in wavelength will produce a sinusoidal variation in the signal that is the result of mixing the light from the two arms of the interferometer.

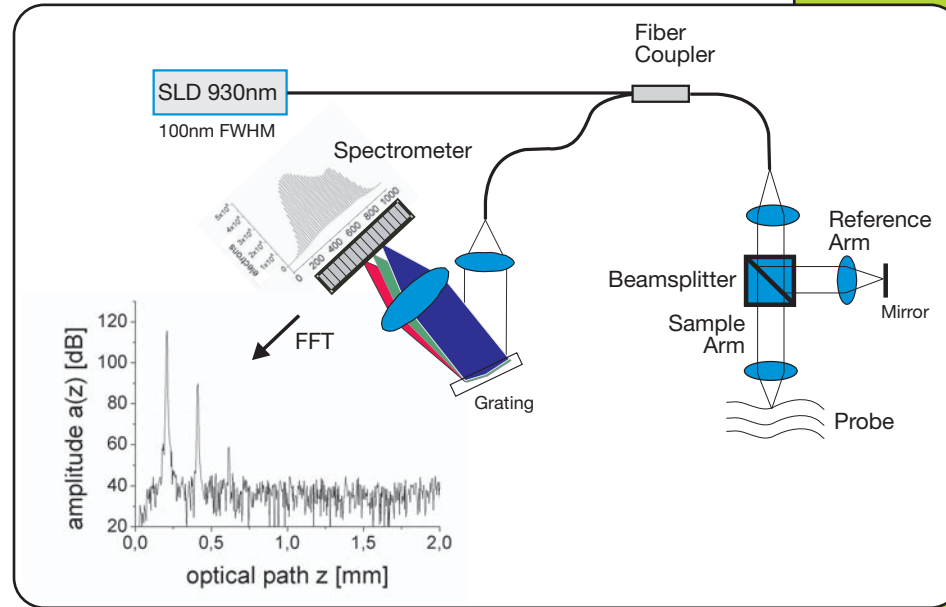


Figure I -Schematic Device

With our system in mind, for a fixed position of the reference mirror, and a fixed point on the sample, the broadband light that is reflected from a given point within the sample will produce a sinusoidal pattern within the spectrometer when it is mixed with light from the reference arm. The frequency of the sinusoidal spectrometer signal will encode the depth, and amplitude will encode the reflection coefficient of the point being considered. Thus light that is back-reflected along the path of illumination will have at each point a characteristic frequency and amplitude within the spectrometer. Applying a discrete fast Fourier transform to the spectrometer signal will provide a complete A-scan of the sample as shown in Figure I.

System Description

The Thorlabs spectral-OCT device is a fully operational imaging system and is depicted schematically to the

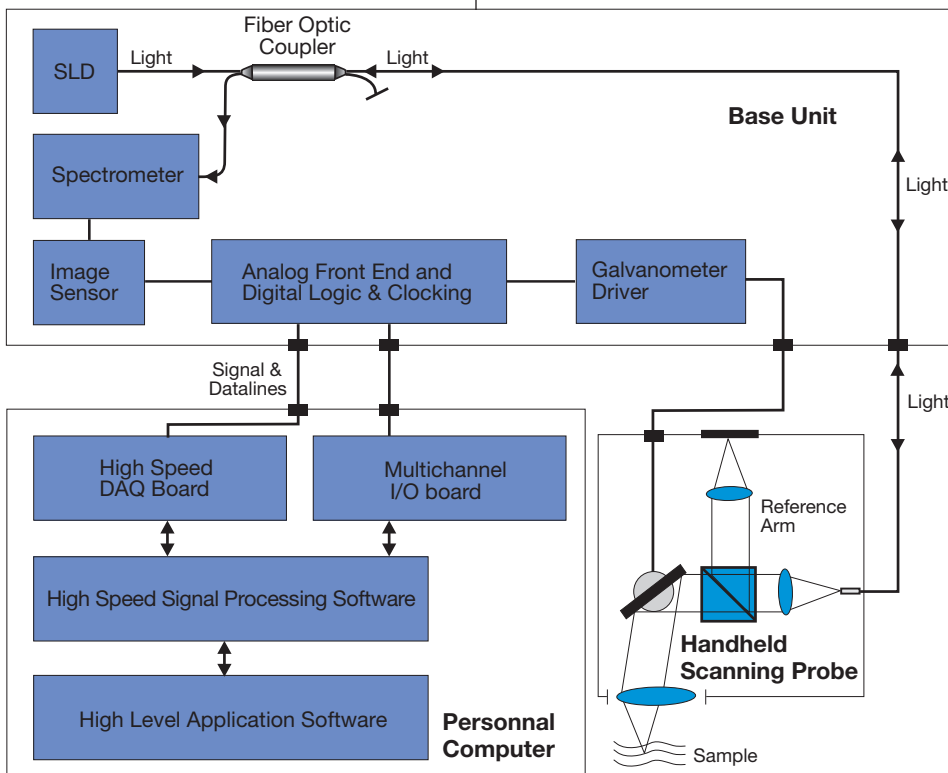


Figure II – Schematic Diagram showing all the major component parts of the Spectral-OCT system.

right in Figure II. The base unit contains the super luminescent diode (SLD) light source. A fiber optic coupler is used to introduce the broadband SLD source into the system as well as to deliver the return signal to the spectrometer (the Michelson interferometer is built within the handheld scanning probe). A spectrometer with 0.140 nm resolution, and high speed linear image sensor form the next two major blocks of the base unit. Additionally the analog as well as the digital timing circuitry, and the drive electronics for the galvanometer scanner (which is located in the handheld probe) are also found in the base unit.

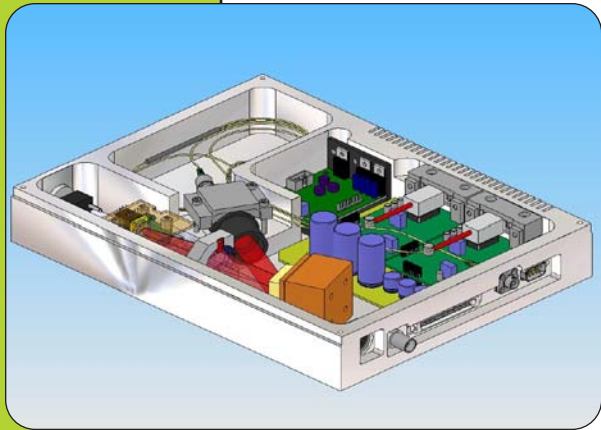


Figure III – Solid Model of Base Unit showing the major components of the system.

can be applied to industrial imaging problems ranging from laminated packaging films to 3-D visualization of mechanical parts. The robust design as well as the compact size of the main housing (210 mm x 270 mm x 60 mm) allows the system to be easily deployed within industrial settings.

The solid-model provides a view of the mechanical design of the system, note that the main housing is machined from a single block and provides a mechanically rugged package for the high performance spectrometer. The base unit is segregated into a number of sections, the spectrometer and linear sensor array is seen in the front area of the solid model with the laser beam depicted as red, it emerges from the optical fiber and is expanded to fill the grating which is mounted on the orange colored tip/tilt mount. The diffracted beam is then imaged onto the sensor array. The upper right portion of the package has room for two SLD light sources which is an optional feature available if higher axial resolution is required.

A single cable connects the main housing to the personal computer (PC) which is included, within the PC resides a high performance data acquisition card that has been optimized for the spectral-OCT application. All the required data acquisition and analysis is performed with the software package that is provided. The resulting 2-D images are displayed on the PC at up to 5 frames per second. Thorlabs is planning to release a 3-D enabled version of this technology in the second half of 2006.

The communication between the base unit and the handheld application system is reduced to one optical fiber and an electronic connection to control the scanning module. Included in the electrical connection is a feedback signal to control and verify the position of the scan mirror. The design architecture assumes that the interferometer itself is integrated into the applicator; included

The wavelength of the SLD in our standard configuration is centered at 930 nm (other center wavelengths available, please call for details), the use of a near-IR broadband source balances the desire for low scattering losses within biological samples with the need for operating inside the wavelength range of commercial silicon based linear sensor arrays. Many biological samples provide sufficient transparency at this wavelength to provide for maximal use of the imaging depth set by the system hardware, which in our standard configuration is set to 1.6 mm.

In principal spectral-OCT can be applied to a wide range of possible applications, the samples need not be biological in nature, the technology can



Figure IV – Photograph of the handheld scanning probe in use imaging a volunteer's arm.

with our standard system is the handheld application system depicted in Photograph B. Locating the interferometer within the handheld probe avoids all the problems usually arising from chromatic and polarization mode dispersion introduced by lengths of optical fiber in the sample and reference arms of the interferometer. The standard handheld application system has originally been designed for in vivo investigations of the human skin, however the same handheld applicator has been used on many other biological and industrial samples. The handheld probe uses a telecentric optical design, this provides a nearly constant illumination spot size on the sample over a broad range of working distances. The handheld application system is shown in Photograph B as well as in the solid model depicted in Figure III.

The software package contains a complete set of functions for controlling the measurement, data acquisition and processing as well as the storing and displaying of the OCT images.

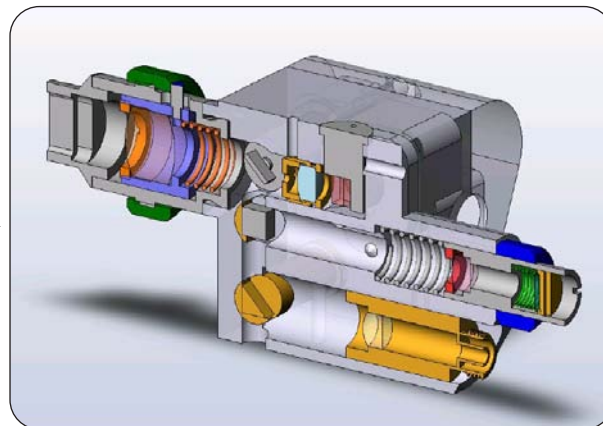
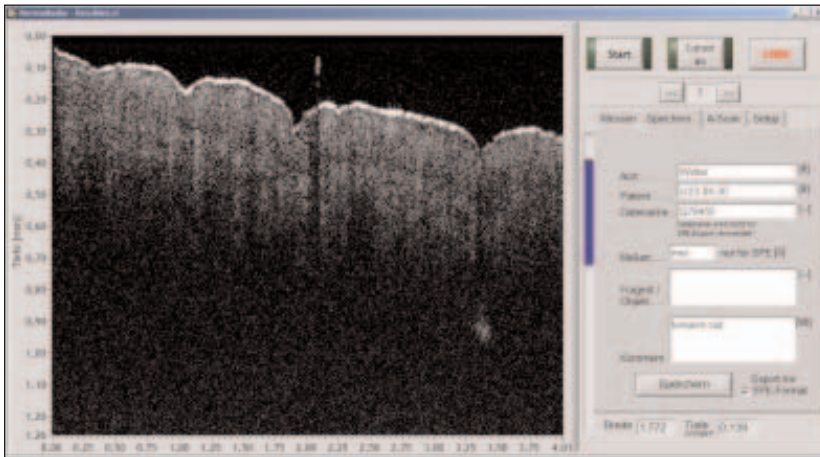


Figure V – Solid model, cross sectional view of the handheld scanner probe that contains the free-space interferometer and telecentric imaging optics.

Utilizing a library of functions this system offers a high degree of flexibility which allows the user to modify the operation of the system to suit their particular needs. With the standard system the lateral scanning range as well as the step width is freely controlled. Several images can be sampled at a time and saved separately with individual comments. The 16 bit data sets are accessible for offline image processing and data analysis.

Also included is a library of sample applications which often serve as a foundation from which custom applications can be developed.

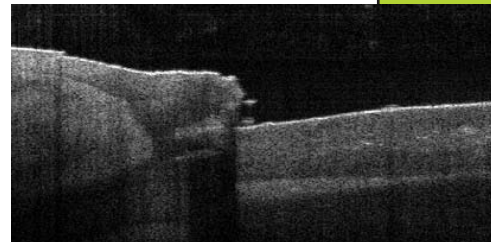
Spectral-OCT Image Gallery



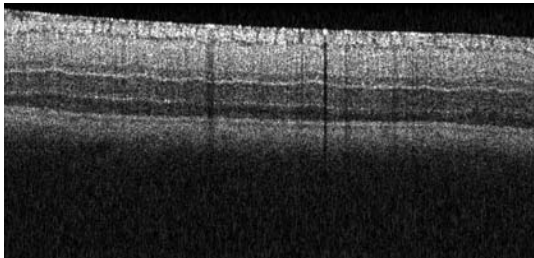
Screen Shot from the Spectral OCT System Software Package.

Measurement options:

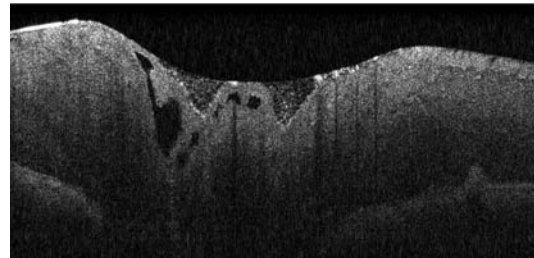
- Creating 2D Images and Datasets of Transparent or Scattering Samples Like Soft Tissue or Structured Semiconductors with a Resolution up to Some Microns
- Measurements of the Absolute Position of the Sample
- Determination of Layer Thickness With a Precision Up to Some Hundred Pico Meter.



Fingernail Fold.



SR-OCT Image of a thumb.



In vitro images from porcine retina and nerve head.

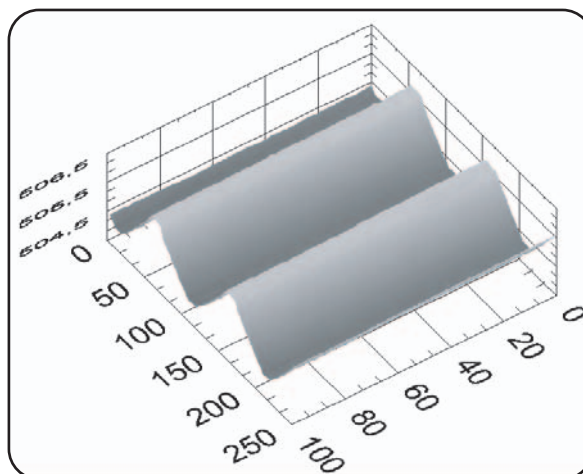


Fig. IV – SR-OCT Surface Measurement of a Sinusoidal Surface.