Real-time high-resolution mid-infrared optical coherence tomography

The potential for improving the penetration depth of optical coherence tomography systems by using light sources with longer wavelengths has been known since the inception of the technique in the early 1990s. Nevertheless, the development of mid-infrared optical coherence tomography has long been challenged by the maturity and fidelity of optical components in this spectral region, resulting in slow acquisition, low sensitivity, and poor axial resolution. In this work, a mid-infrared spectral-domain optical coherence tomography system operating at a central wavelength of 4 µm and an axial resolution of 8.6 µm is demonstrated. The system produces two-dimensional cross-sectional images in real time enabled by a high-brightness 0.9- to 4.7-µm mid-infrared supercontinuum source with a pulse repetition rate of 1 MHz for illumination and broadband upconversion of more than 1-µm bandwidth from 3.58–4.63 µm to 820–865 nm, where a standard 800-nm spectrometer can be used for fast detection. The images produced by the mid-infrared system are compared with those delivered by a state-of-the-art ultra-high-resolution near-infrared optical coherence tomography system operating at 1.3 µm, and the potential applications and samples suited for this technology are discussed. In doing so, the first practical mid-infrared optical coherence tomography system is demonstrated, with immediate applications in real-time non-destructive testing for the inspection of defects and thickness measurements in samples that exhibit strong scattering at shorter wavelengths.

General information

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Noise of supercontinuum sources in spectral domain optical coherence tomography

In this paper, we investigate the effect of pulse-to-pulse fluctuations of supercontinuum sources on the noise in spectral domain optical coherence tomography (OCT) images. The commonly quoted theoretical expression for the OCT noise is derived for a thermal light source, which is not suitable if a supercontinuum light source is used. We therefore propose a new, measurement-based OCT noise model that predicts the noise without any assumptions on the type of light source. We show that the predicted noise values are in excellent agreement with the measured values. The spectral correlation evaluated for the photodetected signal when using a supercontinuum determines the shape of the OCT noise floor, which must be taken into account when characterizing the sensitivity roll-off of a supercontinuum-based OCT system. The spectral correlations using both conventional supercontinuum sources and low-noise all-normal dispersion supercontinuum sources are investigated, and the fundamental physical effects that cause these correlations are discussed.

Potential of contrast agents to enhance in vivo confocal microscopy and optical coherence tomography in dermatology

Distinction between normal skin and pathology can be a diagnostic challenge. This systematic review summarizes how various contrast agents, either topically delivered or injected into the skin, affect distinction between skin disease and normal skin when imaged by optical coherence tomography (OCT) and confocal microscopy (CM). A systematic review of in vivo OCT and CM studies using exogenous contrast agents on healthy human skin or skin disease was performed. In total, nine CM studies and one OCT study were eligible. Four contrast agents aluminum chloride (AlCl) n = 2, indocyanine green (ICG) n = 3, sodium fluorescein n = 3 and acetic acid n = 1 applied to CM in variety of skin diseases. ICG, acetic acid and AlCl showed promise to increase contrast of tumor nests in keratinocyte carcinomas. Fluorescein and ICG enhanced contrast of keratinocytes and adnexal structures. In OCT of healthy skin gold nanoshells, increased contrast of natural skin openings. Contrast agents may improve delineation and diagnosis of skin cancers; ICG, acetic acid and AlCl have potential in CM and gold nanoshells facilitate visualization of adnexal skin structures in OCT. However, as utility of bedside optical imaging increases, further studies with robust methodological quality are necessary to implement contrast agents into routine dermatological practice.
All-depth dispersion cancellation in spectral domain optical coherence tomography using numerical intensity correlations

In ultra-high resolution (UHR-) optical coherence tomography (OCT) group velocity dispersion (GVD) must be corrected for in order to approach the theoretical resolution limit. One approach promises not only compensation, but complete annihilation of even order dispersion effects, and that at all sample depths. This approach has hitherto been demonstrated with an experimentally demanding 'balanced detection' configuration based on using two detectors. We demonstrate intensity correlation (IC) OCT using a conventional spectral domain (SD) UHR-OCT system with a single detector. IC-SD-OCT configurations exhibit cross term ghost images and a reduced axial range, half of that of conventional SD-OCT. We demonstrate that both shortcomings can be removed by applying a generic artefact reduction algorithm and using analytic interferograms. We show the superiority of IC-SD-OCT compared to conventional SD-OCT by showing how IC-SD-OCT is able to image spatial structures behind a strongly dispersive silicon wafer. Finally, we question the resolution enhancement of \sqrt{2} that IC-SD-OCT is often believed to have compared to SD-OCT. We show that this is simply the effect of squaring the reflectivity profile as a natural result of processing the product of two intensity spectra instead of a single spectrum.
Resolution dependence on phase extraction by the Hilbert transform in phase calibrated and dispersion compensated ultrahigh resolution spectrometer-based OCT

Ultrahigh resolution optical coherence tomography (UHR-OCT) is enabled by using a broad band source. Simultaneously, this makes the OCT image more sensitive to dispersion mismatch in the interferometer. In spectral domain OCT, dispersion left uncompensated in the interferometer and detector non-linearities lead together to an unknown chirp of the detected interferogram. One method to compensate for the chirp is to perform a pixel-wavenumber calibration versus phase that requires numerical extraction of the phase. Typically a Hilbert transform algorithm is employed to extract the optical phase versus wavenumber for calibration and dispersion compensation. In this work we demonstrate UHR-OCT at 1300 nm using a Super continuum source and highlight the resolution constraints in using the Hilbert transform algorithm when extracting the optical phase for calibration and dispersion compensation. We demonstrate that the constraints cannot be explained purely by the numerical errors in the data processing module utilizing the Hilbert transform but must be dictated by broadening mechanisms originating from the experimentally obtained interferograms.
Supercontinuum applications in high resolution non invasive optical imaging

Progress will be presented in adapting supercontinuum sources to a variety of applications with emphasis on signal processing procedures. These are customised to alleviate noise and take full advantage of the large bandwidth and large power spectral density of modern supercontinuum sources.

The value of ultrahigh resolution OCT in dermatology - delineating the dermo-epidermal junction, capillaries in the dermal papillae and vellus hairs

Optical coherence tomography (OCT) imaging of the skin is gaining recognition and is increasingly applied to dermatological research. A key dermatological parameter inferred from an OCT image is the epidermal thickness as a thickened epidermis can be an indicator of a skin disease. Agreement in the literature on the signal characters of epidermis and subjacent skin layer, the dermis, is evident. Ambiguities of the OCT signal interpretation in the literature is however seen for the transition region between the epidermis and dermis, which from histology is known as the dermo-epidermal junction.

In this work, we investigate the impact of an improved axial and lateral resolution on the applicability of OCT for imaging of the skin. To this goal, OCT images are compared produced by a commercial OCT system (Vivosight from Michaelson Diagnostics) and by an in-house built ultrahigh resolution (UHR) OCT system for dermatology. In 11 healthy volunteers, we investigate the DEJ signal characteristics. We perform a detailed analysis of the dark (low) signal band clearly seen for UHR- OCT in the DEJ region where we, by using a transition function, find the signal transition of axial sub-resolution character, which can be directly attributed to the exact location of DEJ, both in normal (thin/hairy) and glabrous (thick) skin. To our knowledge no detailed delineating of the DEJ in the UHR- OCT image has previously been reported, despite many publications within this field. For selected healthy volunteers, we investigate the dermal papillae and the vellus hairs and identify distinct features that only UHR- OCT can resolve. Differences are seen in tracing hairs of diameter below 20 μm, and in imaging the dermal papillae where, when utilising the UHR- OCT, capillary structures are identified in the hand palm, not previously reported in OCT studies and specifically for glabrous skin not reported in any other in vivo optical imaging studies.
Two optical coherence tomography systems detect topical gold nanoshells in hair follicles, sweat ducts and measure epidermis

Optical coherence tomography (OCT) is an optical imaging technology that enables real time, high-resolution, cross-sectional and en face investigation of skin by detecting reflected broad-spectrum near-infrared light from tissue. OCT provides micron-scale spatial resolution and millimeter-scale depth of penetration [1]. Several commercial OCT systems with handheld probes targeted for Dermatology are now available [2].

Dispersion free full range spectral intensity optical coherence tomography

Optical coherence tomography (OCT) is a non-invasive imaging technique with many applications and widespread use in ophthalmology [1]. The axial resolution in OCT is inversely proportional to the bandwidth of the optical source used, but the improved axial resolution comes at the price of more significant effects of dispersion stemming from the imaging system and the imaged medium. In recent years, spectral intensity (SI) OCT has been shown, as a classical realisation of quantum OCT, to remove even orders of dispersion intrinsically [2, 3]. One major drawback of SI OCT is however halving of the imaging range which is crucial in spectrometer based OCT which is limited by the spectral resolution, and hence number of pixels of the spectrometer. In this work we demonstrate SI OCT with the full imaging range.
Gabor fusion master slave optical coherence tomography

This paper describes the application of the Gabor filtering protocol to a Master/Slave (MS) swept source optical coherence tomography (SS-OCT) system at 1300 nm. The MS-OCT system delivers information from selected depths, a property that allows operation similar to that of a time domain OCT system, where dynamic focusing is possible. The Gabor filtering processing following collection of multiple data from different focus positions is different from that utilized by a conventional swept source OCT system using a Fast Fourier transform (FFT) to produce an A-scan. Instead of selecting the bright parts of A-scans for each focus position, to be placed in a final B-scan image (or in a final volume), and discarding the rest, the MS principle can be employed to advantageously deliver signal from the depths within each focus range only. The MS procedure is illustrated on creating volumes of data of constant transversal resolution from a cucumber and from an insect by repeating data acquisition for 4 different focus positions. In addition, advantage is taken from the tolerance to dispersion of the MS principle that allows automatic compensation for dispersion created by layers above the object of interest. By combining the two techniques, Gabor filtering and Master/Slave, a powerful imaging instrument is demonstrated. The master/slave technique allows simultaneous display of three categories of images in one frame: multiple depth en-face OCT images, two cross-sectional OCT images and a confocal like image obtained by averaging the en-face ones. We also demonstrate the superiority of MS-OCT over its FFT based counterpart when used with a Gabor filtering OCT instrument in terms of the speed of assembling the fused volume. For our case, we show that when more than 4 focus positions are required to produce the final volume, MS is faster than the conventional FFT based procedure.
Master/Slave: A better tool for Gabor filtering optical coherence tomography imaging instruments

In this report, the benefits that the Master/Slave (MS) implementation of optical coherence tomography (OCT) can bring to a Gabor filtering (GF) imaging instrument are illustrated. The MS allows simultaneous display of three categories of images in one frame: multiple depth en-face OCT images, two B-scan OCT and a confocal like image. The power of MS is illustrated here by showing 3D images of constant transversal resolution from different objects, obtained by merging sub-volumes collected for four different focus positions. By combining the two techniques, GF and MS, a powerful imaging instrument is demonstrated. We show that when more than four focus positions are required, MS can produce fused volumes faster than the conventional FT based procedure.

General information
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Organisations: Department of Photonics Engineering, Fiber Sensors & Supercontinuum, University of Kent, Universite de Bretagne Occidentale, Moorfields Eye Hospital NHS Foundation Trust
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Non-destructive testing of layer-to-layer fusion of a 3D print using ultrahigh resolution optical coherence tomography

Within the last decade, 3D printing has moved from a costly approach of building mechanical items to the present state-of-the-art phase where access to 3D printers is now common, both in industry and in private places. The plastic printers are the most common type of 3D printers providing prints that are light, robust and of lower cost. The robustness of the structure printed is only maintained if each layer printed is properly fused to its previously printed layers. In situations where the printed component has to accomplish a key mechanical role there is a need to characterize its mechanical strength. This may only be revealed by in-depth testing in order to discover unwanted air-gaps in the structure. Optical coherence tomography (OCT) is an in-depth imaging method, that is sensitive to variations in the refractive index and therefore can resolve with high resolution translucent samples. We report on volume imaging of a 3D printed block made with 100% PLA fill. By employing ultrahigh resolution OCT (UHR-OCT) we show that some parts of the PLA volume reveal highly scattering interfaces which likely correspond to transitions from one layer to another. In doing so, we document that UHR-OCT can act as a powerful tool that can be used in detecting fractures between layers stemming from insufficient fusion between printed structure layers. UHR-OCT can therefore serve as an useful assessment method of quality of 3D prints.

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Contributors: Israelsen, N. M., Maria, M., Feuchter, T., Podoleanu, A., Bang, O.
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Phase estimation for global defocus correction in optical coherence tomography

In this work we investigate three techniques for estimation of the non-linear phase present due to defocus in optical coherence tomography, and apply them with the angular spectrum method. The techniques are: Least squares fitting of the unwrapped phase of the angular spectrum, iterative optimization, and sub-aperture correlations. The estimated phase of a single en-face image is used to extrapolate the non-linear phase at all depths, which in the end can be used to correct the entire 3-D tomogram, and any other tomogram from the same system.

Determining the internal quantum efficiency of shallow-implanted nitrogen-vacancy defects in bulk diamond

It is generally accepted that nitrogen-vacancy (NV) defects in bulk diamond are bright sources of luminescence. However, the exact value of their internal quantum efficiency (IQE) has not been measured so far. Here we use an implementation of Drexhage’s scheme to quantify the IQE of shallow-implanted NV defects in a single-crystal bulk diamond. Using a spherical metallic mirror with a large radius of curvature compared to the optical spot size, we perform calibrated modifications of the local density of states around NV defects and observe the change of their total decay rate, which is further used for IQE quantification. We also show that at the excitation wavelength of 532 nm, photo-induced relaxation cannot be neglected even at moderate excitation powers well below the saturation level. For NV defects shallow implanted 4.5 ± 1 and 8 ± 2 nm below the diamond surface, we determine the quantum efficiency to be 0.70 ± 0.07 and 0.82 ± 0.08, respectively.
Extraction of light from a quantum emitter by tailoring the photonic environment

Since the discovery of quantum mechanics it has been a physicists dream to test and exploit the fantastic prediction of entanglement. Applications based on entanglement are quantum key distribution and quantum computing which can exploiting quantum bits based on single photons. To deterministically create this type of quantum bits single photons on demand are essential. This thesis presents the work on controlling the photonic environment of a quantum emitter in order to efficiently extract photons.

We demonstrate increased photon collection efficiencies from single nitrogen vacancy (NV) centers by a factor of up to 1.76 when approaching it with a plane silver mirror made on an optical fiber facet. However, using this method we also show that the non-radiative decay rate of NV centers can be highly dependent on the excitation power, which makes this method a poor broadband approach for obtaining information on the photonic decay rate of the NV center. By further spectrally resolving emission from these systems we observe clear modulations which carry information related to the photonic decay rate where the quantum efficiency can be deduced from.

We carry out three experiments where coupling NV centers to the highly confined mode fields of silver nano-wires (SNWs) are exploited. First, we demonstrate routing of single plasmons fed by a single NV center. Controlled routing is shown by facilitating different beamsplitter configurations where the routing itself is performed on a length scale less than 2 µm. We then measure the coupling between an NV center ensemble and single SNWs through 2-dimensional imaging of the NV center lifetime which outlines the SNW profiles confirmed by atomic force microscopy (AFM). Finally, an attempt to couple a single SNW to NV centers in a micro-fabricated diamond nano-pillar is presented.

The final part of the thesis address experiments on coupling colloidal quantum dots (CQDs) to the gap mode of two Si3N4 waveguides (DSNWs). We demonstrate evanescent-field coupling between spin-coated CQDs and the waveguide. However we are unable to deduce the coupling-related modification of the CQD lifetime due to apparent density dependent CQD interactions which dominate the lifetime distribution. We circumvent this by instead attaching CQDs to an AFM cantilever and scanning this across the DSNWs. By doing this, we obtain a 2-dimensional lifetime map showing an AFM-confirmed outline of the DSNW through the spatially-dependant lifetime variations.
Demonstration of a variable plasmonic beam splitter

In this contribution, we excite surface plasmon polaritons propagating along a silver nano-wire by a single nitrogen-vacancy center located in a diamond nano-crystal. By using the tip of an atomic force microscope, a second nano-wire is brought into the evanescent field of the first wire such that surface plasmons can evanescently couple. In our experiment, we are able to tune the coupling strength from one nano-wire to another by adjusting the gap with the aid of the atomic force microscope. Numerical calculations of the coupling strength are carried out, which support the values found in the experiment.

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Generation and Controlled Routing of Single Plasmons on a Chip

We demonstrate the excitation of single surface plasmon polaritons on a silver nanowire using a nitrogen vacancy center and the subsequent controlled coupling to a second silver nanowire. The coupling efficiency and thus the splitting ratio between the nanowires is controlled by adjusting the gap size between the wires with an atomic force microscope. By numerical methods, we estimate the splitting ratios for different gap sizes, and the results support the values obtained in the experiment.

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Increasing the photon collection rate from a single NV center with a silver mirror

In the pursuit of realizing quantum optical networks, a large variety of different approaches have been studied to achieve a single photon source on-demand. The common goal for these approaches is to harvest all the emission from a quantum emitter into a single spatial optical mode while maintaining a high signal-to-noise ratio. In this work, we use a single nitrogen vacancy center in diamond as a quantum emitter operating at ambient conditions and we demonstrate an increased photon count rate up to a factor of 1.76 by placing a silver mirror fabricated on the end facet of an optical fiber near the emitter.

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Contributors: Israelsen, N. M., Kumar, S., Tawfieq, M., Neergaard-Nielsen, J. S., Huck, A., Andersen, U. L.
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A Variable Single Photon Plasmonic Beamsplitter
Plasmonic structures can both be exploited for scaling down optical components beyond the diffraction limit and enhancing and collecting the emission from a single dipole emitter. Here, we experimentally demonstrate adiabatic coupling between two silver nanowires using a nitrogen vacancy center as a probe source.

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Projects:

High-Speed Time-stretch Optical coherence tomography
Jensen, M., PhD Student, Department of Photonics Engineering
Bang, O., Main Supervisor
Israelsen, N. M., Supervisor
Coherent Coupling of a Nitrogen-Vacancy Center to Gap Modes in Integrated Structures

Israelsen, N. M., PhD Student, Department of Physics
Andersen, U. L., Main Supervisor
Huck, A., Supervisor
Wubs, M., Examiner
Bozhevolnyi, S. I., Examiner
Jelezko, F., Examiner
Institut, Samfinansiering
01/04/2012 → 13/08/2015
Award relations: Coherent Coupling of a Nitrogen-Vacancy Center to Gap Modes in Integrated Structures
Project: PhD

Activities:

Optical Coherence Tomography, General aspects and use in Laryngology
Period: 8 Dec 2017
Niels Møller Israelsen (Lecturer)
Deepak Jain (Other)
Ole Bang (Other)
Department of Photonics Engineering
Fiber Sensors & Supercontinuum
Degree of recognition: International

Related event

WORLD VOICE CONSORTIUM CONGRESS 2017: VII World Voice Consortium Congress is a multidisciplinary voice meeting held in Copenhagen, DK, targeting voice professionals: artists, clinicians, coaches, teachers and scientists.
08/12/2017 → 10/12/2017
Copenhagen, Denmark
Activity: Talks and presentations › Conference presentations

Phase estimation for global defocus correction in optical coherence tomography
Period: 8 Sep 2017
Mikkel Jensen (Speaker)
Niels Møller Israelsen (Guest lecturer)
Ole Bang (Guest lecturer)
Adrian Podoleanu (Guest lecturer)
Department of Photonics Engineering
Fiber Sensors & Supercontinuum
Degree of recognition: International
Documents:
Phase estimation for global defocus correction in optical coherence tomography

Related event

2nd Canterbury Conference on Optical Coherence Tomography: Emphasis on broadband sources
06/09/2017 → 08/09/2017
Canterbury, United Kingdom
Activity: Talks and presentations › Conference presentations

Versatile hand-held master-slave optical coherence tomography instrument for non-destructive testing
Period: 8 Sep 2017
Resolution dependence on phase extraction by the Hilbert transform in phase calibrated and dispersion compensated ultrahigh resolution spectrometer based OCT
Period: 7 Sep 2017
Niels Møller Israelsen (Lecturer)
Michael Maria (Other)
Thomas Feuchter (Other)
Adrian Bradu (Other)
Adrian Podoleanu (Other)
Ole Bang (Other)

Master/slave: a better tool for Gabor filtering optical coherence tomography imaging instruments
Period: 29 Jun 2017
Ramona Cernat (Other)
Adrian Bradu (Lecturer)
Niels Møller Israelsen (Other)
Ole Bang (Other)
Sylvain Rivet (Other)
David-Garway Heath (Other)
Ranjan Rajendram (Other)
Adrian Podoleanu (Other)

Related event
European Conference on Biomedical Optics 2017
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Munich, Germany
Activity: Talks and presentations › Conference presentations

**Non-destructive testing of layer-to-layer fusion of a 3D print using ultrahigh resolution optical coherence tomography**
Period: 26 Jun 2017
Niels Møller Israelsen (Lecturer)
Michael Maria (Other)
Thomas Feuchter (Other)
Adrian Podoleanu (Other)
Ole Bang (Other)

Department of Photonics Engineering
Fiber Sensors & Supercontinuum
Degree of recognition: International

**Related event**

**SPIE Optical Metrology, Internationales Congress Center Munich, Germany, 25 - 29 June 2017**
25/06/2016 → 29/06/2016
München, Germany
Activity: Talks and presentations › Conference presentations