Jakub Czajkowski

OPTICAL COHERENCE TOMOGRAPHY AS A CHARACTERIZATION METHOD IN PRINTED ELECTRONICS
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Academic dissertation to be presented with the assent of the Doctoral Training Committee of Technology and Natural Sciences of the University of Oulu for public defence in Auditorium TS101, Linnanmaa, on 22 November 2013, at 12 noon

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Abstract

This Thesis proposes and describes the use of optical coherence tomography (OCT) as a non-contact and non-destructive characterization technique for printed electronics. It is based on and includes the first published results of such an application of the OCT technique.

Several different types of structures were studied to evaluate the feasibility of the application. The measurement data was used to define the surface topography, physical dimensions of the specimen features, and to evaluate the ability to characterize multi-layered and multi-material structures.

Presented OCT measurements were done for: screen-printed conductive and insulating structures, microfluidic channels, microscopy glass and organic field effect transistors (OFET), both coated with polymer, and inkjet-printed colour filters.

A novel approach to encapsulation inspection was presented. The results show that OCT could be used for full volumetric and non-destructive characterization of the 1-to-2-µm-thin protective layers used in organic and printed electronics.

The measurements presented in the Thesis were done using OCT devices in time and in spectral domains. Despite the focus on studying the application of the technique, as a result of observations and limitations of the existing equipment, a new type of OCT device has been developed. A high data acquisition rate of the spectrometer-based systems (SD-OCT) was combined with a broadband supercontinuum light source, used so far mainly in the time-domain (TD-OCT), to enable the sub-micron-resolution spectral domain optical coherence tomography (SMR SD-OCT). The supercontinuum generation effects with virtually white probing light and enables not only superior resolution, but also, e.g., true-colour OCT imaging. The measurements performed on the inkjet-printed colour filters confirm that despite the absorptive properties of the materials, characterization of the few-microns-thin ink layers is possible using visible range of the electromagnetic spectrum and spectral domain OCT.

The study shows the potential and versatility of OCT in the printed electronics characterization. In addition, the Thesis discusses further development of the technique, needed to fully match the challenging requirements of the on-line quality inspection.

Keywords: encapsulation, imaging, interferometry, non-destructive testing
Tiivistelmä

Väitösyössä sovelletaan optista koherenssitomografiaa (OCT) painetun elektroniikan kontaktitomaoaan ja kohdetta rikkomattomaan karakterisointiin. Väitöstyö pohjautuu tuloksiin, joissa OCT-tekniikkaa on hyödynnetty ensimmäistä kertaa painettavan elektroniikan rakenteen karakterisoinnissa.

Tekniikan soveltuvuutta tutkittiin mittaan kauhollan useita erilaisia näyteitä. Mitattua dataa käytettiin pinnan topografian ja näytteen dimensioihin määritykseen. Lisäksi tutkittiin tekniikan soveltuvuutta monikerrosrakenteiden ja useista eri materiaaleista koostuvien näyteiden mitattavaksi. OCT-mittaukset tehtiin seuraaville näyteille; silkkipainetuille johteille ja eristeille, mikrokanaville, polymeerillä päällystettyille mikroskooppilaseille ja organisista aineista valmistettu kanavatransistoreille (OFET) sekä mustesuihkutulostimella valmistetulla värisuodattimilla.

Orgaaniset materiaalit ja painettava elektroniika suojataan yleensä koteloinnilla. Tässä väitösyössä esiteltään uusi menetelmä koteloinnin tarkastukseen. Tulokset osoittavat, että OCT-tekniikkaa voidaan hyödyntää 1–2 mikrometrin paksuisen eriste kerroksen volumetrisen rakenteen karakterisointiin kohdetta rikkomatta.


Spektrometriin pohjautuvan OCT-laitteen nopeus yhdistettiin laajakaistaisen supercontinuum valonlähteen kanssa, jota on käytetty aiemmin käytännössä vain aikataon OCT-laitteissa. Laajakaistainen valonlähdetä on mahdollista käyttää sekä erinomaisen kohdetta rikkomattaa aikataon OCT-laitteissa, että erinomaisen kohdetta rikkomattaa aikataon OCT-laitteissa.

Väitöskirjatutkimus keskittyy OCT-teknikan monipuolisuuden ja mahdollisuuden painettavan elektroniikan karakterisoinnissa. Lisäksi väitösyö käsittää teknikän jatkokehitystä, jotta se voisi vastata mahdollisimman hyvin reaaliaikaisen laadunvalvonnan tarpeisiin.

Asiakirjat: interferometri, kohdetta rikkomattom testaus, kotelointi, kuvantaminen
Dedicated to my Parents
Acknowledgements

This thesis is a result of several years of research and development done in the Optoelectronics and Measurement Techniques Laboratory at the University of Oulu and during my short research visit in the Center for Optical Research and Education (CORE) at the Utsunomiya University, Japan.

I would like to express my deepest gratitude to Prof. Risto Myllylä for giving me the opportunity to join his research group and for supervising this work.

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I wish to thank my Parents for their love and efforts from the earliest days of my life, for their understanding, encouragement, and for the support in all that I have ever done. I am also grateful to my Family and all my Friends for their support and for their good word.

Oulu, 22nd November 2013
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>2D</td>
<td>two-dimensional, plane</td>
</tr>
<tr>
<td>3D</td>
<td>three-dimensional, volumetric</td>
</tr>
<tr>
<td>A/D</td>
<td>analogue-to-digital</td>
</tr>
<tr>
<td>AFM</td>
<td>atomic force microscopy</td>
</tr>
<tr>
<td>CM</td>
<td>confocal microscopy</td>
</tr>
<tr>
<td>CVD</td>
<td>chemical vapour deposition</td>
</tr>
<tr>
<td>CW</td>
<td>constant wavelength</td>
</tr>
<tr>
<td>DC</td>
<td>direct, non-alternating signal</td>
</tr>
<tr>
<td>DIC</td>
<td>differential interference contrast microscopy</td>
</tr>
<tr>
<td>EDS/EDX</td>
<td>energy dispersive X-ray spectroscopy</td>
</tr>
<tr>
<td>FTIR</td>
<td>Fourier transform infrared spectroscopy</td>
</tr>
<tr>
<td>FWHM</td>
<td>full-width-at-half-maximum</td>
</tr>
<tr>
<td>HOM</td>
<td>holographic optofluidic microscopy</td>
</tr>
<tr>
<td>HPM</td>
<td>Hilbert phase microscopy</td>
</tr>
<tr>
<td>LCI</td>
<td>low coherence interferometry</td>
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<tr>
<td>LED</td>
<td>light emitting diode</td>
</tr>
<tr>
<td>MEMS</td>
<td>microelectromechanical systems</td>
</tr>
<tr>
<td>NIR</td>
<td>near infrared</td>
</tr>
<tr>
<td>OCM</td>
<td>optical coherence microscopy</td>
</tr>
<tr>
<td>OCT</td>
<td>optical coherence tomography</td>
</tr>
<tr>
<td>OFET</td>
<td>organic field effect transistor</td>
</tr>
<tr>
<td>OFM</td>
<td>optofluidic microscopy</td>
</tr>
<tr>
<td>PET</td>
<td>polyethylene terephthalate</td>
</tr>
<tr>
<td>PMMA</td>
<td>polymethyl methacrylate</td>
</tr>
<tr>
<td>PS-OCT</td>
<td>polarization-sensitive optical coherence tomography</td>
</tr>
<tr>
<td>PSF</td>
<td>point spread function</td>
</tr>
<tr>
<td>PSI</td>
<td>phase shifting interferometry</td>
</tr>
<tr>
<td>R2R</td>
<td>roll-to-roll processing</td>
</tr>
<tr>
<td>RFID</td>
<td>radio frequency identification</td>
</tr>
<tr>
<td>RGB</td>
<td>additive colour model based on red, green, and blue</td>
</tr>
<tr>
<td>RIN</td>
<td>relative intensity noise</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
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<tr>
<td>ROI</td>
<td>region of interest</td>
</tr>
<tr>
<td>SD-OCT</td>
<td>spectral-domain optical coherence tomography</td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscopy</td>
</tr>
<tr>
<td>SMR SD-OCT</td>
<td>sub-micron-axial-resolution spectral-domain optical coherence tomography</td>
</tr>
<tr>
<td>SMR TD-OCT</td>
<td>sub-micron-axial-resolution time-domain optical coherence tomography</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
</tr>
<tr>
<td>TD-OCT</td>
<td>time-domain optical coherence tomography</td>
</tr>
<tr>
<td>TOF-SIMS</td>
<td>time of flight secondary ion mass spectrometry</td>
</tr>
<tr>
<td>VSI</td>
<td>vertical scanning interferometry</td>
</tr>
<tr>
<td>XPS</td>
<td>X-ray photo-electron spectroscopy</td>
</tr>
<tr>
<td>XRD</td>
<td>X-ray diffraction</td>
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>D</td>
<td>beam diameter</td>
</tr>
<tr>
<td>G(τ)</td>
<td>temporal coherence function</td>
</tr>
<tr>
<td>I₀</td>
<td>light intensity in the interferometer’s reference arm</td>
</tr>
<tr>
<td>I_signal</td>
<td>detected interference signal</td>
</tr>
<tr>
<td>Iᵣ</td>
<td>light intensity in the interferometer’s sample arm</td>
</tr>
<tr>
<td>Lᵣ</td>
<td>optical path length of the interferometer’s reference arm</td>
</tr>
<tr>
<td>Lₛ</td>
<td>optical path length of the interferometer’s sample arm</td>
</tr>
<tr>
<td>Rₛ</td>
<td>path length-resolved diffuse reflectance</td>
</tr>
<tr>
<td>Ra</td>
<td>arithmetic average roughness</td>
</tr>
<tr>
<td>Rq</td>
<td>root mean squared roughness</td>
</tr>
<tr>
<td>S(ν)</td>
<td>spectral power density</td>
</tr>
<tr>
<td>c</td>
<td>speed of light in vacuum</td>
</tr>
<tr>
<td>f</td>
<td>focal length</td>
</tr>
<tr>
<td>k</td>
<td>wavenumber</td>
</tr>
<tr>
<td>k₀</td>
<td>centre wavenumber value in the wavenumber range</td>
</tr>
<tr>
<td>lₘ,ₗ</td>
<td>coherence length in medium</td>
</tr>
<tr>
<td>lₗ</td>
<td>coherence length of the light source</td>
</tr>
<tr>
<td>n</td>
<td>refractive index</td>
</tr>
<tr>
<td>n₉</td>
<td>group refractive index</td>
</tr>
<tr>
<td>ν</td>
<td>frequency of light</td>
</tr>
<tr>
<td>z_max</td>
<td>single-sided imaging depth</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$\Delta \lambda$</td>
<td>wavelength bandwidth of the light source</td>
</tr>
<tr>
<td>$\Delta k$</td>
<td>total wavenumber range</td>
</tr>
<tr>
<td>$\Delta x$</td>
<td>lateral measurement resolution</td>
</tr>
<tr>
<td>$\Delta z$</td>
<td>the axial measurement resolution</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>draft angle of a microfluidic channel</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wavelength</td>
</tr>
<tr>
<td>$\lambda_0$</td>
<td>centre wavelength of the light source</td>
</tr>
<tr>
<td>$\tau$</td>
<td>time delay</td>
</tr>
<tr>
<td>$\tau_c$</td>
<td>coherence time</td>
</tr>
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List of original publications

This thesis is a summary of the research published in the following five papers:


Author’s contribution to publications:

For Papers I-III the author, together with Dr. Erkki Alarousu and Mr. Tuukka Prykäri, designed and developed the sub-micron-axial-resolution time-domain OCT device. Together with co-authors he planned the experiments and performed the OCT measurements. The author did the literature reviews, processed the measurement data, wrote the manuscripts and produced the final papers. Paper I presents the very first application of optical coherence tomography in characterization of printed electronics. Paper II presents reconstruction of a microfluidic channel demonstrates volumetric artefact correction in OCT data. In Paper III OCT is applied as a novel encapsulation inspection technique. Presented measurements of 1-to-3-μm-thin polymer layers are among the highest axial resolution results reported to date.

For Papers IV-V the author, together with Prof. Barry Cense and Dr. Pauli Fält, designed a sub-micron-axial-resolution spectral-domain OCT device. The author implemented two measurement devices: with Prof. Cense and Dr. Fält in Utsunomiya, Japan and with Mr. Janne Lauri in Oulu, Finland. Together with co-author Janne Lauri, the author developed the measurement control software. The author performed the measurements, conducted literature reviews, processed the measurement data, wrote the manuscripts and produced the final papers. In Paper IV the experimental device
was applied in measurements of printed electronic structures. The paper reports one of the highest axial resolutions achieved with SD-OCT to date (0.98 µm for Parylene C). Moreover, in Paper V 2-to-3-µm-thin absorptive colour-ink layers were successfully imaged.
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1 Introduction

1.1 Background and motivation of the work

Printed electronics is emerging as one of the most promising fields of today’s electronic market (Leenen et al. 2009). However, the first attempts in the field could be traced back to beginning of the XX century, when in 1904 Thomas Alva Edison tried printing graphite pastes on linen paper (Fjelstad 1989).

With the estimated market value of $2.2 billion in 2011 and $44.25 billion forecasted for 2021 (Das & Harrop 2011), it is a rapidly growing sector of business. Thanks to the fabrication techniques and materials used in the process, printed electronics allows for low-cost mass production. It aims at fabrication of simple circuits for the low-end part of the market, e.g., disposable sensors and indicators, light-emitting diodes (LED), solar cells, printed optics, smart textiles, and smart packaging, etc. The important aspects of printed electronics are: high production speed, high throughput, cost-to-functionality ratio, durability, accuracy, reproducibility, etc.

However, it is not only the fabrication cost that makes printed electronics so special. Using a combination of several techniques it is possible to fabricate an all-printed electronic device. Equally important is that printed electronics allows for creation of flexible and even organic-based devices. This may change the way we use and perceive consumer electronics (Forrest 2004).

In 2009 a consortium called PrintoCent was established in Oulu, aiming at combining companies, universities and institutes of the region in a joint effort to research and develop printed electronics. It created a great opportunity to focus our research on problems and aspects related to the application of OCT in that field.

The great benefits offered by printing techniques bring also challenges. Some of them relate directly to the fabrication technology and materials. However, quality control and characterization have equally important roles in the production process, even in research and pilot-phase manufacturing. This requires fast, accurate, reliable, and at the same time cost-effective tools. The existing inspection and characterization methods and devices may not meet all of the requirements. Some could be destructive, while others could be difficult or expensive in application.

Optical coherence tomography presented in this thesis could be an alternative, enabling volumetric insight into product’s structure and properties. The technique
was introduced by Huang et al. (1991) as the imaging modality of low coherence interferometry (LCI). As a non-destructive and non-contact optical characterization method, OCT offers high measurement accuracy and volumetric data. From that data, a variety of information about the surface and internal structure of the analysed object can be retrieved.

At the end of the 1990s OCT established its strong position in bio-medical research (Bouma & Tearney 2002, Brezinski 2006, Drexler & Fujimoto 2008, Tuchin 2013). It is especially popular in ophthalmology, where numerous application and devices have been reported. Recent reviews of the bio-medical application of OCT were published by Fercher (2010) and Wojtkowski (2010). Despite over twenty years of development, the number of industrial oriented applications has been limited. The first review focused beyond bio-medicine was presented by Stifter as late as 2007 (Stifter 2007).

However, in recent years the interest in non-medical use of OCT has increased which can be observed in new publications. Kastner et al. (2004) studied glass-fibre composites with OCT and micro-CT. Wiesauer et al. (2005) presented an evaluation of internal stress in polymer materials using polarization-sensitive OCT (PS-OCT). MEMS structure profiling with OCT was investigated by Jonathan (2006). OCT was also used to study crack propagation in dental composites (Braz et al. 2009). Juuti et al. (2009) and Zhong et al. (2011) presented their work on characterization of pharmaceutical tablets. Fabritius et al. (2010) proposed an OCT-based contact angle measurement method. In the past year Mujat et al. (2012) investigated the freeze-drying process, Nemeth et al. (2012) presented real-time measurement of fluttering foil thickness and Su et al. (2012) studied embedded microchannels in alumina ceramics.

The previous non-bio-medical research in the Optoelectronics and Measurement Techniques Laboratory focused on application of OCT in paper and pulp measurements (Alarousu et al. 2005, Alarousu 2006, Fabritius 2007, Prykäri et al. 2010). This led to the development of a sub-micron-axial-resolution time-domain OCT setup and better understanding of the technique and its industrial application requirements. Even though the device offered uncompromised accuracy by OCT standards, its slow measurement speed limited the application to the controlled laboratory environment.

Typical feature sizes and layer thicknesses in printed electronics are in the range from tens of nanometres to a few microns. This means that even for the biggest or thickest structures, the majority of the state-of-the-art OCT systems are unable to deliver satisfactory results. Furthermore, as stated before, the existing sub-micron-resolution time-domain OCT systems are too slow to consider their application in the industry.
This study assumed that it is possible to combine a sub-micron axial measurement resolution with a high data acquisition rate, offered by spectral-domain OCT systems. Such a combination could make the on-line application of OCT in printed electronics feasible.

1.2 Printed electronics – fabrication process and existing characterization techniques

The business of printed electronics benefits from experience of the paper and printing industry. The majority of techniques and the related issues have been known for many years and have been thoroughly studied. This is one of the reasons why printed electronics is cost-effective and promises a large-volume production. The fabrication process is versatile and compatible with a variety of materials.

The standard substrate for printed electronics is a foil (usually PET). However, coated paper is also used (Trnovec et al. 2009, Tobjörk & Österbacka 2011). The requirements for the substrate in printed electronics are much higher than in standard image printing. Pinhole-free and homogeneous layers are necessary to ensure proper functionality of the devices.

The majority of the fabrication techniques used in printed and flexible electronics can be realized in a roll-to-roll fashion (R2R). Standard fabrication methods include: R2R patterning (e.g., hot-embossing) and R2R printing (e.g., flexography, offset, gravure, and screen printing). In addition, inkjet printing, and laser processing (e.g., cutting, patterning, sintering, etc.,) are used.

Although all printing processes share a common name, the conventional large-scale processes may require different material properties than, e.g., inkjet printing. Typically, roll-to-roll printing is desired for a large-scale production, whereas inkjet printing enables selective or economic deposition of usually expensive materials. This allows for a pixel-by-pixel fabrication of the desired functional structure (Kleper 2004) and contributes to the cost efficient production enabling, e.g., high fabrication speed (throughput), good scalability, high resolution, and additive or selective material deposition.

To maintain high throughput and cost-effectiveness, the fabrication process needs constant monitoring which allows for elimination of the problems in an early stage. However, the number of existing volumetric characterization techniques applicable in printed electronics is limited.
The most robust of the existing volumetric characterization methods would be X-ray micro-tomography (Wang et al. 2001, Kim et al. 2009, Kang et al. 2010) or confocal microscopy (Smolander et al. 2008, Mäkelä & Haatainen 2012). 3D X-ray microscopy (Larson et al. 2002) and electron tomography (Van Bavel & Loos 2010) could also provide the desired information. The microtome, often used for cross-sectional analysis, should be treated as the last resort due to its destructiveness. A review of tomographic imaging techniques can be found in a book edited by Grangeat (2009). It explains the foundations and principles of the techniques and describes industrial applications of X-ray tomography.

Two-dimensional surface imaging and topographic characterization offer a variety of techniques applicable also in printed electronics. Optical methods include: light microscopy, optical profilometry based on vertical scanning (VSI) and phase shifting interferometry (PSI) (Trnovec et al. 2009, de la Fuente Vornbrock 2009), or chromatic aberration imaging (Kemppainen 2009). Scanning electron microscopy (SEM) (Kim et al. 2009, Perelaer et al. 2010, Kang et al. 2010), atomic force microscopy (AFM) (de la Fuente Vornbrock 2009, Kim et al. 2009, Kang et al. 2010, Mäkelä & Haatainen 2012), and stylus profilometry (Kang et al. 2010) are also often used techniques.

Other laboratory test methods include: time of flight secondary ion mass spectrometry (TOF-SIMS), X-ray photo-electron spectroscopy (XPS), X-ray diffraction (XRD) (Kim et al. 2009, Perelaer et al. 2010), SEM coupled with energy dispersive X-ray spectroscopy (EDS/EDX) (Kim et al. 2009), Fourier transform infrared spectroscopy (FTIR) (Lee & Cho 2005), or spectroscopic ellipsometry (Madsen et al. 2011). Despite being chemical characterization methods, these techniques could be used to some extent in quality inspection due to their material identification abilities. The adhesion properties of the specimen could be evaluated destructively, e.g., by using 90° peel, T-peel, or tensile shear (Hassler et al. 2010).

Many of the devices and methods mentioned here are simply expensive or impractical in serial quality inspection and characterization, while some of them require a fully controlled laboratory environment. An interesting, tabularised summary of the current characterization techniques was given by Jørgensen et al. (2008, p. 700).

A typical on-line characterization based on machine vision (de la Fuente Vornbrock 2009) or electrical characterization techniques, e.g., resistance and leakage current measurements (Trnovec et al. 2009, Keskinen et al. 2012) is not always able to provide comprehensive information allowing for pin-pointing a defect.
This leaves room for the development and testing of new quality inspection techniques which could address the drawbacks of the existing methods, or at least fill the gaps between them. This is also where the author has aimed his work in the development of OCT. This idea was recently supported by another research group which also acknowledged OCT as a possible characterization technique in the roll-to-roll fabrication process (Thrane et al. 2012). The dynamic tests performed this year by Alarousu et al. (2013) show the ability of the technique to resolve the structural properties of printed samples at the scanning speeds of up to about one metre per minute.

From the manufacturer’s point of view, the most desirable would obviously be a real-time quality inspection. When considering the feasibility of an on-line application of any characterization technique, the parameters of the fabrication process have to be taken into account. In the case of roll-to-roll processing, a typical width of the web is in the range of hundreds of millimetres and its velocity is measured in tens of meters per second (Tobjörk & Österbacka 2011). This renders the on-line application of any characterization technique as extremely challenging.

1.3 Contribution of the study

Characterization and quality inspection techniques are important elements of the production process. They allow for enhancing the properties of products and for keeping the cost under control by highlighting the fabrication issues. The existing methods are quite often inconvenient in practice, expensive, destructive, or provide a limited amount of information. Optical coherence tomography studied in this Thesis could be an interesting alternative, or an accurate reference for the existing techniques.

The industrial and non-medical applications of OCT are still fairly rare. The use case scenario differs greatly from those already established in the bio-medical research field. Therefore, a lot of difficulties and challenges have to be identified and addressed. However, the great amount of information offered by volumetric imaging, in author’s opinion, is worth the development.

A new industrial application of OCT is introduced and proposed as a valid characterization tool for printed electronics. The results and methods presented in this Thesis suggest that OCT has a potential to become a versatile tool and to offer sufficient parameters for an efficient analysis of the properties of a variety of printed electronics specimens.
This Thesis shows that OCT is able to provide accurate information about the packaging and encapsulation quality, layer homogeneity and thickness, material distribution and adhesion, as well as surface topography. It also demonstrates a novel design for an OCT device which offers a high measurement speed and a sub-micron axial resolution, all of which allow for considering an on-line application of the technique.
2 Optical coherence tomography

Optical coherence tomography is an imaging modality based on low coherence interferometry (LCI) (Huang et al. 1991, Fercher 1996). Like in LCI, the structural information about the object under study is obtained by interfering the back-scattered probing beam with a reference beam.

OCT could be compared to ultrasound imaging, with one to two orders of magnitude better axial measurement resolution and no need for transducing materials. As mentioned in the Introduction, OCT is a non-destructive and non-contact method.

Due to the use of low-coherence light sources, a phenomenon called coherence gating limits the interference to the portion of the light backscattered from a localized region within the sample. In other words, the interference takes place and is recorded only when the difference between the optical path lengths of the probing and the reference beams is within the coherence length of the light source. This allows for localizing the scattering sites and constructing a depth-dependent profile.

By contrast, in confocal microscopy (CM) the imaging of thin layers is achieved by elimination of the out of focus light using objectives of significantly high numerical aperture. The objectives required by CM have very short working distances and require placing the sample just below the surface of the objective. Therefore, the technique would be difficult to apply in industrial scenarios.

As demonstrated by Izatt et al. (1994a) and Schmitt et al. (1995), when needed, OCT and CM can both be implemented in a single device called an optical coherence microscope or OCM. This allows for combining the assets of both techniques and for enhancing the confocal imaging properties of the device. As in OCT, the short temporal coherence of a broad-band light source in OCM allows for rejection of the scattered light. Further improvements allowed for construction of a collinear OCT and confocal fluorescence microscopy devices (Dunkers et al. 2003).

The majority of the OCT devices employ a fibre or free-space Michelson interferometer configuration. In such a case, the interference term of the detected signal can be expressed as a convolution:

\[ I_{\text{signal}}(L_s, L_r) = 2\sqrt{I_s I_r} [\sqrt{R_s(L_s)} \otimes C(L_s - L_r)], \]  

(1)
where \( L_s \) and \( L_r \) are the optical path lengths of the interferometer’s arms, and \( I_s \) and \( I_r \) are light intensities in the sample and reference arms, respectively. The \( \sqrt{R_s(L_s)} \) term represents the approximation of reflectivity profile of the sample. The coherence function, i.e., the response of the interferometer to the mirror-only scenario, is expressed as \( C(L_s - L_r) \). It is often referred to as the point spread function (PSF). The \( \otimes \) symbol denotes a convolution (Pan et al. 1995, Schmitt 1999, Alarousu 2006). In other words, the interference term can be expressed as a convolution of the scattering potential and the envelope of the real part of the coherence function of the light source (Fercher 1996).

The theory behind OCT and examples of its application have been explained in detail in several handbooks (Bouma & Tearney 2002, Brezinski 2006, Drexler & Fujimoto 2008, Tuchin 2013).

The recorded interference signal depends on several object parameters, e.g., on layer thickness, distribution of the refractive index, scattering and absorption coefficients, birefringence, etc. Therefore, besides a simple intensity-based imaging, OCT enables a more complex characterization of the sample and its optical properties. This was the base for development of the functional OCT (see Chapter 2.4).

**2.1 Measurement resolution in optical coherence tomography**

The axial measurement resolution is one of the key parameters when considering industrial application of OCT. As mentioned in the previous section, the ability to localize the object in the depth direction depends on the coherence gating phenomenon. Therefore, the axial measurement resolution in OCT is strictly related to the coherence length of the light source. For light sources with a Gaussian shaped spectra, it can be expressed both in terms of wavenumber and wavelength:

\[
\Delta z = \frac{l_c}{2} = \frac{2}{\Delta k} = \frac{2\ln(2)}{\pi} \frac{\lambda_0^2}{\Delta \lambda} = 0.44 \frac{\lambda_0^2}{\Delta \lambda},
\]

(2)

where \( l_c \) is the coherence length, \( \lambda_0 \) is the centre wavelength of the light source and \( \Delta \lambda \) is the wavelength bandwidth of the source (Fercher 1996, Schmitt 1999, Izatt & Choma 2008). Wavelength bandwidth can be defined as the FWHM of the spectrum, so that:

\[
\Delta k = \frac{\pi}{\sqrt{\ln(2)}} \frac{\Delta \lambda}{\lambda_0},
\]

(3)

where \( \lambda_0 \) can be expressed as \( \frac{2\pi}{k_0} \) (Izatt & Choma 2008).
In addition to assumption of a Gaussian profile, Relationship 2 is only valid in the vacuum. In reality, studied objects are dispersive and their refractive index depends on wavelength. It is especially important when broadband light sources are concerned. The dispersion results in an increase of the coherence length and hence in reduction of the axial resolution. Therefore, the actual coherence length could be expressed as:

\[ l_{c,m} = \frac{l_c}{n_g}, \tag{4} \]

where \( n_g \) is the group refractive index of the medium (Fercher 2010).

The inverse relationship between the coherence length and the bandwidth of the light source is evident from the Relationship 2. Therefore, to increase the axial measurement resolution in OCT, one should use a light source with the lowest possible centre wavelength and the highest possible bandwidth.

The solution to the above requirements is a supercontinuum which was first observed by Alfano & Shapiro (1970a,b). It is essentially a light source with a broad spectrum ranging beyond all visible colours and having the properties of a laser beam. In other words, one can consider a supercontinuum as a spatially coherent white light.

A supercontinuum can be generated by propagating short and high power laser pulses through a non-linear medium, e.g., a photonic crystal fibre (PCF). The unique features of a PCF which make it a perfect supercontinuum source include: a single-mode propagation over a wide range of wavelengths, enhanced modal confinement and therefore increased non-linearity, and ability to engineer PCF’s group velocity dispersion to facilitate continuum generation in a specific region (Dudley et al. 2006, Humbert et al. 2006). Published CW supercontinuum generation results indicate a perspective for future development of the ultra-broadband, yet highly-stable light sources (Cumberland et al. 2008, Lee et al. 2010).

The shape of a supercontinuum spectrum is the result of numerous parameters, e.g., properties of PCF, pumping wavelength, pumping power, accuracy of the alignment and focusing, etc. Therefore, the coherence length of a supercontinuum can only be computed numerically, based on the recorded spectral power density.

Statistically, the coherence length of an arbitrary light source could be defined as:

\[ l_c = c \tau_c = c \cdot \frac{\int_0^\infty S^2(v) \, dv}{(\int_0^\infty S(v) \, dv)^2}, \tag{5} \]

where \( c \) is the speed of light, \( v \) is the frequency, and \( S(v) \) is the spectral power density of the light source. In addition, according to the Wiener–Khinchin theorem, the spectral power density is related to the power spectral density by:

\[ S(v) = \frac{1}{2\pi} \int P(t) \exp(-j2\pi vt) \, dt. \]


power density could be expressed as an integral:

\[ S(v) = \int_{-\infty}^{\infty} G(\tau) \exp(-j2\pi v \tau) d\tau, \quad (6) \]

where \( G(\tau) \) is the autocorrelation function or the temporal coherence function of a light source and \( \tau \) is the time delay (Saleh & Teich 1991, pp. 346-352).

The early results on high-resolution imaging by OCT were published by Izatt et al. (1994b). Since that time, several groups have reported measurements with sub-micron axial resolution by TD-OCT (Považay et al. 2002, Drexler 2004, Unterhuber et al. 2004, Xue & Fujimoto 2008). Such measurements are also reported in Paper III.

Properties of the available light-sources, their spectra, resulting axial resolutions and the quality of final images were studied by Fercher et al. (2003) and Unterhuber et al. (2004). Drexler (2004) discussed in addition the limits of the axial resolution imposed by the chromatic aberrations, group velocity dispersion and polarization properties of the probing beam.

The axial resolution of the spectral-domain OCT systems has stayed for a long time around 3 \( \mu \)m in self-developed devices (Drexler et al. 2003, Leitgeb et al. 2004, Cense et al. 2009) and around 5 \( \mu \)m in commercial devices (e.g., Hyperion, Thorlabs). However, in more recent times a few groups have investigated the possibility of a micron and sub-micron-resolution imaging with SD-OCT (Yadav et al. 2011, Liu et al. 2011). Similar results are reported in Papers IV-V. As demonstrated by Marks et al. (2004), the final axial resolution of the OCT images can be further improved by a numerical apodization of the spectra, thus enhancing the physical resolution of the light source.

The lateral resolution of an OCT device is determined by its optics and is independent of the axial resolution. It can be expressed as:

\[ \Delta x = \frac{4\lambda}{\pi} \left( \frac{f}{D} \right), \quad (7) \]

where \( \lambda \) is the wavelength, \( f \) is the focal length of the objective and \( D \) is the diameter of the probing beam (Izatt & Choma 2008). It is evident that the lateral resolution is wavelength dependent. In broadband light sources, e.g., supercontinuum, chromatic defocusing and aberrations pose a serious concern.
2.2  Time-domain optical coherence tomography

In the time-domain OCT (TD-OCT) the measurement relies on mechanical scanning. The mirror in the reference arm of the interferometer is translated at a constant rate. This shifts the interference signal to the Doppler frequency (corresponding to the translation speed) and allows for separating it from the DC light component. A typical detection in the time-domain OCT is based on a diode followed by a trans-impedance amplifier or a balanced detector. The recorded signal is directed through a band-pass filter centred at the Doppler frequency and Hilbert-transformed in order to create the envelope.

TD-OCT has several benefits. A high detection bandwidth is available due to the use of photodiodes which allows for using broadband light sources and increasing the axial measurement resolution. Another, equally important benefit of TD-OCT is the ability to suppress the intensity noise (RIN) of the light source with the use of dual-balanced detection (Hee et al. 1993). In such a setup, an additional diode is used to record the intensity of the reference beam. As a result, the noise arising from fluctuations in the light source power is greatly suppressed.

TD-OCT measurements also allow for dynamic focusing. Typically, the focusing objective in the sample arm is translated at the same rate as the reference arm of the interferometer (Schmitt et al. 1997). Dynamic focusing is very important in OCT, where high-numerical-aperture optics is used. The movement of the objective in the sample arm compensates for the primary defocus of the unscattered light in the sample, thus enhancing the usable depth range of the measurement.

The drawbacks of TD-OCT arise from the need for mechanical scanning. Scanning significantly reduces the measurement speed and affects the overall stability of the device. The insufficient data acquisition rate and the rapid development of the spectral-domain approach has limited the application of TD-OCT mainly to laboratory environments.

2.3  Spectral-domain optical coherence tomography

In spectral-domain OCT (SD-OCT), in contrast to TD-OCT, there is no need for mechanical scanning in the reference arm. The interference is now recorded as a spectral modulation. In the spectrometer-based OCT all wavelength components are recorded simultaneously, whereas in TD-OCT a profile is acquired in a point-by-point manner. Wavenumber-dependent data is processed using Fourier analysis to reconstruct the approximation for the internal sample reflectivity profile $\sqrt{R(z)}$. 

29
The idea of the spectral-domain acquisition in OCT was presented by Fercher (Fercher et al. 1995). In 2002 Wojtkowski et al. (2002b) reported the first in-vivo measurements of the human retina, and that moment is widely recognized as the beginning of the spectral-domain era in OCT.

While in the SD-OCT the axial measurement resolution stays the same as in TD-OCT, sampling of the interference spectra with a certain, finite resolution $\delta \lambda$ sets a limit on the available depth measurement range. The modulation frequency of the interference fringes increases with depth. Therefore, past a certain depth one will observe a fringe wash-out over the detector pixels resulting in signal-to-noise ratio (SNR) falloff. According to the Nyquist’s criterion, a single-sided imaging depth can be expressed in the form (Hausler & Lindner 1998, Izatt & Choma 2008):

$$z_{max} = \frac{\lambda^2}{4\delta \lambda}.$$  

(8)

To compensate for the SNR falloff, the acquired spectral data is post-processed. The data equidistant for wavelengths must be interpolated into equidistant for wavenumbers. This process is often referred to as "k-space mapping" and the interpolation scale is determined by a special calibration process. Several different calibration and data processing methods, including dispersion compensation, have been proposed (Wojtkowski et al. 2004, Yasuno et al. 2005, Mujat et al. 2007, Liu et al. 2010).

The performance of time and frequency domain OCT systems has been studied by many authors. It has been estimated that the frequency-domain OCT has theoretically a 10-25 dB sensitivity advantage over TD-OCT (de Boer et al. 2003, Leitgeb et al. 2003, Izatt & Choma 2008, Wojtkowski 2010).

Unlike in the time-domain, SD-OCT suffers from artefacts. The most significant is a mirror image of the sample reflectivity profile known as the complex conjugate artefact. A number of approaches has been proposed to discard this artefact and to enable a so-called full-range SD-OCT (Wojtkowski et al. 2002a, Hofer et al. 2009, Watanabe et al. 2010).

A common type of artefact is the self-interference or common-path interference, evident as horizontal lines in the image, at distances from the zero plane equal to the thickness of the layers. This artefact can be corrected in post-processing and treated as a fixed-pattern noise (Moon et al. 2010, Hofer et al. 2011).

Another inconvenience of SD-OCT is related to the dynamic range. While in TD-OCT the optical signal is recorded with a photodiode (capable of handling tens
of milliwatts), SD-OCT utilizes a camera with an a priori set exposure time. The significance of that difference is especially visible when measuring objects of varying reflectance properties. In the case of a glossy surface, the majority of signal power contributes to the DC component. In TD-OCT this component is filtered out before its arrival at the digitizer. However, in the case of SD-OCT, the A/D circuit is built into the camera and exposure is set to a fixed value before the measurement. This often leads to saturation of the detector and has to be considered before performing a measurement. A possible solution, decreasing this effect, would be an all-reflective interferometer design. It would reduce the amount of DC light originating from the device and arriving at the spectrometer and therefore extend the dynamic range available for the measurement.

Based on experience with TD-OCT and due to the requirements of industrial characterization a novel SD-OCT device was developed during this study. The goal was to combine fast data acquisition with a sub-micron axial resolution. Despite the adequate measurement speed, in terms of the axial measurement resolution SD-OCT had been far behind the time-domain devices. While an axial resolution of a few microns may be enough for a physician, it is insufficient in industrial applications. The developed device is described in Chapter 3.2.

2.4 Functional optical coherence tomography

In addition to the standard intensity-based imaging, several functional developments of OCT have been reported. The most wide-spread of the latter is the Doppler optical tomography presented by Wang et al. (1995) and now commonly used in flow measurements and Doppler imaging (Izatt et al. 1997). Another functional type of OCT allows for polarization-sensitive imaging (PS-OCT) (de Boer et al. 1997), enabling, e.g., birefringence detection, studies of polarization properties of specimens and dynamic photoelasticity testing (Stifter et al. 2010). Later developments and integration of Doppler and PS-OCT detection created a so-called multi-functional OCT (Park et al. 2003). In 2011 another modality, i.e., true-colour spectroscopic OCT imaging was demonstrated by Robles et al. (2011) and joined the functional OCT group. However, the use of spectroscopic OCT to measure depth-resolved spectral absorption was reported a few years earlier by Leitgeb et al. (2000).
3 Measurement devices

3.1 Time-domain OCT system with a sub-micron axial resolution

The study began with the experimental time-domain OCT device shown in Figure 1. The device used a Kerr-lens mode-locked Ti-sapphire femtosecond laser, followed by a photonic crystal fibre (PCF). The resulting supercontinuum light source enabled a high output power (around 150 mW after the PCF) and a bandwidth ranging from 400 to 1700 nm. This in turn made the sub-micron axial measurement resolution possible.

The measurement process was controlled by a specially developed LabVIEW™ program (Hosek et al. 2009). The A-scan (i.e., the depth scan) was acquired thanks to the movement of a mirror attached to a piezoelectric scanner in the reference arm. The additional scanner in the sample arm allowed for focus matching. Due to the use of the time-domain OCT method and a free-space cavity femtosecond laser, a balanced detector was employed in order to assure a high signal-to-noise ratio. Following the measurement, the recorded analogue signal was filtered, digitized and further processed by Matlab™ or ParaView™ software. More detailed information about the device can be found in Paper III.
The resolution of the system was proved to be sufficient for a variety of applications. However, the very slow measurement speed rendered it obsolete from an industrial inspection point of view. These two factors led to development of one of the first spectral-domain OCT devices with sub-micron axial resolution.

### 3.2 Spectral-domain OCT system with a sub-micron axial resolution

![Diagram of the experimental SD-OCT device](image)

**Fig 2.** Layout diagram of the experimental SD-OCT device (left): $\lambda/2$ - half-wave plate, GLP - Glan-Laser polariser, OIS - optical isolator, Fo - focusing objective, PCF - photonic crystal fibre, Co - collimation objective, M - mirrors, VND - adjustable neutral density filter, BS - beam splitter, RM - reference mirror, FL - focusing lenses, CS - calibration glass slide, HS - horizontal slit, PH - pinhole. Photograph of the actual device (right).

The developed experimental SD-OCT device utilized virtually the same light source as the previously described TD-OCT device. In the current version, it can be either a femtosecond laser combined with a photonic crystal fibre, or an integrated supercontinuum fibre laser. Both light sources offer similar wide bandwidth. In the SD-OCT device, the data acquisition rate was improved from a few Hz to tens of kHz, while the axial measurement resolution was kept in the sub-micron regime. Figure 2 shows the layout of the device.

To assure a sub-micron axial resolution a spectral region of 400-800 nm was used. The device used therefore virtually white light. Such a broad spectrum complicated the design of the system. In contrast to the majority of OCT systems which are relatively easy to align and can utilize highly-stable fibre based solutions, the supercontinuum light source required an open-space configuration. The developed system was therefore based on a modified Michelson interferometer built as a cage mount system. The current
version of the system uses ultrasonic linear motors for the X-Y scanning. Galvanometer scanners could be an alternative when a higher scanning speed is needed, whereas in an on-line application scanning would be obsolete due to web motion.

The interference was recorded using a fast, self-developed spectrometer, comprising of a diffraction grating, focusing objective and a state-of-the-art line-scan camera, capable of delivering 128,000 A-scans per second.

The measurement process was controlled by a custom program developed in LabVIEW™ which was additionally responsible for the data post-processing. The data processing included mapping of the spectra to equidistant wavenumbers, dispersion compensation, DC removal, noise filtering, Fourier transformation, and logarithmic scaling. More detailed information about the device and data processing can be found in Paper V.
4 Results

4.1 Characterization of printed circuits and structures

Various optical and contact-based methods can be utilized to study the properties of printed products. However, the majority of the methods offer a limited amount of information or are destructive to the specimen. This is where OCT comes in, offering non-destructive, non-contact and volumetric characterization.

*Paper I* presents the first ever measurements of the printed electronics structures done using OCT. A fully-printed RFID antenna was studied (Figure 3). Although the specimen used in the measurements was fabricated using screen printing, the same type of structure could be produced using, e.g., rotogravure roll-to-roll printing as demonstrated by Allen *et al.* (2011).

![Fig 3. The RFID antenna sample fabricated using screen-printing techniques. Markings and numbers correspond to the OCT measurements presented in this Thesis.](image)

The RFID specimen was imaged using the SMR TD-OCT device and studied with reference techniques to justify the accuracy and correctness of the OCT results. Imaging was done in several measurement modes: 3D imaging (volumetric tomography), 2D imaging (cross-sectional tomography), and topography. The obtained results were compared with the data from two commercial surface profiling devices: 3D optical profilometer (Wyko NT3300, Veeco) and stylus profilometer (Dektak 3, Veeco).
Figure 4 shows OCT images of the RFID specimen. The first measurement (top image) covered a distance of 8 mm with a 15 μm lateral measurement step. The tomographic B-Scan image was created using 534 A-scan profiles.

To present the fine structure of the insulating layer and the underlying wires, an additional measurement covering 2.5 mm was performed with a 2 μm measurement step. This produced 1251 depth-dependent profiles. The depth range was determined by the limits of the piezoelectric scanner in the reference arm of the interferometer and equalled 218 μm.

The conductive materials, i.e., the wires and the overlying insulating material can be clearly seen in the picture. The very high axial measurement resolution enabled us to record the fine structure of the layers. A slight boundary is visible mid-way through the depth of the insulation layer.

![Figure 4](image.png)

**Fig 4.** Tomograms of printed conductive wires and an insulating layer deposited on top of them obtained with the SMR TD-OCT device. (Paper I, published by permission of Springer).

In addition to cross-sectional imaging, OCT enables volumetric reconstruction of the sample. An example can be seen in Figure 5. The areas in the image are marked with numbers to allow for easy identification. Observing the images from the left, a topmost wire can be seen first (1). The material used to print the wires, in the case of the analysed sample, contains silver and like most conductive pastes is not transparent to the probing light. Therefore, no underlying structure was revealed. To the right of the top wire one can distinguish an area covered with the insulating material (2). Topographic details of the insulating layer can be clearly seen in the image on the left. The measured area ends with a bare wire visible at the end of the image on the left (3). The insulating layer is transparent and therefore the underlying wire can be seen in the bottom projection (4). Thanks to the volumetric imaging, the OCT data contains
information about the underlying wire’s topography and structure. A characteristic pattern left by the screen-printing process is visible.

To test OCT in the surface characterization task, a topography map of a screen-printed wire was computed based on the measurement data. The amplitude threshold algorithm was used. The obtained surface data was compared with the result from the optical profiling measurement. The results can be seen in Figure 6.

Fig 6. A topography image of a printed wire of the studied RFID antenna sample. Optical profilometer measurement (left) and OCT computed topography map (right). (Paper I, published by permission of Springer).
Optical profilometers of the Wyko series use white-light interferometry to obtain surface topography information. The use of vertical-scanning interferometry (VSI) allows for an axial measurement resolution in the order of nanometres, while phase-shifting interferometry (PSI) enables a sub-nanometre characterization. The lateral resolution is diffraction limited. Some limitations of the optical profilometer are a result of its measurement principle. In most of the cases, only one material should be measured to assure proper results. While the VSI mode is quite robust and uses the maximum signal amplitude, the PSI mode is fairly demanding. Due to the phase shift requirement, it allows for measurement of features significantly smaller than the wavelength of the probing beam (usually \(< 150 \text{ nm}\)). Additionally, if more than one material is encountered, the resolved step height between materials is not measured accurately due to differences in the phase. In the case of the studied sample, both OCT and optical profilometry can be described as very accurate and provide us with complex topography information. Moreover, the benefits of each method were acknowledged by the device manufacturers and one of the commercial optical profilometers combines these techniques (Lambelet 2011).

The optical profilometer test was followed by a stylus profilometer measurement. A distance of 8 mm, across the printed wires, was covered by the measurements. The device employed in the measurement used a stylus to scan across the sample and resolve the surface topography. Vertical movements of the stylus are measured and recorded. The device is very accurate and its vertical resolution fits in the sub-nanometre range. Three measurements were done with different needle pressure values: 10, 20, and 30 mg. The OCT surface profile was computed based on the measured data using the amplitude threshold algorithm. Figure 7 shows a comparison between stylus profilometer data and the OCT results.

The resulting profiles revealed a similar structure. However, this was only a qualitative measure. Therefore, the heights and widths of the wire profiles were determined and used for a quantitative comparison of the results. The values are shown in the form of tables and plots in Figure 8.

Numerical differences between the stylus profiler and OCT results are mainly caused by the inability to exactly overlap the measured areas in these devices. A slight shift of the measurement point can be seen even in repeated profilometer results. In effect, slightly different profiles were determined by the devices.

Despite this problem, the results from both devices were in the same range of values. For both quantities, i.e., wire height and width, OCT provided slightly lower values than
the stylus profilometer. This could be explained as a result of the threshold error of the algorithm used in determination of the OCT profile. The differences may have also arisen from the fact that the stylus profiler used a certain needle pressure to acquire data, whereas in OCT the measurement was performed in a non-contact manner.

After the successful development of the SMR SD-OCT device, the antenna sample was studied again to qualitatively evaluate the difference between the spectral and time-domain measurement systems. In addition to the experimental SMR SD-OCT device a commercial spectral-domain device was used (Hyperion, Thorlabs). Both of the new measurements were performed with a 2 μm lateral measurement step, over a distance of 8 mm. The resulting tomographic images can be seen in Figure 9.

The results show that SMR SD-OCT offers a resolution and sensitivity similar to the previous SMR TD-OCT device (mboxFigure 4). However, the time needed to perform the measurement was reduced by over 100 times (measurement rate was increased from 2 to 200 Hz), assuming a translation velocity of the piezoelectric stage of 1 mm/s. Moreover, the measurement time would be further reduced when using galvanometer scanners and the full available acquisition rate of the Basler camera (128 kHz).
### Fig 8. Dimensions of wires - a comparison between values calculated from the OCT data and obtained by a stylus profilometer.

<table>
<thead>
<tr>
<th>Wire number</th>
<th>Dektak 10 mg</th>
<th>Dektak 20 mg</th>
<th>Dektak 30 mg</th>
<th>OCT calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.19</td>
<td>19.14</td>
<td>20.92</td>
<td>409.73</td>
</tr>
<tr>
<td>2</td>
<td>19.04</td>
<td>12.31</td>
<td>24.28</td>
<td>612.19</td>
</tr>
<tr>
<td>3</td>
<td>20.04</td>
<td>24.17</td>
<td>21.75</td>
<td>576.62</td>
</tr>
<tr>
<td>4</td>
<td>21.28</td>
<td>20.04</td>
<td>20.28</td>
<td>504.34</td>
</tr>
<tr>
<td>5</td>
<td>27.56</td>
<td>23.57</td>
<td>23.85</td>
<td>507.12</td>
</tr>
<tr>
<td>6</td>
<td>25.91</td>
<td>26.25</td>
<td>24.07</td>
<td>453.36</td>
</tr>
</tbody>
</table>

### Fig 9. Tomograms of the screen-printed antenna, obtained with spectral-domain OCT systems: SMR SD-OCT (top) and commercial SD-OCT (bottom). (Paper IV, published by permission of SPIE.)
4.2 Evaluation of the structure and lamination of microfluidic channels

Versatility of the R2R fabrication comes from the fact that it combines a variety of processing methods. An example could be lamination and hot-embossing which are commonly used in the production of microfluidic structures. Such structures are widely used in inexpensive lab-on-a-chip arrangements, enabling easy and robust bio-sensing. They form also a good example of multi-layered structures, when it comes to product characterization. A typical fabrication process of the lab-on-a-chip structure was described by Liedert et al. (2012).

A review of the optical imaging techniques in microfluidics has been recently published by Wu et al. (2012). The techniques presented in the paper include: phase contrast microscopy, HPM, and DIC microscopy. The article outlines the development of digital in-line holography and scanning optical microscopy, including their integration with microfluidic devices in the forms of HOM and OFM. Doppler OCT is acknowledged as a method of flow measurements. A similar application was reported by Lauri et al. (2008). In addition to Doppler imaging, OCT could also be used to study the contact angle of the droplets moving inside the microfluidic channel (Srinivasan et al. 2003).

Fig 10. A microfluidic chip with hot-embossed features, similar to one used in the study. Channels and inlet holes are clearly visible. A rectangle shows the area of the OCT measurement.

In Paper II OCT was used to non-destructively reconstruct the structure of the microfluidic channel shown in Figure 10. All physical dimensions of the structure, including the final volume and draft angle of the channel were successfully determined. In addition, the information gathered during the measurement allowed for evaluation of the lamination quality. Any problem with adhesion between the laminated materials would have caused a local increase in the signal amplitude, sometimes visible as an
additional interface in the depth dependent profile. This is where OCT has an advantage over the classical imaging methods, when studying fully transparent or opaque materials.

Figure 11 shows a tomographic image of the channel. An area of 1500 μm x 1500 μm at the inlet of the channel was measured using the developed SMR TD-OCT. Each lateral measurement point provided a depth-dependent, 272-μm-long vector of 7500 points. The structure was imaged from the substrate side, i.e., opposite to the direction of hot-embossing.

From OCT’s point of view a channel is a multi-layered and a multi-material structure. To accurately reconstruct its volume, changes in the refractive index at all material interfaces have to be taken into account. As mentioned in the OCT theory chapter (Chapter 2), to record an interference, the difference between optical path lengths of photons arriving from the sample arm and those from the reference arm has to be less than the coherence length of the light source. Let us define the refractive index of a medium, \( n \), as a factor by which the velocity of light in that medium is lower than the velocity of light in vacuum. Then the optical thickness of the medium and its inner interface position will be increased proportionally. In Figure 11 the bottom of the channel’s inlet hole seems to be above the actual channel. This is an example of a shift caused by refractive index.

For further data processing and volumetric correction, four vertical regions of interest (ROI) were chosen for interface segmentation. The regions are marked in Figures 11 and 13 for reference.

The surface of the structure was labelled as the first ROI. It provided the information about the position of the inlet hole and was used as a reference for the refractive index...
correction. The second ROI was assigned to the bottom of the inlet hole, shifted due to the lack of a top polymer layer. Finally, both interfaces of the channel itself were named ROI three and four, respectively.

The interface segmentation process, based on the algorithm proposed by Lankton et al. (2007), is demonstrated in Figure 12. For each depth-dependent profile, the point of maximum amplitude was found inside corresponding ROI and was used to localize the interface. Therefore, for each of the interfaces, both the topography and the amplitude maps were determined. Each of the amplitude maps was processed using the same segmentation algorithm to disregard the areas outside the physical interface. This allowed for defining the boundaries for the refractive index correction. Depending on the complexity of the processed interface and the signal-to-noise ratio, the algorithm was iterated between 200 and 400 times.

The initial volumetric reconstruction, based on the raw measurement data, is shown in Figure 13. In addition to 3D rendering, the figure shows the topography map of each interface.
Having sufficient information about the interfaces, the refractive index correction was applied. A refractive index of 1.489 was assumed for PMMA. Each of the A-scan vectors in the volume was interpolated with respect to the interface position and according to the refractive indices. A more robust method could be applied for the refractive index and geometric distortion correction, e.g., as presented by Westphal et al. (2002).

After the correction, the reconstructed volumetric structure should correspond to the physical structure of the sample. However, the initial volumetric reconstruction revealed a wrinkle-like distortion of interfaces. The experimental TD-OCT device required a substantial amount of time to perform the measurement. Therefore, the artefacts, shown in Figure 14, could be attributed to changes in the laboratory environment, e.g., temperature.
The surface topography map shown on the left hand side of the Figure 14 was used to isolate the artefacts. The map was convoluted with a non-uniform filter kernel which performed high-pass filtering in one direction and low-pass in the perpendicular direction. The filter kernel was used in such a way that the high-pass direction was oriented along temperature changes. The result of this non-uniform filtering was then divided in point-by-point fashion by the original map. The original map was low-pass filtered prior to this division. The outcome of the computation represented the magnitude of the artefacts.

The surface of the specimen contained the channel’s inlet hole. Therefore, only one border line profile was chosen and used for correction of the entire volume. Artefact correction was done by shifting the content of each A-scan vector by the estimated distance. The result was an artefact-free volume shown, together with the interfaces, in Figure 15.

The post-processed volumetric data allowed for derivation of all interesting structural parameters of the channel. The average height of the channel itself was determined to be 36.7 µm with a standard deviation of 1.4 µm. The determined height map of the channel, its widths at the top and bottom, and the draft angle values, are plotted in Figure 16.

Assuming a trapezoidal shape for the channel, the draft angle is defined by Equation 9. The mean value of the draft angle was determined to be 72.94 degrees. The non-uniform shape of channel’s inlet and the difficulty in accurate interface segmentation affected the determined values of the draft angle which can be seen at the beginning of the channel as an artificial, oddly shaped peak.
Fig 15. The result of data processing. Final volumetric reconstruction of the microfluidic channel (centre) and the corrected topography maps of all interfaces (around). The size of the bounding box is 1500 µm x 1500 µm x 272 µm. Colour maps are presented in microns. (Paper II, published by permission of SPIE).

Fig 16. Dimensions of the microfluidic channel as obtained from the OCT data. (Paper II, published by permission of SPIE).
\[
\alpha = \arctan \left[ \frac{\text{bottom width} - \text{top width}}{2 \times \text{channel height}} \right].
\] 

(9)

As mentioned at the beginning of this section, due to the refractive index sensitivity, OCT should be very accurate in quality inspection of the lamination. In the case of the studied microfluidic structure, the evaluated area showed no air gaps or other features which could account for defects or delamination, and could thus affect the structural properties and life time of the specimen.

4.3 Quality inspection of the encapsulation in printed electronics

In recent years a lot of research and development efforts in printed electronics have focused on the use of organic materials. Such materials have many useful properties, but, on the other hand, they require appropriate treatment and environmental conditions to work as expected. The majority of the organic materials require some sort of protection against humidity, oxygen, carbon dioxide, etc. In addition, some structures require mechanical protection which increases the robustness of the device.

Thin protective films are usually used to secure proper operation conditions and to isolate the devices made of organic components from the environment and from one another. Such films are referred to as encapsulation layers and their typical thickness ranges from hundreds of nanometres to a few micrometres. The usual encapsulation materials and their properties, as well as packaging and encapsulation techniques are discussed in a book written by Ardebili & Pecht (2009). In addition, the book describes a variety of typical defects and failures related to encapsulation.

It is quite clear that the life expectancy of the device depends strongly on the properties of these layers. Therefore, quality inspection is an extremely important step in the fabrication process. Degradation of organic structures and applicable characterization methods were extensively studied by Jørgensen et al. (2008) in a study of organic solar cells.

In the previous section, OCT was said to be a good technique to investigate lamination quality due to its sensitivity to changes in the refractive index. This same aspect of the technique makes it suitable for inspection of the encapsulation. However, in the case of the standard lamination process relatively thick material layers, tens of micrometres or more, are used. In Paper III OCT was applied to imaging of two-micrometre-thin films which makes a big difference in terms of required axial
measurement resolution. Figure 17 shows a tomogram of a 2.96-μm-thin layer of polymer deposited on a microscopy glass and the corresponding depth-dependent profile.

The initial hypothesis of the encapsulation study was that presence of voids, impurities, and problems with adhesion of the encapsulation layer caused a mismatch in the refractive indices. This in turn affects the magnitude of the interference fringe signal. In OCT, every A-scan acquired during the measurement is a superposition of depth-dependent reflectivity. Therefore, to some degree, the defects could be recognized even when their height was smaller than the axial resolution of the OCT device.
This study started with a test measurement. An altered layer of Parylene C was specially prepared on top of a microscopy glass using chemical vapour deposition (CVD) at the Technical University of Lodz, Poland. A specially tuned fabrication process allowed for formation of artificial gas chambers below the polymer layer. A detailed description of the sample fabrication procedure can be found in Paper III.

An area of 2 mm x 2 mm was measured with the experimental SMR TD-OCT device. The depth range of the measurement was set to 208 µm, while a lateral measurement step of 5 µm allowed for high resolution volumetric imaging.

A computational processing algorithm was implemented to characterize the encapsulation quality, based on OCT measurement data. The location of the encapsulation layer’s surface was resolved using a signal amplitude threshold. So as to derive a surface topography map, the operation was performed for every A-scan vector within the volume. The resulting topography map was then low-pass filtered to discard possible errors and noisy pixels. The filtered topography map was then used to specify a vertical region of interest (ROI) at the interface between the encapsulant and the protected structure.

To characterize the interface, position of the maximum signal amplitude within ROI was computed for every A-scan. The resulting amplitude map could be presented "as is", or further processed to simplify the evaluation (e.g., using binarization algorithms). The topography map of the interface was saved for further reference. A volumetric reconstruction and encapsulation map of the Parylene C-coated glass are shown in Figure 18.

The computed encapsulation map corresponds well with the artefacts visible in the volumetric reconstruction. Moreover, it reveals a number of point type defects, invisible when studying only the surface of the specimen and difficult to assess using, e.g., optical microscopy.

After the successful preliminary tests the OFET structure was used as a representative of the real-life samples. The structure was covered with 1-to-2-µm-thin layer of Parylene C by the CVD process. The sample fabrication and coating processes are described in Paper III.

A 2 mm x 2 mm area was studied with a 5 µm lateral measurement step. The depth range set for the measurement was 73 µm. An amplitude map of the Parylene C - OFET interface was determined using the same algorithm, and in the same way as described above for the microscopy glass sample. The map and the corresponding volumetric reconstruction of the OFET structure is shown in Figure 19.
Fig 18. A volumetric reconstruction of the Parylene C-coated microscopy glass (left, above) with a zoom-in image (right), and the computed amplitude map of the Parylene C - glass interface (left, bottom). The size of the bounding box is 2000 µm x 2000 µm x 208 µm. Coating defects and gas chambers are clearly visible. (Paper III, published by permission of Springer).

Fig 19. A volumetric reconstruction of the OFET structure coated with 2-µm-thin layer of Parylene C (left, above) with a zoom-in image (right), and the computed amplitude map of the Parylene C - substrate interface (left, bottom). The size of the bounding box is 2000 µm x 2000 µm x 73 µm. (Paper III, published by permission of Springer).

The superior axial measurement resolution of the experimental OCT device allowed for resolving the thin polymer film. A zoom-in image on the right hand side of Figure 19 shows how clearly the interfaces were segmented. The volumetric reconstruction of the 1-to-2-µm-thin layer makes it one of the highest resolution OCT measurements reported to date.

When analysing the amplitude map, one would expect to see regions of higher amplitude that would indicate presence of defects. However, in the case of OFET measurement, the situation was more complex. Instead of a binary-like pattern, one could see places of significantly lower amplitude.
The presence of low-amplitude areas could have been caused by roughness of the substrate surface. The amplitude of the signal is proportional to the number of photons scattered and reflected by the sample, and re-coupled into the interferometer. In the case of rough surfaces, sharp edges, or features inclined at large angles with respect to the optical axis of the interferometer, the probing beam may be reflected away. In the case of the OFET structure, roughness originates from the crystalline nature of PTCDI-C5 and silicon. Although the related feature sizes were smaller than the axial resolution of the OCT device, roughness could still affect the amplitude.

The surface of the sample, i.e., the Parylene C layer, was studied in order to evaluate such hypothesis. Local roughness was determined by dividing the surface into areas of 4×4 pixels and calculating the Ra roughness parameter for each of them. This created a local roughness map shown in Figure 20. In addition, this figure shows the amplitude maps of the Parylene C and OFET surfaces, and a thickness map of the encapsulant.

Despite the resolution mismatch, caused by the roughness calculation procedure, a clear correlation between the amplitude and roughness map could be observed. For this
reason, the inspection of encapsulation based on amplitude maps alone is of limited value in the case of samples of highly rough surfaces or of varying roughness.

Although the main hypothesis was not confirmed, it did not undermine the ability of OCT to evaluate the encapsulation quality. The technique has one more advantage. It provides full volumetric information about the structure of the studied specimen. In the case of the OFET structure, the best way to evaluate the quality of the protective film would be its volumetric rendering, as shown in Figure 19, or analysis of its thickness. The latter approach has additional benefits. As mentioned before, the quality of encapsulation is related not only to adhesion, but also to the thickness, uniformity, and continuity of the protective layer. An example thickness map for the OFET sample is shown in Figure 21.

![Thickness map of the Parylene C layer](image1)

![Amplitude map of the OFET surface](image2)

Fig 21. Thickness map of the Parylene C layer (above) and amplitude map of the OFET surface (bottom). (Paper III, published by permission of Springer).

The areas of lower thickness appear above the electrodes due to substrate’s topography. The mean thickness of the encapsulant is slightly higher than expected from the parameters of the deposition process. Furthermore, only a few places whose thickness was lower than 1 µm were registered. This allowed for classifying the encapsulation as successful.

Several reference measurements were done to evaluate the OCT results. The surface of the polymer layer was studied using a scanning electron microscope (SEM) and a classical optical microscope. Figure 22 shows results of these measurements. In addition, the figure shows the amplitude map of the Parylene C surface as determined
from the OCT data. A customized colour map is used to emphasise the similarities between the OCT and microscopy results.

In the SEM measurement (Neoscope JCM-5000, JEOL), no surface structure was revealed due to the non-conductive nature of the polymer. In order to resolve the structure, the specimen would require a relatively complex pre-treatment, e.g., gold sputtering. It would, however, make the evaluation of encapsulation layers with a standard SEM as destructive and unpractical from the industrial point of view.

The optical microscope (Eclipse LV100DA-U, Nikon) image shows a pattern similar to that observed in the OCT amplitude map. However, a standard 2D microscope image does not contain enough information to evaluate the quality of the encapsulation layer. It is difficult to assign the features visible in the image to a particular layer and to justify proper adhesion of the encapsulant. Therefore, standard optical microscopy is not suited for inspection of encapsulation.

To fully characterize the surface of the OFET structure, a stylus profilometer was used (Dektak 3, Veeco). A 8-mm-long profile was measured along the OFET electrodes and the bare substrate space between them. Its result is shown in Figure 23. The resolved profile shows several sharp features rising from the surface of the polymer layer. A gap between electrodes, i.e., an area of bare substrate, can be clearly identified.
A layer of Parylene C was deposited on the OFET structure by the CVD process. Therefore, its thickness should be uniform over the studied area and it should fairly well replicate the features of the substrate’s surface. As expected, the mean size of the surface features of the OFET structure is small, when compared with the axial resolution of the OCT device. For the measured profile of 1600 points the $Ra$ roughness was 186.1 nm, while the $Rq$ roughness was 354.2 nm.

After development of the first SMR SD-OCT device, the Parylene C-coated microscopy glass sample was studied again. As shown in Figure 17, this sample had imperfections in the form of gas bubbles, trapped under a 2-$\mu$m-thin layer of polymer. A cross-sectional measurement was done with a 5-$\mu$m lateral measurement step over a distance of 750 $\mu$m. An example of the depth-dependent profiles, fringe spectra, and a tomogram of the gas bubble are shown in Figure 24.
The physical thickness of the Parylene C layer was measured to be about 2.9 µm which is in good agreement with previous TD-OCT results. The refractive index of 1.639 was assumed in the calculation of the Parylene C thickness. Both the image and the depth-dependent profile show clear segmentation of all interfaces. Such result proves the ability to implement imaging with a sub-micron axial resolution and a high data acquisition rate in a single OCT device. This was also one of the first demonstrations of sub-micron-scale imaging with SD-OCT.

4.4 Characterization of inkjet-printed colour filters

The colour filter structure shown in Figure 25 was inkjet-printed into a pool-like structure. Substrate structure was fabricated using photolithography techniques. A detailed description of the fabrication process is given in Paper V.

![Fig 25. A microscope image of the substrate after patterning (left) and the final filter structure with green, red and blue inks separately printed and dried on a patterned substrate (right). (Paper V, published by permission of SPIE).](image)

Colour filter was chosen for the study because of its fabrication technique and its interesting parameters. Its structure is a challenging object for a spectral-domain OCT characterization and allows for testing of the technique under adverse imaging conditions.

The first aspect of SD-OCT imaging is the varying reflectivity characteristics of the specimen. As discussed in this Thesis, SD-OCT is so far the most feasible approach for implementing the OCT technique in industrial quality inspection. In most of today’s SD-OCT devices camera’s exposure time and the power of the probing beam are set before the measurement. Therefore, the dynamic range of the detector should be considered fixed. All changes in the amount of light scattered and reflected from the
specimen have a strong influence on the final result of the measurement. Two extreme consequences of this are underexposure (resulting in a limited SNR) and saturation of the detector (resulting in side-lobes, loss of resolution, and other artefacts).

Another difficulty in the characterization of the filter structure comes from its purpose, i.e., attenuation of light. SMR SD-OCT in contrast to a conventional NIR based SD-OCT device uses the visible range of the electromagnetic spectrum. Therefore, the spectrum of the probing beam and the attenuation profile of the filter overlap. In the case of an RGB pattern, there could be a significant difference in the amount of scattered light and in the shape of the recorded spectra in different regions of the sample. This could lead not only to a loss of signal amplitude, but also indirectly to a loss of the axial measurement resolution.

Characterization of the filter structure using OCT began with cross-sectional measurements aimed at determining the thickness of the ink layer and checking whether the axial measurement resolution of the device was high enough to separate the interfaces between different materials. Resulting tomograms are shown in Figure 26.

Side-lobes visible in the top panel of that figure result from a much higher reflectance of the empty pools’ surfaces. The oscillation artefacts visible in the interfaces are caused by vibration of a faulty piezoelectric scanning stage during the measurement. Despite these artefacts, the axial resolution of the experimental SMR SD-OCT device was good enough for successful measurements and for segmenting all material interfaces. The boundaries of the ink layer and the pool walls can be clearly seen in the image. The
thickness of the ink layer was 1.5-2.5 \( \mu m \) in the reference measurement with an optical profilometer.

In addition to the high axial resolution, the SMR SD-OCT device used fairly high numerical aperture optics. A combination of these factors allows for accurate imaging and volumetric reconstruction. Figure 27 shows a complete volumetric reconstruction of the colour filter structure. Both the ink volume in the pools and the shape of the walls separating the pools were resolved.

![Fig 27. a) Analysed filter pattern, b) Optical profilometer measurement, c) volumetric reconstruction based on SMR SD-OCT data, d) volumetric reconstruction based on commercial SD-OCT data. The size of the volumes is 500 \( \mu m \) x 500 \( \mu m \) x 100 \( \mu m \), while the area imaged with the optical profilometer was 635 \( \mu m \) x 475 \( \mu m \). (Paper V, published by permission of SPIE).]

To emphasize the difference between the areas, the presented structure contained empty pools and pools with inkjet-printed green colour. The contrast between the regions can be easily observed in the figure.

OCT data could be used to determine the thickness of the ink layer in two ways. The first, direct method would require volumetric information and measure the vertical spacing between the surface and the bottom interface of the ink layer. A second method
would be based on surface topography analysis and on estimation of the difference between the surface positions of the empty pools and those printed with ink, similarly to the method used in standard optical profilometers. Therefore, thickness of the ink layer could be determined even if its value was smaller than the axial measurement resolution of the OCT device.

Figure 28 shows a comparison between the results obtained with the OCT device and a commercially available optical profilometer. The full-field measurement principle employed in the optical profilometer shows its clear superiority over mechanical lateral scanning as in the experimental OCT device. The latter often suffers from vibration and measurement step inhomogeneity artefacts. Nevertheless, the results are clearly correlated, thus demonstrating the accuracy of OCT in surface characterization.

Fig 28. Measurement of the thickness of ink layer. A profile determined from the OCT data (dashed line) and a result of the optical profilometer measurement (solid line).
5 Discussion

The continuous process of invention and innovation leads to rapid development of technology. Nowadays, items seen previously only in science-fiction movies are at our fingertips. This is the case with printed electronics which allows for fabrication of flexible devices, smart textiles, multi-functional packaging etc. However, the development in production technologies calls for development of characterization and quality inspection methods. Accurate and cost-effective techniques are the key to an optimized fabrication process and thus allow for lowering the production costs. This is especially important in the case of printed electronics, where cheap and large-scale production is the key to success.

This Thesis proposes OCT as a possible cost-effective, accurate, versatile and non-destructive quality inspection technique. It is based on a novel and original application of OCT in characterization of printed electronics introduced in 2010. To prove the feasibility of such an application a variety of specimens was studied.

5.1 Measurements

The ability of OCT to provide volumetric reconstruction is a well-known fact. Paper I reports SMR TD-OCT measurements aimed to show the potential of the technique when applied to printed objects. It demonstrates that the data acquired during the measurement contains a variety of information about the surface and the structure beneath it. A printed RFID antenna was chosen as the object for the study. In the case of such a structure, the thickness of the insulating layer, profile of the underlying wires, the adhesion between materials, etc. could be evaluated. In addition, as demonstrated by Alarousu (2006), OCT could be used for accurate analysis of the surface and its roughness.

Tomographic measurement of the RFID structure was repeated in Paper IV after the development of a new SMR SD-OCT device. The TD-OCT and SD-OCT data were compared with each other and with those from a commercial SD-OCT device. The results show that in the case of an RFID sample the layers are thick enough even for the standard OCT device. All three devices successfully delivered images of the structure, while the SLD-based commercial system had the highest sensitivity and exhibited the lowest amount of noise.
Any tomographic image based on OCT data can be used for further processing. Over the time a variety of different algorithms (enabling, e.g., automated segmentation and feature recognition) have been presented, allowing for efficient extraction of the desired information.

Based on RFID imaging results, it has to be noted that conductive materials used in printed electronics are opaque to the probing light. This means that the structure underneath will be shadowed by their presence and will appear as a void in the images. Nevertheless, the majority of other materials used are either transparent or scattering, allowing for successful OCT imaging.

Another known characteristics of OCT is its sensitivity to discontinuities in the refractive index (Schmitt 1999). This phenomenon can be utilized in the imaging of otherwise transparent or opaque multi-layer and multi-material objects. Changes in the refractive index increase the amplitude of the recorded interference signal. Therefore, the position of the material interfaces can be relatively easily retrieved using a signal threshold or segmentation algorithms.

In Paper II this approach was utilized to perform a volumetric reconstruction of a microfluidic channel. The lengthy measurement time, caused by the use of a TD-OCT device, revealed additional challenges in the evaluation of polymer-based structures. During the several hours required to complete the measurement, the environment in the laboratory and the temperature changed multiple times. This introduced volumetric artefacts in the OCT data. The problem was identified and the related artefacts were successfully removed during post-processing. A full volumetric image of the channel was presented and its key volume parameters were derived. No signs of delamination or problems with adhesion were observed.

The refractive index sensitivity of OCT was the basis for a novel application of the technique in the inspection of encapsulation proposed in 2011. Paper III demonstrates the use of OCT in the characterization of a few-microns-thin layers of polymer. These layers are a very important part of the final package in printed and organic electronics as they provide mechanical, moisture and chemical protection for the actual structure underneath. Any imperfection in these layers could significantly affect the functionality or shorten the life expectancy of the final product.

It was demonstrated that, using OCT, it is possible to evaluate the quality of encapsulation by computing the amplitude map of the encapsulant-structure interface or by studying the thickness of the layer. A small thickness value means that the latter
approach requires sub-micron axial resolution in OCT devices. As demonstrated with the experimental device in Paper IV, it is possible to use SD-OCT in the process.

Results reported in Paper V show that even demanding printed structures such as colour filters can be studied with OCT. Despite the attenuation of light by inks in the very spectrum of the probing beam, few-microns-thin layers were successfully imaged. The SMR SD-OCT device used for the measurements employs the visible light and spectral detection. Therefore, it would be possible to perform true-colour imaging with OCT, thus extending its already broad characterization properties (Robles et al. 2011).

5.2 Time and spectral-domain OCT in industrial quality inspection

The study began with the experimental SMR SD-OCT device, capable of imaging with an axial resolution well below 1 µm. This allowed for thinking about the industrial measurements applications, where the size of features is usually out of reach for today’s commercial OCT devices.

Joint research projects and laboratory experiments revealed that despite the sufficient resolution, TD-OCT is not adequate for high volume characterization. Considering the feasibility of on-line application, the data acquisition speed of TD-OCT is simply no match for the fabrication devices.

This led to the development of a new experimental OCT system. The results prove that it is possible to benefit from the extreme bandwidth of a supercontinuum light source and a fast data acquisition rate in a single spectral-domain device (SMR SD-OCT). Furthermore, presented measurements show that SD-OCT is capable of sub-micron-resolution imaging. SMR SD-OCT could enable a variety of application scenarios which have not been possible so far, with either time or spectral-domain OCT devices. In addition to the superior resolution, the developed supercontinuum-based SD-OCT device works in the visible range of light. Thanks to the use of a spectrometer in data acquisition, spectral information about the studied specimen is provided. Spectral information could be utilized to characterize and localize materials and, as mentioned before, has the potential for true-colour OCT measurements.

One of the issues with SMR SD-OCT may be its noise performance. Whereas in TD-OCT balanced detection was responsible for maintaining a low RIN noise level, SD-OCT lacks this key improvement. Any intensity change at the output of the femtosecond laser is transformed and often magnified by PCF. This can be observed
as fluctuation of the spectra emitted by the supercontinuum light source. Preliminary tests show that the supercontinuum generation process may not allow for performing shot-noise-limited measurements. However, considering the amount of available power it should be possible to achieve sufficient sensitivity. The performed tests show that the phase stability of the light source is satisfactory which should allow for efficient noise cancelling in data processing and developing a full-range SMR SD-OCT.

An ideal solution to the noise performance issue would be use of a thermal light source, similar to the one used by Vabre et al. (2002) in the full field OCT. However, such light sources are difficult to collimate and offer a fairly limited probing beam power. In the case of supercontinuum-based systems, powers ranging from hundreds of milliwatts to tens of watts are possible (Cumberland et al. 2008). Being a pulsed light source, supercontinuum could enable combined or simultaneous applications, e.g., analysis of pulse response or ablation of the specimen.

The alignment stability of the free-space devices used in the study was evaluated and can be described as high. However, to make the on-line quality inspection with OCT feasible, use of fibre components should be considered.

The most expensive element of the sub-micron-axial-resolution OCT device is the femtosecond laser. However, the market provides us with an alternative in the form of integrated "turn-key" supercontinuum light sources. Such solutions are available at a much lower price than a femtosecond laser, bringing the cost of the SMR SD-OCT system closer to that of a commercial OCT device. In the case of possible application of OCT in on-line characterization, the ability to identify fabrication issues and to avoid faulty products should compensate for the device costs.

Reported data acquisition rates in the frequency domain allow consideration on-line application of OCT. Apart from the record-breaking multi-MHz systems (Ohbayashi et al. 2008, Wieser et al. 2010), typical rates for SD-OCT (Považay et al. 2008, An et al. 2011) are 100-500 kHz and 100-400 kHz for SS-OCT (Huber et al. 2006, Potsaid et al. 2010). Combined with real-time data processing (Sylwestrzak et al. 2010, Watanabe et al. 2010), this should allow for fast and accurate characterization.

5.3 Future research

As demonstrated in this Thesis, OCT has great potential in 2D and 3D imaging. However, many aspects of the technique require careful consideration, review and possible updates. Although the resolution and data acquisition speed should be sufficient for a number of
measurements, possible on-line application would still be a great challenge. It would require integration of the OCT device with the fine-tuned and dynamic environment of the production line.

Recently the concept of holoscopy has been refreshed and proposed as an upgrade for OCT (Hillmann et al. 2011). Holoscopic OCT combines a full-field, swept-source OCT with digital holography, allowing for reconstructing a volume with diffraction-limited resolution. Holography combined with a wavelength sweep brings all information required to perform a volumetric reconstruction. The superiority of holoscopy over the full-field OCT is due to the imaging principle.

Standard OCT imaging is limited by the depth of field of the focusing optics. This imposes a compromise between the lateral resolution and the imaging depth. Refocusing at different planes (i.e., dynamic focusing) could be a solution. However, it would increase the complexity of the design and would complicate the measurement routine and data processing. By contrast, a collimated probing beam, often used in holoscopy, would eliminate that issue. Additionally, one-step volumetric reconstruction based on re-sampling of the data points, prior to Fourier transformation, should allow for fast imaging.

The important milestone in the development of an industry-ready OCT device would be the introduction of a broadband swept-source laser in the visible range of the electro-magnetic spectrum. This would allow for sub-micron-axial-resolution SS-OCT and holoscopic imaging. Having balanced detection, as is standard in SS-OCT devices, would bring us closer to shot-noise-limited measurements.

In parallel to the on-line oriented development, further research work could focus on the implementation of additional modalities into the SMR SD-OCT system. Sub-micron-resolution Doppler imaging and polarization-sensitive detection in the visible range of light could bring interesting applications and results.
6 Summary

Characterization and on-line quality inspection are key elements in the fabrication processes in all sectors of the market. The aim of this Thesis was to propose optical coherence tomography as an efficient characterization technique for printed electronics.

It was demonstrated that OCT could produce a handful of data about the analysed object. As a volumetric measurement technique, OCT is able to reveal information inaccessible to the majority of other techniques which suffer from transparency or opaqueness of the specimen.

This is where OCT shows its full potential. An example is the novel approach in inspection of encapsulation proposed in the study. Thanks to the use of OCT, one is able to locate and pin-point a defect with a micrometre precision. This should allow for an accurate identification of its source and thus simplify the investigation and fabrication adjustment process, saving a considerable amount of money.

Although measurement artefacts are common in OCT, this Thesis tries to discuss and address the majority of these issues. In the case of the measurements performed here, all data processing steps leading to ambiguity-free results are presented. The study and development of the technique aim at a possible on-line application of OCT. In this case, the awareness of the expected structure and its important parameters should simplify data analysis and processing. The availability of volumetric information and a non-contact measurement allows for an easy adaption to new tasks and specimens.

During the study the need for a precise and fast OCT device became apparent. The issue was addressed with the development of a new SD-OCT system, capable of imaging with sub-micrometre axial resolution at a data acquisition rate exceeding 100 kHz. This allows for consideration of an on-line application of the technique.

Due to the high speed of the fabrication process in printed electronics, this task will be very challenging. It is fair to assume that issues unknown at this point will appear and will have to be addressed. The devices developed during the study offer sufficient imaging parameters. However, further development is necessary to assure proper stability, noise performance and compactness for an on-line implementation of OCT. Although the existing devices require optimization and development, OCT as a technique has proved its capacity to be a strong alternative to existing characterization methods, and an accurate quality inspection tool for printed electronics.
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OPTICAL COHERENCE TOMOGRAPHY AS A CHARACTERIZATION METHOD IN PRINTED ELECTRONICS