Integrated-optics-based optical coherence tomography

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Summary

Optical coherence tomography (OCT) is a high resolution, imaging technique that has developed over the last 20 years from a complicated laboratory setup into a ready-to-use commercially available device. Instead of using electronic time gating as being used by ultrasound (US) imaging, in OCT, the optical analogue of US imaging, determines the time of flight using low coherence interferometry. To date, OCT has many clinical applications and is widely used in urology, cardiovascular imaging, dentistry, dermatology and ophthalmology. Currently OCT devices are bulky and expensive, which limits the use of OCT, not only in its existing applications, but also in many application areas such as process control, biometrics or forensic science. Integrated optics can offer a significant cost and size reduction for many bulk optics components and integrate them in a single platform. As a result, integrated optics can make OCT systems smaller, robust, more cost efficient. Integrated optics even can add more functionality to OCT systems, which would be too difficult or complex to realize in bulk optics. In the thesis entitled “Integrated-optics-based optical coherence tomography” the goals of our research is 1) to integrate and miniaturize OCT devices in integrated optics, 2) to explore the new OCT functionalities in both integrated optics and bulk optics.

In chapter 1, we present the principles on which OCT is based and emphasize the need of photonic integration in OCT for low-cost, hand-held and improved functionality OCT systems. We also discuss integrated optics and its applications to OCT. Finally, our research goals and structure of this thesis are presented.

Chapter 2 shows the design, fabrication, and characterization of integrated optics elliptic couplers in silicon oxynitride (SiON), which are used to focus light from a chip into the off-chip environment. The optical fields at the output of the elliptic coupler are simulated and measured. Finally, elliptic couplers are employed in a Fizeau interferometer for OCT depth-ranging measurements with a moveable mirror. Good agreement is observed between the measured OCT signal as a function of depth and calculations based on the optical field at the end of the elliptic coupler.

We designed and fabricated arrayed-waveguide gratings (AWGs) in SiON as a spectrometer for spectral-domain OCT (SD-OCT) as described in chapter 3. The AWGs operate at center wavelengths of 800 nm and 1300 nm and have sizes of 2.6 x 2.1 cm² and 3.0 x 2.5 cm², respectively. Free-space SD-OCT measurements performed with AWGs demonstrated that imaging up to a maximum depth of 1 mm with an axial resolution of 25 μm and 20 μm for 800 nm and 1300 nm ranges, respectively, was possible. Using the 1300 nm AWG spectrometer combined with a fiber-based SD-
OCT system, we demonstrate cross-sectional OCT imaging of a multi-layered scattering phantom.

In chapter 4 we simulated, fabricated, and characterized integrated optics 2x2 and 3x3 directional couplers for swept-source OCT (SS-OCT) in SiON. The output spectra of directional couplers are measured and the wavelength dependence of the splitting ratio is determined. We discuss the possibility of designing wavelength-independent 2x2 directional couplers based on asymmetric 2x2 directional couplers. Finally, an integrated optics 3x3 directional coupler is employed in interferometric measurement in SS-OCT which demonstrates that the integrated optics 3x3 directional coupler can be used to remove depth degeneracy in Fourier-domain OCT (FD-OCT).

The highest photonic integration achieved in this thesis we demonstrate in chapter 5 with the integrated-optics-based SS-OCT system. We designed, fabricated, and characterized integrated-optics-based SS-OCT systems in TriPleX™ technology operating in backscattering and off-axis OCT geometries. The complete OCT chip contains waveguide structures for interferometric depth ranging and balanced detection and has a footprint of 0.4 x 1.8 cm². With an external 1300 nm swept-source coupled to the OCT chip, light from the chip is focused onto the sample using an aspheric lens and OCT measurements are performed with a moveable mirror. We achieved sensitivities for integrated-optics-based SS-OCT are -80 dB in backscattering geometry and -79 dB in off-axis OCT geometry. In both integrated-optics OCT systems, the maximum imaging depth is 5.09 mm. Corrected for dispersion, the measured OCT axial resolutions are in good agreement with the bandwidth limited resolution. Finally, we demonstrate cross-sectional OCT imaging of a multi-layered tissue phantom with the integrated-optics-based SS-OCT system in both geometries.

The quantification of optical properties from OCT images is one of the important applications for a low-cost OCT device in screening and diagnostics. Therefore in chapter 6 we explore a novel function of OCT by using transmission and backscattering OCT geometries to distinguish and quantify dependent and multiple scattering effects in turbid media. With transmission OCT the dependent scattering coefficient for various monodisperse silica solutions is determined. An excellent agreement is observed between the measured dependent scattering coefficients and dependent scattering calculations based on the Percus-Yevick radial distribution function. Backscattering OCT measurements are fitted using the extended Huygens-Fresnel (EHF) model and the dependent scattering coefficients obtained from the transmission OCT measurements. Good agreement between the model and backscattering OCT measurements is observed. The rms scattering angle \( \theta_{rms} \) obtained from the EHF fit is in good agreement with \( \theta_{rms} \) from the transmission OCT data for large particles.
In *chapter 7* the results of this thesis are put in a broader perspective and we discuss the limitations of the studied integrated optics components, the possible added functionality, as well as their future integration in optical coherence tomography devices. Finally, we present a number of new applications that can become a reality with further photonic integration of optical coherence tomography.