Improving optical coherence tomography theories and techniques for advanced performance and reduced cost

Abstract

Optical coherence tomography (OCT) has been developed as a high-resolution three-dimensional imaging technique for clinical diagnosis. This thesis proposes several theoretical discoveries and technical improvements to current OCT systems aiming to drastically reduce system costs while achieving state-of-the-art performance.

Polarization-sensitive OCT (PS-OCT) is a functional extension of conventional OCT which offers depth-resolved birefringence imaging capability. To resolve local retardation in tissue sample, current PS-OCT system illuminates the sample with two multiplexed polarization states and detects the backscattered light with two detection channels. We observed that the polarization state of light after round-trip propagation through a birefringent medium frequently aligns with the employed input polarization state but "mirrored" by the horizontal plane of the Poincaré sphere. We explore the predisposition for this mirror state and demonstrate how it constrains the evolution of polarization states as a function of the round-trip depth into weakly scattering birefringent samples, as measured with PS-OCT. The constraint enables measurements of depth-resolved sample birefringence with PS-OCT using only a single input polarization state, which offers a critical simplification and cost reduction compared to the use of multiple input states. Without the employment of the bandwidth-deteriorating polarization states multiplexing techniques, the single input state system can achieve even higher axial resolution compared to current two input states PS-OCT. We demonstrated the capability of polarization mirror state in local birefringence restoration with birefringent phantom imaging, swine retina imaging *ex vivo* and human intravascular imaging *in vivo*.

If we take transpose for both sides of the Jones transmission equation of PS-OCT system with two input states and two detection channels, the mirror state constraint still holds while the input and output states exhibit interchangeability, which implies that depth-resolved birefringence imaging is possible with only one detection channel, if the sample is illuminated with two orthogonal polarization states. Considering the high cost of spectrometers and the difficulty of pixel alignment between two detection channels, the transposed mirror state constraint helps to further cut the cost and complexity of spectral domain PS-OCT system.

Inspired by the mirror state constraint, we realized that the polarization states of detected sample light, after propagating through a stochastically moving reciprocal optical path, would not distribute evenly on the Poincaré sphere, but tend to aggregate around the mirror state. This can be used to solve a long-standing problem that the detected interferograms of fiber-based OCT suffer from the fading effect due to misalignment of the light polarization states between the two interference arms which results in sensitivity degradation and intensity variation. The existence of mirror states implies the location of optimal polarization state of the detected reference light. If the reference light is aligned with the polarization mirror state on the Poincaré sphere, a 3.5 dB signal-to-noise ratio

improvement can be expected.

The axial resolution, being a critical parameter to the resolving power of OCT system, is determined by the light spectral shape and bandwidth. The pursuit of higher axial resolution leads to exponentially increasing system cost, and sometimes is even impossible because of the unavoidable gaps in the wavelength range of illumination, transmission, and detection. We demonstrate that the axial resolution deteriorated by gaps in OCT spectra can be restored by adopting the gapped amplitude and phase estimation (GAPES) algorithm. The algorithm estimates the missing parts between separated spectral bands and obtains a tissue axial profile with reduced sidelobe artifacts and significantly improved axial resolution over the individual bands. This technique may make it possible to combine spectrally separated sources and detectors to improve axial resolution in OCT images, hence greatly reduce the cost of ultrahigh-resolution OCT system.

In conclusion, this thesis proposed several methods to reduce the cost of current OCT system with advanced performance in terms of state-of-the-art contrast, sensitivity and resolution, which has been demonstrated with phantom imaging and biological tissue imaging both *ex vivo* and *in vivo*.

Publication

Journal:

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1. Nanshuo Wang, Xinyu Liu, Qiaozhou Xiong, Linbo Liu, "*Polarization management to mitigate misalignment induced fringe fading in fiber-based optical coherence tomography*", SPIE BiOS 2018, San Francisco, CA, USA. 2018, Oral.
2. Nanshuo Wang, Linbo Liu, et. al, "*Optical coherence tomography with gapped spectrum*", SPIE BiOS 2016, San Francisco, CA, USA, Poster.
3. Nanshuo Wang, Xinyu Liu, Qiaozhou Xiong, Linbo Liu, "*Local Retardance Determination Using Single Input Polarization Sensitive Optical Coherence Tomography*", CLEO-PR, OECC and PGC, 2017, Singapore, Poster.
4. Nanshuo Wang, Xinyu Liu, Xiaojun Yu, Si Chen, Shi Chen, Linbo Liu, "*Optical Coherence Tomography with Gapped Spectrum*", CLEO-PR, OECC and PGC, 2017, Singapore, Poster.
5. Nanshuo Wang, Linbo Liu, et al, "*Adaptive filter technique to restore images of SDOCT with high resolution*", Photonics Global Conference 2015, Singapore, Oral.

Patent and technical disclosure:

1. Xinyu Liu, Nanshuo Wang, Qiaozhou Xiong, Linbo Liu, Martin Villiger, Brett Bouma, *Method And Apparatus For Performing Depth Resolved Tissue Local Birefringence Properties Measurement Using Single Shot Polarization Sensitive Optical Coherence Tomography*, US provisional application 62/615. 473 filed on 10 Jan 2018
2. Linbo Liu, Atsushi Tanaka, Nanshuo Wang, *Color Optical Coherence Tomography*, Reference number: TD/275/16.