**Extending depth range of optical coherence tomography**


## Abstract

Optical coherence tomography (OCT) is a noninvasive diagnostic imaging tool that has been established in various clinical fields. The most commonly cited issue of OCT in clinical practices is the short depth range. This thesis proposes four novel techniques to significantly extend the depth range without compromise other imaging performances.

The OCT depth range is fundamentally limited by two main factors, which are focal range and system sensitivity. In the standard OCT systems, the focal range can only be improved by decreasing the numerical aperture (NA) of the focusing optics, which unfortunately sacrifices the transverse resolution. To achieve a high transverse resolution over an extended depth range, efforts have been made from both the focusing engineering and digital refocusing approaches.

The elliptical beam design is developed to extend the intensity depth range optically. By angling the fiber terminal facet by $\theta$ with respect to the fiber axis, the effective NA in the XZ plane of the output will increase as the incident angle $\theta$ increases. However, in the YZ plane, the NA remains as the case of $\theta=0°$. Such an anisotropic NA of the beam will produce approximately elliptical beam cross-sections in both the pupil plane and the focal plane of the focusing optics. Therefore, the intensity depth range can be significantly extended with respect to the standard circular beam based OCT, without compromising the transverse resolution in the X direction. For those OCT operating primarily in the B-mode, the elliptical beam technique can also mitigate the problems caused by other optical aberrations, including but not limited to chromatically focal shift, higher-order spherical aberrations, and field of curvature.

In addition to the elliptical beam, a dual-foci optical design is proposed to extend the focal range of endoscopic OCT. We exploited the broad spectral bandwidth of the output from a supercontinuum source and. In the fiber probe, the foci of the 750-1000 nm and 1100-1450 nm inputs were chromatically shifted axially. The interference signals from the two spectral bands were measured with a Si camera-based spectrometer and an InGaAs camera-based spectrometer, respectively. Therefore, two images of different focal depth are acquired simultaneously. By compounding the two acquired frames, the resulted shows an extended focal region of 2 times larger than that of the single focus probe.

An additional effort has been made to implement a digital refocusing technique, termed multiple aperture synthesis, in a fiber optical endoscopic probe to extend the OCT focal range. We designed and fabricated a novel fiber-optic probe in which a calcite beam displacer was used to create two sub-apertures. The optical aberrations in the depth domain were digitally corrected between the interferometric signals acquired through the two apertures using a pathlength encoded method. The feasibility of extending the depth range is demonstrated using tissue phantoms.

To improve system sensitivity, a spectrometer-input OCT was designed and developed. The input light was coupled in the system via the 0-order of the spectrometer grating. Under the condition that the light source power is enough to provide maximum permissible exposure in the sample, we demonstrate that the proposed OCT system design is advantageous in sensitivity over the standard OCT by 1.5dB.

In conclusion, this thesis proposes four methods to significantly extend the OCT depth range while maintaining the state-of-art performance in other aspects, which has been demonstrated with phantom imaging and biological tissue imaging *ex vivo*.

**Publication**

Journal:

1. Jinhan Li, Yuemei Luo, Xianghong Wang, Nanshuo Wang, En Bo, Si Chen, Shufen Chen, Shi Chen, Meng-Tsan Tsai, and Linbo Liu (2018). “Extending the depth of focus of fiber-optic optical coherence tomography using a chromatic dual-focus design,” Applied Optics, 57(21), 6040-6046.

2. En Bo, Yuemei Luo, Si Chen, Xinyu Liu, Nanshuo Wang, Xin Ge, Xianghong Wang, Shufen Chen, Shi Chen, Jinhan Li, and Linbo Liu, "Depth of focus extension in optical coherence tomography via multiple aperture synthesis," Optica 4(7), 701-706 (2017).

3. Jinhan Li, Jun Xie, and Linbo Liu "Fiber-tip interferometer for spectral domain optical coherence tomography," Submitted to Journal of Lightwave Technology.

Conference:

1. Jinhan Li, Linbo Liu, “Depth-of-focus Extended Common-path Probe OCT System”, CLEO-PR,OECC and PGC, Jul.31-Aug.4, 2017, Sands Expo and Convention Centre, Singapore, Oral

2. Jinhan Li, Linbo Liu, “Depth-of-focus extended chromatic dual-foci OCT”, SPIE BiOS 28 Jan- 2 Feb, 2017, San Francisco, CA, USA, Oral

Patent and technical disclosure:

1. Linbo Liu, Yuemei Luo, Jinhan Li, “High Resolution Optical Coherence Tomography Endoscopic Catheter”, Reference number: TD/179/16.

2. Linbo Liu, Jinhan Li, “Method and apparatus to mitigate aberration problems in laser scanning imaging systems and spectrometers”, Reference number: 2019-130.