Advancing Optical Coherence Tomography through Opto-Electronic Frequency Shifting

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Abstract. Optical Coherence Tomography (OCT) stands out for its ability to combine the high resolution of microscopy with the penetration-depth of clinical imaging. However, in practice this is still limited to a few millimetres. Interestingly, the imaging-depth of the latest swept-source systems is not limited by their spectral width but by the analog-to-digital sampling rate. In lieu of slow reference arm length adjustments, we leverage opto-electronic frequency shifting. This allows for depth adjustments on the microsecond timescale and a modest detector bandwidth of 200 MHz. The opto-electronic scheme immediately gives us access to an 8 mm range, a fourfold increase over the nominal 2 mm range of the source. Moreover, by circumventing the need for a mechanical reference arm, changes in the axial displacement of the sample can be compensated in real-time. This makes it attractive for imaging arbitrarily-curved surfaces. We showcase this with wide-field OCT imaging of the curved retina.

1 Introduction

Optical Coherence Tomography (OCT) combines the low-invasiveness of light with the ability to image hundreds of micrometers deep into tissue with excellent resolution. Its unique position (Fig. 1A), helped ensure the widespread adoption of OCT for medical diagnosis in ophthalmology, dermatology, and endoscopy.

Spectral OCT exhibits many advantages over time-domain OCT, notably improved speed and sensitivity. The downside of spectral OCT is that the depth scan (A-scan) range is limited by the spectral resolution. The optical linewidth of swept source lasers can be made much smaller than the resolution of most spectrometers, making swept source the obvious choice for long range applications. However, the imaging range is ultimately limited by the sampling rate of the data acquisition card.

Here, we show how electro-optical phase modulation (EOM) can be used to dynamically adjust the axial imaging depth of swept-source OCT. By not relying on mechanical adjustment, the imaging system can rapidly track curved surfaces such as the human retina. The change of optical path length with lateral scan angle is a significant roadblock to ultra-widefield retinal OCT. Dynamic position adjustment means the required OCT range is determined by the thickness of the retina, rather than the overall size and shape of the eye.

2 Optical frequency shifting

Until recently, dynamically adjustable reference arm implementations were limited to mechanical solutions [1, 2], severely limiting their suitability due to their restricted speed. In Swept-source OCT, regions outwith the A-scan range produce high-frequency oscillations in the optical signal. It was recently shown that the limitations of the analog-to-digital conversion of the detected signal can be circumvented by frequency-shifting the recorded interferogram signal [3]; however, the bandwidth of the photodetector still limits the accessible range.

To overcome this, we apply the shift in the optical domain. This decouples the accessible imaging depth range from the bandwidth of the photodetector. In sharp contrast to slow mechanical translation, we were able to demonstrate depth adjustments on the microsecond scale. To this end, an opto-electronic phase modulator was incorporated in a conventional swept-source OCT system. High-frequency modulation of the reference arm enables homodyne depth-selection, unconstrained by the detector.

We implemented this using a Micro-electromechanical (MEMS) vertical cavity surface emitting laser (VCSEL). These novel sources exhibit unprecedented coherence lengths [4]. As with most swept-sources, the frequency sweep is not perfectly linear. This causes a variation in the beat-frequency during the sweep, ultimately blurring the image axially. If the variation of beat-frequency were known in advance, the blur could readily be corrected computationally. Although the variability is unpredictable, we show that it can be determined from the raw image using time-frequency analysis [5].

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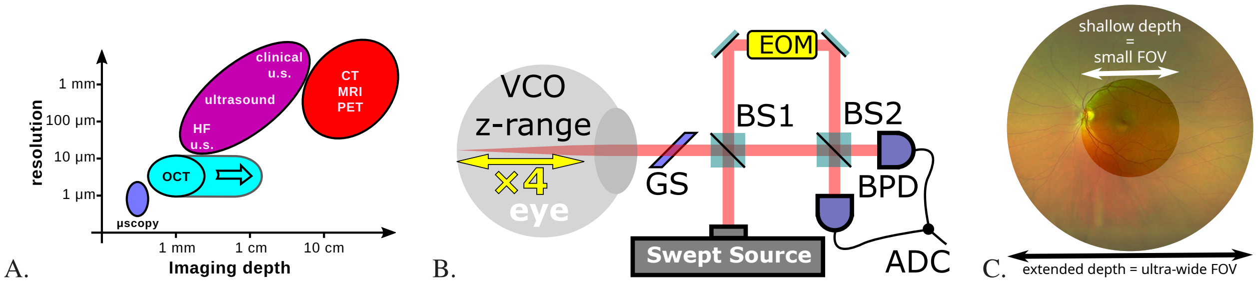

Figure 1. A. Resolution versus imaging depth of medical imaging techniques. Optical Coherence Tomography uniquely combines high resolution with an imaging depth in the millimeter range. **B.** Extending the OCT depth-range digitally. The swept source laser light is split into a sample and reference arm using a 90:10 beamsplitter (BS1), the sample arm is transversally scanned using galvo mirrors (GS), recombined with the reference on a 50:50 beamsplitter (BS2) and detected using a balanced photo-detector pair (BPD) and an analog-to-digital convertor (ADC). Electro-optical modulation (EOM) allowed us to extend the depth-range by a factor of 4, limited by the frequency range of the voltage-controlled oscillator (VCO). **C.** The increase in imaging depth translates into a significantly wider field-of-view (FOV).

3 Dynamically extended imaging depth

Phase modulation generates a series of harmonic components that are described by the Jacobi-Anger expansion. The amplitude and frequency of the harmonic components is controlled by the amplitude and frequency of the modulating signal. In our application, each harmonic component interferes with the sample wave, yielding a distinct harmonic image. The axial offset between the images is proportional to the modulation frequency. We use an electronic low-pass filter to isolate the image corresponding to the lower frequency sideband, removing higher frequency harmonics and the fundamental harmonic.

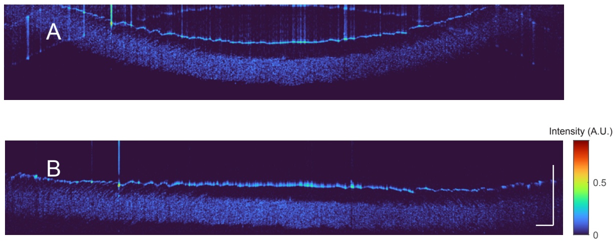

Figure 2. A. Frequency-shifted image of eye phantom without flattening. **B.** Same frequency-shifted image, this time with flattening applied, the retina is kept fully in frame during the lateral scan. Scale bars: 1 mm.

We demonstrate the speed and efficacy by opto-digitally tracking the curved surface of a model retina during imaging. Conventional OCT would 'see' a curved image that would quickly crossover into the conjugate mirror image (Fig. 2A). In contrast, opto-digitally tracking the surface in real-time neatly separates out the conjugate image that hampers conventional OCT imaging (Fig. 2B). Variations in sweep-speed lead to an axial blur in the raw data. This is removed numerically by detecting the variations from the image and correcting it accordingly.

4 Conclusion

Digital acquisition bandwidth restricts the A-scan length of conventional swept-source OCT systems. We overcome this by pairing high-frequency phase-modulation with digital reconstruction. This enables us to dynamically shift the imaging depth in real-time.

When using a source with a 2 mm range, the accessible imaging depth range of our prototype was 8 mm. Commercially available radio-frequency synthesizers could in principle extend it to 80 mm, a 40-fold increase over the nominal range of the source. The ability to image curved objects opens a world of possibilities for wide-field ophthalmic imaging.

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