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Towards high-speed optical coherence tomography through downconversion master slave and bidirectional sweeping

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1. Introduction

A swept source can sweep from red to blue or blue to red, i.e., forward or backward sweep. 'Unidirectional sweeping' refers to the use of only one of the sweeps, as opposed to both. The majority of swept sources on the market are unidirectional, some with duty ratios of less than 50% [1]. Making the tuning bidirectional increases the duty ratio and doubles the tuning rates. However, high-speed swept sources and bidirectional multi-MHz MEMS-VCSELs present two fundamental challenges that the method presented here can effectively address, paving the way for improved OCT imaging:

(a) The ability to use forward and backward sweeping demands precise phase corrections due to the asymmetry in the two-tuned spectra. Therefore, signal processing requires different phase corrections for forward and backward sweeping to be applied during each sweep, that take time and limit the real time processing of ultra fast swept source OCT systems.

(b) Another problem for unidirectional and bidirectional sweeping lasers is that the high sweeping rate demands high-speed digitizers, and complex software to display the image in real time. Due to the narrow linewidth of these sources, a long axial range exceeding many cm becomes attainable. Therefore, a densely modulated channeled spectrum (CS) may be generated at the interferometer output. This can lead to a radio frequency spectrum of many GHz of the photo-detected signal. A high-speed digitizer required to sample 2 GHz can exceed $10,000. This increases the cost of fast-sweeping solutions, limiting fast OCT technology to research purposes only.

(c) Yet another concern is the instability in the tuning curve of the swept source, which requires frequent calibration. Using k-clocks can address the nonlinearity variation over time, but that is only possible if digitizers with input for k-clocks are used.

Hence, new OCT protocols are needed to address or alleviate the problems listed above. In this paper, we present a solution to address the challenges listed above, raised by the high sweep rates and those raised by bidirectional sweeping. Using a second interferometer for any depth of interest, driven by the same swept source, as for the OCT interferometer, signal with similar chirp to that in the OCT interferometer is created. By multiplying the photodetected signals delivered by the two interferometers, depth-resolved information is obtained according to the protocol of Master Slave (MS) OCT. This consists in calculating the product of the photodetected signals from both interferometers, and integration of values over the sweeping time, τ. In this way, the processing frequency bandwidth is largely reduced from the large frequencies present in the two signals (over tens of GHz) to a maximum frequency comparable with inverse of τ . We refer to such a method as downconversion master-slave (DMS). The issue of specific processing required for forward and backward sweep is also automatically addressed as the same swept source drives both interferometers. However, in order to address the dilemma of signal processing speed, that is exacerbated by bidirectional sweeping, the DMS is implemented here using analogue mixing.

2. Methods

The problems of sweeps and time instabilities are addressed in a modified Master Slave configuration [2]. The method proposed here is inspired by the Master-Slave protocol, where a channeled spectrum (called mask) is generated in real-time using another interferometer called Master. In principle, many Master interferometers can be used to produce such masks corresponding to different optical path difference (OPD) values in real-time and generate as many *en-face* images as the number of Master interferometers.

In practice, to achieve DMS, the integration of the product of the two CSs is performed using an RF analogue mixer, see Fig 1(a). Such a mixer produces the product of the two RF signals, obtaining signals pulsating at the addition and subtraction of the frequencies of the two RF signals. The subtraction signal is called the downconverted signal. Hence, the method is referred to as downconversion Master-Slave OCT [3].

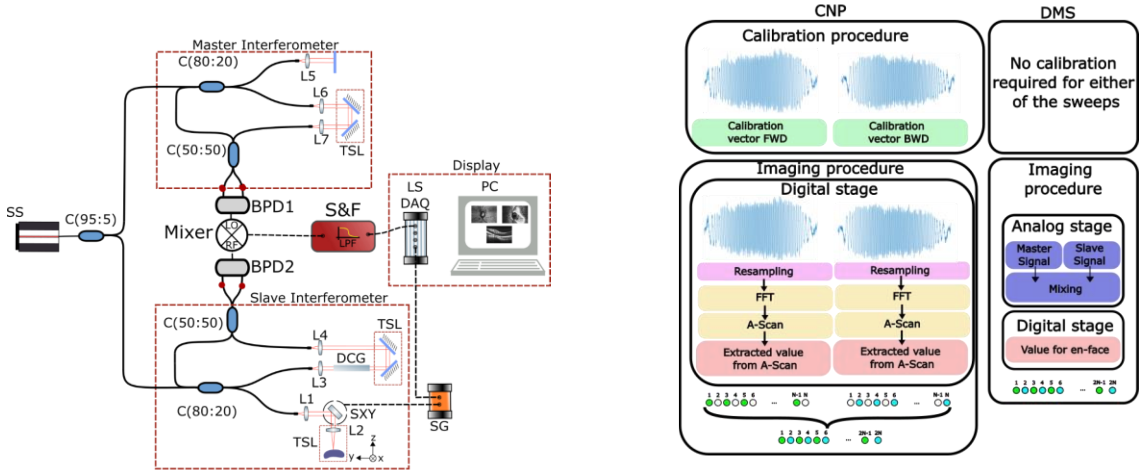

Figure 1. (a) Schematic of the DMS-OCT system. SS: MEMS-VCSEL swept source, Interferometers (C: couplers, TSL: translation stage launcher, DCG: dispersion compensating glass, SXY: 2-D Lateral scanning head, L1-8: lenses, DCG: dispersion compensating glass), Display (LS DAQ: slow digitizer, BPD: balanced photodetector, PC: Computer, S&F: Signal amplifier and filter); SG: Dual signal generator. (b) Comparison of conventional numerical protocol (left) and downconversion (right). Green and blue dots meaning sweep was used, forward and backward respectively. White dot meaning, no sweep was used while having the sweep.

Figure 1(b) provides a flow chart graphical representation of the two methods under consideration, namely the conventional numerical protocol (CNP) and DMS. On the left, conventional numerical procedures, based on Fourier transform (FT) or complex Master Slave (CMS) are shown; the two columns of steps illustrate the need for separate processing steps for each sweep. When using a fast FT (FFT), calibration handles a separate vector of data for backward and forward sweeping, that will slow the signal processing and may require saving data before processing it offline later. In FFT, the calibration vector contains data resampled according to each sweep. Only after data is resampled, a FFT can be computed. For CMS, this may mean different masks. CMS uses raw data but requires masks to perform the CMS protocol on each sweep. Superiority of the DMS is shown by the illustration of interleaved points along the lateral scan of both sweep directions, with no extra procedure required. Conventional FFT based or CNP CMS methods would require some time to interleave data, which using an analogue mixer, succession of points for opposite sweep direction complete the T-scan in each C-scan.

3. Conclusions

Two alternative imaging approaches are compared, both based on the MS protocol. We refer to the 1st approach as Complex Master Slave, where complex masks are obtained from several experimentally collected spectra followed by a numerical synthesis. Its calibration procedure replaces the step of resampling and linearization of data, widely used by the OCT community before applying a Fourier Transform. CMS uses masks obtained by employing the same interferometer for both calibration i.e., generation of experimental spectra followed by calculation of masks as well as for imaging. Once masks are generated, A-scans, B-scans and C-scans can be obtained, similar to the FFT-based method. (FFT based method also uses a single interferometer, for calibration with a mirror and imaging when the mirror is replaced by the object to be imaged). When driven by bidirectional sweeping lasers, we demonstrate here that even minor variations in sweep between forward and backward scans can substantially influence image quality, hence the need for separate processing of signal obtained from each sweep direction, which slows down the processing.

DMS presents a promising solution for bidirectional sweeping lasers thanks to its simplicity. This approach eliminates the need for resampling, additional calibration, or processing of the two sweeps separately. Moreover, it offers a cost-effective implementation by reducing the task of digitization process from many GHz and tens of GHz to $2/\tau$. Despite its limitations, such as generating a single *en-face* OCT image and potential dispersion mismatches between the Slave and Master interferometers impacting axial resolution, more master interferometers can be utilized with careful interferometric design. Here DMS may only be used as a low cost alternative, eliminating the high cost of the digitizer with an accepted compromise of limited information delivered in a single or a few *en-face* OCT images, depending on how many Master interferometers are assembled.

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