Master/slave: the ideal tool for coherence revival based optical coherence tomography imaging instruments

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ABSTRACT

In this communication, we present the utility of the Master/Slave (MS) method in combination with the coherence revival technique to perform full axial range Optical Coherence Tomography (OCT). The MS method eliminates two major drawbacks of the conventional Fourier Transformed (FT) based OCT technology when applied to the coherence revival technique: the need of data re-sampling as well as the need to compensate for unbalanced dispersion in the interferometer.

1. INTRODUCTION

Both OCT implementations, spectrometer (Sp) based (spectral domain) and swept source (SS) (Fourier domain) respectively, can be used to produce cross-sectional OCT images with high speed and high sensitivity. SS-OCT has some advantages over the Sp-OCT including a higher imaging speed, longer axial range and a more uniform sensitivity over the axial range, which enables deeper structures to be visualized in a single A-scan. Although SS-OCT technology seems to win over Sp-OCT in most of the cases, there are some applications that could benefit from an even more extended imaging range. Due to the finite coherence length of the swept lasers used, the axial imaging range is still limited. An exception from this makes the new vertical-cavity surface-emitting lasers (VCSEL) and akinetic light sources, which can provide a long axial range, exceeding 1 cm. However, both VCSEL and akinetic light sources commercially available at the moment, are more costly than the microelectromechanical system (MEMS) SSs widely available and do not cover yet all spectral ranges of interest for OCT.

An elegant solution to increase the axial range in SS-OCT is the application of the coherence revival (CR) technique, exhibited by some commercially available external cavity tunable laser (ECTL) swept sources [1-5]. The CR method employs the interference between the waves reflected from the interferometer arms that originate from waves that suffered different multiple reflections inside the swept laser cavity. For the interference to occur, the difference between the optical path lengths of the interferometer arms are mismatched by an integer multiple of the roundtrip laser cavity length. This method is easy to implement, as only the optical path difference (OPD) between the two arms of the interferometer needs to be altered. As no additional hardware is required, the axial resolution is in principle not affected while the sensitivity drop is negligible.

However, there are two penalties in implementing the CR via the conventional Fast Fourier Transform (FFT) based method. The CR principle employs the intrinsic modulation of several hundred MHz created by tuning the laser cavity. Therefore, the frequency of the k-clock equipping the ECTL swept source is too low for correct data digitization. As another problem, large dispersion compensation is required, as the laser cavity, of 8 cm in fiber, becomes part of the interferometer. While for compensating for the dispersion in the interferometer, in general, both hardware optical methods and software methods can be implemented, to compensate for the dispersion due to the laser cavity, only software solutions can be used.

In the present report, we demonstrate the utilization of the recently introduced MS method [6] in combination with the CR technique [7]. A total different operation is employed by the MS technology (Fig. 1, right), where the FFT operation is replaced by a parallel batch of comparator operators. The channeled spectrum (CS) is compared with P masks producing P signals along P separate electrical wires, for the P points of the needed A-scan, all signals delivered in parallel. The masks are CS replicas measured with a mirror placed at different optical path difference (OPD) values (as explained more below). The serially provided signal in conventional technology is replaced by multiple signals, a signal for each OPD point along a line in depth in the object investigated. The MS method has three advantages:

(i)   direct display of *en-face* OCT images;

(ii)   based on comparing like with like, the MS method is tolerant to nonlinearities in the process of coding the OPD into the wavenumbers in SS-OCT and to nonlinearities in decoding the wavenumbers to OPD in Sp-OCT, so there is no need of any resampling/linearization;

(iii)   there is no need for dispersion in the interferometer to be corrected;

(iv)   calculations can be limited to the exact number of depths needed in the B-scans.

We show here that when the MS method is combined with the coherence revival, the two disadvantages of the CR, manifest when using the conventional FFT based method, are eliminated.
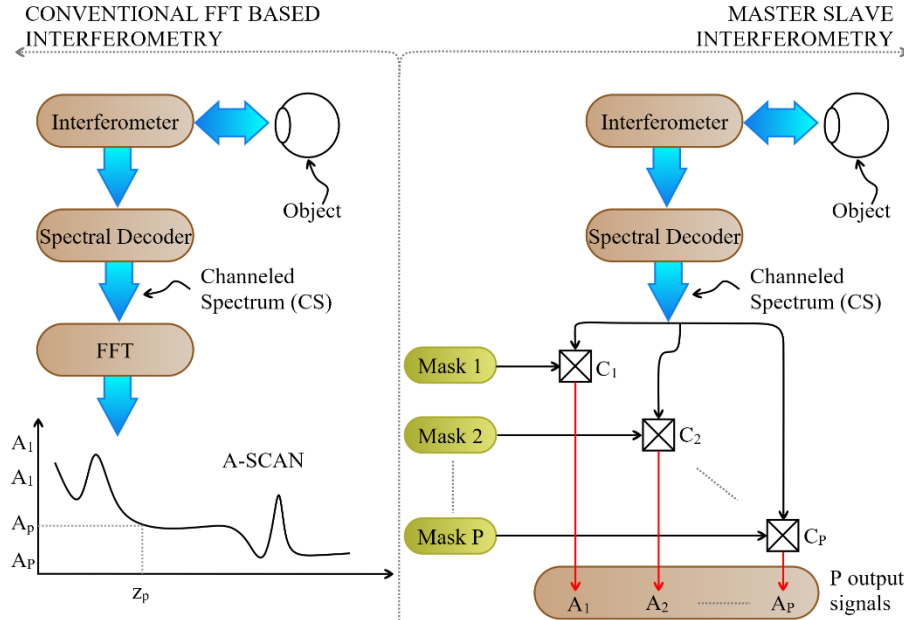

Figure 1. Hardware difference between the conventional SD(FD)-OCT (left) and MS-OCT (right). Left: A FT delivers an A-scan, i.e. all A_p points are obtained along a single wire; Right: A-scans can be made from P inferred results delivered by P processors implementing each a comparison (correlation) operation for each p-depth, where each A_p is delivered along a separate wire.

In conventional OCT, to obtain the reflectivity profile, A(z), versus depth z, the integral of the product between the channeled spectrum $CS(\varphi_{k,z})$ from the sample and the kernel function e^{jkz} has to be calculated, where $\varphi_{k,z}$ is the phase of the measured channeled spectrum.

$$A^{chirped}(z) = \int_{-\infty}^{+\infty} CS(\varphi_{k,z}) \cdot e^{jkz} dk \qquad (1)$$

Due to nonlinearities in the decoding procedure, from spectrum to time, typical for a real spectrometer in Sp-OCT or in coding path differences to spectrum in SS-OCT, the CS is chirped. A second source of nonlinearity in wavenumber k is that due to dispersion in the interferometer. Therefore, the phase is not directly proportional to k, but expressed in a general way as $\varphi_{k,z}=g_k z+h_k$. The parameters g_k and h_k take into account the non-linear dependence of the phase on the wavenumber and on dispersion left unbalanced in the interferometer respectively [8]. For the FFT technique to provide correct results, the chirp has to be eliminated. This is achieved by resampling each CS followed by its multiplication with a function that cancels the dispersion effects (Fig. 2). The kernel function e^{jkz} is left untouched. If combined with CR, the last step becomes extremely important and the large dispersion requires more attention than usual.

In opposition, the MS method is immune to the amount of unbalanced dispersion in the system or to the non-linearities of the spectra. Its implementation is the same in both conventional and CR based SS-OCT systems. The MS strategy consists in modifying the kernel function e^{jkz} in Eq. (1) rather than processing the CS. To produce a single point in the A-scan, instead of a FFT, an integral of the product between the CS and a new kernel function $\tilde{M}(\varphi_{k,z})$ (denoted as a complex mask) is performed [7].

PRIOR TO DATA ACQUISITION | AFTER DATA ACQUISITION

Fast Fourier Tranform

Step 1	Step 2	Step 3	Step 4
Resampling vector is produced	Each channeled spectrum is resampled	Dispersion compensation	A-scan: FFT(CS[non-chirped])

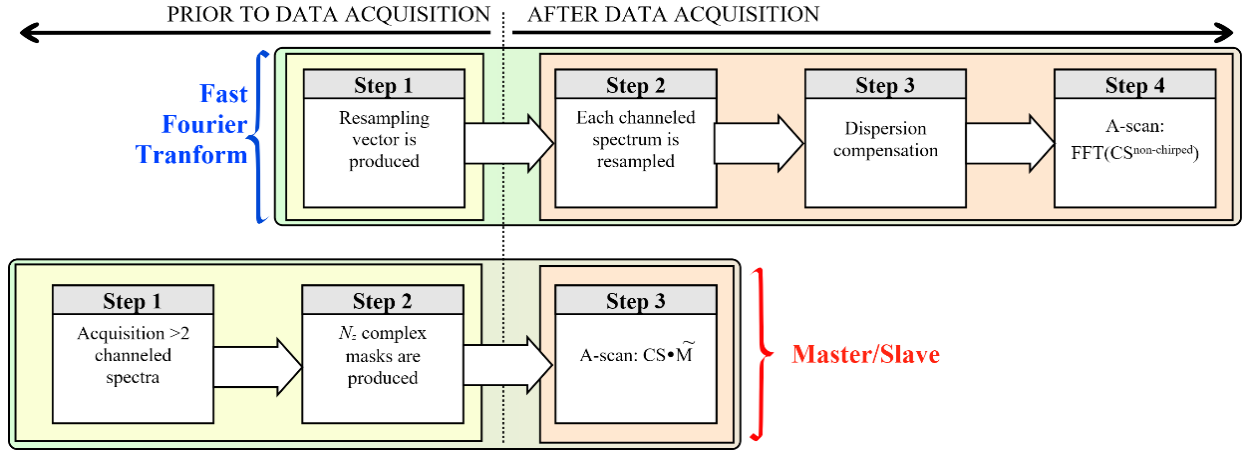| Step 1	Step 2	Step 3
Acquisition >2 channeled spectra	N_z complex masks are produced	A-scan: CS•$\tilde{M}$

Master/Slave

Figure 2. Procedure steps required to produce an A-scan profile using the FT based OCT (top) and to produce a single reflectivity value using the MS method (bottom).

As shown in Fig. 2, the MS-OCT method requires a single processing step once data acquisition is performed, while the conventional FFT-OCT method is more time demanding, as several sequential steps are required in order to produce an A-scan. The procedure to produce an A-scan using the MS method is much simpler than that based on the traditional FFT based method.

The MS method is implemented along the following steps:

1. With a high reflector as object, two or more experimental channelled spectra corresponding to different axial positions of the object are stored in the memory of the computer. This step is performed only once for a given experimental set-up, before data acquisition.

2. The experimental CS recorded at the step above are then used to theoretically infer N_z complex masks ($\tilde{M}$) [7]. This step, which is normally performed before data acquisition, needs to be repeated only if the axial range of the image is modified or the M number of axial points the A-scans is changed.

3. A cross-sectional image can be produced by multiplying two matrices [6-7], one containing the experimental channelled spectra while the other the masks M produced at step 2.

2. EXPERIMENTAL SET-UP

A schematic diagram of a CR based SS-OCT imaging system assembled for this study is depicted in Fig. 3. As optical source, an ECTL swept source (Axsun Technology) exhibiting coherence revival was employed. It has a central wavelength of 1060 nm, a sweeping range of 106 nm (at 10 dB according to the manufacturer) and 100 kHz line rate. In Fig. 3, the optical cavity present within the swept source is also depicted.

Using this system, the sensitivity drop-off profile vs. the axial position z was produced (Fig. 4) for a roundtrip of the waves through the cavity (CR order +1) as well as for the non-CR case (order 0). Due to the roundtrip of the waves through the cavity, the channelled spectra exhibit an amplified chirping in top of that due to the unbalanced dispersion in the interferometer.
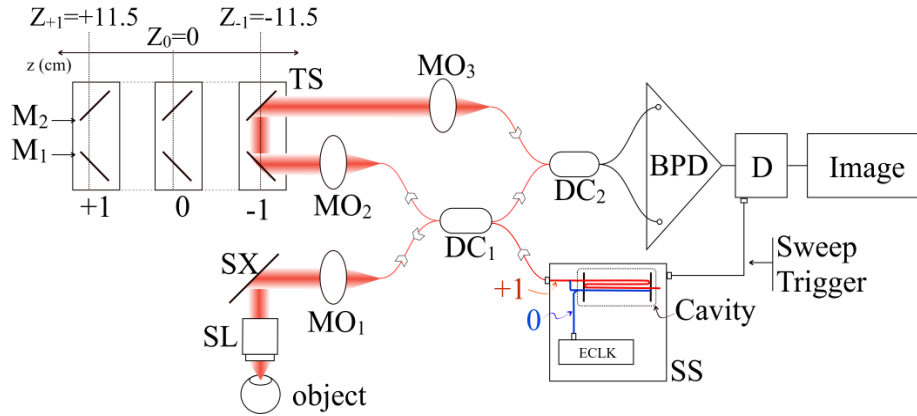
Figure 3. Schematic of the SS-OCT imaging system used in the present study. SS: swept source; DC1-2: directional couplers; BPD: photodetector; D: digitizer; MO1-3: microscope objectives; TS: translation stage; M1-2: flat mirrors; SX: galvo-scanner; SL: scanning lens; ECLK: clock block.

3. RESULTS

The amount of the chirping due to the cavity is unknown so it impossible to correct for, unless complex mathematical methods are used. As the clock circuit in the commercial SS targets the order 0 (no roundtrip through the cavity), its frequency is limited and cannot be used to sample the larger modulation frequency of the channeled spectrum in the CR set-up. Although the amount of chirping introduced by the cavity is large, no dispersion compensation was applied, and no resampling procedure, the MS technique outputs sharp and nice thin reflectivity profiles from a highly reflective mirror, throughout the whole axial range (Fig. 4). The peak sensitivity is achieved at around z = 6.0 mm, where the sensitivity reaches 101.3 dB. The FWHM corresponding to the axial resolution of the system was measured for each sensitivity profile curve leading to a value of 6.85±0.62 µm (where 0.62 µm is the standard deviation).
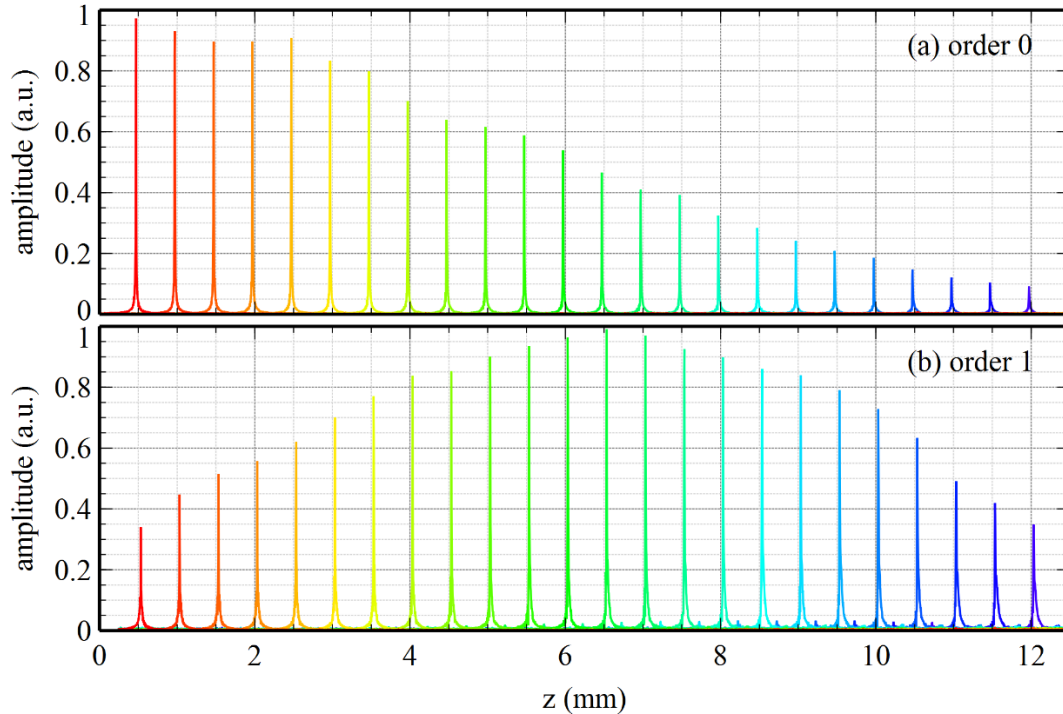

Figure 4. Sensitivity fall-off measurements vs axial position z, measured for the CR order 0 (a) and order +1 (b).

Figure 5 shows two images of the ocular anterior segment. Both images were produced for the revival order +1, with maximum sensitivity set at z = 6 mm. Although our full axial range is around 12.4 mm with little decay in sensitivity from 0 to 12.4 mm, depending on the axial position of the eye, different parts of the anterior chamber are brightened up. The CR images exhibit the property that the maximum sensitivity is in the middle of the image (and of the axial range), in comparison with conventional OCT images, where the maximum sensitivity is closer to OPD=0.
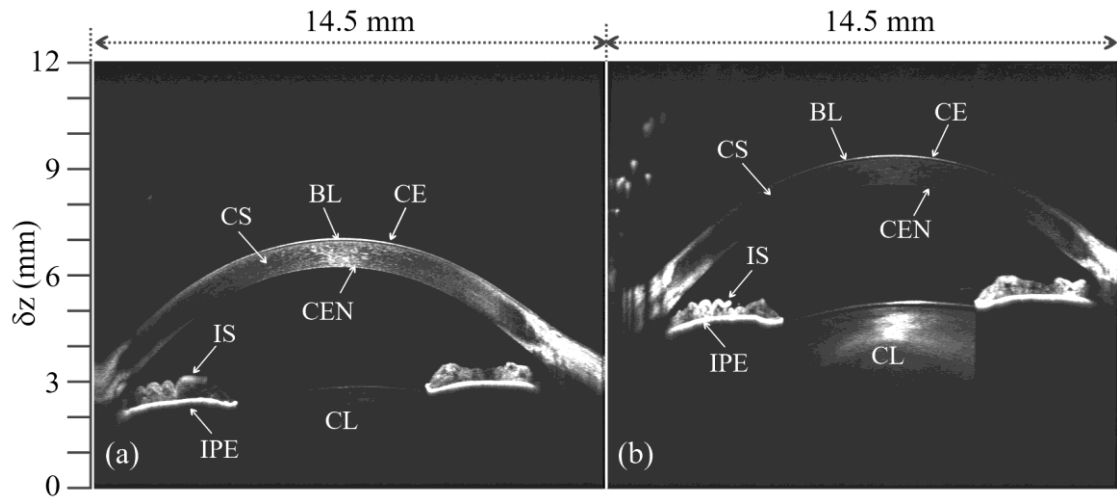

Figure 5. B-scan images of the ocular anterior segment. CE: corneal epithelium, BL: Bowman's layer, CS: corneal stroma, CEN: corneal endothelium, IS: iris stroma, IPE: iris pigment epithelium, CL: crystalline lens

4. CONCLUSIONS

The MS-OCT can be an ideal tool for CR-OCT imaging systems. The coherence revival makes the production of long axial range cross-sectional images possible. These images are also mirror term free. The MS technique simplifies the CR procedure, as it eliminates the need of data resampling and the need for dispersion compensation. This brings speed in the production of OCT images and simplification in assembling CR OCT systems.

As reflectivity of a single point only is delivered by such an integral calculation, the MS method may look slower than the FFT based method. The apparent disadvantage in speed of the 1st report [6] was initially fully compensated by using graphic cards [5], later on by developing a simplified faster correlation algorithm [10] and more recently by invoking fast multiplication of matrices [7] that can be calculated on CPUs. Even more, here we demonstrate that for some sets of number of sampling points, the method is faster in displaying cross section OCT images than the FFT based OCT methods. In addition, the Master/Slave method eliminates the disadvantages of the FFT method in terms of dispersion compensation and data resampling, as well as provides *en-face* images direct (not shown here).

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