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Artifacts removal with a piezoelectric fiber stretcher in Fourier domain OCT

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Abstract

This paper reports the study of a Swept Source Optical Coherence Tomography (SS-OCT) setup. One of the main drawbacks of SS-OCT is its inability to differentiate positive and negative depths. Some setups have already been proposed to remove this depth ambiguity by introducing a modulation by means of electro-optic or acousto-optic modulators. In our setup, we implement a piezoelectric fiber stretcher to generate a periodic phase shift between successive A-scans, thus introducing a transverse modulation. The depth ambiguity is then resolved by performing a Fourier treatment in the transverse direction before processing the data in the axial direction. It is similar to the B-M mode scanning already proposed for Spectral-Domain OCT[1] but with a more efficient experimental setup.

Keywords: Optical Coherence Tomography, Swept Source OCT, Depth Ambiguity, Piezoelectric Fiber Stretcher

1. Experimental setup

Our SS-OCT setup is described on figure 1.

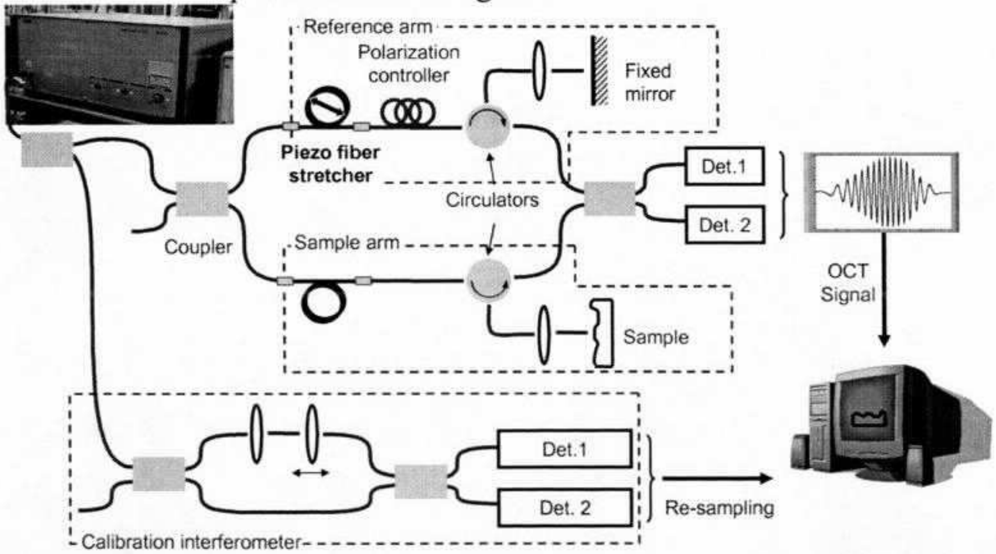

Fig. 1 – Experimental setup: The swept source is a Thorlabs one with a 1325 center wavelength and a 85 nm bandwidth. The repetition rate is 16 kHz. The discrete phase step between two consecutive A-scans is provided by the piezo fiber stretcher.

This is a Mach-Zehnder fiber-based interferometer. The source is a Thorlabs swept-source with a 1325 nm center wavelength and a 85 nm FWHM. The theoretical axial resolution is $\delta z = 9.1\ \mu m$ in air. The A-scan rate is 16 kHz when using both the backward and the forward wavelength scans. The setup is fitted with a piezoelectric fiber stretcher (PFS). The PFS is from Optiphase (PZ1-STD-FC/APC). Around 10 m of fiber are wound around a cylindrical piezoelectric transducer. Figure 2 gives the shape of the low voltage applied to the PFS. The PFS drive voltage is adjusted to achieved a $\pi/2$ phase shift between two consecutive forward wavelength scan interferograms. The system operates at a reduced rate of 8 kHz since we only use the forward wavelength scans.

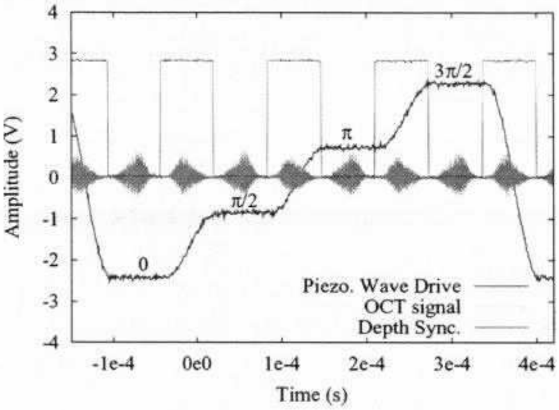

Fig. 2 – Red: PFS DriveWave, Green: OCT signal, Black: Depth synchronization. The PFS drive wave is synchronized with the depth sync. signal. Each step of the PFS drive wave happens for a forward wavelength scan.

2. Signal processing

The signal processing is basically the same as the one used in Yasuno et al.[1]. It has some similarity with phase shifting interferometry. It can be illustrated with the simple case of a single reflector. For a B-scan, a simplified version of the interferometric signal is:

$$i(x,\nu) = k_0 + \cos(k_x x + k_\nu \nu) \tag{1}$$

where k_0 is a constant that includes the autocorrelation terms, k_x is linked with the phase shift introduced by the PFS, x is the transverse position, k_ν is linked with the wavelength sweeping of the source and ν is the optical frequency.

We, first, compute the transverse Fourier transform (along x):

$$I(u,\nu) = \mathcal{F}_x[i(x,\nu)] = k_0\delta(u) + \frac{1}{2}\cdot\delta(u-k_x)\cdot\exp(-ik_\nu\nu) + \frac{1}{2}\cdot\delta(u+k_x)\cdot\exp(ik_\nu\nu) \tag{2}$$

where u is the Fourier conjugate of x, $k_0\delta(u)$ is the DC component, the second term on the right hand side is the OCT data, and the last term is the complex conjugate of the second one.

A high-pass filtering with a rectangular window is then performed to keep only the data corresponding to the OCT signal to yield:

$$\hat{I}(u,\nu) = \frac{1}{2}\cdot\delta(u-k_x)\cdot\exp(-ik_\nu\nu) \tag{3}$$

Then, we compute the inverse transverse Fourier transform

$$\hat{i}(x,\nu) = \mathcal{F}_x^{-1}\left[\hat{I}(u,\nu)\right] = \frac{1}{2}\cdot\exp(-ik_x x)\cdot\exp(-ik_\nu\nu) \tag{4}$$

Finally, the axial Inverse Fourier transform is evaluated:

$$\hat{I}(x,z) = \mathcal{F}_z^{-1}\left[\hat{i}(x,\nu)\right] = \frac{1}{2}\cdot\exp(-ik_x x)\cdot\delta(z-k_\nu) \tag{5}$$

where z is the Fourier conjugate of ν and corresponds to the depth position. To obtain the OCT image, we keep the amplitude of the complex number $\hat{I}(x, z)$ obtained in equation (5).

3. Experimental results

Figure 4 shows the onion image obtained with the PFS setup before and after signal processing. Here the DC artifact is completely removed and the mirror image is greatly reduced. The cells of the onion can be clearly seen.

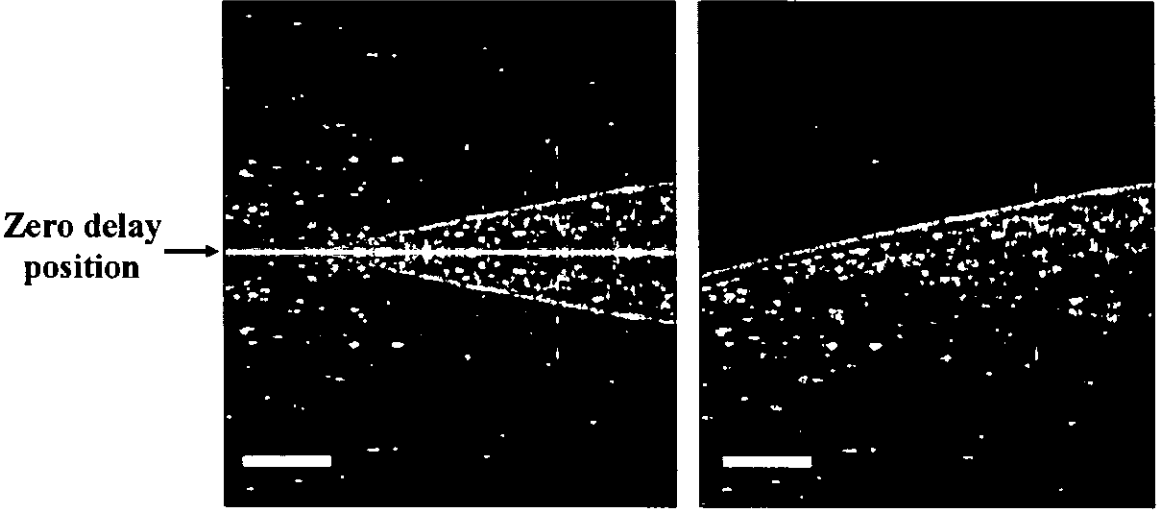

Fig. 4 – Images of an onion with the PFS setup. Left: raw data without processing. Right: with processing. Images are 2.5 mm wide and 3 mm depth. The horizontal white line at the bottom left of each image is 500 μm.

4. Conclusion

To conclude, we can say that an implementation of a B-M type scanning with a piezoelectric fiber stretcher in an SS-OCT setup provides images with greatly reduced artifacts. The main advantages of using such a technique to remove artifacts are the following:

- The setup is an all-fibered interferometer (low power losses and very easy to implement).
- We use low voltage (< 10 Volts) which it is not so often with the use of piezoelectric transducer.
- There is no polarization effect in the fiber stretching process as we are stretching the fiber over a span of λ.
- It is applicable to SD-OCT.

Reference

1. Y. Yasuno, S. Makita, T. Endo, G. Aoki, M. Itoh, and T. Yatagai, "Simultaneous B-M-mode scanning method for real-time full-range fourier domain optical coherence tomography," Applied Optics 45(8), pp. 1861–1865, 2006.