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Dual Ultrahigh Speed Swept-Source & Time Domain Optical Coherence Tomography system using a time stretch laser and a KTN deflector

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ABSTRACT

We present an ultrahigh-speed swept source optical coherence tomography (SS-OCT) system that allows a volume rate of 400 Hz paired with a time domain (TD) subsystem. For the SS-OCT, a 40 MHz swept source is used, while for the TD-OCT, a broadband source. Both systems employ a scanning system that consists of a KTN scanner paired with a galvoscanner. The KTN crystal scans the beam laterally at 100 kHz. This allows B-scan OCT repetition rate, while with the galvoscanner 200 lines are obtained at 400 Hz in the *en-face* display of both SS-OCT and TD-OCT systems.

Keywords: swept source, optical coherence tomography, high speed imaging

1. INTRODUCTION

In the last decades, the use of optical coherence tomography (OCT) increased exponentially. This is due to the capacity of its non-destructive method to produce volume images of a sample with high resolution. Recently, the community developed interest for the improvement of the imaging speed. This could lead to faster volume acquisition reducing the disturbing effects of sample movements. A faster system could also enable large area scans in a reasonable time. Novel swept sources reaching multiple MHz[1] have been developed to answer this need. At such sweeping speeds, however, traditional scanners such as galvoscanners are too slow to avoid overlapping of pulses. To tackle this issue, we investigate the use of a fast lateral scanner based on a KTN crystal.[2] Paired with a 40 MHz swept-source previously developed, a 400 Hz volume production rate is demonstrated.

2. METHODS

The experimental set-up is presented in Fig. 1. The swept source consists of a time-stretch laser that sweeps at 40 MHz.[3] Pulses from a femtosecond laser are coupled into a photonic crystal fiber. Nonlinear effects in the fiber generate a spectrum of 100 nm at -3 dB, and 200 nm at -10 dB, centered at 1060 nm. The spectrum is then stretched in time using 2.7 km of single-mode fiber 980XP. The output of the stretcher is then amplified up to 20 mW and launched into the OCT system. The ytterbium fiber used for optical amplification cannot cover the whole spectrum and an output spectral bandwidth of is obtained. However, the output spectral bandwidth is reduced to 48 nm at -3 dB, and 80 nm at -10 dB, because the ytterbium fiber cannot cover the whole spectrum.

Due to the limited data transfer and processing speed, the swept source OCT (SS-OCT) system cannot deliver an en-face image in real-time. Therefore, a time domain OCT (TD-OCT) system was used to guide the initial positioning of the sample. The path modulation created by lateral scanning of the optical beam is used to generate phase modulation, necessary to encode the interference strength.[4] The switch of the mode of operation from the SS-OCT to TD-OCT involved swapping the swept source with a broadband continuous wave source, with a 40 nm bandwidth centered at 1050 nm (ALS−1050−S, Amonics) delivering 17 mW of optical power to

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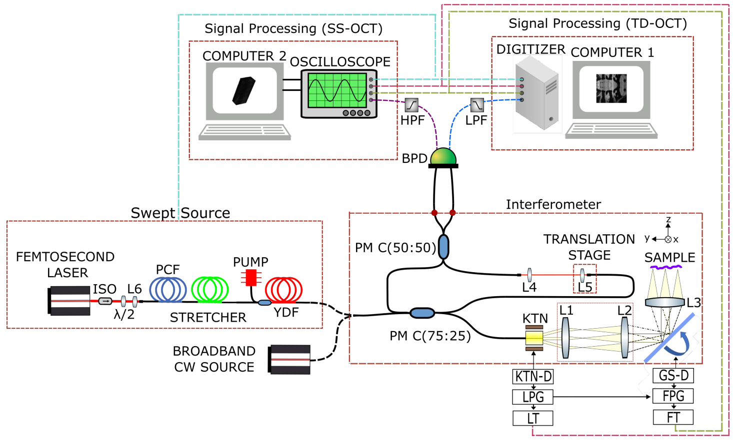

Figure 1. **Experimental set-up.** SS: swept-source; TD: Time domain, Interferometer (KTN: beam deflector using a KTN crystal, GS: galvanometer scanner, PM C: polarization maintaining couplers); Signal processing block (BPD: balanced photodetector, HPF: High pass filter, LPF: Low pass filter); Triggers (LT: line, FT: frame); Pulse generators (LPG: line, FPG: frame); Drivers (KTN-D: KTN, GS-D: galvanometer scanner). Lenses: L1, L2, L3, L4, L5 and L6 of focal lengths 3 cm, 7.5 cm, 4.5 cm, 1.5 cm, 1.5 cm and 4.51 mm respectively.

the interferometer. Two separate signal processing blocks were used for each of the two regimes of operation, SS-OCT and TD-OCT. The interferometer employs two directional couplers, C, of 25/75 and 50/50 based on polarisation maintaining fiber, PM, (PANDA PM980-XP, AFW). In the sample arm, 25% of the light from the optical source is guided towards the object to be imaged, via two lateral scanning devices, a KTN crystal, (KTN−1D, NTT Advanced Technology Corporation) for fast line scanning, and a galvanometer scanner, GS, for the frame scanning. The deflection angle of the KTN scanner is determined by delivering high voltage signal to the crystal. A 200 V sinusoidal driving voltage at 100 kHz is applied, producing a full deflection angle of 124 mrad on top of a −240 V DC bias. Due to the dependence of deflection to polarisation, the KTN crystal is connected to a suitably oriented PM fiber. This has also determined the choice of PM fibre in the array of both couplers. The KTN assembly includes a cylindrical lens to reduce the beam astigmatism, and provides at the output a small diameter beam of 1 mm. To improve the transversal resolution, a telescope comprised of two achromatic lenses (L1 and L2) of 30 mm and 75 mm focal length respectively, provides ×2.5 magnification. The lens L3 of 45 mm focal length focuses the fan of rays onto the sample. The two scanners, separated by the telescope, create a raster of N_y lines in the frame, each line consisting of N_x pixels. The GS is driven by a 400 Hz sawtooth signal of 2.5 V amplitude, which considering the period of 10 μs of the sinusoidal signal applied to the KTN crystal, determines $N_y = 250$ horizontal lines in the frame and an extension along Y over the sample of 6.6 mm. For the 200 V applied to the KTN deflector, the lateral extension of scanning along X is 2.95 mm. The interferometer signal is detected using a 23 GHz balanced photodetector. For the SS-OCT, a 20 GHz oscilloscope is used to digitize the signal, which is connected to a computer and the data is transferred for post-processing. Complex master slave is used for phase calibration of the channelled spectrum.[5]

3. RESULTS

A coin is used as a sample to perform OCT topography. The coin is slightly tilted and therefore the narrow coherence gate led to fragmented en-face OCT images. The bright patch in the en-face OCT images represents a projection of the coherence gate on the sample. Two such cuts are shown, corresponding to the z position of the coin base Fig.2 (b) and corresponding to the z position of the top of the letters Fig. 2 (c).

The axial resolution and axial range are measured to be 10 μm and 0.61 mm respectively. The lateral resolution is measured using an USAF target and *en-face* time domain OCT images, see Fig. 2 (e), obtaining 23 μm in the x-direction and 18 μm in the y-direction. Some difference in the lateral resolution along the two directions is expected due to the cylindrical lens. As the B-scan images in Fig. 2 (b1,b2) show, the axial range is sufficient to cover the tilt of the coin and the height of the letters on the coin. The volumes contain (400 × 250 × 53) voxels. However, the vertical distance between the forward and backward scan of the KTN is calculated to be 16 μm, which is lower than the lateral resolution of 18 μm. Therefore, only the forward scan is presented in the *en-face* images of Fig. 2.

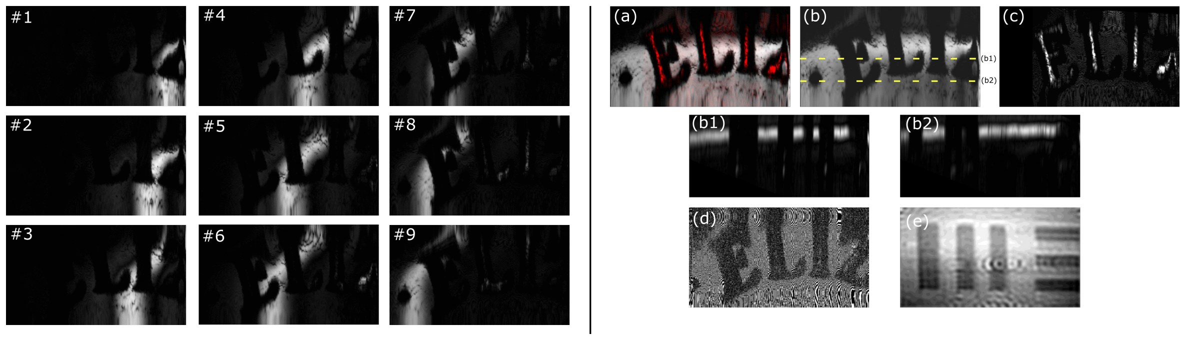

Figure 2. *En-face* OCT images of a tilted coin in which the coherence gate is seen bright # 1-9. (a) Corrected *en-face* image for tilt of the coin, bottom surface coin in grey and top surface coin in red. (b) Corrected *en-face* image for tilt of the coin, showing the bottom surface coin with (b1,b2) B-scans at the yellow positions. (c) Corrected *en-face* image for tilt of the coin, showing the top surface coin. (d) Time domain OCT image using broadband continuous wave source. (e) USAF Target *en-face* image using time domain OCT.

4. CONCLUSION & OUTLOOK

In this paper, an ultrahigh speed OCT system with a volume rate of 400 Hz is presented. It is based on the use of a 40 MHz swept source paired with a fast KTN scanner. A time domain subsystem enables proper adjustment of the sample, before imaging with the high speed SS-OCT system. Due to the high-frequencies that the SS-OCT system can achieve, high-speed electronics are needed which complicates the acquisition and therefore, the real-time visualization. In future works, methods that allow real-time display of the SS-OCT should be considered.

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