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High-Speed Time-Domain En Face Optical Coherence Tomography System Using KTN Optical Beam Deflector

Masato Ohmi[1], Yusuke Shinya[1], Jun Miyazu[2], Seiji Toyoda[2], Tadashi Sakamoto[2]

[1]Course of allied Health Science, Graduate school of Medicine, Osaka University, Yamadaoka, Suita, Osaka, Japan
[2]NTT Device Innovation Center, NTT Corporation, Morinosato Wakamiya, Atsugi, Kanagawa, Japan
Email: ohmi@sahs.med.osaka-u.ac.jp

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Abstract

We developed high-speed time-domain (TD) en face optical coherence tomography (OCT) system using KTN optical beam deflector. The KTN optical beam deflector operates at a high repetition rate of 200 kHz with a fairly large beam deflection angle. We proposed a high-speed en face OCT system that used a KTN optical deflector as the sample beam scanning. In the experiment, we obtained en face OCT images of human fingerprint with a frame rate of 800 fps, which is the fastest speed obtained by a TD-OCT imaging. Furthermore, a 3D-OCT image was also obtained at 0.2 s (=5 volumes/s) by our imaging system.

Keywords

Optical Coherence Tomography, En Face OCT, KTN, Optical Beam Deflector

1. Introduction

Since the proposal of optical coherence tomography (OCT) [1], OCT has been developed intensively for clinical diagnoses in ophthalmology [2]. There are three types of data acquisition and image processing by OCT: Time domain (TD) OCT [1] [2]; Fourier domain (FD)/spectral domain (SD) OCT [3]; and Swept source (SS) OCT [4]. SS-OCT offers the highest speed for data acquisition due to the wavelength-tuning speed of a swept source. Recently, Microelectromechanical Systems (MEMS) vertical-cavity surface-emitting laser swept source provides sweeping speed of 60 kHz to 1 MHz [5]. The Fourier domain mode-locked laser (FDML) is considered to have the highest sweeping speed in the range of up to multi MHz [6]. Another imaging method for OCT is en face OCT, also known as optical coherence microscopy (OCM) [7], which performs perpendicular sectional imaging of a sample. Generally, a CCD camera is used as a detector that captures en face images of the depth direction of the sample to movement of a reference mirror, and acquires three-dimensional information. This imaging technique has a comparatively low S/N ratio due to the low amount of radiation power used to illuminate a sample.

The $KTa_{1-x}Nb_xO_3$ (KTN) crystal has a very large electro-optic (EO) effect, which changes its refractive index when a voltage is applied and bends the path of a light beam in a new direction. The deflection effect of the KTN is caused by a non-uniform electric field generated by injected carriers, and exhibits a fast response of up to several hundred MHz and a fairly large beam deflection angle [8] [9] [10]. Considering this performance, we proposed a high-speed en face OCT system that used a KTN optical deflector as the sample probe [11]. The OCT data acquisition rate of 400 frames/sec (fps) was obtained. In this paper, the highest frame rate of 800 fps was obtained by use of heterodyne detection of the interference OCT signals. Furthermore, the 3D-OCT image of sweat gland was also obtained at 0.2 s by our imaging system.

2. En Face OCT System Configuration

The high-speed en face OCT system configuration is shown in **Figure 1**. The light source of the Mach-Zehnder interferometer is a super-luminescent diode (SLD) light which is linearly polarized and has the spectral width of 56 nm around a central wavelength of 1.31 μm. The output power of the SLD light is 20 mW. Light from the SLD is split by a 99/1 coupler into one beam being transmitted down a sample arm and the other beam being transmitted down a reference arm. Acousto-optic (AO) modulator is placed on the reference arm in order to heterodyne detection of the interference signal. The modulation frequency is 40 MHz. Both beams are reflected by the reference mirror, and the sample beam is separated by optical circulators (CIR). Polarization controllers (PC) are used to adjust the polarization states of the beams in each arm. Light from the two arms interferes at a 50/50 coupler, whose outputs are detected by a balanced photo-detector. The detected interference signal is amplified and fed to an AD

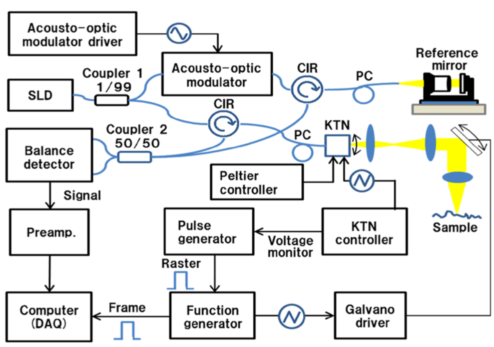


Figure 1. High-speed TD en face OCT system configuration. CIR: Circulator; PC: Polarization controller; DAQ: Data acquisition system.

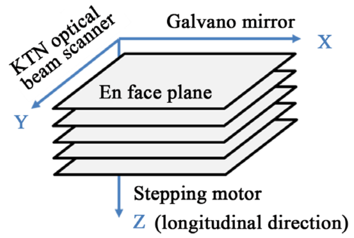


Figure 2. En face scanning for 3D-OCT dada.

converter. The sampling rate of the AD converter is 400 MHz with 14-bit digitizer.

In the en face OCT imaging, the sample light is scanned along the x-axis by a galvanometer mirror and along the y-axis by a KTN optical beam deflector, as shown in **Figure 2**. In our imaging system, the fast scanning was performed at 200 kHz along the y-axis, while the slow scanning was performed at 800 Hz along the x-axis. For 3D-OCT imaging, the reference mirror was moved along the z-axis by a stepping motor during the en face OCT imaging.

3. Optical Arrangement of the Sample Arm

The KTN deflector operates by exploiting electrons trapped in the KTN crystal. The electrons are injected and kept trapped by supplying a DC voltage to the KTN prior to the application of a high frequency AC voltage for scanning. We pre-charged the KTN crystal by applying ±400 V DC for 10 s, and then scanned the laser beam by applying a ±300 V triangle wave voltage to the KTN deflector [8] [9]. This resulted in the beam deflected by an angle of 112 mrad. KTN simultaneously exhibited the characteristics of a cylindrical convex lens because of the trapped electrons [10]. We compensated for this convex lens effect with a cylindrical concave lens. **Figure 3** shows the beam propagation and optical arrangement of the sample arm. To enlarge the input beam diameter of the focusing lens, we use ×3 magnification relay optical system include f_1 and f_2 plano convex lenses.

In the experiment, the sample light is scanned along the x-axis by a galvanometer mirror and along the y-axis by a KTN optical beam deflector. The lateral resolution of the en face OCT system can be measured by determining the smallest element of the test chart (USAF 1951) that can be clearly resolved. **Figure 4** shows the test chart and the en face OCT image of the object. From the smallest resolvable element, a horizontal (x-direction) resolution of 13.9 μm and a vertical (y-direction) resolution of 17.5 μm were obtained, respectively. We also measured the sensitivity of the en face OCT system by inserting a neutral-density (ND) 4.6 filter into a sample arm. The signal-to-noise ratio (SNR) is given by the expression [12]

$$\mathrm{SNR} = 20\log_{10}\left(\frac{\text{Signal amplitude}}{\text{Standard deviation of the noise}}\right) + P_{ND}\,[\mathrm{dB}] \tag{1}$$

where P_{ND} is the signal power with the ND filter. A measured the SNR was −67.31 dB, as shown in **Figure 5**.

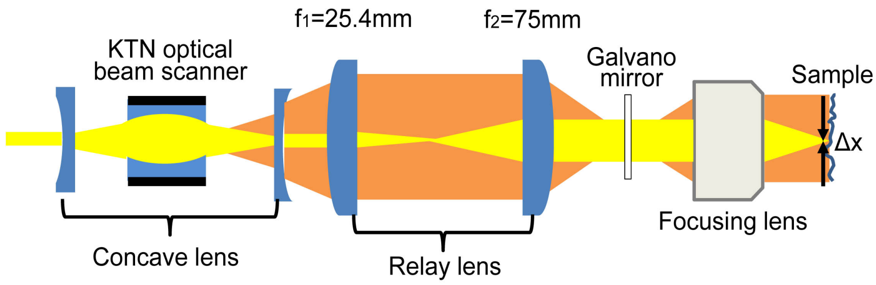
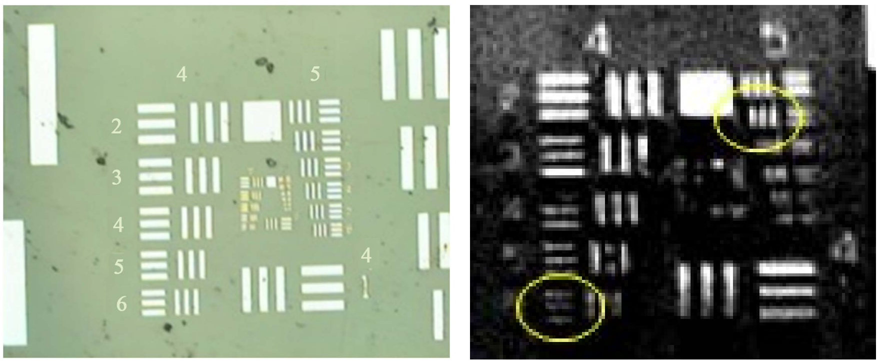


Figure 3. Beam propagation and optical arrangement of the sample arm.



(a) (b)

Figure 4. En face image of test chart (USAF 1951). (a) Photograph of test chart; (b) En face image of test chart.

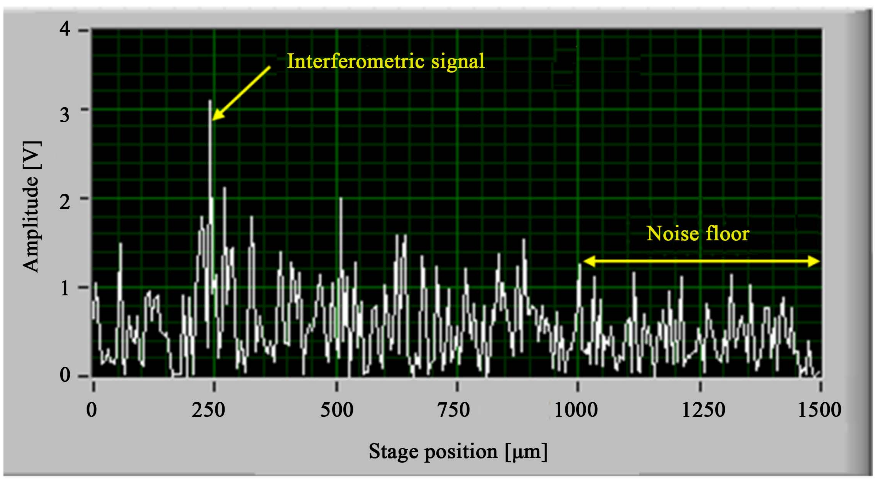


Figure 5. The measured signal-to-noise ratio (SNR) of the en face OCT system.

4. High-Speed TD En Face OCT Imaging of Human Fingertip

In the experiment, we acquired human fingerprint images using en face OCT system. The 250 × 500 pixel images covered a sample area of approximately 1.9 mm × 1.9 mm (x, y). The KTN beam deflector operated at 200 kHz in the y-direction, whereas the galvanometer scans operated at 800 Hz in the x-direction. Figure 6(a) shows the en face OCT image of the human fingerprint of x-y plane. Figure 6(b) and Figure 6(c) show the OCT image of y-z plane and

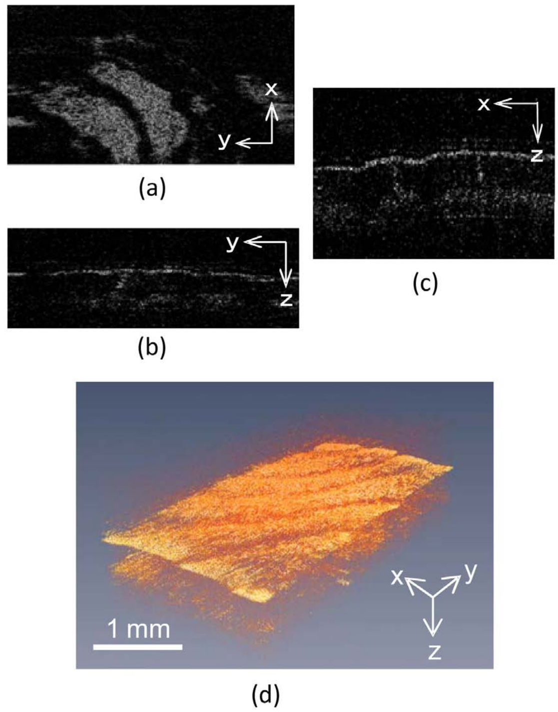


Figure 6. High-speed en face OCT images of human fingerprint. (a) En face OCT image of x-y plane; (b) OCT image of the y-z plane; (c) OCT image of x-z plane; (d) Constructed 3D-OCT.

x-z plane, respectively. The image acquisition rate was 800 fps, which is the highest speed obtained using en face OCT imaging and is comparable to the speed of SS-OCT systems. Furthermore, during 3D imaging, in addition to the operation of the galvanometer mirror and the KTN beam deflector of the sample arm, a reference mirror is moved for stacking en face OCT images. All the data from3D-OCT scanning was stored in the data acquisition board. As shown in Figure 6(d), the volume size of a 3D image was 250 × 500 × 160 voxels (x, y, z) with a 3D data acquisition rate of 5 volumes/s. The measurement ranges were 1.9 mm × 1.9 mm × 1.5 mm. The surface profile of the human fingerprint is seen clearly, and sweat gland in the stratum corneum and epidermis are recognized.

5. Conclusion

In conclusion, we proposed and demonstrated high-speed TD en face OCT system using KTN optical beam deflector. In the imaging system, the KTN beam deflector operates at 200 kHz in the y-direction, while the galvanometer scans at 800 Hz in the x-direction. This OCT imaging system essentially follows the TD method. The OCT data acquisition rate obtained is 800 fps, which is the highest frame-rate obtained by a TD en face OCT imaging. In the experiment, human fingerprints were presented as examples of en face and 3D-OCT images obtained at a volume rate of 5 volumes/s. Our efforts are directed at the development of a compact en face OCT system which conducts two dimensional scanning using only KTN beam deflectors.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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