Optical Delay Line for Rapid Scanning Low-Coherence Reflectometer

Kitsakorn Locharoenrat and I-Jen Hsu

***Abstract*—In this contribution we proposed and performed an optical delay line including all reflective components for long-range scanning without walk-off problem. The optical delay line is composed of a retro-reflector, an inclined reflection mirror and a scanning mirror. The size of the optical delay line is within 2 cm × 2 cm and the scanning range can reach 2.9 mm when the beam is incident at the pivot of the scanning mirror and the vibration angle of the scanning mirror is 9.6 degrees. The scanning range can be further increased when the pivot of the scanning mirror is laterally deviated from the incident beam. The optical delay line possesses the merits that it is compact, easy to fabricate and can perform rapid scanning in large scanning range without walk-off problem. The optical delay line was showed with a low-coherence reflectometer where the scanning rate was 400 Hz. A higher scanning rate was achieved when a scanning component with higher scanning rate is applied.**

***Index Terms*—Biomedical imaging, interference, low-coherence reflectometer, rapid-scanning optical delay line, time-domain approach.**

I. Introduction

Optical delay line is an optical component which can provide phase variation of an optical signal via variable optical path length. In practice, the optical path length can be changed discretely or continuously. Imaging techniques such as white-light interferometry [1] and phase-shifting interferometry [2] usually need optical components for discrete phase shift. On the other hand, low-coherence reflectometry [3] and phase-resolved interferometry [4] usually need a continuous scanning optical delay line to provide an axial scanning.

The optical delay can be achieved with a piezoelectric transducer (PZT), a stepper motor stage or a linearly motorized translation stage. The piezoelectric transducer can perform a rapid scanning due to its high vibrating frequency, however, the traveling range of a piezoelectric transducer is usually limited in the scale of micrometer. On the other hand, the stepper motor stage and linearly motorized translation stage can perform long-range scanning, but the translation speeds of such stages are usually limited in the order of centimeter per second. In many applications, an optical delay line which can perform a rapid scanning in the millimeter range is valuable. Furthermore, the optical delay line has better to be stable, compact and easy for maintenance.

Different designs of optical delay lines were proposed for large scanning range with high frequency. A diffraction grating-based rapid-scanning optical delay line (RSODL) was proposed for the axial scanning of time-domain optical coherence tomography [5], [6]. In the typical configuration of an RSODL, a diffraction grating and a scanning mirror are arranged on two focal planes of a lens, respectively. By use of such an arrangement, the group-delay and phase-delay of the optical signal can be controlled independently. Nevertheless, even if an achromatic lens is introduced to reduce the chromatic aberration, the offset of the ray from the pivot point of the scanning mirror will cause a walk-off effect. In other words, the direction of the beam returned from the diffraction grating deviates from the direction of the incident beam and leads to stray intensity modulation during scanning [7].

Various configurations for the optical delay lines were developed to enhance the scanning rate and scanning range such as using a rotating cube [8], a polygonal scanner [9]-[11], a multiple-pass cavity delay line [12] or a combination of curved mirror and scanning mirror [13], [14]. Several groups used a rotary array of mirrors [15], [16], prisms [17], [18] or corner reflectors [19] to enhance the scanning rate. Although most of these techniques can provide high-frequency and large-range scanning, some configurations are difficult to fabricate or difficult to construct in small size. Moreover, the walk-off problem usually causes variation in intensity of optical signal during scanning which may result in measurement errors when the intensity of light is under investigated.

Herein we proposed and showed an all reflective optical delay line which is compact, easy to fabricate and avoid the intensity loss during scanning. The scanning range of 2.9 mm is achievable when the vibration angle of the scanning mirror is 9.6 degrees. The scanning range can be further increased when the pivot of the scanning mirror deviates from the incident beam. The optical delay line provided a scanning rate of 400 Hz and is demonstrated with a low-coherence reflectometer. A higher scanning rate can be achieved when a galvoscanner with higher scanning rate is applied.

II. Design and Fabrication of Optical Delay Line

Optical delay line is composed of a retro-reflector, an inclined reflection mirror and a scanning mirror, as shown in Fig. 1(a). The retro-reflector is fabricated with two right-angled prisms assembled on an aluminum jig where a reflection mirror inclined at 60 degrees is integrated. Fig. 1(b) shows the photograph of the retro-reflector assembled with

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the reflection mirror where one can see that the size of the entire system is within 2 cm × 2 cm. As shown in Fig. 1(a), the light beam is incident at 30 degrees downward on the scanning mirror. After reflecting by the scanning mirror and the retro-reflector, the beam is reflected by the scanning mirror again. Finally, the beam is normally incident on the inclined reflection mirror such that the reflected beam is collinear with the incident beam. Since the reflected beam is guaranteed to be collinear with the incident beam regardless the tilted angle of the scanning mirror, no walk-off problem will be generated in such an optical delay line. Further detailed design was mentioned somewhere else [20].

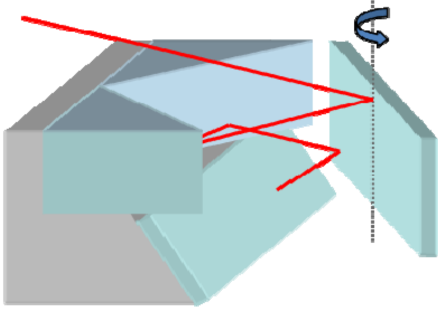

Fig. 1(a). Design of optical delay line.

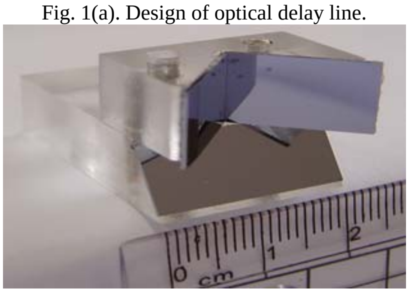

Fig. 1(b). Photograph of retro-reflector assembled with reflection mirror.

III. Experiment

In Fig. 2 we show the experimental setup of the low-coherence reflectometer with the use of the proposed optical delay line. In our system, a superluminescent diode (Superlum, D890-HP) with output power of 3.3 mW, center wavelength of 890 nm and spectral width of 150 nm was used as the light source. A He-Ne laser was used to calibrate the nonlinearity of the optical delay relative to the tilted angle of the scanning mirror. The galvoscanner was driven by a function generator which generated a continuous sawtooth waveform. The waveform was also used as a trigger to synchronize the acquisition of the interference signal received by the photodetector.

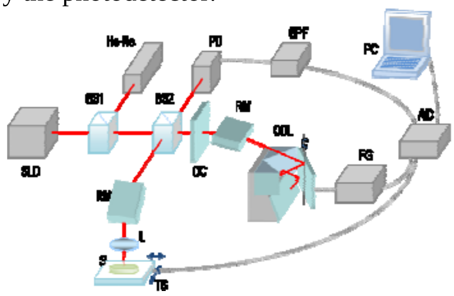

Fig. 2. Schematic of low-coherence reflectometer. SLD, superluminescent diode; He-Ne, He-Ne laser; BS1, beamsplitter (90/10); BS2, beamsplitter (50/50); RM, reflection mirror; L, lens; S, sample; TS, two dimensional translation stage; DC, dispersion compensator; ODL, optical delay line; FG, function generator; PD, photodetector; BPF, band-pass filter; A/D,A/D converter

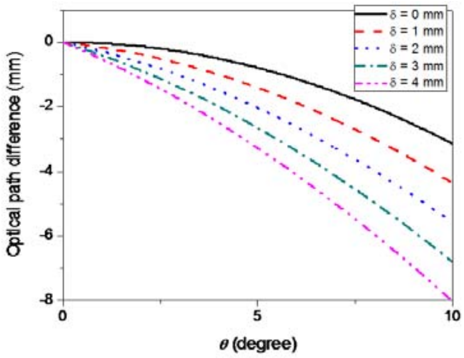

Fig. 3. Optical path difference (ΔL) with respect to the tilted angle of the scanning mirror (θ) with different lateral deviation (δ) of the pivot of the scanning mirror from the incident beam.

Scanning rate of the optical delay line is determined by the scanning rate of the galvoscanner. In this experiment, a galvoscanner (GSI Lumonics, M3S) with 20 mm beam aperture mirror was used to perform a scanning rate of 200 Hz and the tilted angle was between 0 and 10 degrees. As shown in Fig. 3, there were two A-scans performed in opposite directions in each cycle of scanning. Thus, the scanning rate of the low-coherence reflectometer in the experiment was doubled to be 400 Hz. The scanning rate of the optical delay line can be improved without changing the configuration of the system when a higher scanning rate of the galvoscanner is applied.

IV. Results and Discussion

In Fig. 4(a) we show the intensity of the reflected beam from the reference arm of the low-coherence reflectometer during scanning. The uniformity of the intensity during scanning verifies that there was no walk-off effect in the system. The indentations occurred at the tiled angles around 0 and 10 degrees represent the effects beyond the allowable scanning range. On the other hand, Fig. 4(b) shows the interference signal when a He-Ne laser was used as the light source.

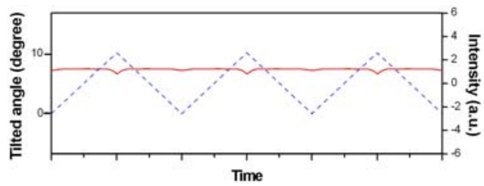

Fig. 4(a). Intensity of the reflected beam from the reference arm of the low-coherence reflectometer during scanning (line) and the tilted angle of the scanning mirror (dashed line).

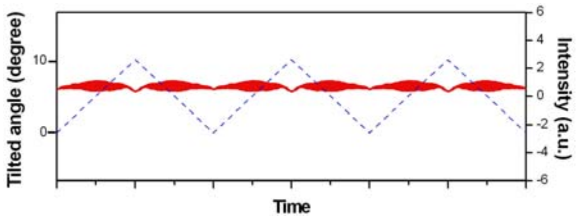

Fig. 4(b). Interference signal when a He-Ne laser was used as light source (line) and the tilted angle of the scanning mirror (dashed line).

In order to show the performance of the low-coherence reflectometer, various samples were introduced for scanning.

Fig. 5(a) shows the interference signal of a reflection mirror. The dynamic range of the low-coherence reflectometer was estimated to be 20 dB. It was mentioned that the scanning depth of the optical delay line could achieve 2.9 mm when the vibration angle of the scanning mirror was 9.6 degrees. When the distance between the retro-reflector and the scanning mirror is reduced, the allowable scanning angle is increased and the scanning range can be further improved. On the other hand, Fig. 5(b) shows the interference signal when two slides were introduced as the sample. The thickness of one slide was measured to be about 1.1 mm, thus the scanning range larger than 3 mm was achieved when the refractive index of the slide was assumed to be 1.5. Fig. 6 demonstrates the two dimensional image of a stack of 11 coverslips.

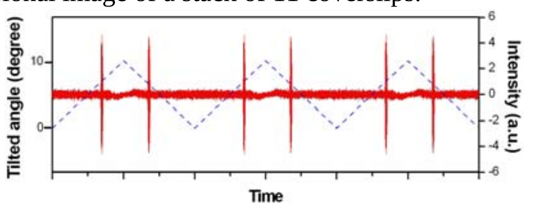

Fig. 5(a). Interference signals when a reflection mirror was used as the sample (line) and the tilted angle of the scanning mirror (dashed line).

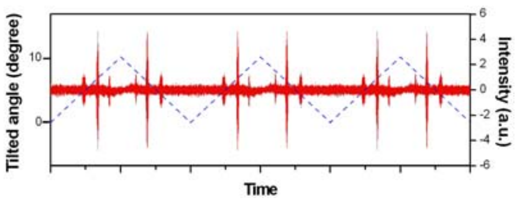

Fig. 5(b). Interference signals when two slides were used as samples (line) and the tilted angle of the scanning mirror (dashed line).

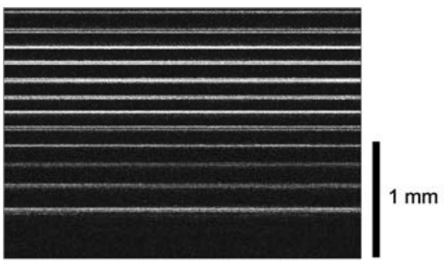

Fig. 6. Two dimensional image of a stack of 11 coverslips. The refractive index was assumed to be 1.5.

V. Conclusion

In this paper, we proposed and constructed an optical delay line for rapid scanning low-coherence reflectometer. In the optical delay line, a retro-reflector and a reflection mirror were integrated in an aluminum jig. A galvanometer was used to drive the scanning mirror as a scanning component which performed a scanning rate of 400 Hz in our system. The size of the optical delay line is within 2 cm × 2 cm. As the vibration angle of the scanning mirror is 9.6 degrees, the achieved scanning range of the low-coherence reflectometer can be larger than 3 mm. The optical delay line possesses the benefits that it is compact, easy to fabricate and can avoid walk-off problem during scanning. The low-coherence reflectometer with the proposed optical delay line can perform a rapid scanning imaging and two dimensional image of a stack of coverslips was demonstrated.

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