Rotary mirror array for high-speed optical coherence tomography

Nan Guang Chen and Quing Zhu

University of Connecticut, Department of Electrical and Computer Engineering, Storrs, Connecticut 06269

Received November 9, 2001

We have developed a simple, high-speed, high-duty-cycle, linear optical delay line suitable for optical coherence tomography and optical Doppler tomography. Periodic longitudinal scanning is achieved by use of a tilted mirror array rotating at a constant speed. With a typical motor speed of 4000 rpm, our system has demonstrated a 2-mm axial scanning range, a 2400-Hz repetition rate, 94% duty cycle, and less than 0.1% nonlinear errors. Much higher repetition rates can be readily achieved by use of high-speed motors. © 2002 Optical Society of America

OCIS codes: 110.4500, 170.3880, 120.5800, 220.4830.

Optical coherent tomography (OCT) permits exceptionally high-resolution subsurface imaging of tissue microstructures. Optical Doppler tomography is an extension of OCT, and it tracks Doppler shifts arising from the moving scatterers inside blood vessels. In many clinical situations, successful use of OCT and optical Doppler tomography depends on the design of fast delay lines, which can provide real-time imaging and, therefore, suppression of motion artifacts. Parameters associated with the design of fast delay lines are scanning range, linearity, duty cycle, and cost. Often, compromises among these parameters have to be made.

A primitive delay line is a translating mirror, which is driven by a linear motor, an actuator, or a piezoelectric transducer. As the mirror moves back and forth, the power consumption required for generating acceleration increases dramatically with frequency and scanning range. This increase is the reason that most commercially available linear motors and actuators can provide a repetition rate of only ~30 Hz when a 2–3-mm scanning range is required.[1] Although piezoelectric transducers can be driven at much higher frequencies, they can provide only a limited scanning range. Resonant scanners have been demonstrated to achieve a frequency of 1200 Hz and as great as 3-mm optical length difference.[2] The drawback to resonant scanners is that the optical path-length change is a time-dependent sinusoidal function. As a result, the Doppler frequencies of interference signals are depth dependent and vary within a wide range, which may cause difficulties in signal filtering and introduction of more noise. More-sophisticated delay lines convert a small-angle rotation into a longitudinal optical path-length change. This conversion can be achieved by use of either a retroreflector[2] or a combination of gratings and lenses.[3,4] The former implementation requires a complicated arrangement of mirrors and lenses and precise alignment. Grating-based delay lines have the flexibility to adjust group delay and phase delay independently. Repetition rates of 2000 (Ref. 3) and 4000 (Ref. 4) scans/s have been reported for such delay lines with a galvonometer (driven with a 1-kHz triangle waveform) and a 4-kHz resonant scanner, respectively. It appears that without resonant scanners, vibrational motion–based mechanical scanning cannot readily achieve a speed high enough to meet real-time data acquisition requirements. It is a great idea to use rotational motion–based devices instead of vibrating devices to generate optical path-length scanning. Once a steady rotation speed has been reached, a small amount of energy is required for maintaining rotation speed. Rotating cubes,[5,6] rotating roof prisms,[7] and a combination of a polygonal mirror and a glass cube[8] can scan up to 28.5 kHz. However, these methods suffer from rather low duty cycles and (or) considerable nonlinearity of optical path-length change. Recently, an OCT system without any moving parts for depth scanning was proposed,[9] and a high-repetition scanning rate of 500 kHz was achieved in a scanning range of 25 mm by use of optical frequency comb generators. However, the depth resolution (100 μm) and signal-to-noise ratio of this system need to be improved. In addition, the cost of this system is high because of the use of expensive components, such as gigahertz electronics and electro-optical modulators.

In this Letter we present a novel design for implementing a periodic modulation of the optical path length in the reference arm, which consists of a dc motor, a mirror array, and a convex lens. We use a regular motor with a speed of 4000 rpm in our current OCT system to demonstrate the feasibility of real-time scanning with our new design. As many as 2400 A lines were acquired every second in a 2-mm range, without noticeable nonlinear effects. A much higher scan rate can be readily obtained by replacement of our current motor with high-speed motors, e.g., with speeds of 20,000–100,000 rpm.

The principle of our delay line is quite simple, as is illustrated in Fig. 1. Shown in Fig. 1(a) is a segment of an infinite linear mirror array. Mirrors are deployed uniformly on a planar base. Their reflective facets are tilted at a small angle α with respect to the base. The optics of the reference arm is arranged so that the reference beam hits a mirror surface perpendicularly and is reflected back along the same path into the optical fiber. When the mirror array moves at a

0146-9592/02/080607-03$15.00/0

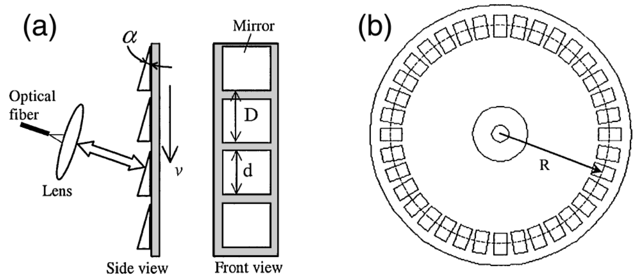

Fig. 1. (a) Optical delay line with a section of an infinite linear mirror array. (b) Rotary mirror array derived from the linear array.

constant speed ν, the optical path length will be modulated periodically. Within each period, the change of optical path length is a linear function of time. The scanning range, ΔL, and speed ν_l are given by

$$\Delta L \approx d \sin \alpha \,, \tag{1}$$

$$\nu_l = v \sin \alpha \,, \tag{2}$$

respectively, where d is the length of the mirror in the direction of movement. The repetition rate is inversely proportional to the spatial period D:

$$f = \nu/D \,. \tag{3}$$

Of course, an infinite mirror array is not practical. However, one can make a local approximation by bending a section of an infinite linear mirror array into a ring [see Fig. 1(b)], forming a circular array of discrete rotational symmetries. When the mirror array rotates at a constant angular speed ω, the linear translation speed at the light-illumination point is $\nu = \omega R$, where R is the equivalent radius. In each duty cycle, the one-way optical path length can be expressed as a function of time δt with the origin at the moment when the incident beam illuminates the center of the mirror:

$$\begin{aligned} \Delta l &= R \sin \alpha \sin(\omega \delta t) \\ &\approx R \sin \alpha [\omega \delta t - (\omega \delta t)^3/6] \,. \end{aligned} \tag{4}$$

Since the rotation angle $\omega \delta t$ is approximately in the range $[-d/2R,\, d/2R]$, the maximum value of the relative nonlinear error is approximately $d^2/24R^2$, which is as small as 0.1% for our experimental system ($R =$ 50 mm and $d = 8.2$ mm). To the best of our knowledge, this has never been achieved by other mechanical fast-scanning devices.

A schematic diagram of our fast OCT system is shown in Fig. 2. A superluminescent LED (SLED1300S5A, Opto Speed) is used as low-coherence source and yields better performance than the erbium-doped fiber amplifier used in our previous system.[10] The center wavelength and the −3-dB bandwidth are 1300 and 40 nm, respectively, resulting in a coherence length of 18.6 μm. The typical output power of the system, ~2.5 mW, is coupled into a single-mode optical fiber. A 2 × 2 optical coupler distributes input light evenly into the reference and the sample arms. In the reference arm, longitudinal scanning over a 2-mm range is achieved with our rotary mirror array. The mirror array consists of 36 identical small mirrors tilted at a 14° angle with respect to the base plane and the direction of the local linear velocity. The equivalent radius R is 50 mm, and D is ~8.7 mm for each mirror. A fairly high duty cycle of 94% was measured, in good agreement with the theoretical prediction. The mirror array is directly driven by a permanent magnet dc motor (GNM 2636A, MicroMo Electronics). The maximum continuous speed of the motor is 4000 rpm, which provides a repetition scanning rate of 2400 Hz. At the sample arm, a galvanometer scans the light beam laterally on a sample to yield two-dimensional images. We use a 10-Hz sawtooth waveform to drive the galvanometer so that a B scan, consisting of 240 A lines, can be acquired in 0.1 s. Reflections from both arms are superimposed at the output fiber, and then the interference signals are detected by a low-noise photodetector (D400FC, Thorlabs). Since the original interference signals have a center frequency of ~7.8 MHz , we used a heterodyne detection scheme to reduce the speed requirement on a digitizer. The heterodyned signals (~300 kHz in center frequency) are converted to digital signals by a PCI data acquisition card (PCI-MIO-16E-1, National Instruments). Further signal processing and A-line segmentation are conducted by a personal computer. We used a reflective optical sensor together with a mark on the periphery of the rotating base to generate feedback signals for timing purposes. With such an arrangement (not shown in Fig. 2), individual A lines can be selected from continuous waveforms with high accuracy and repeatability.

To validate our new design, we conducted a series of imaging experiments. In one experiment, a small piece of transparent film fixed upon a glass plate served as a simplified sample. The thickness of the transparency film was 127 μm, and a 255-μm gap existed between the back surface of the transparent film and the glass plate [Fig. 3(a)]. Shown in Fig. 3(b) is a cross-sectional image acquired with the setup given

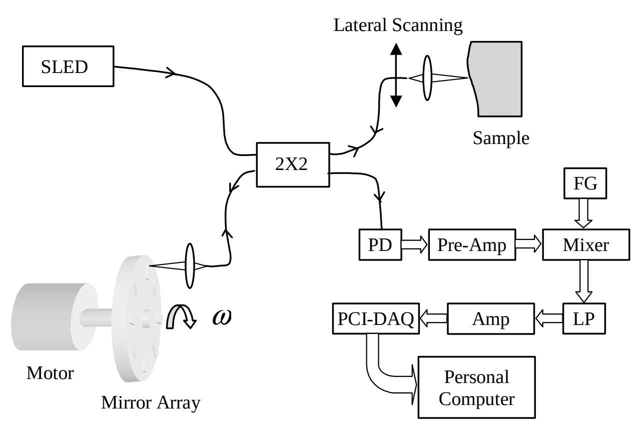

Fig. 2. Schematic diagram of our fast OCT system. SLED, superluminescent LED; PD, photodetector; Pre-Amp, pre-amplifier; FG, function generator that supplies reference signals of ~7.5 MHz; LP, low-pass filter; Amp, amplifier; PCI-DAQ, PCI data acquisition card.

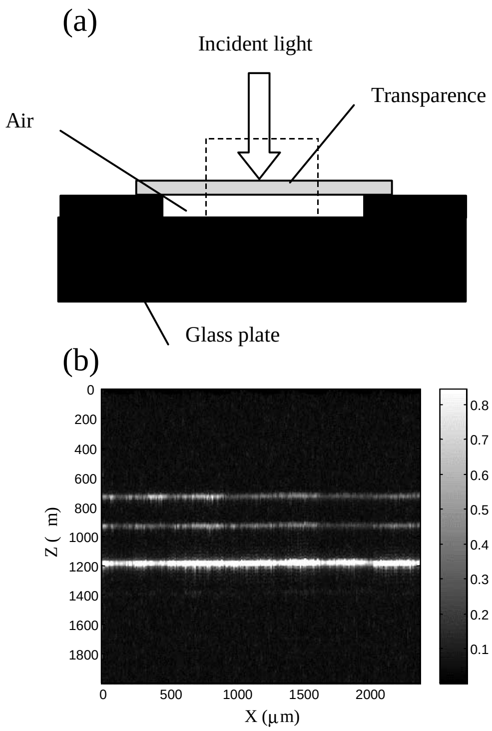

Fig. 3. (a) Simple sample for imaging. The dashed square indicates the imaging area. (b) Cross-sectional image acquired with our fast OCT system.

in Fig. 2. The interfaces of the transparent film and the glass plate with the air can be identified clearly. The refractive index of the transparent film is 1.55, so the thickness that appears in the image is 196.5 μm.

The advantages of our fast-scanning delay line over existing technologies are numerous. First, video-rate image acquisition can be readily achieved. We are planning to use a high-speed motor ($\sim$20,000 rpm) in the next version of the OCT system. As a consequence, an $\sim$12-kHz scan rate will be obtained. If 300–400 A lines are used for one B scan, the imaging frame rate will range from 30 to 430 frames/s. Although this speed is adequate for most clinical applications, there are no mechanical difficulties in rotating the mirror array at an even higher speed. The practical speed will be limited only by the light-source power and the signal-to-noise ratio of the entire system. The scanning range can be extended to 3 mm by a slight increase in the size of the mirror array. Second, since the optical path length is modulated in a linear fashion, the frequencies of interference signals are depth independent and are limited to a relatively narrow band. These features are highly desirable for optical Doppler tomography. In addition, a narrow-band filter can be used to achieve a high signal-to-noise ratio. Third, the duty cycle of our system is high, and a duty cycle of more than 94% is feasible. Fourth, in setting up and maintaining high-speed rotation, much more energy is saved than in vibrating devices. Mechanical vibrations and noises can also be reduced. Finally, our delay line does not suffer from group-velocity dispersion, which is desirable for retaining spatial resolution.

In conclusion, we have demonstrated a novel design for a high-speed optical delay line for OCT systems. A repetition scan rate of 2400 Hz over a 2-mm range has been achieved with our prototype system. Excellent linearity and high duty cycles are obtained. We are quite confident that much higher speed can be readily achieved with high-speed motors, so that images can be acquired at a video rate. The application of this delay line will not necessarily be limited to OCT. In fact, it can replace many fast delay lines used in a variety of optical systems.

We thank graduate student Daqing Piao for his help with the optical system setup. We thank the U.S. Department of Defense Army Breast Cancer Program (grants DAMD17-00-1-0217 and DAMD17–01-1-0216) and the National Institutes of Health (grant NIH 1R01 DE11154-03) for their funding support. N. G. Chen's e-mail address is chenng@engr.uconn.edu.

References

1. J. M. Schmit, IEEE J. Sel. Top. Quantum Electron. **5,** 1205 (1999).
2. R. Windecker, M. Fleischer, B. Franze, and H. J. Tiziani, J. Mod. Opt. **44,** 967 (1997).
3. G. J. Tearney, B. E. Bouma, and J. G. Fujimoto, Opt. Lett. **22,** 1811 (1997).
4. A. M. Rollins, M. D. Kulkarni, S. Yazdanfar, R. Ung-arunyawee, and J. A. Izatt, Opt. Express **3,** 219 (1998), http://www.opticsexpress.org.
5. C. B. Su, Opt. Lett. **22,** 665 (1997).
6. J. Szydlo, H. Bleuler, R. Wälti, and R. P. Salathé, Meas. Sci. Technol. **9,** 1159 (1998).
7. H. Harde and H. Burggraf, Opt. Commun. **38,** 211 (1981).
8. N. Delachenal, R. Wälti, R. Gianotti, S. Christov, P. Wagner, R. P. Salathé, U. Dürr, and G. Ulbers, Opt. Commun. **162,** 195 (1999).
9. S. J. Lee, B. Widoyatmoko, M. Kourogi, and M. Ohtsu, Jpn. J. Appl. Phys. **8B,** L878 (2001).
10. D. Q. Piao, Q. Zhu, N. Datta, S. K. Yan, and L. Otis, Appl. Opt. **40,** 5124 (2001).