Published in final edited form as:

Opt Lett. 2009 October 15; 34(20): 3196–3198.

Scanning fiber angle-resolved low coherence interferometry

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Abstract

We present a fiber-optic probe for Fourier-domain angle-resolved low coherence interferometry for the determination of depth-resolved scatterer size. The probe employs a scanning single-mode fiber to collect the angular scattering distribution of the sample, which is analyzed using the Mie theory to obtain the average size of the scatterers. Depth sectioning is achieved with low coherence Mach–Zehnder interferometry. In the sample arm of the interferometer, a fixed fiber illuminates the sample through an imaging lens and a collection fiber samples the backscattered angular distribution by scanning across the Fourier plane image of the sample. We characterize the optical performance of the probe and demonstrate the ability to execute depth-resolved sizing with subwavelength accuracy by using a double-layer phantom containing two sizes of polystyrene microspheres.

Elastically scattered light from tissue carries morphological and spectroscopic information that can be used to assess tissue health. A variety of optical techniques have been developed that use singly scattered light (light scattering spectroscopy) [1,2] or diffuse light (elastic scattering spectroscopy, also known as diffuse reflectance spectroscopy) [3,4] for effective identification of precancerous and cancerous growths in the epithelial layer of tissue where the majority of human cancers originate. As another “optical biopsy” technique, angle-resolved low coherence interferometry (a/LCI) combines the sizing capability of angular light scattering with the depth resolution of optical coherence tomography (OCT) to obtain quantitative morphological and optical information about the biological scatterers from epithelial and subepithelial layers, and it has been effectively applied to diagnose intraepithelial neoplasia [5]. To enable clinical applications of this technique, previous a/LCI systems have employed Fourier-domain low coherence interferometry to reduce data acquisition time. The incorporation of a fiber bundle further improves system speed by parallel detection and makes possible the endoscopic application of the technique [6].

In this Letter, we present an implementation of Fourier-domain a/LCI by the use of a scanning fiber probe to collect the angular scattering from the sample. Unlike the fiber-bundle-based probe, whose length and cost may be subject to manufacturing capability, the proposed probe is not restricted by length and has the potential of reduced cost. More importantly, the single-mode fiber-based configuration maximizes its compatibility with standard OCT systems, which permits the a/LCI system to directly incorporate the many hardware and software platforms already developed for OCT.

Figure 1 illustrates the system configuration, which is based on a modified fiber-optic Mach–Zehnder interferometer consisting of two 90:10 single-mode fiber couplers, FC1 and FC2. FC1 splits the output from an 830 nm superluminescent diode (SLD: Superlum Diode, Ltd., $\Delta\lambda_{FWHM}=17$ nm) into the reference and sample arms. The reference arm connects the 10% ports of both couplers using a pair of collimators, C1 and C2, with C1 mounted on a linear

translation stage for path-length matching. The intensity of the reference arm can be adjusted by insertion of a neutral density filter (NDF). The sample arm, in contrast, arranges the two 90% ports in reflection mode with the port from FC1 illuminating the sample and that from FC2 collecting the backscattering, respectively. The reference and sample signals are then mixed at FC2 to generate interference for detection by a fiber-coupled miniature spectrometer (SP: OceanOptics HR4000, 3648 pixels). Because the angular scattering distribution is polarization dependent, the incident polarization is controlled in order to effectively use Mie scattering models for data analysis. A polarization controller (PC) is used to evenly distribute the input energy into p and s polarizations so that the Mie model based analysis can be implemented as the average of the two orientations. If linear polarization is desired, it can be achieved by the use of an in-line fiber polarizer and polarization-maintaining fibers and couplers.

Figure 1 (inset) shows the probe tip schematic where both the illumination fiber (IF) and the collection fiber (CF) are positioned in the focal plane of a drum lens (L: 3 mm length, 2.4 mm diameter, 2.2 mm focal length). The lens illuminates the sample (S) with a collimated beam traveling at an angle relative to the optical axis and collects the light scattered at the specific angle θ back into the collection fiber, which is translated perpendicular to the optical axis by a motorized actuator to acquire the angular distribution. For convenience, θ is defined as the supplement of the conventional scattering angle; i.e., $\theta = 0$ rad corresponds to backscattering. The interfiber distance d is scanned through the range [0.25 mm, 1.35 mm] at a speed of 0.1 mm/sec, collecting spectra at approximately 116 angles in 12 sec. This scanning profile results in a useful range of [0.27 mm, 1.23 mm], or [0.088 rad, 0.406 rad] correspondingly, and an angular resolution of 0.0032 rad.

The signal intensity detected by the spectrometer, after resampling into wavenumber space, can be written as

$$I(k, \theta) = I_r(k) + I_s(k, \theta) + 2\eta \sqrt{I_s(k, \theta) I_r(k)} \cos[\Delta\varphi(k, \theta)], \quad (1)$$

where $I_r(k)$ is the reference arm intensity at wavenumber k and is independent of d and θ , $I_s(k, \theta)$ is the sample scattering field at angle θ , $\Delta\varphi(k, \theta)$ is the phase difference between the two fields, and η is a factor reflecting the system coupling efficiency and interference efficiency that we assume is a constant. In our system, $I_s(k, \theta)$ is negligible, and hence signal processing involves the removal of only $I_r(k)$. The resultant interferometric term is then Fourier transformed to produce a depth scan for each scattering angle θ . Upon collection of the angular distribution across the full range allowed by the system, the result is compared with a Mie scattering database to determine the closest size match.

To obtain optimized depth resolution, the system dispersion needs to be compensated for prior to Mie theory analysis. This is done based on the fact that the dispersion is the nonlinearity of $\Delta\varphi(k, \theta)$, or equivalently $\delta\varphi(k, \theta) = \Delta\varphi(k, \theta) - kL$, where L is the wavelength-independent best estimate of the optical path-length difference between the reference and sample arms. To find L , we first record the interference using a mirror as sample and obtain the unwrapped phase $\Delta\varphi'(k, \theta)$, which differs from actual phase difference $\Delta\varphi(k, \theta)$ by $2m\pi$, where m is a positive integer. We hence write

$$\delta\varphi(k, \theta) = \Delta\varphi'(k, \theta) + 2m\pi - kL. \quad (2)$$

Equation (2) is a least-square fitting problem that can generate an initial estimate of m and L . [7] We round m to the nearest integer, $[m]$, and use it as a known parameter in Eq. (2) for

another linear regression to find the best estimate of L . The dispersion $\delta\phi(k, \theta)$ then follows accordingly. Since the scanning fiber alters the sample arm path only minimally, we assume $\delta\phi(k, \theta)$ is independent of θ and hence apply the same dispersion compensation to all angles.

In the mirror experiment, we found it is sufficient for this system to fit $\delta\phi(k)$ with a third-order polynomial. After dispersion compensation, the FWHM of the mirror peak is improved from an uncompensated $23.2\ \mu\text{m}$ to $18.5\ \mu\text{m}$, which is consistent with the theoretical depth resolution of $18.1\ \mu\text{m}$ obtained from the source autocorrelation function. It is worth noting that the dispersion only mildly degrades the theoretical value by approximately 28%. By better matching the two arms, e.g., reducing the free space between C1 and C2, it is possible to minimize this degradation and eliminate the need for dispersion compensation completely.

Depth and angular detection range are also important parameters for an a/LCI probe. Here we introduce an efficient method to evaluate these parameters by the use of a “scattering standard” that generates uniform angular scattering intensity across the probe’s angular range, such as the $0.26\ \mu\text{m}$ microspheres (Thermo Fisher Scientific, Inc., 10% standard deviation) used in this experiment. The microspheres are suspended in a density-matching mixture of 80% water and 20% glycerol and used to fill a 1-mm-thick chamber sandwiched by a No. 1 coverslip and a microscope slide. To avoid detecting reflection from the interfaces by the collection fiber, the sample is slightly tilted out of plane. Figure 2(a) shows the depth-resolved angular scattering intensity, where the front and back surfaces are evident possibly due to the scattering from the glass surface and the dust particles on it as well. Starting from the back surface of the coverslip, we divide the sample into $250\ \mu\text{m}$ bins and plot the average angular distribution (normalized to the corresponding total intensities) for each bin in Fig. 2(b). Uniform scattering across the detected angular range is observed up to a depth of $670\ \mu\text{m}$ into the sample, indicating equal collection efficiency across the entire angular range. Beyond this depth, scattering intensity gradually declines at high angles as a result of the limited lens aperture. With this information we can determine the maximum working depth that does not require collection efficiency correction curves to compensate for the loss of signal at high scattering angles.

The depth-resolved sizing capability of the scanning fiber probe is demonstrated using a double-layer phantom. Constructed in a similar fashion [Fig. 3(a) inset] to the one described above, the phantom consists of two chambers filled with solutions of NIST traceable microsphere size standards (Thermo Fisher Scientific, Inc.) that have mean diameters of $7.979\ \mu\text{m} \pm 0.055\ \mu\text{m}$ and $10.00\ \mu\text{m} \pm 0.05\ \mu\text{m}$ and standard deviations of 1.1% and 0.9%, respectively. Each chamber has the same thickness as a No. 1 coverglass ($\sim 150\ \mu\text{m}$).

Figure 3(a) shows the depth-resolved angular scattering distribution of the phantom, where a multilayer structure is clearly identified. Inside the two chambers, strong scattering can be observed with the periodicity of the angular oscillations indicating different sizes. To determine the size of the scatterers, we analyze the scattered light from the first $19\ \mu\text{m}$ (matching the depth resolution) of scattering signal from both chambers using the Mie theory [Figs. 3(b) and 3(c)]. The results, $7.96 \pm 0.36\ \mu\text{m}$ and $10.04 \pm 0.27\ \mu\text{m}$, are in excellent agreement with sample specifications and demonstrate a/LCI’s depth-resolved sizing capability with subwavelength accuracy.

In summary, we present an implementation of Fourier-domain a/LCI technique based on a scanning fiber probe and a modified Mach–Zehnder interferometer. This configuration offers several advantages: first, and most important, is its compatibility with current OCT schemes, which links a/LCI with many existing hardware and software platforms; second, it eliminates the probe length restriction and could potentially lower the cost of fabrication, especially for long probes; and finally, the all-fiber implementation, as well as the use of a single-channel spectrometer rather than an imaging spectrometer, results in a simplified and compact system

design. The trade-off of this approach is that the scanning probe is not capable of parallel angular scattering data acquisition. As a result, it currently takes approximately 12 sec for a full-scan cycle including forward scanning and reset. In the future, the speed can be significantly improved using fast-line scan cameras and the variety of scanning mechanisms that have been developed for OCT and fiber-optic confocal microscopy.

Acknowledgments

This work was supported in part by the National Institutes of Health (NIH) (National Cancer Institute) under grants R33-CA 109907 and R01CA138594, as well as a grant from the Coulter Translational Partnership.

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Fig. 1.
Configuration of the scanning-fiber a/LCI system and the probe tip assembly (inset).

Fig. 2.
 (Color online) Depth-dependence of the angular range. (a) Depth-resolved angular scattering from a single chamber filled with 0.26 μm microspheres. (b) Angular scattering intensity at various sample depths (relative to the back surface of the coverslip) indicating a decreasing angular range.

Fig. 3.

(Color online) Double-layer phantom test. (a) Depth-resolved angular scattering distribution of the double-layer phantom; inset, two-layer phantom made of coverslip (CS) and microscope slide (MS). (b), (c) Mie analysis of the measured scattering pattern for each sample layer.