Japanese researchers develop non-scanning OCT method

In conventional optical coherence tomography (OCT), the requirement of scanning limits image-acquisition time. Thus, Kin Pui Chan and his fellow researchers at Japan Science and Technology Corp. (Kawaguchi, Japan) and Yamagata University (Yonezawa, Japan), are working to develop a real-time OCT system with no moving parts for scanning. Although their efforts still require some improvements before being of practical use, Chan and colleagues have demonstrated non-scanning OCT imaging using a time-of-flight cross-correlator based on off-axis interferometry in conjunction with an angular dispersion method. "In a conventional OCT system, the reflectance profile is measured by scanning the reference mirror in the depth direction, and a cross-sectional image is produced by scanning the light beam across the sample while recording the reflectance profile at each transverse position," Chan explains. "Our objective was to achieve the same imagery without scanning."

In normal OCT systems, the interference fringe must be recorded in order to measure the correlation peak. But Chan’s new system eliminates the need to record the fringe because the angular dispersion imaging method enables them to demodulate the cross-correlation function. "In an off-axis interferometer, the signal wave and the reference wave are incident upon an angular dispersion device, such as a grating, from two opposite sides," says Chan. The dispersion angle $\theta$ results in a first-order diffraction at an angle $\beta$ as given by

$$\sin \theta + \sin \beta = \lambda / d$$

where $d$ is the spacing of the grating.

"By choosing an incident angle of $\theta = \sin^{-1} (\lambda_0/d)$," says Chan, "we can calculate that the lightwave at the center of wavelength $\lambda_0$ will be diffracted at an angle of $\beta = 0$." The diffraction angle of the other wavelength components is $\beta = \lambda - \lambda_0 / \lambda_0 \sin \theta$. Chan says the group sets the diffraction angle for $\lambda = \lambda_0$ normal to the grating to downshift the spatial frequency of the superposition of the signal and reference waves to approximately zero.

Basically, the university team’s non-scanning OCT system consists of an off-axis Mach-Zehnder interferometer that uses a latex bead in an optical trap to probe a sample. The interplay between optical forces and thermal random forces allows the probe to enter any cavity larger than the probe itself and make in vivo measurements of forces between the probe and sample that are three to four orders more sensitive than that of an AFM. Spatial resolution is limited primarily by the size of the probe—typically between 50 nm and 1 µm.

This work takes the greatest limitation of scanning probe microscopes—random movement of the probe due to thermal fluctuations—and uses a high-speed interferometric sensor to turn these fluctuations into an object-scanning system that differs from traditional raster-scan approaches used by AFMs.

Initially, the sensitivity of PFM s to external forces was considered a hindrance to force and spatial resolution. The ability of the PFM to sense extremely small force fluctuations meant that the same thermal gradients that push an AFM probe by 1 nm send a PFM latex bead probe careening around the volume of the optical trap.

EMBL’s Alex Rohrbach and his associates have turned that bane into a benefit by using the thermal fluctuations as sort of a scanning head. While an AFM achieves high lateral resolution through raster scanning, a PFM sets the optical trap close to the sample surface, pushing the probe against the sample. The PFM then collects probe location data at rates of up to 1 MHz, allowing the instrument to create a 3-D surface map of the sample (typically 100 nm²) in as little as 0.5 s. "We can also get information about the local environment. If the local viscosity changes or external (binding) forces interact with the probe, then the thermal fluctuations of the probe are altered in a specific manner," Rohrbach says.

A quadrant photodiode behind a condenser lens collects interference pattern data created by scattered and unscattered light from an IR laser—the same laser that creates the optical trap. High numerical-aperture (equal or greater than 1.2) optics submerged in water or liquid of a similar refractive index are used to reduce aberrations in the optical trap. After calibrating the trap and the detection system, the 3-D position of the probe can be determined to within 3 nm based on these interference patterns. The axial position of the probe can be evaluated by exploiting

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Heidelberg, Germany), researchers like Ernst Stelzer have joined the search to understand cellular processes by helping create a third-generation photonic-force microscope (PFM) that uses a latex bead in an optical trap to probe a sample. The interplay between optical forces and thermal random forces allows the probe to enter any cavity larger than the probe itself and make in vivo measurements of forces between the probe and sample that are three to four orders more sensitive than that of an AFM. Spatial resolution is limited primarily by the size of the probe—typically between 50 nm and 1 µm.

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One of a few suitable materials for stepper/scanner lenses operating at 157 nm for large-scale production, calcium fluoride (CaF₂) is of great interest to the semiconductor industry. However, initial reports based on single-point measurements revealed stress-induced birefringence, as well as unsuspected high levels of intrinsic birefringence in CaF₂ that would seriously affect lens design and performance in 157-nm lithography systems (see oemagazine, March 2002, page 23).

“O ur 2-D image shows the advantage of our method,” says Chan. “With our system, the incident wave is focused with a cylindrical lens, forming a narrow line strip on the sample surface. The CCD camera records the image where the horizontal coordinate corresponds to the depth direction of the sample, and the vertical coordinate corresponds to the one along the strip line.”

Chan’s first experiment evaluated a sample consisting of three roughly 30-µm-thick plastic films attached to a glass slide. The team used a CCD camera to record a 2-D image that resolved each of the plastic films. The result showed that the depth resolution was about one-half the light source’s coherence length.

“Both [intrinsic and stress-induced birefringence] increase significantly at short wavelengths,” says John Burnett, staff scientist at the National Institute of Standards and Technology (NIST; Gaithersburg, MD). “It is also possible that there is an interaction between the two effects. A UV birefringence mapping system would be important for characterizing the stress-induced birefringence at the UV wavelength of use, and helpful to explore the possibility of more complicated interaction effects.” — Phillip B. Espinasse

2-D mapping system confirms CaF₂ birefringence

Using a prototype nitrogen-purged deep-ultraviolet (DUV) birefringence measurement system equipped with an XY translation stage, the team recorded 400 data points measured per-square-inch surface area. They observed significant variation in birefringence in the <110>-oriented samples (see figure) and lower levels of birefringence for the <001>-oriented samples.

This birefringence map of a 1-in. CaF₂ cube, <110>-orientation, displays its intrinsic birefringence at 157 nm. The map shows that the mean intrinsic birefringence for CaF₂ is 12 nm/cm. The sample’s maximum total retardation is 32.5 nm, with a minimum of 25.3 nm, and an average of 28.7 nm, which shows considerable variation throughout the sample.

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Chan’s team also found that a larger incident angle resulted in a wider detection range. In contrast, larger incident angles in conventional off-axis interferometers just yield higher spatial frequencies.

“Chan’s method appears to provide a non-mechanical means of scanning the optical path length in an OCT imaging system. If it performs well and is practical to implement, his method could indeed impact our future products,” says Joseph Schmidt, chief technology officer at Light Lamp Imaging LLC (Westford, MA).

Several practical issues such as the effect of amplitude modulation remain to be solved or improved, Chan admits. “But our work offers a new approach to non-scanning real-time OCT imaging.” — Charles Whipple

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The team used a pair of lenses to collimate the beam to about 5 mm in diameter, then split it into signal beam and reference beam. The signal beam was focused onto the sample through a cylindrical lens (f = 15 mm). A reference beam sent from the opposite side at the same 30° angle interferes with the signal light on the surface of the grating.

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