OPTICAL COHERENCE TOMOGRAPHY:
OCT supports industrial nondestructive depth analysis

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Abstract

Optical coherence tomography (OCT) has evolved to a standard non-invasive biomedical analysis technique yielding a detail-rich cross-sectional image of living tissue. It spreads with breathtaking velocity and advances in the industrial market. Promising industrial applications of OCT are emerging as cost-efficient quality improvement tools for in-line inspection of multi-layered objects in manufacturing processes. For these tasks, advanced high-speed InGaAs cameras are universally suited.

What is OCT

Optical Coherence Tomography (OCT) is an emerging, non-destructive imaging technology capable of producing real time, high resolution subsurface images of opaque samples. The approach is analogous to ultrasound, but instead of using sound it uses light, delivering images of a much higher resolution – well into the micrometer realm. The penetration depth achievable with OCT is determined by the type of material under test and the wavelength used. OCT penetration can reach 6 mm and more. Thus, OCT is able to bridge the realms of confocal microscopy and ultrasound, as well as other computer tomography (CT) methods such as magnetic resonance imaging (MRI) (Figure 1).

Medical Applications

Since its invention in 1991 by Prof. James Fujimoto’s group of the Massachusetts Institute of Technology, it became immediately clear that OCT can deliver detail-rich images from the deeper layers of living tissue. From the very beginning, OCT has been widely adopted, indispensable diagnostic technique for imaging the layered tissues in the human eye. Around 20.000 ophthalmic OCT system are installed in eye clinics around the world and its deployment in ophthalmology is growing at rate of 2000 new installations per year.

Another important application of OCT in medical imaging is blood vessel imaging. Using intravascular imaging catheter, OCT creates high-resolution images of coronary arteries which helps cardiologists to diagnose, treat and follow-up coronary artery diseases. In this area, OCT is expected to replace the existing ultrasound based technology, as OCT provides up to 10 times greater resolution than ultrasound (4-20 µm compared to 110 µm)

Apart from the established applications in eye and blood vessel imaging, evaluation of OCT in other medical fields such as dentistry, cancer detection, glucose monitoring and dermatology has shown significant promises. For each of these new applications, OCT has a potential to become a principal imaging technology in the hospitals to deliver improved healthcare.

Industrial Applications

Optical coherence tomography has been mainly developed by researchers in biomedical optics, who focused primarily in medical applications. As experts in material characterization becoming familiar with this technology, potential uses of OCT for a host of upcoming exciting industrial applications are discovered. Next in line is a multitude of industrial applications. The advantages of OCT in industrial process monitoring will come in the form of cost saving and quality improvement realized through an accelerated process flow.

Example1 Industrial Application

OCT delivers cross-sectional images of material objects without the need of touching them or using destructive procedures. Figure 2 shows several cross sections of a MEMS pressure sensor at various depth levels (above left) achieved by penetrating it through its membrane [3]. As a consequence, OCT is opening innovative ways for industrial quality assurance and process control. Real-time OCT can be used to monitor continuous manufacturing and assembly processes.

Example2 Industrial Application

The Fraunhofer-Institut ILT [5] has investigated the properties of a three-layer, 2.3 mm thick plastic part, that serves as the wall of a liquids container in the context of a project to explore resource-saving manufacturing methods in the plastics industry. The test samples consist of a high-density poly-ethylene material plus a 100 µm thin EVOH (ethyl vinyl alcohol) layer as diffusion barrier. The objective was the development of an "Interferometric Inline Control System in the Production of Multi-layer Plastic Foils.“ In this application, OCT is used to measure the thickness and uniformity of individual thin layers in real time during a production run. Besides achieving significantly higher process security, the Fraunhofer researchers say, this OCT-enabled control technique will save material supplies amounting to 100,000 euros per year even when deployed in a medium-capacity production facility.

NIR Sensors in InGaAs Technology

At first glance (when looked at in the visible realm) such plastic foils and the containers made of the foils appear relatively opaque. However, this optical surface barrier can be penetrated when hit by a light beam of an appropriate wavelength in the near infrared region.

For the measurement of these near infrared spectra the usual CMOS or CCD image sensors are not appropriate since their sensitivity is limited to the visible realm. A significantly higher NIR sensitivity is offered by sensors in InGaAs technology (Figure 5). They are currently available as linear detector and 2D cameras. Highly sensitive and fast linescan and 2D infrared cameras are key technologies in OCT for deep imaging.

Detector Technology

OCT imaging is based on spectral or low coherence interferometry.
Of the many possible formats to achieve this interference effect, Figure 3 shows the most common configuration as spectral-domain OCT

Line sensor camera

Output from a spatially coherent broadband light source is split with a beam splitter into a reference beam and a sample beam. The sample beam is sent onto the sample under investigation. Then backscattered light from the sample is combined with the reference beam reflecting from a mirror. The spectrum of the interference is measured using a spectrometer. A line camera in the spectrometer converts the interference pattern to an electrical intensity signal. Out of this spectral information, a Fourier transformation generates the depth profile. By scanning the beam over the sample using scan mirrors, 3D volumetric images are created. The axial resolution in spectral domain OCT improves by using broader light sources. To accommodate a broadband light source, linescan camera with a large number of pixels is necessary in the spectrometer. Xenics Lynx series linescan cameras offers the only InGaAs linescan camera with 2048 pixels, which enables two times improvement in axial resolution compared to 1024 pixel cameras. Linescan cameras operate at rates > 10 KHz which enable imaging of fast moving samples.

2D OCT camera

OCT imaging with higher axial resolution can be achieved using full-field OCT. Full-field OCT produces tomographic images in the en-face orientation (orthogonal to the optical axis). In contrast to conventional OCT, the entire field of the image is illuminated with low temporal and spatial coherence light. One possible arrangement is based on a Michelson interferometer with identical microscope objectives (MO) in both arms, as depicted in Figure 4. Several interferometric images are acquired successively with the 2D camera, with the phase being changed in the interferometer between each image acquisition. The phase shift is accomplished by displacing the reference mirror with a piezoelectric actuator. The tomographic image is then calculated by combining these interferometric images.
Full-field OCT is essentially an interference microscope illuminated by a simple white-light source, such as a tungsten-halogen lamp. Since thermal light sources have very broadband spectrum, very short interference lengths lead to ultrahigh axial resolution (1-2 µm). Short acquisition time of each image frame is necessary to prevent blurring of the interferometric signal. The state of the art, the fastest infrared 2D camera in the world with 640 x 512 pixels, Cheetah-640CL from Xenics delivers 1,730 full frames per second [6]. High speed cameras transform OCT into a dynamic, real-time control method for manufacturing processes.

For reduced dark current, Xenics sensors come standard fitted with one-stage thermoelectric cooling. If a very high signal/noise ratio is required to increase penetration depth, Xenics offers upgraded camera cooling up to three thermoelectric stages.

Conclusion

With different sensor types to choose from, ROICs with various parameter settings and multi-stage thermoelectric cooling, today's InGaAs cameras are scalable OCT platforms. They are suited for a host of scientific, industrial and medical applications enabling direct imaging and spectroscopy. Most important, they include sensors that deliver a resolution of or below one micrometer, at a penetration depth of more than the current standard of 6 mm. This empowers the system designer to implement OCT as a meaningful and detailed analysis tool for hidden structures to increase quality, throughput and yield in manufacturing processes.

Figures

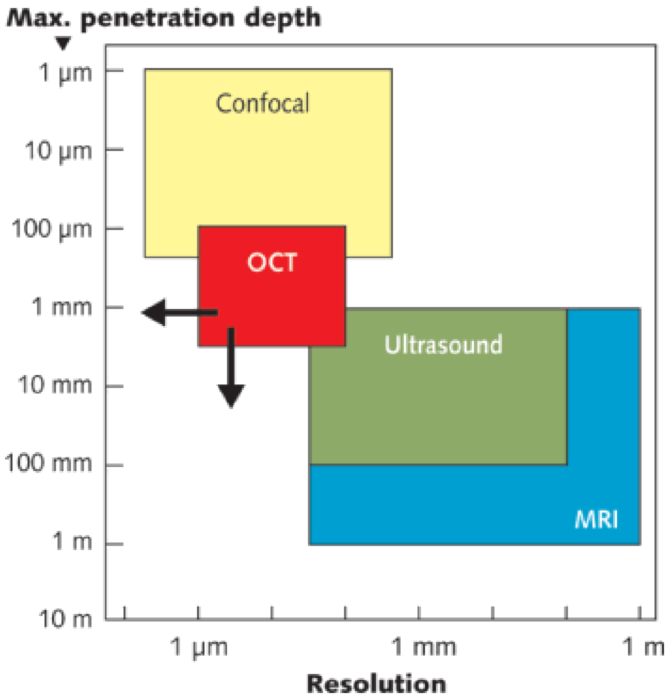

Figure 1. Examination methods for analyzing depth structures, penetration depth and resolution.

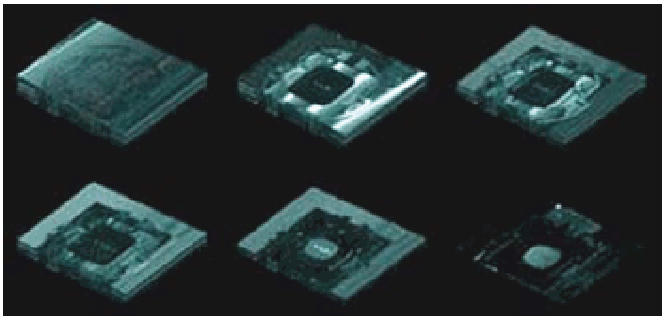

Figure 2. Penetrating the membrane of an MEMS pressure sensor (above left), OCT yields cross-sectional images at various depth levels to unveil details of its internal structure.
Source: National Physical Laboratory

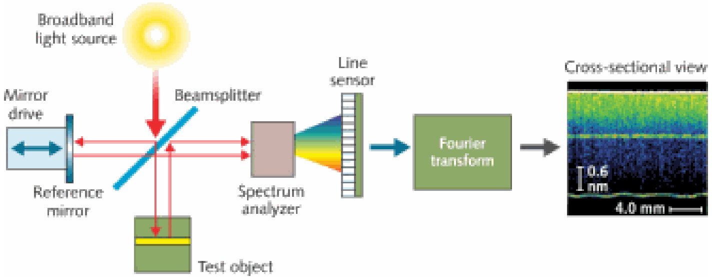

Figure 3. Principle of spectral domain optical coherence tomography (OCT) with spectrometer and high-resolution line camera Lynx, used for a cross-sectional examination of a plastic, three-layer container wall.
* Source of cross sectional image: Fraunhofer ILT

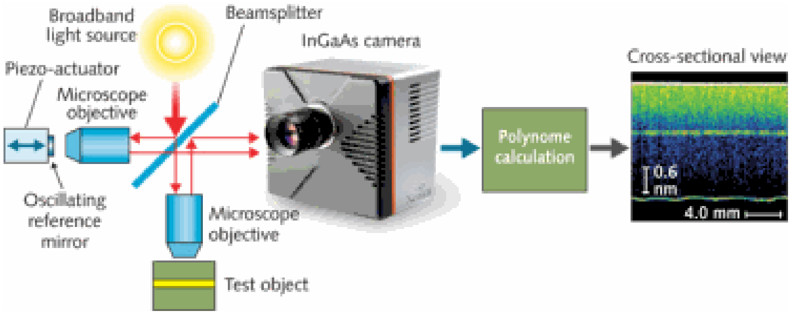

Figure 4: Full-field OCT with a very fast 2D camera Cheetah-640 CL (MO = microscope objective)

Literature

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