

Moving from biomedical to industrial applications:

OCT Enables Hi-Res Non-Destructive Depth Analysis

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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.

1 The Promising Potential of OCT

That OCT has an enormous future potential is proven by a study carried out by the Millennium Research Group and published in October 2010 [1]. According to their five-year forecast the OCT market will see average growth rates of 60 percent per year. Obviously, this extremely positive estimate is based primarily on the market segment of medical electronics, which has become the first broad application area of OCT since it was introduced in 1991 by Dr. James Fujimoto of the Massachusetts Institute of Technology (MIT).

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At that time it became immediately clear that OCT can deliver detail-rich images from the deeper layers of living tissue – which is of special value and utility to ophthalmologists. Next in line is a multitude of other medical applications, such as measuring the thickness and uniformity of functional layers in pharmaceutical products, which is of importance for the controlled dispensing of certain agents. Another promising application of OCT is the examination of blood vessels, or three-dimensional imaging of the kidneys [2].

There is a strong indication that OCT imaging will have an impact on a multitude of established medical procedures, which in turn will change current practices. Just one example: today's "gold standard" in the early detection of cancerous growth in the larynx is performing a biopsy - extracting a small, suspicious tissue probe and treating it to a microscopic examination in the lab. However, a biopsy of larynx tissue is a serious invasive procedure that necessitates local anesthetics and may leave the patient permanently hoarse.

Here, OCT combined with video laryngoscopy can serve as a much milder alternative replacing biopsy by an outpatient tomography of surface and deeper tissue irregularities - without the need for anesthetics and avoiding direct physical contact with the affected tissue. The example is a good pointer to the industrial uses of OCT, where similar examination constraints may apply. The advantages of OCT will come in the form of cost saving and quality improvement realized through an accelerated process flow.

As a high-frequency analog to and a possible replacement of ultrasound examination techniques optical coherence tomography delivers images of a much higher

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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 (Figure 1). 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).

2 OCT - how it works

OCT delivers cross-sectional images from within 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.

Figure 3 delineates the fundamentals of optical coherence tomography. It is based on the interference of a direct light beam from a light source striking the object under test with the light beam reflected by the object through a semi-transmissive mirror (or beam splitter).

Line sensor camera

Of the many possible formats to achieve this interference effect, Figure 3 shows just two of them. In the upper part of Figure 3, a broadband light source radiates light of a low coherence length through a semi-transmissive mirror onto the object under test. A part of this beam is reflected by the beam splitter and guided to a reference

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mirror, which feeds it via the semi-transparent mirror to the input of a spectrum analyzer. There, the light reflected by the test object interferes with the reference beam. As a result, the spectrum analyzer outputs the spectrum of this interference pattern, which is then converted by an optoelectronic line sensor to an electrical intensity signal. Out of this spectral information a Fourier transformation generates the appropriate spatial intensity data. A disadvantage of this setup is the relatively large travel range of the mirror, which can be several millimeters to cover the entire intended examination depth within the object under test.

2D OCT camera

Considerably faster is an OCT procedure depicted in the lower part of Figure 3. It uses diffractions gratings and a 2D camera in InGaAs technology [4]. This 2D camera setup works without a depth scan mechanism. The relatively small-band light beam of superluminescence diode (at a wavelength of 1,310 nm and a 3-db bandwidth of 30 nm) is led through a beam splitter yielding a reference beam going to the left, and a test beam going downwards. A cylindrical lens (not shown in Figure 3) widens the test beam to form a line on the test object. The reference beam is deflected by the diffraction grating, which is positioned in a way that a higher-order diffraction image is directed towards the camera.

Thus, the 2D camera sees an interference pattern generated by the reference and test beams. By evaluating several of these interference images, which show different phase relations, the object under test is optically examined. Diffraction gratings with micro actuators, made of a piezo ceramic, enable a mirror small travel range in the realm of a few micrometers. Three interference images, each representing a shift of

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a third of the wavelength used, will suffice to derive an OCT image by calculating a second-order polynomial from the measured values.

The calculation of the polynomials and the Fourier transformation suited for both procedures shown in Figure 3 can be done by a regular multi-purpose computer and its appropriate programming or via a dedicated hardware solution based on a field programmable gate array (FPGA), which performs just this one function, but in a very rapid fashion.

Test object, used as an example

A three-layer plastic part, about 2.3 mm thick, that serves as the wall of a liquids container, was chosen a test object for an OCT demonstration. It consists of a high-density poly-ethylene material plus a 100 µm thin EVOH (ethyl vinyl alcohol) layer as diffusion barrier. The Fraunhofer-Institut ILT [4] has investigated the properties of this structure in the context of a project that is to explore resource-saving manufacturing methods in the plastics industry.

The objective was the development of an "Interferometric Inline Control System in the Production of Multi-layer Plastic Foils." 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.

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3 SWIR Line 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 realm. This will cause molecular resonances whose absorption spectra are typical for a given material, allowing a secure differentiation of various molecular structures.

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 SWIR sensitivity is offered by sensors in InGaAs technology (Figure 4). They are currently available as linear detectors (Lynx) with up to 2048 pixels and as a 2D camera (Cheetah-640CL) featuring 640x512 pixels.

The high resolution achieved by the Lynx line sensor is extending the application area of OCT towards higher spatial resolution (as indicated in Figure 1 by an arrow pointing to the left). And the worldwide fastest SWIR 2D camera Cheetah-640 CL, which delivers 1,730 full frames per second, transforms OCT into a dynamic, real-time control method for manufacturing processes.

These sensors come standard fitted with one-stage thermoelectric cooling. If a very high signal/noise ratio is required to increase penetration depth (indicated in Figure 1 by an arrow pointing downwards), the camera cooling can be upgraded to three-stage thermoelectric cooling.

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4 Flexible Evaluation Circuitry

Whereas InGaAs is a perfect choice for SWIR-sensitive photodiodes in line sensors, it is not really suited to integrate the read-out circuitry on the same chip. Therefore, an external read-out IC (ROIC) based on CMOS technology serves as evaluation circuitry for the InGaAs line sensor. The analog ROIC front-ends can be optimized to function as detector interfaces, and their parameter values are software settable in wide margins to cover various pixel sizes and application demands.

Figure 5 gives a simplified block diagram of the ROIC's analog functionality needed for the multi-stage pre-processing of the sensor signal. The InGaAs photodiode, featuring n-well-capacities of 0.7 to 2 million electrons, is held at a constant voltage level by the current-to-voltage converter. The converter is equipped with five charge integration capacities (5 fF, 25 fF, 100 fF, 500 fF and 2000 fF). They can be selected at runtime, either singly or combined. This results in the wide converter characteristics needed to adapt the ROIC to various pixel sizes and applications.

The subsequent stage performs a correlated double sampling (CDS), thereby compensating the offset variations of the current/voltage converter and also eliminating its reset noise. Since kTC noise is noticeable especially at the smaller integration capacity of 5 fF, the CDS stage is a must. With the larger integration capacities it is the read-out noise that becomes more prominent.

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Next in line is the sample/hold stage. It decouples integration and read-out. Thereby, the charge of the actual frame exposure can be integrated while the preceding frame is being read out simultaneously. Finally, an analog multiplexer and pad driver transfer all pixel values via the IC output to an external analog/digital converter.

5 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.

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Captions

Maximum Penetration depth

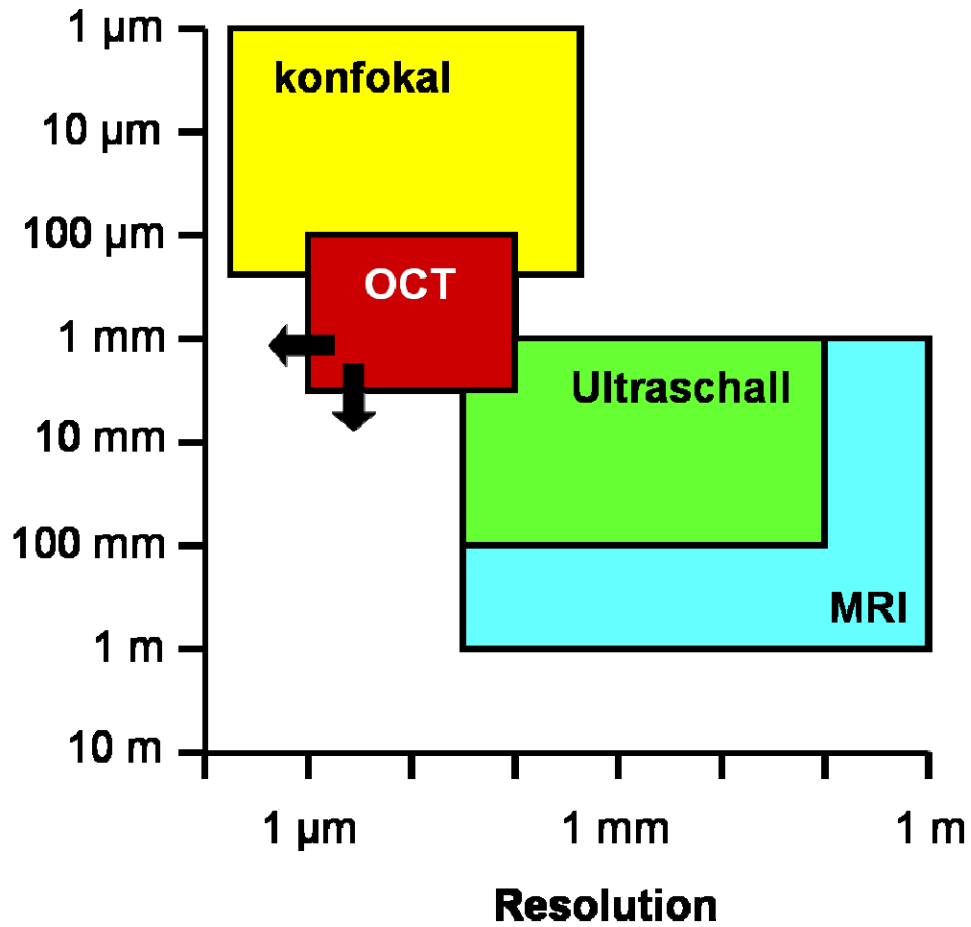


Figure 1. Examination methods for analyzing depth structures, penetration depth and resolution.

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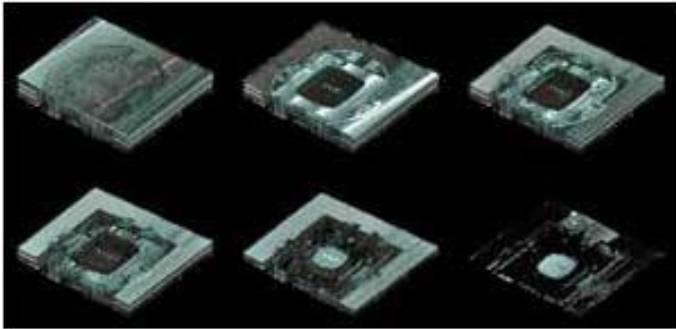


Figure 2. Penetrating the membrane of an MEMS pressure sensor (above left), OCT yields cross-sectional images at various depth levels to unveil details of its internal structure.

Source: National Physical Laboratory

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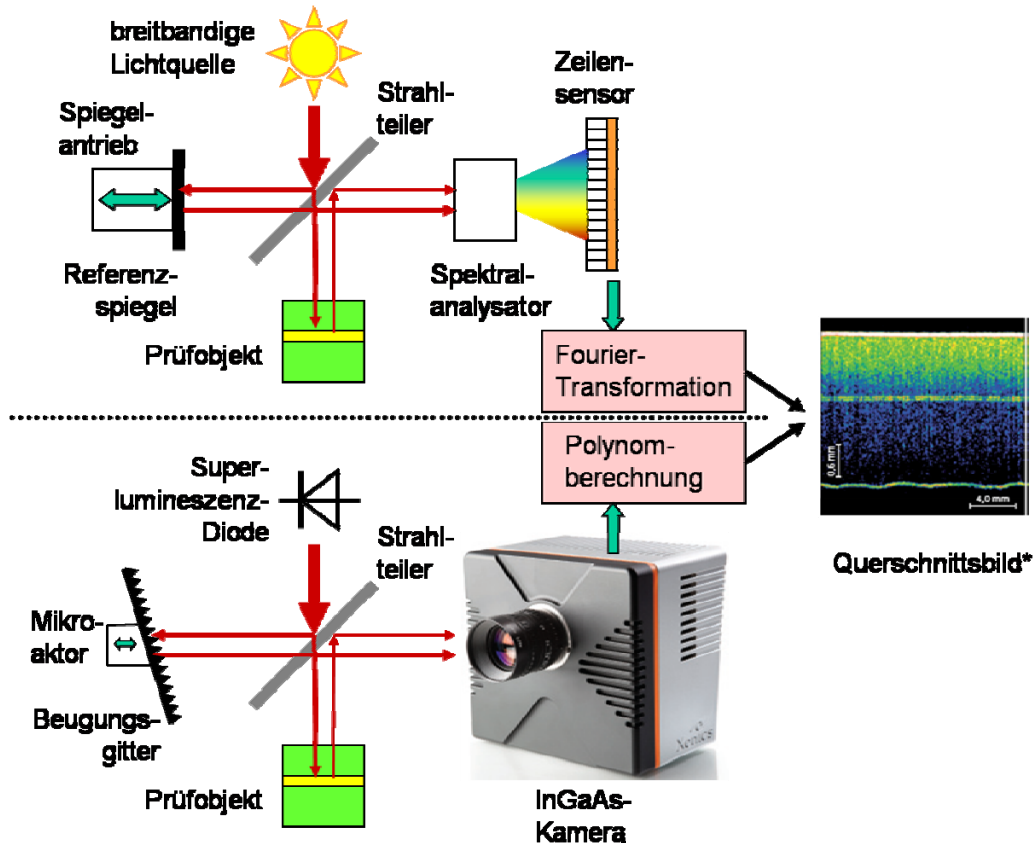


Figure 3. Two concepts of optical coherence tomography (OCT): high-resolution line camera Lynx and very fast 2D camera Cheetah-640 CL, used for a cross-sectional examination of a plastic, three-layer container wall.

Source of cross sectional image: Fraunhofer ILT

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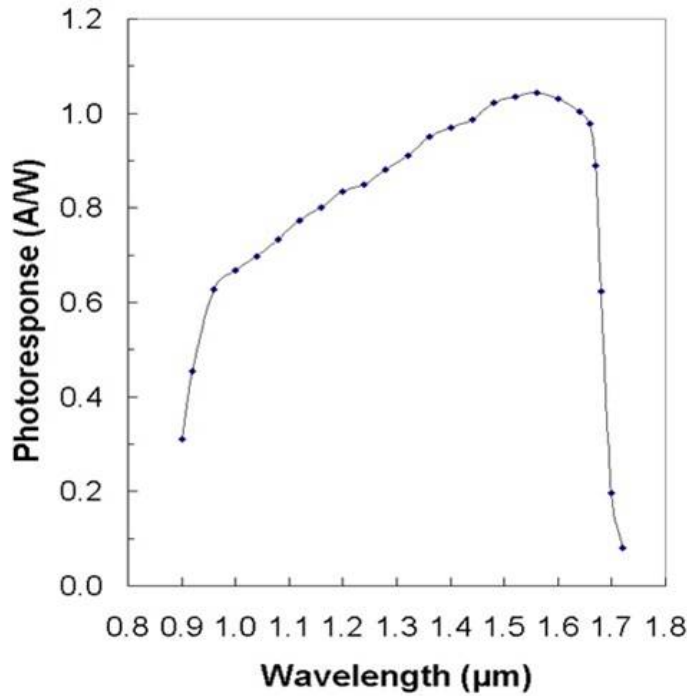


Figure 4. An InGaAs image sensor can operate in the near infrared realm.

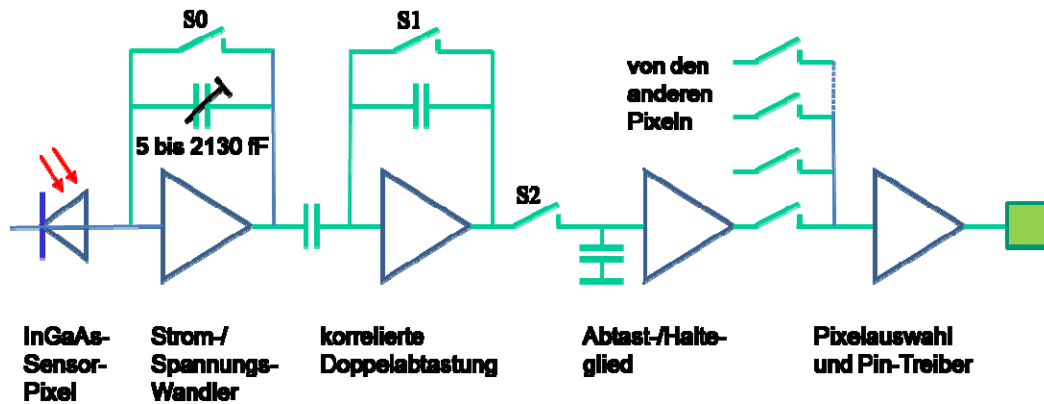


Figure 5. Pre-processing the sensor signal of a pixel with various software-settable parameters accommodates the camera to different applications.

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6 Literature

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