Research Article

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High-resolution InGaAs sensor pushing biomedical infrared optical coherence tomography

Abstract: Optical coherence tomography (OCT), a spectroscopy technique, has been used in biomedical applications for about 20 years. It has evolved to a standard non-invasive examination procedure yielding detail-rich cross-sectional images of living tissue. With longer wavelengths in the IR spectrum and the availability of InGaAs detectors and cameras, OCT scanners now penetrate even deeper into the human tissue. This article presents technical improvements on an IR line-scan camera, which specifically benefits OCT applications.

Keywords: biomedical applications; OCT performance; Optical coherence tomography.

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1 Introduction

OCT performance and its suitability for biomedical uses, especially in the near-infrared (IR) realm, are largely determined by detector technology and camera design. Now expanding to the short-wave IR (SWIR), or near-IR (NIR) spectrum, OCT applies an illumination beam of a wavelength around 1300 nm to penetrate opaque tissues at a depth of up to several millimeters enabling a spatial resolution in the micrometer range. Deployed as a dermatology or dentistry diagnosis tool, OCT takes cross-sectional images of lower, hidden layers of the living tissue without physical contact or surgically invasive procedures. It is, for example, a perfect tool to be integrated in the medical systems for the early skin cancer detection. The wavelengths are only restricted by the absorption barrier caused by the water content of the tissue at around 1400 nm, which limits the application of any IR analysis tool in this wavelength region. The impact of OCT imaging on the established medical procedures is expected to grow significantly. This, in turn, will change the current practices, such as the early detection of a cancerous growth.

2 Basic principles of OCT

As a high-frequency electromagnetic equivalent of the ultrasound probing techniques, optical coherence tomography (OCT) delivers images of high resolution – well into the micrometer regime. The penetration depth is dependent on the material to be examined and the wavelength used. In the infrared (IR) spectrum, the OCT penetration depth can easily reach more than 6 mm for human tissue inspection. As a consequence, OCT is able to bridge the realms of confocal microscopy and ultrasound, as well as the other computer tomography (CT) methods such as magnetic resonance imaging (MRI) (Figure 1).

The principle of this imaging technique in the frequency domain is delineated in Figure 2. The Fourier transform OCT is an interferometric method that uses spectrometric information, which is obtained from the interference of two white light rays (generated by a single high-brightness LED with short coherence length or a pulsed laser), one of them being reflected by the tissue to be examined.

Interference between the direct ray from the light source and the second ray reflected by the object through a semitransmissive mirror (or beam splitter) delivers a spectral response, which is captured by a high-density, line-array, or 2D detector with high sensitivity.

The sensor signal contains spectrally encoded information about the examined layer composition. A subsequent Fourier transform of the spectral data delivers a spatial distribution pattern. This yields to images structured as a sequence of single layers, much like the tissue slices

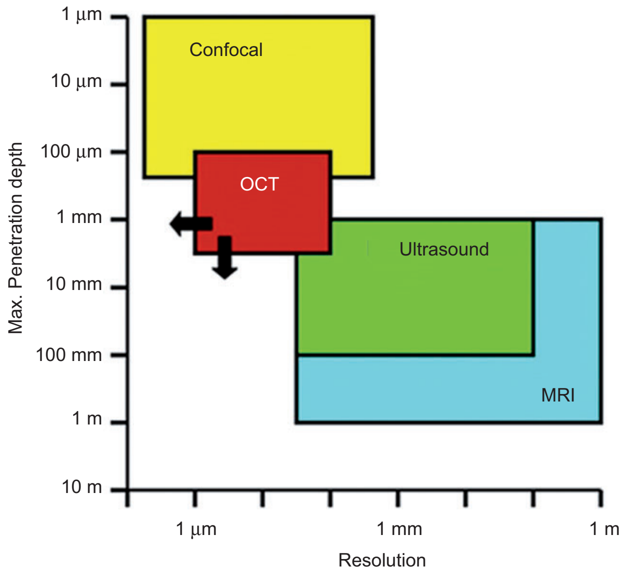

Figure 1 The OCT bridges the gap between confocal microscopy, ultrasound, and MRI insertion (Universiteit Gent).

under a microscope, which show cross-sectional optical reconstructions of the deeper layers of the test object.

3 Technical improvements for OCT application

For the detection of (short-wave) near-IR spectral signals, classical CMOS or CCD image sensors are not sufficient as their sensitivity is limited to the visible spectrum. Significantly higher short-wave IR (SWIR) sensitivity is achieved with sensors in the InGaAs technology.

One of the latest InGaAs line cameras offer a linear 2,048-pixel array with 1 inch length, arranged in a 12.5 µm×12.5 µm-pixel format (Figure 3). The higher resolution of the camera sensor is extending the range of OCT toward the higher spatial resolution applications. Figure 4 offers a glimpse at the interior of the otherwise hermetically sealed package of the InGaAs sensor, which is fitted

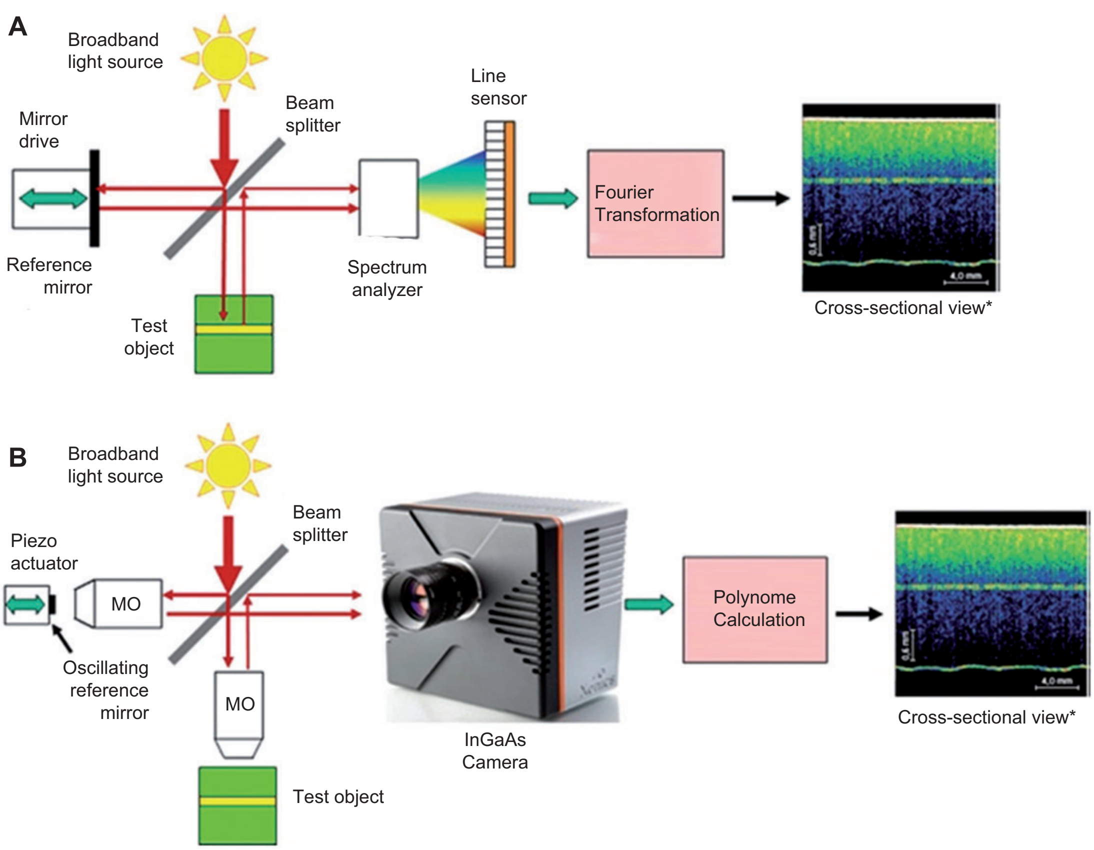

Figure 2 (A) The Fourier transform IR OCT with a high-density linear array (www.octnews.org). (B) The two concepts of OCT: high-resolution line camera Lynx and very fast 2D camera Cheetah-640 CL, used for a cross-sectional examination of a plastic, three-layer container wall (source of cross sectional image: Fraunhofer ILT).

Figure 3 Line-scan camera Lynx (Xenics).

with a clear window. To the right, there is a detailed view of the connection of the sensor line with its two readout integrated circuits (ROICs) fitted.

3.1 High-resolution sensor for biomedical applications

The new camera contains a linear InGaAs detector array with a specifically designed CMOS read-out circuitry. The tight connection and closeness between the sensor and ROICs combine the advantages of the two technologies. First, the sensitivity of the InGaAs sensor extends well into the near-IR (NIR) (SWIR) covering the wavelengths between 0.9 μm and 1.7 μm. This is far beyond the reach of CMOS and CCD. Second, as laid out in the CMOS technology, the ROIC optimizes the analog signal preprocessing by complementing it with an integrated digital functionality.

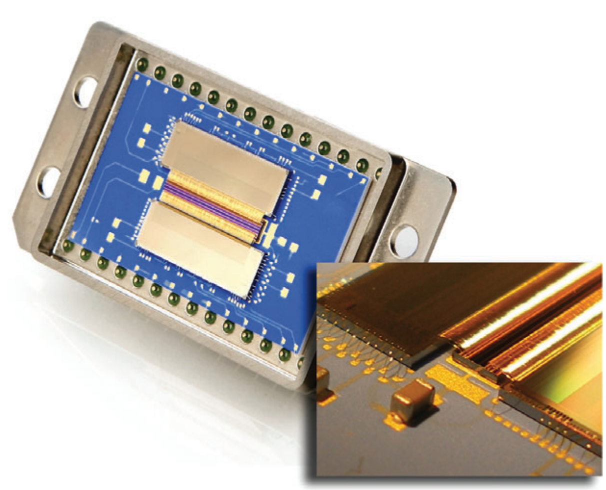

Figure 4 Details of the InGaAs-line-scan sensor.

The actual focus in camera development is on the high-resolution line scan and the 2D cameras and detectors for the short-wave (SWIR) region. This suits the targeted biomedical applications such as ophthalmology seen in Figure 5, dermatology, and dentistry. Specifically, in biomedical applications, there are two further considerations: first, the light has to penetrate the tissue as deep as possible; second, as the measurement and image capture are based on the spectrometric interference, speed and spectral resolution are required to obtain an excellent depth resolution combined with the sensor speed for the surface resolution. The sensor or system speed is a must for surface scanning at reasonable acquisition times; a high spectral resolution is required to allow the careful examination of the small features in the tissue to be examined.

In this sense, the optical resolution of 12.5 μm is an optimum because it matches the pixel pitch of the sensor array. It improves the resolution of the interference patterns that are being mapped. Thus, next to the appropriate SWIR wavelength of the illumination source, there is the need to preserve all the data that contain the depth information, which is given by the pixel pitch.

All these factors taken together, including the speed of the scan, will make the final resolution of the resulting diagnostic image. In summary, there is an optimum combination of the wavelength (to penetrate deeply into the tissue), pixel pitch (delivering the depth profile), and scan speed (determining resolution).

Besides that, the high line rates of up to 40 kHz yields to a high resolution in the time domain. In many cases, this leaves sufficient resources for multiple sampling, thereby increasing the dynamic range.

The small outline of the InGaAs sensor also leads to lower-cost optics at the same field of view. It enables a greater variety in available lenses.

3.2 Signal processing and noise reduction

Whereas InGaAs is a perfect material choice for SWIR photodiodes for line sensors, it is not suited for integrating the readout circuitry in the same chip. Therefore, two separate ROICs in the CMOS technology are provided to serve as the front-end evaluation circuitry. This optimizes signal preprocessing of the analog signal output of the

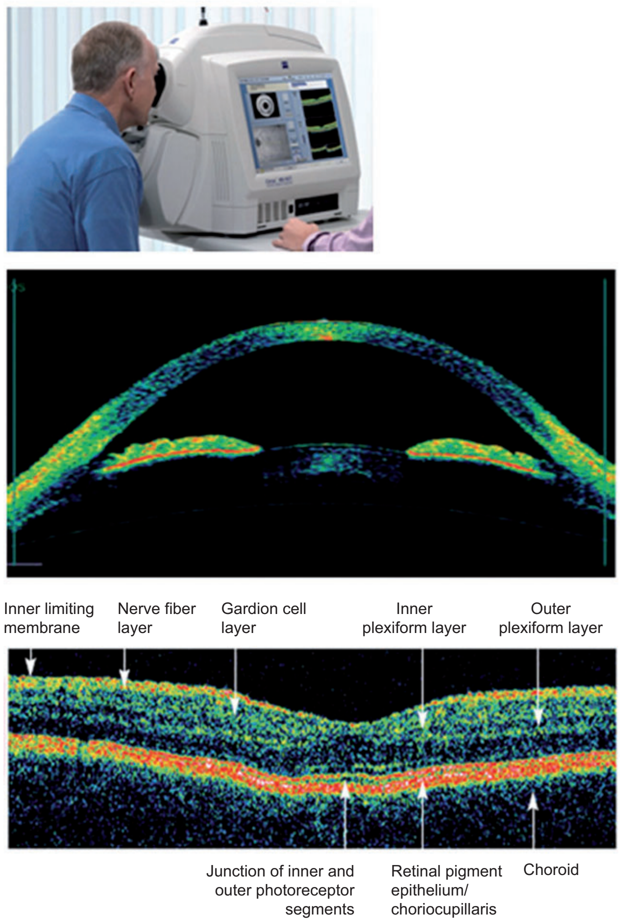

Figure 5 Eye examination though OCT scanning in the visible realm.

InGaAs photodiodes by complementing it with a highly integrated digital functionality.

Of special value in medical applications is the flexibility provided on-chip in terms of various gain settings. Up to 15 such settings are selectable in the new sensor. Depending on the tissue to be examined, light is scattered in higher or lower intensity during the measurement. As a rule of thumb, the more scattered light is available for the measurement, the more a camera with a high dynamic range is valued. The less light there is, the more a high-sensitivity camera is preferred. The sensor allows changing incrementally between these two limits. For that purpose, the ROICs offer five integration capacitors, which are selectable individually or collectively, at runtime. This front end can be functionally optimized as its parameter values are software settable in wide margins to cover various pixel sizes and application demands.

The camera also provides flexibility in terms of integration time, as opposed to only certain preset integration values. However, as OCT with high line rates is limited anyway to shorter integration times, it is not of utmost importance having very short and very long exposure times. Hence, the system provides exposure times in steps of 1 μs from the shortest value.

3.3 ROIC configuration

When operating the camera at high gain settings, there is an important advantage in appropriately reducing the noise in the readout signal. Correctly recording the OCT interference patterns needs a high-resolution sensor – which implies low noise. To provide the signal quality at the required speed and resolution, the amount of the noise stemming from the amplification must be reduced.

Hence, the ROICs perform five preprocessing steps on the sensor signal:

- The InGaAs photodiode works with n-well capacities of 7×10^5 up to 2×10^7 electrons (capacity ratio 1:28).
- The current-to-voltage converter (CVC) is equipped with five different capacitors as charge integrators. They can be selected at runtime, singly or in any combination, yielding values of 5 fF, 25 fF, 100 fF, 500 fF, and 2 pF. The capacitance values vary with the detector version (either 1024 pixel or 2048 pixel).
- Correlated double scan (CDS) compensates for the offset variations in the CVC and eliminates the reset noise.
- The sample/hold stage decouples the integration and readout so that the charge of the actual frame is

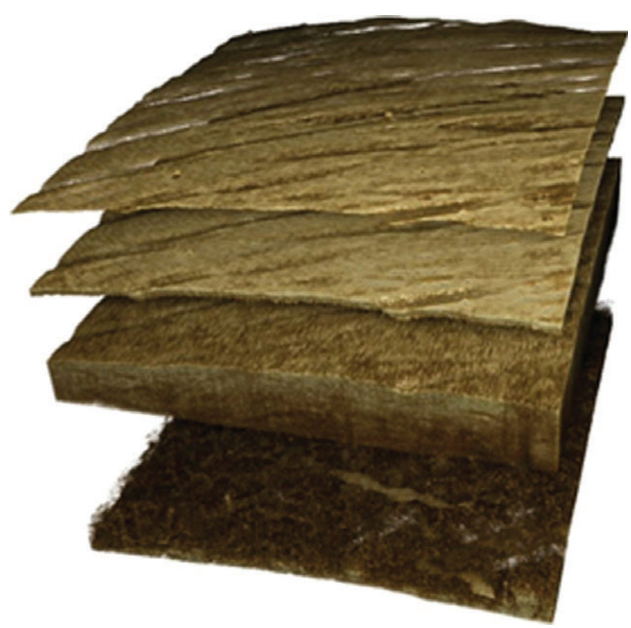

Figure 6 Image from a handheld scanner for melanoma detection.

integrated, while the previously integrated frame is read out.

– An analog multiplexer and pad driver feed all the pixel values sequentially to the output and further to an external analog-to-digital converter.

4 Conclusion

Although the OCT devices are on the market for many years now, the technical advancements will lead to a broader application of the OCT imaging in the biomedical areas to replace or complement some of today's diagnostic tools and medical procedures. It could also lead to the development of future devices such as the handheld OCT scanner to detect and visualize nonmelanoma skin cancer (NMSC) (Figure 6). For this reason, a new linear InGaAs camera was developed, which is particularly well adapted for OCT applications. The camera is widely configurable to adapt the detector parameters for a higher system performance during system design or even at runtime. As the sensor comprises CMOS-readout circuitry, it can be specifically tailored for the applications by the implemented digital integrated on-chip preprocessing functionality.

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