Linear OCT System with down conversion of the fringe pattern

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Abstract

OCT sensors traditionally use scanning optical delay lines with moving parts and a single detector. Compared to this OCT systems with a linear detector array (linear OCT or LOCT) are very simple and robust, but a detector with approximately 10^4 pixel is needed for a imaging depth of 2 millimeter. We present a new system for LOCT which extends the measurement range of LOCT systems by attaching a mask on the image sensor. The mask essentially performs a down conversion of the spatial frequencies by multiplication with a second spatial frequency. We use this effect to reduce the fringe frequency of the OCT signal so that sampling and calculating the modulation of the signal can be done with relatively few pixels. The theory for this approach is addressed and first measurements are presented.

1 Introduction

Optical coherence tomography (OCT) allows the visualization of tissue structures with a resolution better than 15 µm. An interferometer and a low-coherence light source are used for an optical gating of the photons, which were reflected from tissue structures in different depth[1]. Usually the sample is placed in one arm of a Michelson interferometer and the depth gating of the sample is done by a mechanical scanning device in the reference arm of the interferometer. The output of the interferometer is recorded by a detector and the depth information is derived from the temporal modulation of the signal. Therefore, this approach is called time domain OCT (TDOCT). To avoid moving parts with all their disadvantages the use of image sensors was proposed. Haeusler et. al. measured the output of the interferometer with a spectrometer and called this method spectral radar[2].

In another set of systems the depth information, can be reconstructed from spatial interference patterns[3-6]. In a recently introduced OCT system the interferences pattern is generated by the superposition of two point sources, one emitting the backscattered light from the probe and the other emitting the reference light (Fig. 1). In the interference pattern the A-

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scan is coded as a spatially varying intensity instead of a time dependent signal. In these, so called linear OCT (LOCT)[4,5] system, the intensity in the detector plane $I(x)$ can be described as:

$$I_F(x) = I_P + I_R + 2\sqrt{I_P I_R}\sin(\kappa_I x + \varphi_I)\cdot\gamma(x) \tag{1}$$

I_P is the probe intensity, I_R is the reference intensity and $\gamma(x)$ is the amplitude of the modulation which is determined by the coherence of light. From Fig. 1 the spatial frequency κ_I of the interference pattern can be calculated by:

$$\kappa_I = \frac{2\pi\alpha}{\lambda} \tag{2}$$

Where α is the angle enclosed by the two beams and λ the wavelength of the light. For a low coherence light source, a

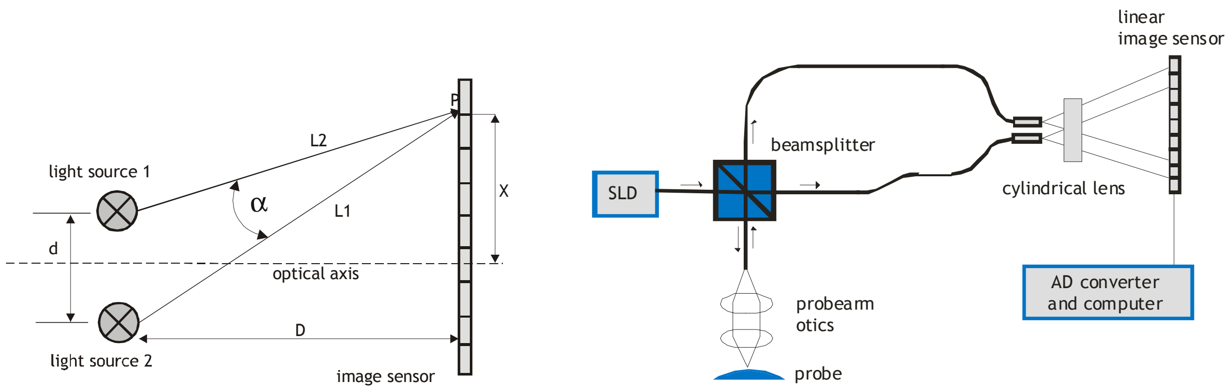


Fig. 1a: Principle of LOCT: Probe and reference intensity interfere as planar waves on the surface of an image sensor. The spatial fringe pattern resembles the A-scan in TDOCTs. 1b: Interferometer setup of an LOCT system. The cylindrical lens is used to increase the efficiency of the linear image sensor.

modulation is only detected, when the optical distances in both arms of the interferometer are matched. Therefore reflections from different depth of the sample will cause local modulation at different locations of the detector. In order to detect the modulation, the pixel frequency has to be at least two times the modulation frequency κ_I to fulfill the Nyquist criterion. Therefore for a certain measurement depth range Δd at least $4\Delta d/\lambda$ pixel are needed. A measurement range of 2 mm at a wavelength of 830 nm requires an image sensor with 10^4 pixels. Although sensors with that many elements are available, an OCT system utilizing them would be rather bulky. Additionally, readout and processing of that many data points per A-scan requires a high bandwidth of the AD converter and the successive data processing unit.

The image information, which is coded in the modulation $\gamma(x)$ of the fringe pattern has a considerably lower spatial frequency than the modulation frequency κ_I For a coherence length of 11 µm 360 pixel (2x2mm/11µm) would be sufficient to represent the image information, if the envelope of the carrier could be sampled directly. Therefore it is possible to reduce the carrier frequency without information loss.

2 Theory

The sensitivity of an array detector for a certain spatial frequency is described by the modulation transfer function (MTF). The MTF is the Fourier transform of the point spread function (PSF) of the sensor. This corresponds to the well known relationship between the frequency response and the impulse response of a system. For an image sensor the PSF can be measured by moving a focused beam over the sensor and reporting the measured values for the pixel. For accurate results the beam waist diameter has to be substantially smaller than the pixel size

For an ideal pixel one would expect a rectangular spatial pixel sensitivity. Then the MTF would be a SinC function. The measured modulation decreases with increasing spatial frequencies of the fringe pattern and reaches zero, when the period of the fringes equals the width of one pixel. The image sensor used for the experiments has a bell shaped PSF. Therefore the MTF is also bell shaped and has virtually no side lobes. Measurements with good contrast are therefore limited to spatial frequencies significantly below the pixel frequency.

To reduce the number of pixels needed for the acquisition of the intensity modulations a way to reduce the carrier frequency of the interference pattern has to be found. In principle it's possible to sample a signal with rates below the nyquist frequency (under sampling). But the steep drop of the MTF of linear image sensors towards higher frequencies, renders this approach unfeasible.

Therefore the frequency of the interference pattern has to be reduced before sampling. Changing the carrier frequency of a signal is a well know procedure in radio technology. In this field it's usually called mixing, and with respect to the reduction of frequencies sometimes down conversion. The principle is that the signal with the unwanted carrier frequency is multiplied with a second signal chosen, so that the emerging difference frequency is the wanted one. The well known effect of moiré pattern is the closest match to this formalism in optics. Moiré pattern are low frequency pattern emerging from at least two patterns of similar frequencies. For our case the multiplication of the interference fringe pattern with a second wave can be realised by placing a mask with a spatial sinusoidal transparency function in front of the image sensor. For a formal description the spatial transparency of the mask can described as:

$$T(x) = \frac{1}{2} + \frac{1}{2}\sin(\kappa_M x + \rho_M) \tag{3}$$

where κ_M is the spatial mask frequency and ρ_M is the phase of the mask. The mask has an average transparency of 50% and varies between 0 and 100% for different locations. The intensity distribution behind the mask I_M is derived by multiplying the mask function with the interference pattern described by Eq. 1:

$$\begin{aligned} &I_M(x) = I_F(x)\cdot T(x) = \\ &\tfrac{1}{2}\left[(I_P + I_R) + 2\sqrt{I_P I_R}\sin(\kappa_I x + \rho_I)\cdot\gamma(x)\right] + \tfrac{1}{2}(I_P + I_R)\sin(\kappa_M x + \rho_I) + \\ &\tfrac{1}{2}\sqrt{I_P I_R}\,\gamma(x)\left[\sin((\kappa_I - \kappa_M)x + \rho_I - \rho_M) + \sin((\kappa_I + \kappa_M)x + \rho_I + \rho_M)\right] \end{aligned} \tag{4}$$

The first term in the second row of Eq. 4 is an intensity offset. The second term describes the fringe pattern transmitted through the mask with an average transmission of 0,5. The second term represents the shadow of the mask cast by the incoherent intensity offset of the interference pattern. The terms in the third row correspond to the wanted intensity modulation at the difference frequency, and the modulation at the sum frequency. This set of intensity modulations is than sampled by an image sensor with a certain point spread function PSF(x). For a formal description the intensities have to be convoluted with PSF(x):

$$I_S(x) = I_M(x) \otimes PSF(x) \quad \Leftrightarrow \quad MTF_{Sys}(\kappa) = FOUR(I_M(\kappa)) \cdot MTF_{Sensor}(\kappa) \tag{5}$$

As stated on the right side of the equation the spectrum of the measured spectrum is equal to the spectrum of the intensity distribution behind the mask multiplied with the MTF of the sensor. If κ_I and κ_M are substantially higher than the Pixel frequency of the sensor all higher frequency components from Eq. 4 are reduced by the sensor MTF to a level beyond the sensitivity of the system so that they can't be detected. Though if κ_I and κ_M are carefully chosen the difference term will be at a frequency were it can be detected by the linear image sensor. Under these assumptions the intensity distribution actually measured by the sensor can be approximated by:

$$I_S(x) = \tfrac{1}{2}(I_P + I_R) + MTF(\kappa_I - \kappa_M) \cdot \tfrac{1}{2}\sqrt{I_P I_R}\,\gamma(x) \cdot \sin((\kappa_I - \kappa_M)x + \rho_I - \rho_M) \tag{6}$$

From comparison with Eq. 1 it gets clear that the amplitude of the modulation is reduced to a least 25%. This is caused by the lost of 50% of the light due to the average transmission of 0,5 of the mask and the fact, that the second half of the intensity modulation is transformed to the sum frequency where it can't be detected due to the sensor MTF. Both effects together cause a reduction of the interference contrast to 50% and a reduction of the average intensity offset of 50%. The signal to noise ratio of a shot noise limited OCT systems is proportional to the ratio of the interference amplitude and the square root of the average intensity. Therefore down conversion reduces the SNR by at least 9 dB. And additional decrease of contrast and SNR is caused by the MTF at κ_I - κ_M . The actual reduction depends on the properties of the used image sensor.

Instead of a mask with a spatial sinusoidal transparency function a mask with an square wave transparency function can be used. In this case a number off additional term arise from the higher orders of the Fourier components of the square wave, but as before all high frequency components are damped by the MTF of the sensor, so that the basic principle remains untouched.

3 Methods

To test this new principle we attached a custom made masks to a CMOS sensor (Photon Vision Systems LIS 1024, pixel size 8µm x 125µm, 1024 pixels). The mask was manufactured from 2 mm thick glass plates by structuring a chromium layer on one side with an electron beam. The period of the resulting transmittance pattern was 2.66 µm, which is a third

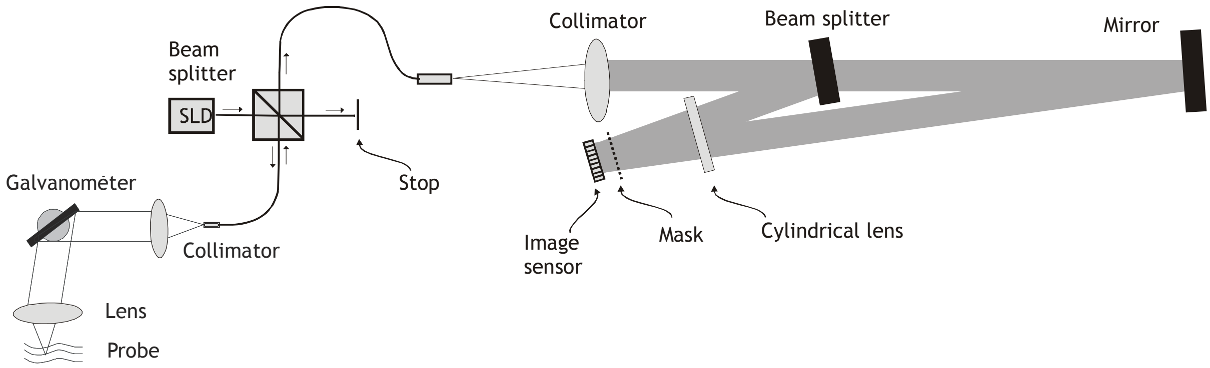
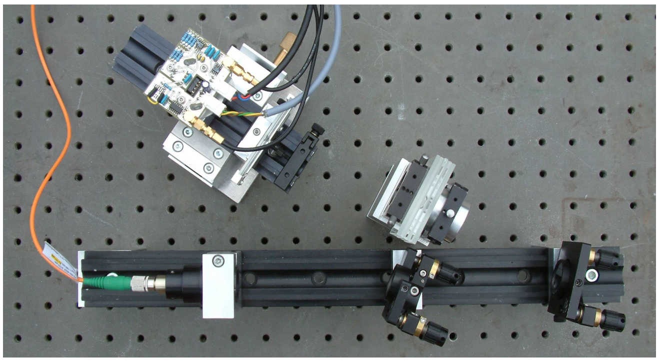
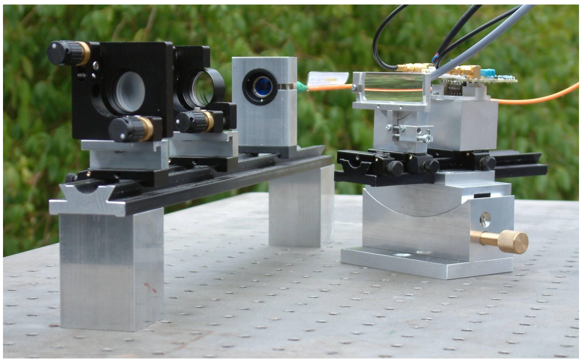


Fig. 2: Schematic of the interferometer used for validating linear OCT with optical down conversion.



a)

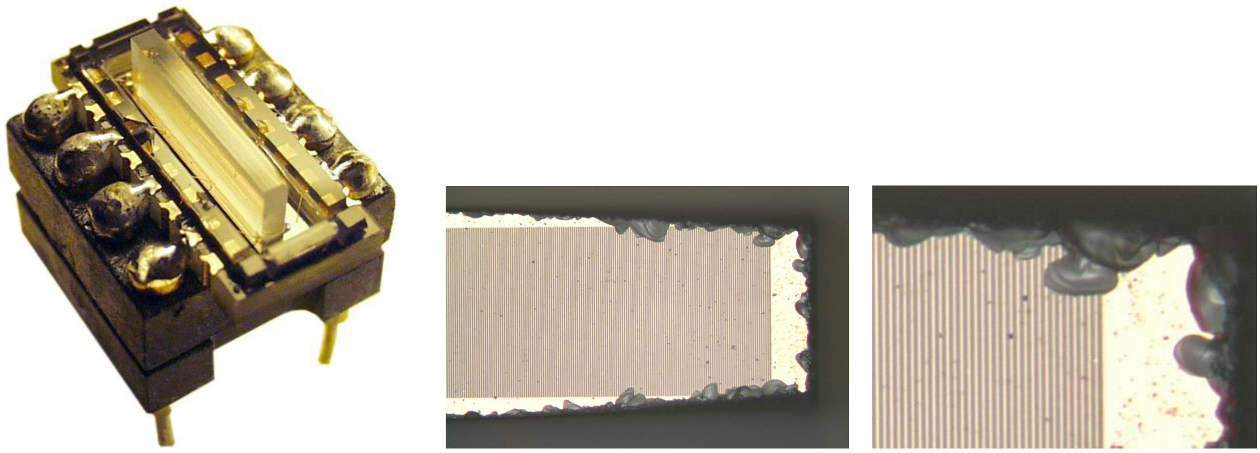


b)

Fig. 3a:Left: Photography of the detection unit of the OCT System. Probe and reference light are coupled via mono mode fiber into a collimator (bottom left). The Probe light is reflected with a 50% beam splitter (bottom center) towards the image sensor (top center). The reference light is directed towards the sensor by a mirror (bottom right). The reference light passes through a stack of substrates (above beamsplitter) to compensate for dispersion in the applicator optics. Fig. 3b: same setup from a different perspective. The substrate stack was removed to allow a clear view on the cylindrical lens and the image sensor.

of the pixel period. After structuring, the glass plates were cut into pieces of 8 mm x 1.5 mm. The mask was glued on top of the image sensors after the cover window had been removed. The image sensor with the attached mask is depicted in Fig. 4.

Fig. 3 shows the basic optical set up of the experiment. The light of a superluminescence diode (Superlum SLD37MP, λ_c=830 nm, FWHM=45 nm) is directed via a fiber coupler to the probe. The reference wave is generated by the back reflection of the fiber tip in the probe arm. This approach has the advantage that probe and reference intensity travel the same path from their origin to the detection unit and therefore all dispersion and path length dependent effects in the fibers are cancelled out. In the detection unit the light is partitioned by a 50% beam splitter. Both parts are focused by a cylinder lens on the linear image sensor. The difference frequency κ_I - κ_M can be adjusted via κ_I by changing the enclosed angle between the reference and the probe beam (Fig. 1). The angle between the two beams is chosen so that κ_I equals 3.25 fringes per pixel. The mean path length difference between the two beams is equal to the path length difference established between the probe- and reference light in the probe arm of the interferometer. A disadvantage of this interferometer design is that both beams consist of both, reference and probe light, but only probe light reflected from the beam splitter can interfere with reference light reflected from the mirror. The other components only contribute to the incoherent intensity offset of the system. This halves interference contrast and SNR.

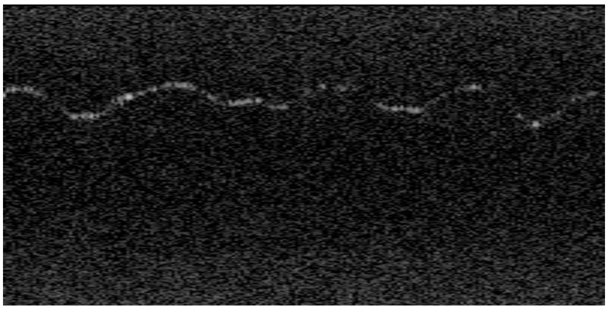


a) b) c)

Fig 4a: Image of the linear image sensor with removed cover glass and mask glued to light sensitive area. Fig 4c: Image of the side of the mask, which carries the rectangular transmission structure. Fig 4b: Enlarged region of the upper right corner of the mask

4 Results

With a first measurements the performance of the setup was determined. For this purpose a cover slip with an optical thickness of 190 µm was placed in probe arm of the interferometer. In this case the reference intensity reflected from the tip of the probe fiber and the intensities from the front and back surface of the cover slip are about the same. The interference contrast defined as the ratio between the maximum amplitude and the average intensity was approximately 8.5%. The dynamic range of the sensor was calculated as the ratio between the standard deviation of the noise floor and the peak value of the cover slip signals to 47 dB. The optical SNR of the system, defined as the ratio between the signal of a mirror in the probe and the noise floor is about 75 dB, if one puts into account that the peaks of the cover slip are already 28 dB smaller than a peak caused by a mirror. The measurement range of the system can be determined from the distance of the two peaks to approximately 1,07mm. The axial resolution was 11 µm, which is close to the theoretical limit set by the spectral width of the used SLD.



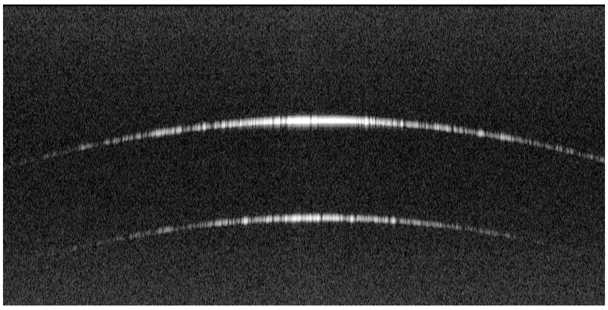


Fig. 5: B-scan measurements of human skin and a contact lens. It can bee seen that with the relative poor dynamic range of the system only the air tissue boundary of the skin can be measured. In contrast the setup can resolve the surfaces of technical probes like the depicted contact lens with a sufficient accuracy. The image dimensions are 940µm x 2mm at a lateral resolution of 10µm. The readout rate of the image sensor was 200 kHz. At a duty cycle of 50% 100 A-scans a second were acquired.

5 Conclusion

We have shown, that down conversion of the fringe pattern with a mask placed in front of the image sensor is a method to decrease the number of photo detectors for a LOCT systems almost by an order of magnitude. Therefore standard image sensors can be used to implement OCT systems with a measurement range of more than 1 mm.

A very small and simple OCT-system can be build with a custom design linear image sensor, when the mask is implemented as a metal layer directly on the semiconductor surface. Since metal layers are an integral part of the CMOS production process, a mask on top of the optical active region could be implemented within in the standard manufacturing process. Our LOCT-system then only would consists of a lens, two beam splitters and the sensor, which makes it very simple compared to other OCT devices. The system can also be very fast. Approximately 20.000 A-scans are possible with the used sensor.The major disadvantage of the technique is a loss in SNR compared with TDOCT systems. For an ideal layout the SNR is reduced by about 9dB compared to a traditional set-up.

For application where a stable and simple systems without the ultimate dynamic are needed, LOCT with optical down conversion may be an interesting alternative to conventional OCT systems.

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