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Comparison of three different Swept-Source interferometers for Biometric Measurements

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Abstract:

This study reviews the development of Swept-Source interferometers and compares three different Swept-Source interferometer designs for biometric measurements of the eye. Principles characteristics, conveniences and accessibilities of the three developed systems are presented.

The main difference between the three Swept-Source systems is the method of tuning the wavelength at the broadband optical amplifier.

The implementation of a "quasi-phase-continuous method" (QPC) for wavelength tuning led to longer measuring depth but was more time-consuming. The wavelength tuning using a rotating polygon mirror scanner was faster.

The wavelength tuning via Fourier Domain Mode Locking (FDML), where the tuning frequency f_t of the filter must be matched to the inverse cavity roundtrip time τ, achieved the widest tuning range combined with a rather better resolution and signal to noise ratio (SNR).

The swept sources were compared using a fiber-optic based Michelson interferometer setup. Measurements of a self-made human model eye demonstrate excellent capturing of the biometric data, with all interfaces of eye optical components and their contours being clearly detected.

Keywords: measuring depth; model eye; quasi-constant phase; Fourier Domain Mode Locking.

Introduction

Partial coherence interferometry (PCI) is a noninvasive high resolution optical measuring technology. New developments have produced gains in resolution by decreasing the necessary measuring time. Therefore several implementations of PCI systems are available for biometric measurements in ophthalmology.

Time domain PCI (TD-PCI) and frequency domain PCI (FD-PCI) [1–4] based systems are commonly used: in the TD-PCI the interference signal is generated by varying the length of the reference path of the interferometer, whereas the reference path is constant in FD-PCI.

The FD-PCI itself is divided into two different types. The first type is called spectral domain PCI. The interference signal is detected by spectral decomposition of the interference spectrum, which is modulated by the path difference between sample and reference paths [1]. The second type is called swept source PCI (SS-PCI). This type uses an interferometer with a tunable narrow bandwidth light source and a photodiode as a detector for recording the spectral beat signal, which is acquired by Fourier transformation.

Due to the necessary mechanical length variation inside the reference path of the time domain PCI the measuring time is significantly longer compared to frequency domain PCI. In the FD-PCI system the mechanical movement is replaced by a spectral decomposition of the light sources.

Whereas the length information is directly correlated in case of the TD-PCI system the FD-PCI system needs further calculation based on the detected photocurrent.

The measured signal at the detector is a function of the optical frequency which is given by [5]:

$$I(\omega) \sim | E_s(\omega) + E_R(\omega) |^2$$

$$I(\omega) \sim |Es|^2 + |E_R|^2 + 2\mathrm{Re}\{Es\, E_R^*\} \qquad (1)$$

where E_s and E_R are the electric field of measurement beam and reference beam, and A_s and A_R their Amplitudes.

$$\mathrm{Re}\{E_s E_R{}^*\} = A_s A_R \cos(2k_s l_s - 2k_R l_R) = A_s A_R \cos(2\pi \frac{l_s - l_R}{\lambda / 2}) \qquad (2)$$

with $k_s = k_r = \frac{2\pi}{\lambda}$

The term $E_s E_R \cos(2\pi \frac{l_s - l_R}{\lambda / 2})$ in (2) indicates that the frequency of the recorded spectral beat signal is proportional to the path difference $l_s - l_R$ and thus to the laser frequency tuning.

In SS-PCI only positions within the 'coherence gate' can be measured: this is referred to as the coherence length L_C and is defined by:

$$L_C = 0{,}44 \cdot \frac{\lambda_C{}^2}{\delta\lambda} \qquad (3)$$

where λ_c is the central wavelength and $\delta\lambda$ the wavelength range. The coherence length is directly correlated to the measurement range.

Due to the options of SS-PCI, it has been one of the most intensively investigated measuring systems [15]

The main advantages of swept source PCIs are high signal to noise ratio, short measuring time, and strong competitive light efficiency. However, the swept source designs differ significantly in their convenience and accessibility.

The aim of this study was to assess the quality of biometric measurements of a model Eye made using three different setups of Swept-Source systems, taking into account the efficiency and cost of these systems.

An important factor is the optimal wavelength range selection for reliable detection of the biometric data of the eye. Another aspect is the total measuring time using the swept source technology. Because the eye is constantly in motion, the measuring time must be kept extremely short.

Materials and methods

In order to compare and evaluate the swept-source systems, three setups based on Semiconductor Optical Amplifiers (SOA) with different central wavelengths (800nm, 1060nm and 1300nm) and tunable optical filters were built to measure the axial length inside a model eye.

SS-PCI system 1:

The tunable optical filter of the first system consists of a reflective diffraction grating with 1800 lines/mm, two Littrow prisms and a rotating polygon mirror (Fig.1). A SOA (type: SOA-382-SM-DBUT-800, central wavelength 800 nm, Superlum Co. Cork, Ireland) is used as a broadband gain medium.

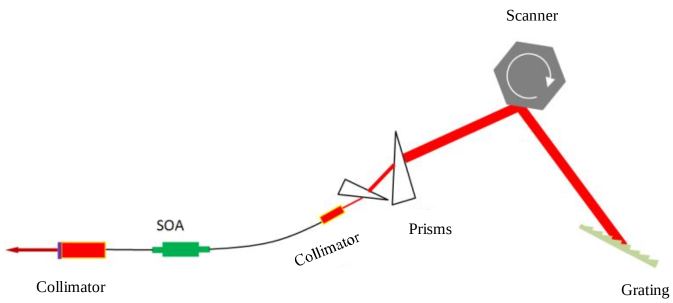

Figure 1: Setup of the SS source with rotating polygon mirror scanner.

An individual wavelength spectrum with a specific bandwidth of $\delta\lambda$ is periodically selected out by the above described tunable filter which feeds it back into the SOA. The SOA amplifies the selected spectrum and couples it back into an optical fiber.

The spectral resolution of the filter increases depending on the number of illuminated grating lines N and interference order m [5]:

$$\frac{\lambda}{\delta\lambda} = mN, \tag{4}$$

(λ = wavelength of the light source)

The rotating polygon mirror in Figure 1 can be replaced by a rotating polygon grating with 1800 lines/mm. This reduces the setup by one component, because grating and mirror are combined in a single component.

SS-PCI system 2:

A tunable optical filter in the second system consisting of a reflective diffraction grating with 1800 lines/mm, two Littrow prisms and a scanner (dynAXIS SCANLAB AG) was used (Figure 2). The SOA, type SOA-1060-100-PM-24dB (central wavelength1060 nm, Innolume, Germany) was used as a broadband gain medium. The relationship between the distances L

and H in figure (2) ensures that the phase is nearly constant across the selected bandwidth. This is called a "quasi-phase-continuous method" (QPC) [4]:

$$H = \frac{\cos\theta_c}{\tan^2\theta_c - 1}\cdot L \tag{5}$$

With: $$\theta_c = \operatorname{asin}\left(\lambda_c / 2\cdot a\right), \tag{6}$$

λ_c : central wavelength = 1060 nm

a : grating constant = 5.55×10^{-7} m

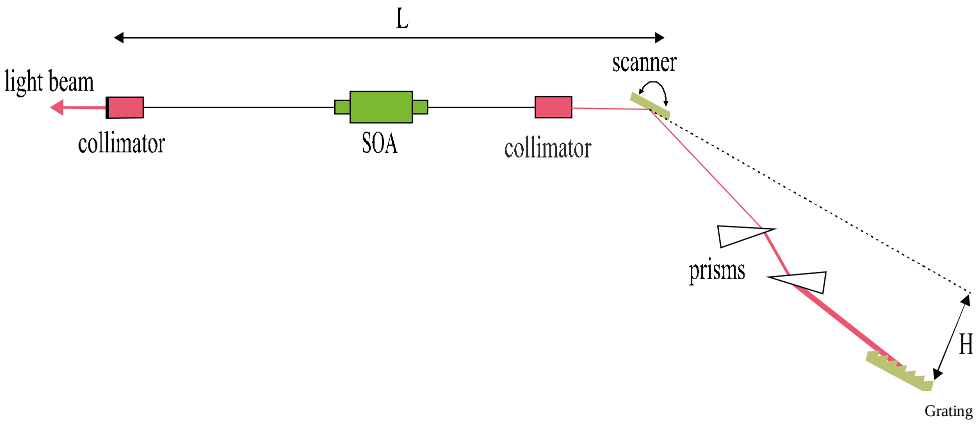

Figure 2 Setup of the SS source using the concept of quasi-phase-continuous method (QPC).

SS-PCI system 3:

The third system is based on the concept of Fourier Domain Mode Locking (FDML) (Fig.3). It includes a long fiber-ring (L) with a broadband SOA (S9FC1132P, central wavelength 1300 nm, Thorlabs, Germany) as a gain medium and a fiber Fabry-Perot filter (Lambda Quest LLC) as a tunable, narrowband optical band-pass filter [6]. In the chosen setup the laser tuning range is 80 nm, and the Light source is swept from 1280 nm to 1360 nm.

In this method the tuning frequency f_t of the filter must be matched to the inverse cavity roundtrip time τ [6, 7].

$$f_t = \frac{1}{\tau} = \frac{c}{n} \cdot L. \tag{7}$$

where n is the refractive index.

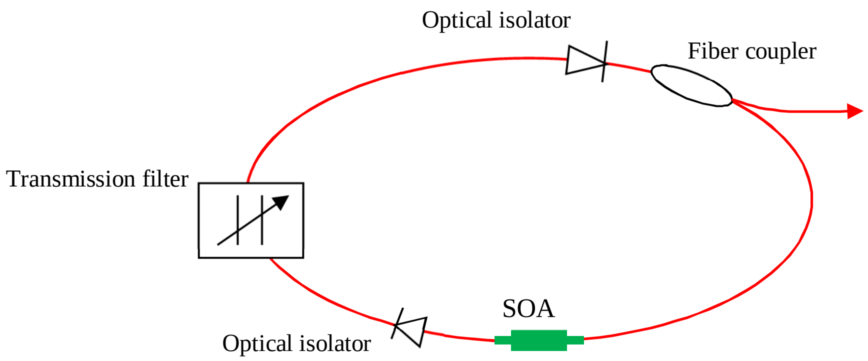

Figure 3 Setup of the SS source using the concept of Fourier Domain Mode Locking (FDML).

Interferometer:

To compare the different types of swept sources the same fiber-optic based Michelson interferometer was used in each case (Fig.4). The laser light coming from the swept source is divided by a fiber coupler into the measurement path and the reference path. The reflected or scattered fraction of the laser light from the sample path interferes with the reflected portion from the reference path. The interference pattern is detected by means of a Balanced Amplifier Photodetector (InGaAs PDB450C-AC, Thorlabs, Germany). After amplification and digitization, the signal is transferred to a PC for a fourier transformation of the signal which corresponds to a given scan depth.

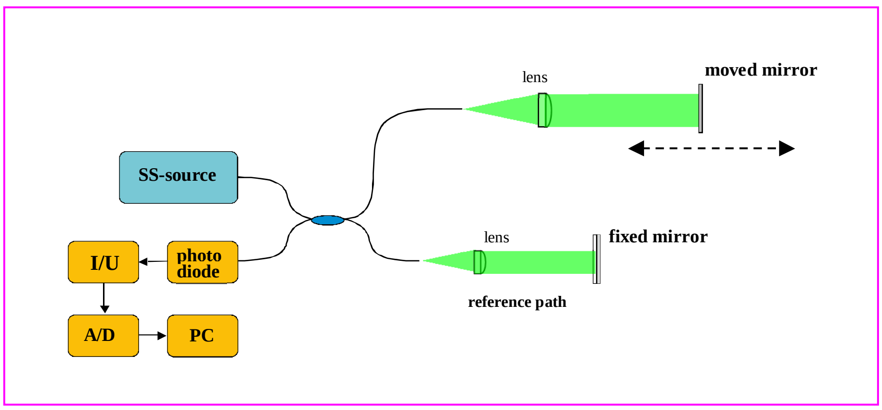

Figure 4 schematic setup of SS-PCI-Systems motion calibration.

Resolution characterization

The systems were calibrated using a fixed mirror in the reference path and a moving mirror mounted on a piezoelectric motor (PI-type M-663 Compact Linear Translation) in the measuring path. The spatial resolution of the piezoelectric motor is 0.1 µm.

The theoretical spatial resolution can be described by the following equation:

$$\delta z = 0{,}44 \cdot \frac{\lambda_C^2}{n \cdot \lambda_T} \qquad (8)$$

By the movement of the piezoelectric motor in one direction, several measuring positions within the coherence length L_c can be selected. At each measuring point, the associated interference signal is taken and subjected to the Fourier transformation.

The smallest possible detectable variation in frequency during displacement defines the resolution of the system.

The SNR was calculated by analyzing the signal amplitude of a good reflected surface (mirror) and the common background noise [13,14].

$$\mathrm{SNR} = 10 \cdot \log\left(\frac{\text{signal}}{\text{Noise}}\right)^2 \quad \textit{in dB} \qquad (9)$$

The capabilities of the systems were tested by measurements of a self-made human model eye with interfaces comparable to those of a biological eye, which was mounted into the measuring path. The cornea in the model eye is represented by a hard PMMA contact lens with a typical radius of curvature (8.04 mm). The intraocular lens (IOL) is simulated by a 42 D hydrophobic (water-repellent) artificial lens. A diffuser is used as retina and the space between them was filled with water [8].

Results

Figure (5) shows the measurement on the model eye using the third system as an example. The laser parameters are in accordance with the relevant safety standards. The measurements show clearly the interfaces of the optical components and their contours. The measurement of the whole eye using the SS-PCI system 3 takes place in two segments, which are subsequently combined.

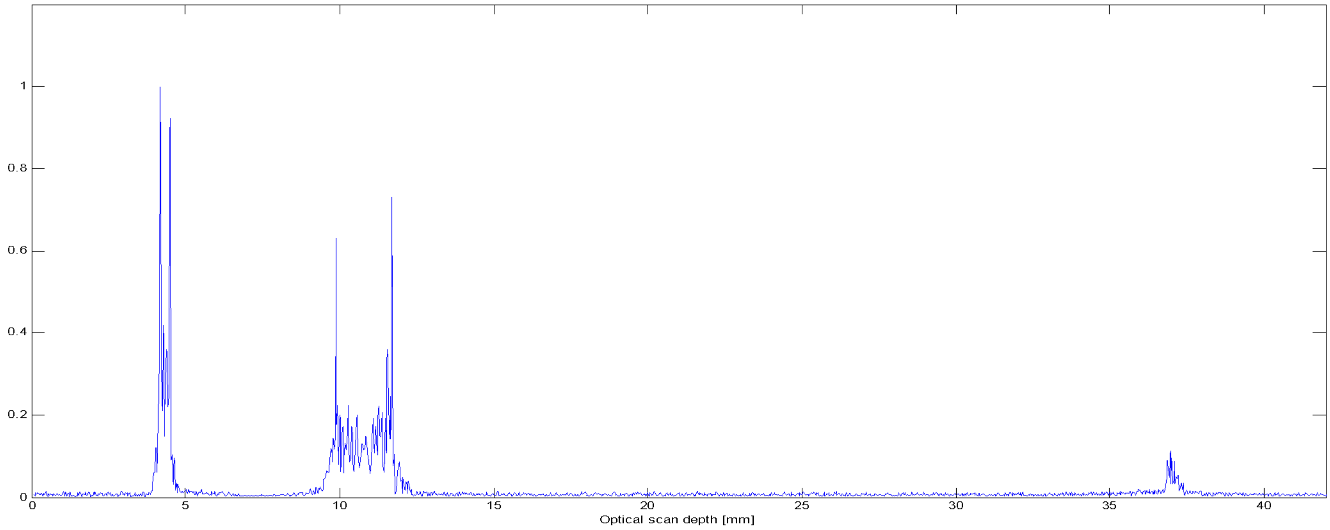

Figure 5 shows the measurement of the model eye using the third (Fig.3) system, made according to relevant safety standards

The results regarding measurement of depth, measuring time, resolution and SNR are listed in table 1.

System	**Measuring depth/mm**	**Measuring time/ms**	**Resolution /µm**	**SNR/dB**
1. System (rotating polygon mirror)	12	<0.2	10	62
2. System (scanner)	40	1	9	57
3. System (FDML)	16	<0.01	7	88

Table 1. The measuring depth, measuring time and the signal to noise ratio (SNR) of the three swept source setups.

The theoretical measuring depth of the second system was the largest due to the use the quasi-phase-continuous method. However, this system is limited by the speed of the scanner. The biometric measurement can be achieved in one single measurement, whereas for system 1 and 2 two separate measurements have to be combined to one total length measurement. The measuring depth for one sector is comparable.

Systems 1 and 3 show the smallest measuring ranges, since the phase is not constant and this instability leads to small coherence length L_c, but fortunately their other capabilities (speed of measurement, resolution and SNR) were favorable.

The measuring time for system 3 is the shortest. It is shorter by a factor of 100 as compared to the slowest system (System 2).

System 3 is the fastest measuring SS-PCI system with the best resolution and SNR but a limited measuring depth.

Discussion

Water is the main component of biological tissues. Its absorption is minimal between 800 and 900 nm, therefore light sources with this wavelength range are particularly suitable and mainly used for retina detection. [9, 10]. For the anterior chamber, wavelengths longer than 800 nm, such as 1300 nm are frequently used too.
Near-infrared wavelengths such as 1300 nm enable clear imaging through pigmented biological tissue which are opaque at shorter wavelengths, since tissue scattering decreases with increasing wavelength.
The real benefit of using the 1300 nm range is the availability of low-cost components, due to widespread use of this wavelength range for telecommunication.

For imaging the retina, light sources with central wave length at 1060 nm have also been used . Beneath the relative absorption minimum of water at a wavelength of 1060 nm optical scattering is relatively low [11].

All three systems, using the optimal measurement wavelengths, demonstrate excellent results for biometric measurements inside the eye. However, the systems differ significantly in their convenience and usability.
All applications of the systems are considered with regard to the relevant safety standards. For imaging of the retina at a wavelength of 830 nm a maximal power of 0.7 mW at the cornea is allowed. At 1060 nm it increases to 2 mW [11].
For imaging the anterior chamber at 1300 nm the limit is set at 15 mW [12].
The tuning range λ_T of the third SS-source has the widest range, and as a result its resolution and SNR are the best. This is well-defined with equation (8).

The best result was achieved with system three, but this is the most expensive so the three systems. This system can be very effective in imaging procedures of the whole eye which means for the anterior part and also for the retina.

The measured SNR of all three systems was less than predicted [12]. This can be explained because no digital filters were applied for all measurements.

To achieve a higher scanning depth Δz, the interference signal must contain a minimum number of measuring points / tuning range (N_S). Therefore the Nyquist-Shannon theorem has to be taken in account. [12]

$$\Delta z = \frac{\lambda_C^2 \cdot N_S}{4 \cdot n \cdot \lambda_T} \tag{10}$$

A setup using a rotating polygon mirror and a suitable gain is a good choice, to achieve a acceptable measuring accuracy at a reasonable cost. The Implementation of a "quasi-phase-continuous method" (QPC) as used in the second setup extends the coherence length L_c and thus the measuring depth Δz.

It is necessary to find a compromise between the gained depth resolution and achieved measurement depth, since depth resolution is limited by high measurement depth or rather longer coherence length. For imaging of large volume samples with sufficient depth resolution, the SS-PCI system based on the concept of the Fourier Domain Mode Locking (FDML) should be selected. To capture the biometric data of the eye taking commercial considerations such as cost/benefit into account, the SS-PCI system using the (QPC) concept would perhaps be preferred.

Acknowledgments

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