Signal post processing in frequency domain OCT and OCM using a filter bank approach

Bernd Hofer[1,2], Boris Považay[1], Boris Hermann[1], Angelika Unterhuber[1], Gerald Matz[2], Franz Hlawatsch[2], Wolfgang Drexler[1]

[1] Biomedical Imaging Group, Department of Optometry & Vision Sciences, Cardiff University, Wales, UK

[2] Institute of Communications and Radio-Frequency Engineering, Vienna University of Technology, Austria

Phone: +44 2920 232306, E-mail: DrexlerW@cardiff.ac.uk

Abstract:

Current signal post processing in spectrally encoded frequency domain (FD) optical coherence microscopy (OCM) and optical coherence tomography (OCT) uses Fourier transforms in combination with non-uniform resampling strategies to map the k-space data acquired by the spectrometer to spatial domain signals which are necessary for tomogram generation.

We propose to use a filter bank (FB) framework for the remapping process. With our new approach, the spectrometer is modeled as a critically sampled analysis FB, whose outputs are quantized subband signals that constitute the k-space spectroscopic data. The optimal procedure to map this data to the spatial domain is via a suitably designed synthesis FB which has low complexity. FB theory additionally states that 1) it is possible to find a synthesis FB such that the overall system has the perfect reconstruction (PR) property; 2) any processing on critically sampled subband signals (as done in current schemes) results in aliasing artifacts.

These perspectives are evaluated both theoretically and experimentally. We determine the analysis FB corresponding to our FD-OCM system by using a tunable laser and show that for our grating-based spectrometer – employing a CCD-line camera – the non-uniform resampling together with FFT indeed causes aliasing terms and depth dependent signal attenuation. Furthermore, we compute a finite impulse response based synthesis FB and assess the desired PR property by means of layered samples. The resulting images exhibit higher resolution and improved SNR compared to the common FFT-based approach. The potential of the proposed FB approach opens a new perspective also for other spectroscopic applications.

Keywords: Filter bank, Spectrometer, Spectroscopy, Optical coherence microscopy, Optical coherence tomography, Frequency domain, Tunable lasers, Fourier Transform, Aliasing, FFT

Introduction

Optical coherence tomography (OCT) detects reflective sites in tissue, analogous to ultrasound imaging. Being a non-invasive, optical technique, it has much higher resolution (2 orders of magnitude) but is limited to superficial organ regions (with typical penetration depths in the millimeter range). Invented in the early 1990ies on the principles of white light interferometry, it has rapidly developed to an important imaging modality for detecting early, subtle pathological morphological (structural) tissue changes and is used in a variety of medical fields because of its high sensitivity. Historically OCT has been extremely successful in ophthalmic diagnosis, due to the fact that the eye allows easy optical access especially to the retina that is situated at the posterior portion of the eye, where no competing technology can give access to.

State of the art frequency domain (FD - also referred to as spectral domain or Fourier domain) OCT is able to perform three-dimensional high resolution (less than 10 micrometer) retinal imaging. FD-OCT systems encode depth resolved tissue reflectivity information (needed for 2D cross-sectional or 3D tomograms) in optical frequency, wavelength or wavenumber (being just different representations). This enables significantly higher acquisition speeds accomplishing 3D imaging by maintaining resolution and sensitivity as compared to time-domain OCT systems. FD-OCT manages to suppress noise due to its higher sensitivity, caused by significantly better exploitation of information when measuring in the frequency domain[i],[ii],[iii]. A schematic representation of the considered FD-OCT system is shown in Fig. 1.

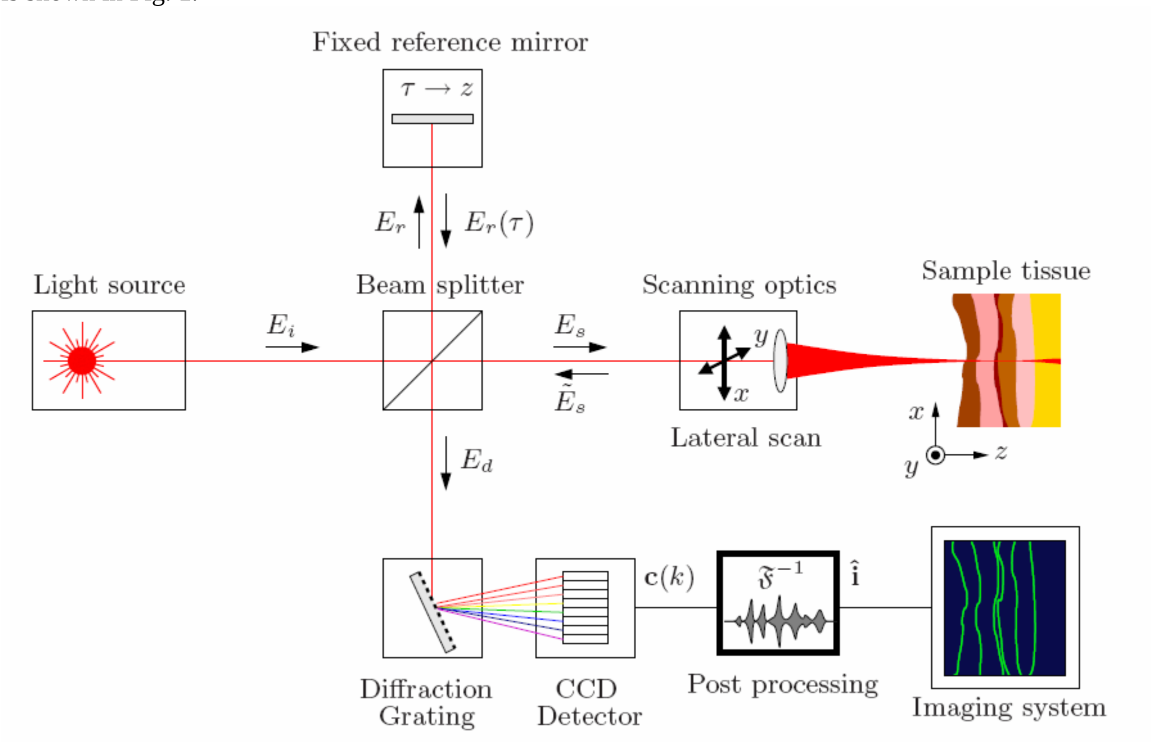

Figure 1. Spatially encoded FD-OCT system: A broadband laser light source emits broadband laser light which enables OCT depth ranging. The incoming laser beam (or electric field vector of the electromagnetic wave) E_i is diverted into a reference field E_r and a sample field E_s at a beamsplitter which constitutes the central element of the interferometric measurement setup. The position of a fixed reference mirror determines the optical delay τ of E_r and thereby also the relative so-called zero delay position z. Reference field and sample field combine at the beam splitter, the resulting interference field is the detection field E_d. The spectral content of E_d is analyzed by a spectrometer, consisting of a diffraction grating — for spatial separation of the spectral components of E_d — and a CCD detector which also samples and quantizes the spatial encoded interference spectra. The resulting discrete digitalized interference spectra c_k are interpreted as nonuniform k-space samples of the spectral encoded reflectivity profile from the sample tissue i (or its magnitude, depending on the specific implementation of the OCT-system, i.e. complex-domain or real-valued OCT-system). The time-domain reflectivity profile is reconstructed via a nonequispaced FFT (almost approximated via resampling procedures followed by conventional FFT). From several adjacent recorded interference spectra, 2D tomograms and even 3D representations of the tissue morphology as represented by local and varying tissue reflectivity can be reconstructed.

There is a fundamental problem with FD OCT techniques, though, in terms of how the spectral data is acquired – more specifically, when the spectrum is sampled. Imperfections of distortions imposed by physical limitations like gratings, imaging optics, etc. in the measurement system or the light sources lead to incorrectly sampled datasets that are furthermore suffering from crosstalk in the different spectral channels.

This sampling problem degrades image quality in terms of resolution, sensitivity and absolute measures.

The proposed application of a filter bank (FB) framework[iv] is an approach that can solve this fundamental data acquisition problem, resulting in a significant improvement of image quality.

In the following we provide a description of FD OCT signal acquisition in perspective of FB system modelling. We propose a method for characterizing of the grating based spectrometer used within our system in terms of an analysis FB. Finally we derive a perfect reconstruction synthesis FB which allows us to transform the spectral domain data back to spatial domain reflectivity profiles. We apply this synthesis FB on datasets from mirror measurements at different positions and also show the applicability on an in vivo tomogram of a human retina. These results are compared with the standard Fourier transform (FT) based processing scheme.

Filter bank framework for FD-OCT

In our spectral encoded FD-OCT system a broadband light source is used together with a grating based spectrometer (as shown in Fig. 1.). The interference spectrum is analyzed and digitized via the spectrometer, i.e. the interference spectrum is 'sampled' in parallel. This scheme can be interpreted as a nonuniform critically sampled analysis FB with its outputs (the subbands) constituting the digitized and sampled interference spectrum.

This means that each pixels output of the CCD detector is associated with a subband of the analysis FB. The subband signals arise from bandpass filtering of the optical interference signal within a limited frequency range (determined by the bandwidth of the low coherent light source). This modelling not only reflects the conversion from optical carrier frequency range to electrical baseband signal frequency range via the CCD detector but also incorporates the sampling and quantization process (analog-to-digital conversion) as well as the transfer properties of the entire optical measurement system (predominantly the wavelength dependent responsivity of the CCD detector and the transfer function of the beam splitter based interferometer).

A method for characterizing the analysis FB transfer-functions is depicted in Fig. 2. We employ a tuneable narrow-band light source. At each optical frequency the CCD outputs are recorded. These outputs form a frequency sampled representation (sampled frequency response) of the analysis FB transfer-functions. A complex valued convolution matrix[v] equivalently describing these transfer-functions can be found via

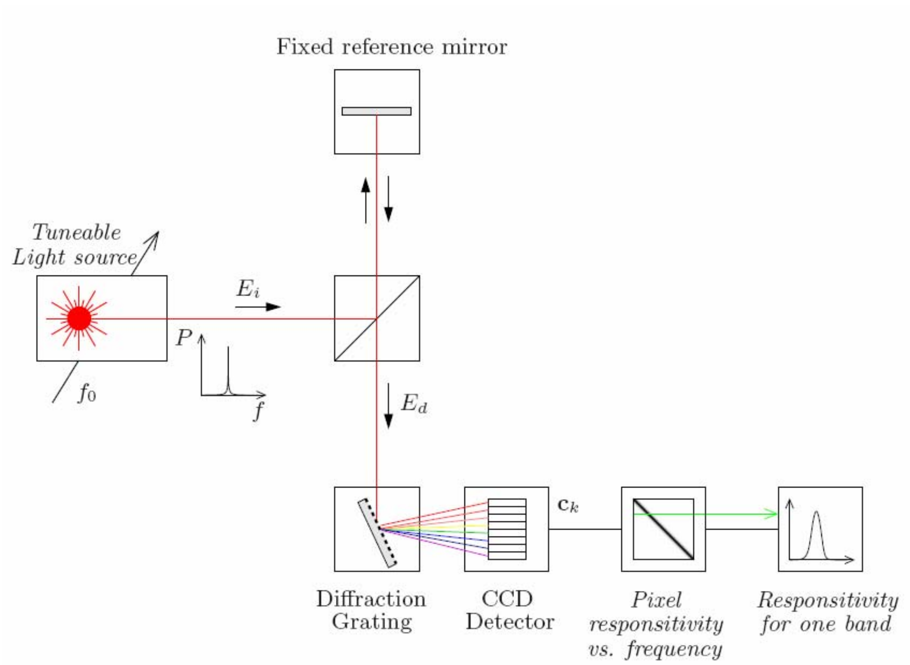

Figure 2. Measurement setup. for characterizing our spectral encoded FD-OCT with a wavelength swept lightsource. The tunable light source used for characterization (Superlum Broadlighter 840) delivered a spectral tuning range of more than 50 nm @ 5mW and had a spectral linewidth of less than 0.04 nm.

application of frequency sampling based finite impulse response method and application of the Hilbert transform. This analysis FB convolution matrix can be inverted via the least squares method[iv]. The resulting

synthesis convolution matrix forms a perfect reconstruction synthesis FB. The perfect reconstruction property means, that for any given input signal the output signal after passing analysis and synthesis filter bank system, should be nothing else as a delayed but undistorted replica of the input signal.

Results

We first use a position varying sample mirror for determination of the depth dependent signal roll off (see Fig. 3.). The reflectivity profiles obtainded with the conventional FT-based processing and the proposed FB processing are depicted in Fig. 4. The upper part shows the dramatic signal roll off produced by the standard FT-based processing (non-uniform resampling of the interference spectra and FFT).

The results obtained with the FB are depicted in the lower part of Fig. 4. One can observe a significant reduction of signal roll off and depth varying fringe wash out.

Fig. 5. demonstrates the application of the proposed FB processing to in vivo data. The depth dependent signal loss visible in the FT-processed upper image can be reduced by FB processing, as demonstrated in the lower image. Quantitative SNR improvement of about 6 dB was obtained. Here the SNR improvement was measured as difference of the dynamic range calculated in both images. The dynamic range was defined as ratio of pre-foveal noise energy to peak signal energy in the lower half of each image (area around retinal pigment epitelium).

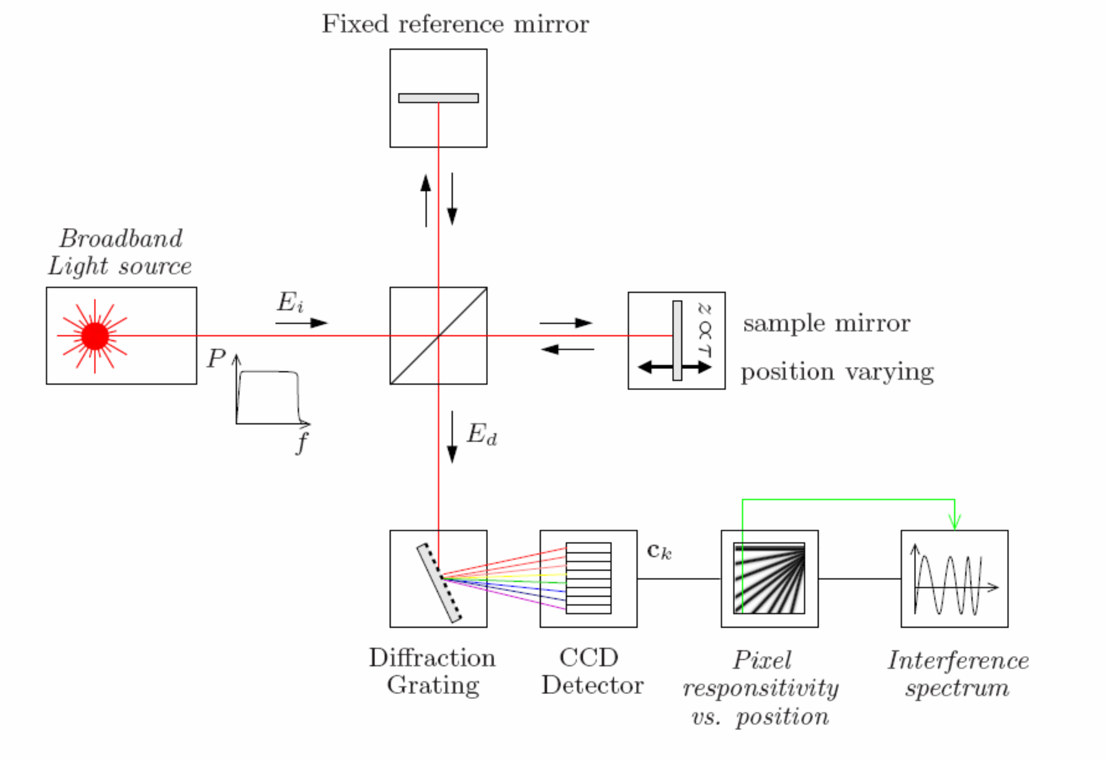

Figure 3. Setup for mirror measurement; the mirror was manually positioned to obtain reflectivity profiles from different positions within the depth-range.

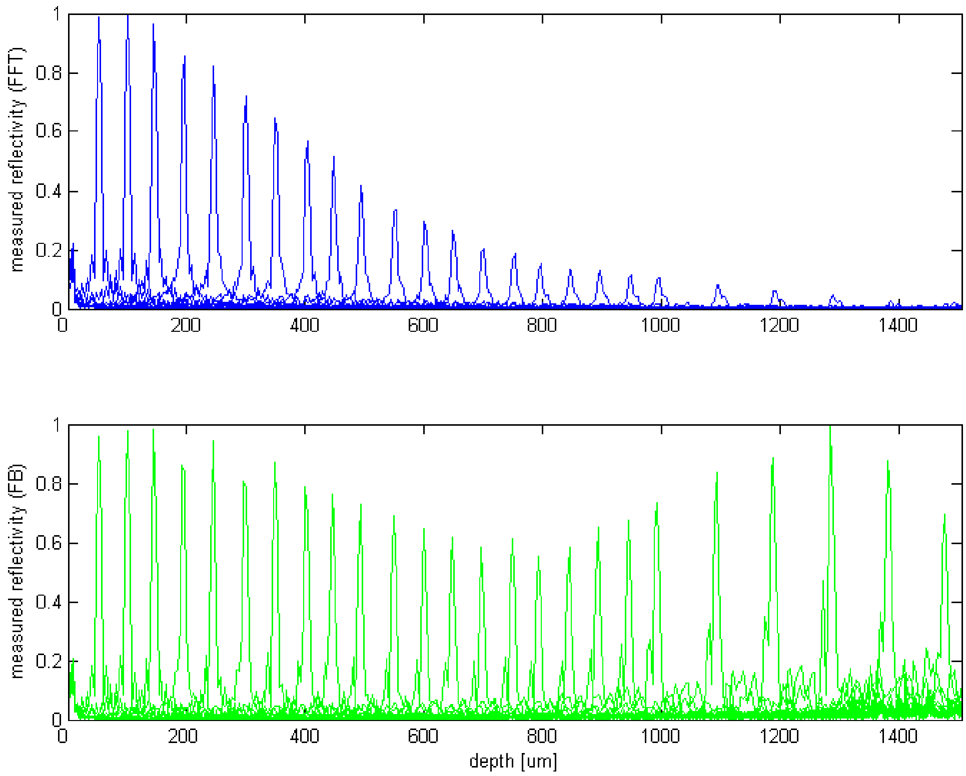

Figure 4. Mirror results –reconstructed reflectivities (upper blue: FT-based processing, lower green: FB-based processing).

Conclusions

A filter bank framework can be applied for modelling of FD-OCT systems. A synthesis FB can be calculated, that optimal relates critically sampled subband signal values with spatial domain reflectivity profiles. Preliminary results demonstrate the potential of the proposed approach and show that FB processing outperforms currently used FT based processing. Supported in part by Cardiff University; EC-P nanoUB sources, FP6-2004-IST-NMP-2, STREPT (017128); the Christian Doppler Society; FEMTOLASERS, GmbH; CARL ZEISS Meditec, Inc.; and Superlum, Ltd.

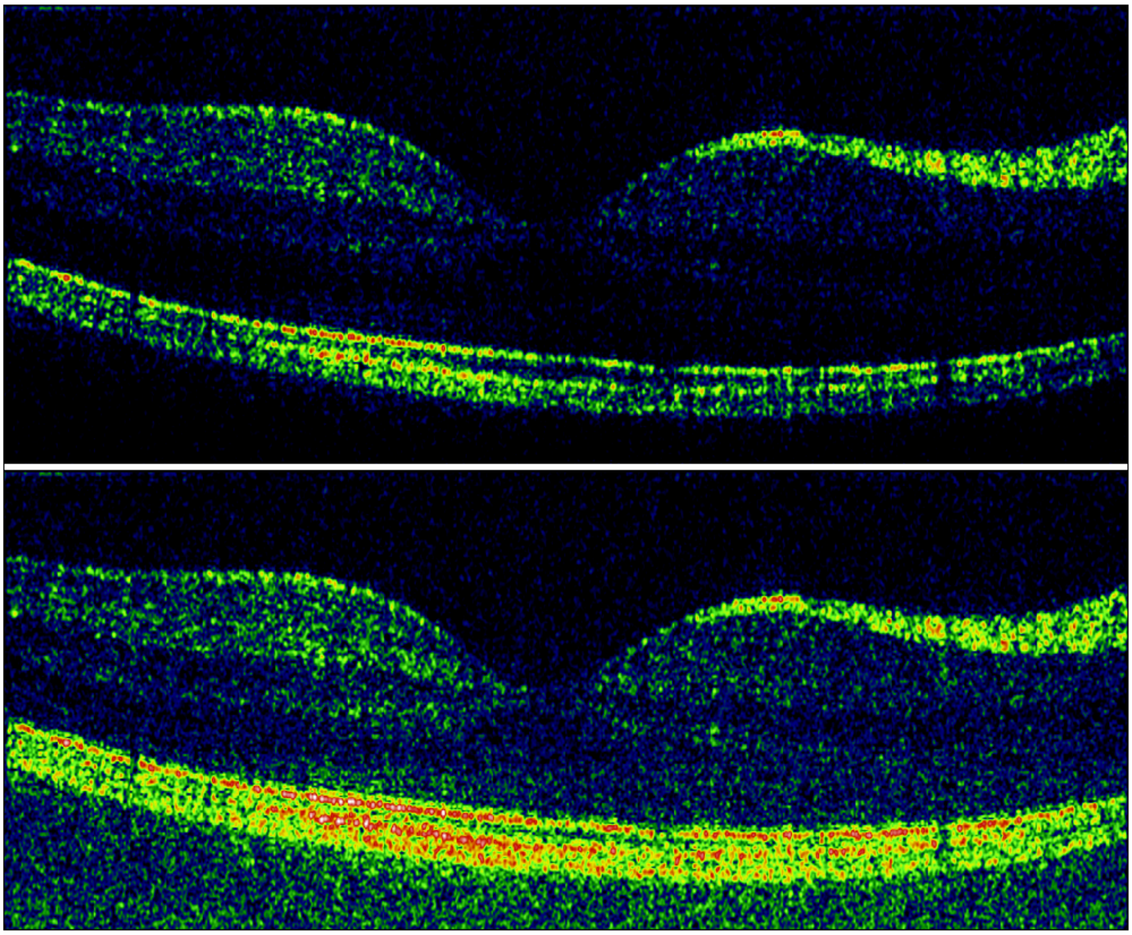

Figure 5. Results for in vivo tomogram (fovea centralis of a healthy human). Filter bank (lower image) gives a SNR increase of 6 dB compared to the conventional approach based on FFT (upper image).

REFERENCES

i R. A. Leitgeb, C. K. Hitzenberger, A. F. Fercher, "Performance of Fourier domain vs. time domain optical coherence tomography," *Optics Expr.* 11, 889-894 (2003).

ii M. A. Choma, M. V. Sarunic, C. Yang, J. A. Izatt, "Sensitivity advantage of swept source and Fourier domain optical coherence tomography," *Optics Expr.* 11, 2183 (2003).

iii J. F. De Boer et al., "Improved signal-to-noise ratio in spectral-domain compared with time-domain optical coherence tomography," *Opt. Lett.* 28, 2067-2069 (2003).

iv P. P. Vaidyanathan, "Multirate Systems and Filter Banks," *Prentice-Hall,* New York (1993).

v M. Vetterli, C. Herley, "Wavelets and Filter Banks: Theory and Design," *IEEE Trans. on Signal Processing* 40, 2207- 2232 (1992).