Acousto-optic filtration in low-coherence spectral-domain interferometry

L Burmak
Scientific and Technological Centre of Unique Instrumentation, Russian Academy of Sciences, Leninsky Prospect 14, Moscow, 119991, Russia
E-mail: burmakliu@yandex.ru

Abstract. The basic principles of measurements in spectral-domain low coherence interferometry (optical coherence tomography, optical coherence microscopy) based on acousto-optic filtration are discussed. Relations for extracting information about sample's spatial structure from a series of spectral interference images acquired with spectral tuning are given. The implementation of measurements in spectral domain using acousto-optic filtration is considered. The effect of the acousto-optic filter characteristics on depth measurement range and depth resolution is estimated. The results of modelling of the interference signal and experimental data obtained in the scheme with acousto-optic filtration of interfering beams at the output of Michelson interferometer are presented.

1. Introduction
Acousto-optical tunable filters (AOTF), which allow selecting a narrow spectral component from a broadband light in accordance with the frequency of electrical driving signal applied to ultrasound transducer, are widely used in spectroscopy and spectral imaging. One of the possible applications of acousto-optic filtration is in low-coherence spectral-domain interferometry like optical coherence microscopy/tomography (OCT) [1–4]. Such interferometric techniques are used to quantify the heights, thicknesses, and refractive index of the material of objects when light is reflected from them. Usually spectral-domain interferometric schemes are a two-beam interferometer, in which the object under study is placed in one of its channels. To implement measurements, a series of spectral interference images of inspected object is acquired and processed with Fourier transform. The paper addresses the using of acousto-optic filtration for acquiring interference images in spectral domain in such schemes.

2. Spectral-domain low-coherence interferometry basics
The use of acousto-optic filtration at the input or output of interferometer together with a broadband light source when inspecting the objects in the reflection mode allows measurements by OCT technique. It is used for surface profilometry of reflecting objects or studying the inner layer structure of partially transparent objects [3, 4].

The scheme of spectral-domain low-coherence interferometry based on acousto-optic filtration of interfering beams at the output of Michelson interferometer is shown in figure 1. The broadband light from illumination channel (1) is split with beamsplitter (2) into a reference I₁ and sample I₂ beams. The beam in the reference channel is reflected from the reference mirror (3). In the sample channel the beam
is reflected from the object under study (4). The reference and sample beams are combined together by the beamsplitter and simultaneously filtered by the imaging AOTF (5). Then beams go to the registration channel (6) where they form an image of the inspected object on camera sensor. A series of spectral interference images is recorded with AOTF spectral tuning.

In case of reflective non-transparent sample in air (when the scheme operates as profilometer) at each point of the acquired image \((x, y)\) the spectral dependence of the interference signal has the general form:

\[
I(k) = \left[ I_1(k) + I_2(k) + 2\sqrt{I_1(k) I_2(k)} \cos(k \cdot 2(h + \Delta z)) \right] \text{rect} \left( \frac{k - k_{\text{central}}}{\Delta k} \right),
\]

(1)

\(I_1(k)\) and \(I_2(k)\) are intensities of reference and sample beams, \(\Delta k\) is spectral tuning range, \(k_{\text{central}}\) is a center of tuning range, \(\Delta z = z_S - z_R\) is geometrical path difference between reference and sample channels, \(\Delta z(x, y) = z_0 + \tan\alpha \cdot x + \tan\beta \cdot y\), \(\alpha, \beta\) are tilt angles of reference mirror relative to \(x\) and \(y\) axes introduced to get finite-width interference fringes, \(z_0\) is initial path difference introduced to separate constant and target parts of reconstructed signal, \(h\) is a height of object profile (in the highest point \(h = 0\)). Typically, light sources used in OCT (such as halogen lamps) have a weak spectral dependence within tuning range compared to the oscillating interference component. So, it can be assumed \(I_1(k) = I_1, I_2(k) = I_2\). Hereafter, an approximation that does not take into account the variance of visibility of the interference pattern is used.

First, consider a continuous signal \(I(k)\) bounded by the spectral measurement range \(k_{\text{central}} \pm \Delta k/2\). To make a conversion from spectral domain to spatial domain \(I(k) \rightarrow I(z)\), the inverse Fourier transform is applied to (1)

\[
I(z) = |\mathcal{F}^{-1}[I(k)]| = |\mathcal{F}^{-1}[A + B]| = |\mathcal{F}^{-1}[(I_1 + I_2) \text{rect} \left( \frac{k - k_{\text{central}}}{\Delta k} \right)]| + \mathcal{F}^{-1}[2\sqrt{I_1 I_2} \cos(2k(h + \Delta z))] \otimes \mathcal{F}^{-1} \left[ \text{rect} \left( \frac{k - k_{\text{central}}}{\Delta k} \right) \right] = |A + B|.
\]
The first term $A$ is a constant component (independent of the pathlength difference between interferometer channels) centered at $z = 0$ (which corresponds to the plane of the zero pathlength difference)

$$A \sim \text{sinc} \left( \frac{z \Delta k}{2} \right).$$

The second term $B$ describes the maximum of the target signal intensity located at the points $z = \pm 2(h + \Delta z)$

$$B \sim \exp \{ j(z + 2(h + \Delta z))k_{central} \} \text{sinc} \left( \frac{(z + 2(h + \Delta z))\Delta k}{2} \right)$$

$$+ \exp \{ j(z - 2(h + \Delta z))k_{central} \} \text{sinc} \left( \frac{(z - 2(h + \Delta z))\Delta k}{2} \right).$$

Reconstructing the dependence $I(z)$ at each point of the image and finding the distance $z/2 = h + \Delta z$ (division by 2 considers the round-trip propagation of light in reflection mode), we can calculate the height of the profile relative to the "highest" point ($h = 0$).

Figure 2 (left column, upper row) shows an example of a simulated signal for a reflecting sample. $A$ is a normalized spectrum of a halogen lamp (taken from reference datasheet) and $B$ is oscillating term. The geometric difference in the lengths of the interferometer channels is $\Delta z = 15 \mu m$, point height is $h = 0$ and the signal spectral range is $\Delta k = 8.38$–$13.96 \mu m^{-1}$ ($\lambda = 0.45$–$0.75 \mu m$).

In case of a partially transparent layered object (when the scheme operates as tomograph), the intensity of the sample beam consists of the multiple components reflected from each layer (multiple reflections are not taken into account)

$$I_{2} \sum_{m=0}^{M} \chi_{m},$$

$\chi$ is the coefficient describing the transmittance along the path of beam propagation in the sample to the $m$-th reflecting layer and back, $M$ is the number of layers, $m = 0$ corresponds to the surface of the sample. For the sample surface $\chi_{0} = R_{0}$ is equal to the surface reflection coefficient. For the first layer $\chi_{1} = (1 - R_{0})^{2}R_{1}T_{1}^{2}$, $T_{1}$ is the transmittance of the material when light propagates along the path $(h_{1} - h_{0}) / n_{1}, n_{1}$ is the refractive index of the medium from the surface to the first layer. For the second layer $\chi_{2} = (1 - R_{0})^{2}(1 - R_{1})R_{2}T_{1}^{2}T_{2}^{2}$, propagation path is $[(h_{1} - h_{0}) / n_{1} + (h_{2} - h_{1}) / n_{2}]$ and so on.

The intensity distribution (1) for a homogeneous multilayer object with a refractive index ($n_{1} = n_{2} = \ldots = n_{m} = n$) in air ($n_{0} = 1$) has the form

$$I(k) = \left[ I_{1} + I_{2} \sum_{m=1}^{M} \chi_{m} \right] + 2\sqrt{I_{1}I_{2}} \sum_{m=0}^{M} \chi_{m} \cos(k \cdot 2(h_{m}/n_{m} + \Delta z))$$

$$+ 2I_{2} \sum_{m=0}^{M-1} \sum_{p=m+1}^{M} \chi_{m}\chi_{p} \cos(k \cdot 2(h_{p} - h_{m})/n) \text{rect} \left( \frac{k - k_{central}}{\Delta k} \right).$$

The first term is the constant component, the second describes the interference of the reference beam with each component of the sample beam reflected from each layer, and the third describes the mutual interference of the components of the sample beam.

The inverse Fourier transform of the intensity distribution also consists of three components

$$I(z) = |\mathcal{F}^{-1}[I(k)]| = |A + B + C|,$$

$A$ is a constant term, $B$ is a cross-correlation term containing a target signal (information about the position of the layers on depth), $C$ is an autocorrelation term describing the parasitic interference between the layers. Autocorrelation term is located near $z = 0$ as the term $2(h_{p} - h_{m})/n$ is negligible compared to $\Delta z$. 


Figure 2. Typical appearance of spectral interference signal (upper row) and reconstructed intensity-on-depth dependence (bottom row) separately for each component of interference signal for profilometry (left column) and layered structure (right column).

In figure 2 (right column) an example of a simulated signal for a sample with $M = 2$ reflecting inner layers is given. The geometric difference in the lengths of the interferometer channels is $\Delta z = 15 \mu m$, $h_0 = 0 \mu m$, $h_1 = 5 \mu m$, $h_2 = 10 \mu m$, $R_0 = R_1 = R_2 = 0.5$, no absorption losses, $n = 1.5$.

The described basic signal formation is similar for any spectral-domain OCT schemes, whether based on tunable light source or a tunable filter.

3. Acousto-optic filtration in low-coherence spectral-domain interferometry

Let us consider the specific properties of acousto-optic filtration when implemented in the OCT technique and estimate the effect of the AOTF characteristics on depth measurement range and depth resolution.

The depth measurement range depends on the AOTF transfer function and is limited by the length of the temporal coherence of the light after acousto-optic filtration and the ability of the system to resolve high-frequency oscillations.

Each monochromatic component transmitted in accordance with the transfer function of the AOTF forms its own interference pattern. These patterns have interference maxima shifted relative to each other. When superimposed, maxima blur the resulting interference pattern [5]. The maximum depth $z_{max}$, at which the total interference pattern is still distinguishable, is determined by the length of the temporal coherence of light transmitted through the AOTF

$$2z_{coherence} = \frac{2\pi \lambda f^2}{n \delta k n \delta m_{max}},$$
δk and δλ are the full-width half-maximum (FWHM) of AOTF transfer function in wave numbers and wavelengths, λe is the wavelength, which the AOTF is tuned to, n is the refractive index of the medium in which the radiation propagates along the path 2zm. 

For example, a wide-angle non-collinear TeO2 filter (diffraction "o" → "e"), incident light angles θ1 = 63.64°, θ2 = 0°, ultrasound beam angles γ1 = -12.36°, γ2 = 0°, width of the ultrasound beam L = 12 mm, spectral tuning range Δk = 7.39−8.49 μm−1 (λ = 0.74–0.85 μm) has the FWHM of the transfer function δλ ≈ 1.8 nm. So, it can provide the maximum measurement depth 2zm ≈ 350 μm. To use full measurement depth range, the step of the spectral tuning should be dk < π / (2nzmax) = δk / 2.

The system sensitivity decrease with depth is associated with the shape of the AOTF spectral transfer function TAO, which is described by sinc2 function [6]. Thus, the intensities of the interfering beams are the sum of the intensities of the spectral components within the spectral range selected by AOTF

\[ I'_1(k_f) = \int T_{AO}(k - k_f)S_1(k)dk, \]
\[ I'_2(k_f) = \int T_{AO}(k - k_f)S_2(k)dk, \]

k_f is the AOTF wavenumber, S₁, S₂ are values proportional to the beam intensities (they take into account the light source spectrum, losses during the propagation of light through the rest of optical system other than AOTF and quantum efficiency of the sensor). Sensor’s quantum efficiency is usually selected so as to have a weak spectral dependence in the range of AOTF spectral tuning and can be considered constant. Strictly speaking, the AOTF transmission functions are not the same for both beams, but here, for the sake of simplicity, they are assumed to be the same. With this, the spectral dependence of the interference signal (1)

\[ I'(k_f) = \int T_{AO}(k - k_f)\left[S_1 + S_2 + 2\sqrt{S_1S_2}\cos\left(k_f \cdot 2(h + Δz)\right)\right] \text{rect}\left(\frac{k_f - k_{central}}{Δk}\right)dk. \]

In spectral domain it is equivalent to the convolution of the signal I(k_f) with AOTF transfer function, while in the spatial domain it is equivalent to their product

\[ I'(k_f) = I(k_f) \otimes T_{AO}(k - k_f). \]

The inverse Fourier transform of AOTF transfer function has a shape close to triangular (figure 3 left column in the middle). The deviation from triangle depends on the value of the parameter Γ proportional to the amplitude of the ultrasound wave and the length of the acousto-optic interaction L. An example of the calculated system sensitivity decrease with increasing depth is shown in figure 3, bottom row. The values are calculated for a wide-angle non-collinear AOTF described above with a spectral tuning step dk = 0.009 μm−1. The halogen lamp was used as the light source (spectrum from reference datasheets). Figure 3 right column shows experimental data for a low-coherence spectral-domain profilometer with AOTF at the output of interferometer [4]. A flat mirror was used as the object under study. Reference mirror was moved with a step ~6 μm. At each reference mirror position a series of interference images was acquired. Each series corresponds to one single response on figure 3 bottom. The AOTF transfer function was measured using a spectrometer with a resolution ~0.6 nm.

The axial depth resolution for OCT measurements depends on the width of the reconstructed single response (which is the reflection from the mirror in the sample channel) on A-scan. It can be assumed that two reconstructed single responses are resolved if they are separated from each other along the z axis at a distance equal to the FWHM of reconstructed response. According to (2), the single response is approximately described by the sinc function

\[ \text{sinc}\left(\frac{(z-2(h+Δz))Δk}{2}\right). \]
Figure 3. Intensity of reconstructed response vs depth: simulated (left column) and experimental (right column) results.

The factor $\Delta k/2$ ($\Delta k$ is the tuning range of the AOTF) gives a dilation when $\Delta k/2 < 1$ and a squeezing at $\Delta k/2 > 1$ of the sinc function along z-axis. So the width of the single reflection response function inversely depends on the tuning range. To achieve a higher resolution, a larger spectral tuning range should be utilized. The axial resolution of the system in the air will be proportional to

$$2\delta z \sim 2/\Delta k,$$

where the coefficient 2 stands for the round-trip propagation of light in reflection mode.

For previously described TeO$_2$ filter the calculated resolution is $\delta z = 3.6$ $\mu$m in air when using its full tuning range (octave) $\Delta k = 6.28$–8.49 $\mu$m$^{-1}$ ($\lambda = 0.74$–1.00 $\mu$m). In experiment (figure 3 right) spectral tuning range was $\Delta k = 7.39$–8.49 $\mu$m$^{-1}$ ($\lambda = 0.74$–0.85 $\mu$m); FWHM of reconstructed response was $2\delta z \sim 9$ $\mu$m which corresponds to depth resolution $\delta z = 4.5$ $\mu$m.
4. Conclusion
In this paper we have discussed the implementation of interference spectral-domain measurements by acousto-optic spectral filtration. In spectral-domain techniques such as OCT, a series of spectral interference images is acquired with AOTF spectral tuning. Images are processed together with Fourier transform to convert spectral domain into spatial domain and reconstruct intensity distribution of the reflected signal over the depth of the sample. When measuring the intensity distribution of the reflected signal over the depth of the sample, the depth measurement range and the depth resolution depend on the characteristics of the AOTF. The depth measurement range is physically limited by the length of the temporal coherence of the light source transmitted through the AOTF, which is inversely proportional to the FWHM $\delta k$ of the AOTF spectral transfer function. For the "full use" of this range, it is necessary to provide a step of spectral tuning of the AOTF (the step of sampling the signal along the wavenumber axis) $d k \leq \delta k/2$, otherwise the system will not be able to resolve high-frequency oscillations of the intensity of the interference pattern at a great distance from the plane of the zero path difference and the depth measurement range will be reduced. The depth resolution of the system is inversely proportional to the spectral range of the AOTF tuning, so to achieve a higher resolution, the full range of the AOTF tuning (octave) should be used. When designing low-coherence interference systems with broadband light source and spectrally tunable AOTF, these considerations should be taken into account.

Acknowledgments
This study is supported by Ministry of Science and Higher Education of the Russian Federation (project 0069-2019-0010).

References
[1] Drexler W and Fujimoto J G 2015 Optical Coherence Tomography: Technology and Applications, 2nd edition (Springer International Publishing Switzerland) p 2571
[2] Povazay B, Unterhuber A, Hermann B and Sattmann H 2006 Full-field time-encoded frequency-domain optical coherence tomography Opt.Exp. 14(17) 7661–9
[3] Machikhin A S, Pozhar V E, Viskovatykh A V and Burmak L I 2015 Acousto-optical tunable filter for combined wideband, spectral and optical coherence microscopy Appl.Opt. 54(25) 7508–13
[4] Viskovatykh A V, Machikhin A S, Pozhar V E and Pustovoit V I 2015 A multifunctional contactless profilometer based on a tunable acousto optical image filter Instr. Exp.Techn. 58 114–7
[5] Bytikov E I and Kalitievsky N I 1986 Optics: Textbook for High Schools [In Russian] (Vusshaya Shkola Moscow) p 512
[6] Yariv A and Yeh P 1984 Optical Waves in Crystals (John Wiley & Sons Inc. New York) p 616