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Suppression of image autocorrelation artefacts in spectral domain optical coherence tomography and multiwave digital holography

V.M. Gelikonov, G.V. Gelikonov, D.A. Terpelov, D.V. Shabanov, P.A. Shilyagin

Abstract. **An improved method for suppressing image artefacts in spectral domain optical coherence tomography (SD OCT) and multiwave digital holography, caused by the influence of coherent noise in the course of successive registration of an autocorrelation component and informative signal is reported. The method allows complete suppression of all types of coherent noises, provided that the sample of values used to record the autocorrelation component satisfies the conditions of Kotelnikov's theorem: in SD OCT – for the transverse structure of the studied medium, in multiwave digital holography – for the envelop function of the radiation source frequency tuning spectrum.**

Keywords: *autocorrelation artefacts, optical coherence tomography, digital multiwave holography.*

1. Introduction

The origin of optical coherence tomography (OCT) is associated with the paper [1] of the same name, published in the Science journal in 1991. OCT technology is positioned as a method of noninvasive observation of internal structure of media, scattering optical radiation, primarily, biological ones [2]. OCT has found most wide application in ophthalmology, since it appeared to be the only noninvasive method of eye fundus imaging with the resolution of 1–10 micrometres [3]. With the appearance of spectral methods in OCT [4] the imaging rapidity increased by hundreds of times as compared with earlier used correlation method [1] due to more complete employment of the optical radiation power, backscattered by the medium under study [5]. However, possessing evident advantages in rapidity and sensitivity [5, 6], the spectral method is not free of shortcomings, one of which is its high sensitivity to the presence of coherent noise. These artefacts are caused by the parasitic modulation of spectrum, the origin of which is not associated with the interference between the reference radiation and that scattered in the medium [7, 8]. In spite of a relatively large number of methods of coherent noise suppression, developed to date [9], the search for efficient methods for eliminating these artefacts is continuing. In particular, this is confirmed by recent publications [10, 11]. In multiwave digital holography, where the principle of spectral doamin (SD OCT) is used to get high longitudinal resolution [12, 13], the influence of coherent noise on the resulting images is also essential. Obviously, both in multiwave digital holography and in SD OCT the problem of coherent noise suppression may have a general solution.

In [14] an efficient method for eliminating OCT image artefacts, caused by coherent noise, was described. However, this method is well applicable only in the case, when during the interval between two or more successive A-scans no essential changes occur in the spectral structure of the radiation, backscattered by the object of study. In the OCT-based instruments the rate of recording images is inversely proportional to the number of A-scans, so that probing with the transverse step essentially smaller than the probing beam diameter significantly decreases the operation speed of the system. Therefore, direct application of the method described in [14] appears to be difficult. In multiwave digital holography the mentioned method is also well applicable only in the case, when the step of wavelength variation is small enough in comparison with the spectral bandwidth of the probing radiation.

In the present paper we propose a method for selecting a useful signal against the background of coherent noise during successive registration of informative and noise components of the signal in SD OCT, when the transverse spatial scanning step is comparable with the diameter of the probing beam, and in multiwave digital holography, when the frequency scanning step is comparable with the scale of irregularities in the spectrum of frequency tuning of the radiation source.

2. Description of the problem

The technique of compensation for the coherent noise [14] consists in separate measuring the informative and noise components of the signal. The noise component of the signal is registered during the selected exposure of the spectrum on the photodetector under the modulation of the reference arm length of the measuring interferometer. With the modulation law described in [14] this leads to averaging of the interference phase difference between the reference and sample waves and, as a consequence, to nulling the cross-correlation component in the recorded signal.

The value of the output signal U of an individual CCD element is proportional to the intensity of registered radiation. The radiation registered by an individual photodetector is a sum of the interfering reference light waves and light waves reflected by the object, the waves having the wavenumber k. Formally it may be presented as a sum of three terms,

V.M. Gelikonov, G.V. Gelikonov, D.A. Terpelov, D.V. Shabanov, P.A. Shilyagin Institute of Applied Physics, Russian Academy of Sciences; BioMedTech, Llc., ul. Ul'yanova 46, 603950 Nizhnii Novgorod, Russia; e-mail: gelikon@ufp.appl.sci-nnov.ru, paulo-s@mail.ru, terpelov@ufp.appl.sci-nnov.ru, dvshab@ufp.appl.sci-nnov.ru

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namely, the useful or cross-correlational component of the interference signal $U_{CC}(k)$, the intensity of the spectral component (determined by the sum of intensities of the reference wave and locally scattered returned waves) $U_{AC}(k)$ and the intensity component determined by mutual interference of the whole ensemble of locally scattered waves, $U_{SCC}(k)$:

$$U_{CC}(k) = 2\xi E^2(k) r \int_0^{\tau_{\exp}} \int_{-\infty}^{\infty} D(z)\cos(2kz)\,\mathrm{d}z\,\mathrm{d}t,$$

$$U_{AC}(k) = \xi E^2(k) \int_0^{\tau_{\exp}} \left[\left(\int_{-\infty}^{\infty} D(z)\exp(2\mathrm{i}kz)\,\mathrm{d}z\right)^2 + r^2\right]\mathrm{d}t, \quad (1)$$

$$U_{SCC}(k) = \xi E^2(k) \int_0^{\tau_{\exp}} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} D(z) D(z_0) \times\{\exp[2\mathrm{i}k(z - z_0)] - \delta(z - z_0)\}\,\mathrm{d}z\,\mathrm{d}z_0\,\mathrm{d}t,$$

where ξ is the coefficient taking into account the capacity, quantum efficiency and susceptibility of the photoelectric cell; r is the coefficient characterising reflection in the reference arm of the measuring interferometer; $E(k)$ is the amplitude of electric field of radiation incident on the object; z is the optical path length with the refraction in the object taken into account; $D(z)$ is the coefficient characterising the fraction of the radiation field, returned into the interferometer as a result of backscattering from the depth z with losses taken into account. The origin of the z axis corresponds to the zero path difference of interfering waves, related to the position of the exit window of the scanning system. Below, following the terminology proposed in [4], the sum of artefact components $U_{AC}(k)$ and $U_{SCC}(k)$ will be referred to as an autocorrelation component.

In [14] it is shown that introducing the phase modulation into the reference wave in accordance with the law $\varphi(t) = mF(t)$ (m is the amplitude of the phase modulation and $F(t)$ is the dimensionless modulating function varying within the interval [–1; 1]) it is possible to zero the integral over time in the expression for the cross-correlation component, which takes the form:

$$\overline{U}_{CC}(k) = 2\xi E^2(k) r \int_{-\infty}^{\infty} D(z) \int_0^{\tau_{\exp}} [\cos(2kz + mF(t))]\,\mathrm{d}t\,\mathrm{d}z. \quad (2)$$

In this case the artefact components $U_{AC}(k)$ and $U_{SCC}(k)$ remain unchanged. Subtracting the obtained signal $\overline{U}(k)$ from the signal $U(k)$, recorded at another moment of time, we get autocorrelation terms in both signals cancelled out, leaving only the useful cross-correlation component $U_{CC}(k)$. However, one should keep in mind that this is true only in the case, when the registration of informative and noise components is performed using the same optical tract or the same wavelength of the analysed radiation.

The presence of transverse scanning in the case of SD OCT or tuning of the radiation wavelength in multiwave digital holography makes it impossible to observe the useful and autocorrelation components of the signal with the absolutely identical parameters. In the first case, due to transverse scanning in the process of successive recording of the components the detected radiation is scattered by different features of the internal structure. This leads to the change in the scattered radiation intensity and the longitudinal distribution of the mutual interference of the scattered components. As a result, in transverse scanning by mechanical systems, whose inertial properties do not allow stopping and moving the probing beam in the transverse plane instantaneously (compared to the exposure time), the errors of useful component selection arise. In the second case, the radiation wavelength changes, causing the change in its total intensity. The inertial properties of the system, controlling the radiation frequency tuning process, lead to difficulties at the moment of instantaneous stop of radiation frequency sweeping.

Below for simplicity the recalculation of the autocorrelation component will be performed for SD OCT. By formal change of variables the results may be extrapolated onto the case of digital multiwave holography, where the wavelength of the probing radiation is varied.

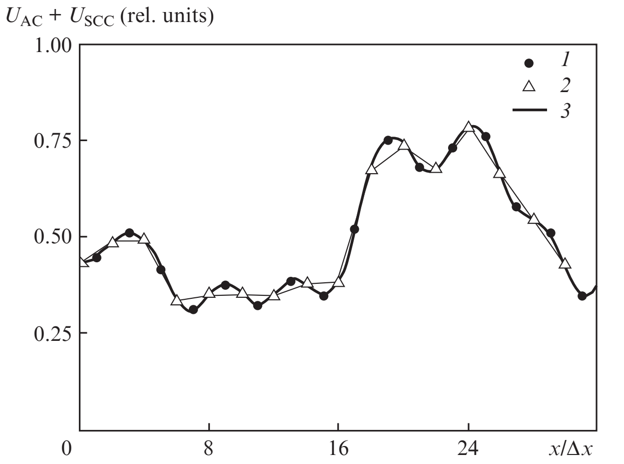
Since the structure of the studied object is, generally, inhomogeneous in the transverse direction, the quantities $U(k)$ in Eqn (1) depend also on the transverse coordinate x, i.e., $U(k, x)$. As a consequence, in the case of transverse scanning the quantities $U(k, x)$ become time-dependent, $U(k, x(t))$. This leads to incomplete compensation of coherent noise when calculating the difference $U(k,x(t_1)) - \overline{U}(k,x(t_2))$. The transverse scanning does not affect the component $U_{AC}(k)$, since the parameters of the radiation source and the optical tract remain constant during the time intervals of the order of a single-frame acquisition time. The total intensity of radiation from individual scatterers varies inessentially due to their great number. The transverse scale of the artefact component $U_{SCC}(k, x)$, caused by the mutual interference of scattered waves, coincides with the transverse scale of the structure of the cross-correlation component (see the selected fragment of the image in Fig. 2a). This may lead to incomplete compensation of the component $U_{SCC}(k, x)$ in the course of transverse scanning. In [15] the influence of the artefact component $U_{SCC}(k, x)$ is reduced at the expense of decreasing the specific power of the scattered radiation (increasing the power of reference radiation). However, because of the limited dynamical range of CCD-based photo-receiving elements, such a technique seems inefficient, since it leads to decreasing signal-to-noise ratio in the system.

3. Description of the technique

For efficient suppression of coherent noise during the transverse scanning it is proposed to use a procedure of recalculating the noise components $\overline{U}(k,x_{AC})$ to moments of time, corresponding to registration of the informative signal $\overline{U}(k,x_{CC})$. It is necessary to note that in all methods of numerical correction certain requirements are imposed on the original realisation, namely, it should satisfy the conditions of Kotelnikov's theorem. Below it is assumed that in the process of the sample scanning these conditions are fulfilled for the noise component in the transverse direction.

Linear interpolation of the reconstructed function values is the simplest one from the point of view of implementation and minimisation of computational load. However, this method gives satisfactory results only for functions that weakly change in the sampling interval, which only slightly widens the applicability of the basic technique, described in [14].

Figure 1 presents a fragment of the transverse structure of the autocorrelation component (thick curve). Triangles show the moments of registration of the autocorrelation component, circles show those of the cross-correlation one. To illustrate the linear interpolation, the measured values of the autocorrelation component are connected with rectilinear segments. Insufficient efficiency of using linear interpolation is illustrated in Fig. 2b, where in the selected segment of the image the trace of incompletely compensated autocorrelation component $U_{SCC}(k, x)$ is clearly seen.



Fragment of the transverse structure of the autocorrelation component [(*1*) are the moments of registering the cross-correlation component, (*2*) are the moments of registering the autocorrelation component, (*3*) is the profile of transverse structure of the autocorrelation component].

A method, much more efficient from the point of view of the restoration accuracy of missing values, is described in [16]. It is based on using the discrete Fourier transform of the initial array of the autocorrelation component values with respect to the argument x:

$$\overline{U}(k,x_{AC}) \xrightarrow{\text{DFT}} \overline{V}(k,K). \qquad (3)$$

The obtained array of values is completed by adding zero elements in the region of high spatial frequencies ($K > K_{max}$), which, after using the inverse Fourier transform, leads to increased effective sampling rate in the restored realisation.

Under multiple increase in the number of readings, the readings of the initial realisation are saved and the intermediate values are calculated. This makes the method particularly convenient in the case of by-turn registration of autocorrelation and cross-correlation components.

However, in spite of using optimised transformations with potentially relatively low computational load, the volume of additional computations necessary for an image with dimensions, characteristic for OCT, appears rather large. Essential reduction of the volume of necessary computations is possible if, instead of increasing the number of readings in the spectral domain followed by Fourier transform of completed array and picking the intermediate values from the obtained realisation, one will calculate the intermediate values directly.

This is possible by introducing an additive phase increment in the spectral domain with the value, proportional to the transverse spatial frequency of the OCT image:

$$\overline{V}^{+}(k,K) = \overline{V}(k,K)\exp\left(\mathrm{i}\frac{\pi}{2}\alpha\frac{K}{K_{max}}\right). \qquad (4)$$

The weight coefficient α is determined by the ratio of the autocorrelation component sampling rate to that of the cross-correlation component. In the case of by-turn registration of these components $\alpha = 1$. The use of inverse Fourier transform for the resulting array of values returns only the values, intermediate for autocorrelation component:

$$\overline{V}^{+}(k,K) \xrightarrow{\text{iDFT}} \overline{U}(k,x_{CC}). \qquad (5)$$

Estimates show that the computational load of the described method for a large number of readings in the transverse direction is 1.5 times lower than that of the method, described in [16].

4. Experimental approbation

Experimental approbation of the described technique was implemented with the OCT setup equipped with a flexible changeable OCT probe and the optical scheme with the mutual optical path for the reference and sample waves [17] and with the setup for multiwave digital optical holography [12]. The implementation of the optical scheme implies using an auxiliary Michelson interferometer, compensating the additional optical path in the measuring Fizeau interferometer, which arises between the face of the optical fibre at the distal end of the probe and an individual scatterer inside the studied medium. The application of fibre scheme for implementing the auxiliary interferometer allowed modulation of the reference arm length when registering the autocorrelation component by the aid of piezo-fibre phase modulators. We used the source of probing radiation (Superlum) with the central wavelength 1277 nm, and the spectrum of radiation was registered within 100 nm. Recording of autocorrelation and cross-correlation components was performed by-turn, as shown in Fig. 1.

Figure 2 presents the images obtained in the experiment with the model medium, composed of a polymer strongly-scattering film on a metallic substrate. In Fig. 2a, the coherent noise is not compensated. Besides the artefacts, constant in the transverse direction and corresponding to the component $U_{AC}(k, x)$, which are seen as horizontal fringes, the component $U_{SCC}(k, x)$, caused by the interference between the waves scattered by the polymer film and the wave, reflected from the metallic surface, is also well observable. The region of significant presence of the component $U_{SCC}(k, x)$ is indicated by an oval frame. The image in Fig. 2b is obtained using the basic

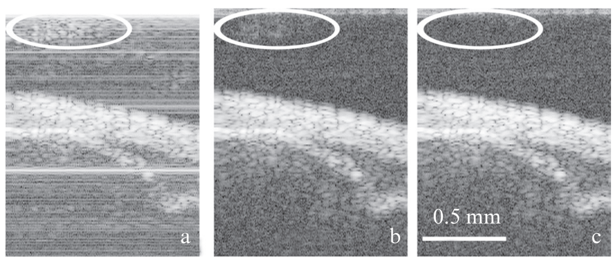


Figure 1. OCT image of a polymer film on a strongly-scattering substrate in the absence of coherent interference compensation (a), upon compensation of coherent interference using linear interpolation (b), and upon compensation of coherent interference in the spectral domain (c). The regions of strong influence of mutual interference of scattered waves are selected.

technique, described in [14]. In the selected segment the trace of undercompensated component $U_{SCC}(k, x)$ is observed, which in the clinical practice could be interpreted as the presence of scattering medium. The image presented in Fig. 2c is obtained using the technique of reconstruction of intermediate values of the autocorrelation component, described here. It is clearly seen that in the selected region the artefact image is absent.

Figure 3 presents different 2D projections of the 3D image, obtained using the digital multiwave holography method. All kinds of coherent noise are completely compensated. The tuning range of the BS840-02 source (Superlum) used in the setup and based on narrow-band acoustooptical tuneable filter appeared to be 825–875 nm.

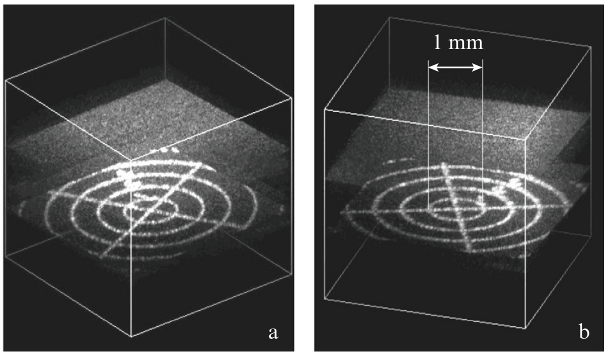


Figure 2. Viewpoints (2D projections) of a 3D image of the test target structure, deposited onto glass, in the extracted volume 1 mm^3, using the exposure through a matted polymer film.

5. Conclusions

We have proposed a method for suppressing the coherent noise in the spectral optical coherence tomography with transverse scanning of the studied medium, allowing complete suppression of coherent noise under the condition that the sample of values, used to record the autocorrelation component, satisfies the conditions of Kotelnikov's theorem; in the SD OCT – for the transverse structures of the studied medium, in the digital multiwave holography – for the envelope function of the tuning spectrum of the radiation source. The computational load of the method is 1.5 times lower than that of the method based on the effective increase in the sampling rate.

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