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FEMTOSECOND OPTICAL TOMOGRAPHY

Фемтосекундна оптична томографія

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The aim of the work is development of medical optical tomography technologies. The physical principles, tasks, and boundary possibilities of the optical tomography systems are considered. The autors propose to use the femtosecond lasers, operating in the «optical comb» mode, as a lught source in optical tomography system. The advantages of this source uses were analyzed and resolution power of femtosecond optical tomographs was calculated in the artical.

Статтю присвячено розвитку технологій оптичної томографії медичного призначення. Розглянуто фізичні принципи, завдання та граничні можливості оптичних систем томографії. Наведено напрямки та шляхи розвитку оптичної томографії. Запропоновано використання фемтосекундних лазерів, що працюють у режимі «оптичної гребінки» як джерела випромінювання в ситсемах оптичної томографії. Проаналізовано переваги використання цих джерел та виконано розрахунки роздільної здатності фемтосекундних оптичних томографів.

Ключові слова: *оптична томографія, фемтосекундний лазер, роздільна здатність, довжина хвилі, корегентність випромінювання, інтерферометр, чутливість, офтальмологія.*
Keywords: *optical tomography, femtosecond laser, resolution, wavelength, radiation correction, interferometer, sensitivity, ophthalmology.*

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INTRODUCTION

Tomography is a widely used in medicine method for step by step imagination of the object internal structure. There are irradiation (X-ray, ultrasound computer X-ray, radionuclide methods) and unirradiation tomography methods (ultrasound and magnetic resonance methods).

The irradiation methods have a high spatial resolution and give the accurate structural information. But, for example, X-ray tomography doesn't allow the classification of tumors and isn't used for patients younger than 30 years old. The magnetic resonance method can determine the chemical composition of the tissue, but it doesn't detect such important element as oxygen. Positron emission tomography has a low spatial resolution but it's very expensive and can produce a false result when a patient has diabetes. The development of optical tomography (or optical coherence tomography) methods (OT) can be a solution for these and anouther similar problems [1].

The OT method is the process of optical illumination of biological object and calculation of radiation reflection degree as a function of scanned medium layer depth. The main feature of OT is an ability to study the objects and mediums when the depth of optical radiation propagation is the several millimeters and a significant part of radiation is diffuse scattered and absorbed. The advantages of OT are based on the short wavelength and coherence of radiation.

Visible and near-infrared (IR) light with low level of radiation density is safe for biological tissuses and A human body is well adapted to this type of radiation. Light of this range penetrates well into biological tissue and, when it interactes with various structural and dynamic components, carries information about structural and dynamic changes which are the results of illness. Such processes as the diffusion, diffraction, interference, fluorescence, spring quasi-molecular and molecular dissipation are spoken in a biological middleware and are the sourses of information about pathological processes.

OT is used in dermatology, ophthalmology, cardiology, dentistry and other fields of medicine. OT method is most effective in ophthalmology because of optical transparency of the retina and visual organ media [2]. For three-dimensional imaginatination of eye it is done the scanning in the longitudinal and transverse directions. Modern OT allows to do more than 25 000 linear scans per one second. The OT methods resolution in axial length reache 3-8 microns, and in the transverse length — about 10-15 microns, which is much higher than the possibilities of ultrasonic methods. OT allows to determine and evaluate the morphological changes of the retina and nerve fiber layer and the thickness of these structures, parameters of the optic disc, anatomical structures of the anterior segment of eye and their spatial relationship.

The development of OT systems is going along the several waes. The first way is a researching the new sources, especially with a wide radiation spectrum, which have a small coherence length and can increase the resolution. The second direction is development of high-sensitivity and high-speed systems. They develop the OT systems that can in real-time observe and analys three-dimension objects and inhomogeneous mediumes that change their state.

The aim of the article is researching the possibilities of using the femtosecond lasers in optical tomography.

1. PRINCIPLES AND CHARACTERISTICS OF OT

The main part of the OT systems is the low-coherence Michelson interferometer with a wide-spectrum radiation source (Fig. 1). In the interferometer radiation is divided into a measuring wave that illuminates the object, and a reference wave, the optical path length of which can change with the controlled movement of the interferometer mirror.

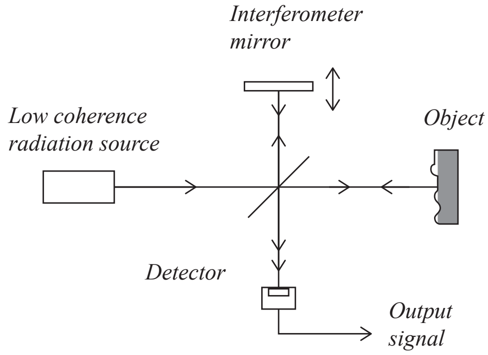

Fig. 1. Michelson interferometer scheme
Рис. 1. Схема інтерферометра малої когерентності

The low-coherence interference bands are observed when the optical path lengths of the measuring and reference waves are equal within the coherence length. Position of interferometer mirror, which achieves the maximum of bandwidth visible, characterizes the distance to the reflecting surface or the boundary of inner reflecting layer of medium. In this case there is only one perspective of probing the object in the depth with determination of distance to the reflecting layer. For formation and processing of low-coherence interferometric signals, different methods are used, especially methods of interference modulation, phase shift, and optical nonlinearity.

Another approach to layer-based sensing in the one perspective is based on the use of spectral interferometry methods. A spectral device is placed at the output of the low-coherence interferometer (Fig. 1). This device emits a narrow spectral interval for each wavelength value, which is determined by the resolution of spectroscope and recording system. In this case, the selection of the layers reflection in depth is reduced to the frequency selection of periodic spectrum components.

With a non-zero fixed optical path difference of the measuring and reference waves, the intensity output light depends on the wavelength value, that is, on the number of wavelengths within that difference. As the wavelength changes within the spectral range of radiation, bands of equal chromatic order (groove spectrum) are observed, the frequency of which is proportional to the optical path difference. In the case of inhomogeneous medium volume reflection the groove spectra for the medium are summed up and the resulting spectrum contains information about the medium inhomogeneity or about the distribution of radiation reflection degree by the depth. The advantage of spectral interferometry technique is that there is no need to move the reference reflector of the interferometer. Example of tomographic researching results is given at Fig. 2.

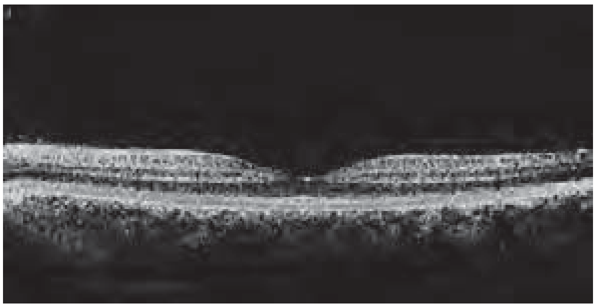

Fig. 2. Linear scan of the retina macular area
Рис. 2. Лінійний скан макулярної області сітківки в нормі

One of the main characteristics of OT is the resolution, that differs significantly in different directions: axial (longitudinal) and lateral, (transverse). In the longitudinal direction, or in the optical axis direction, the resolution δz is limited by the length of time coherence l_c:

$$l_c \approx \lambda_0^2/\Delta\lambda, \quad (1)$$

where: λ_0 is a central wavelength, $\Delta\lambda$ is a radiation line width.

In the transverse direction the resolution δx is determined by a focused beam waist diameter (Fig. 3) [1].

The selection of reflected radiation along the depth is provided by limiting of the probe radiation coherent properties. Only radiation that comes from the region of space bounded in the longitudinal direction by the temporal coherence length l_c (1) can interfere with the reference wave and can be detected. Optical inhomogeneities with sizes smaller than the temporal coherence length l_c can't be recognized by OT.

The focused beam waist has finite size, which depend on the light wave properties — the central wavelength λ_0, and focusing MO numerical aperture:

$$NA = n\cdot\sin\theta, \quad (2)$$

where n is a refractive index of medium.

Knowing λ_0 and $\Delta\lambda$, it is possible to estimate the length of focused beam waist or theoretical limit of the longitudinal resolution:

$$\delta z = l_A/2. \quad (3)$$

This value determines the allowable depth of scanning, like a depth of field in microscopy or photography.

The focused beam waist diameter, which determines the theoretical resolution limit in the transverse direction, can be estimated by the formula:

$$\delta E \approx 0,61(\lambda_0/NA). \quad (4)$$

Using the formulas (1)—(4) we can estimate the resolution parameters of the typical OT systems. For systems with $\lambda_0 = 850$ nm, $\Delta\lambda = 50$ nm, $NA = 0,1$. $\delta E \approx 5,18$ µm, $\delta z \approx 15$ µm. These results show that the resolution along the depth and along the transverse direction is significantly different. The equation (3) shows that practically the only way to increase the longitudinal resolution is to increase $\Delta\lambda$, that is, to extend the source radiation spectrum.

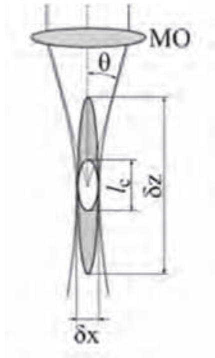

Fig. 3. Parameters defining the spatial resolution, where MO is a micro lens
Рис. 3. Параметри, що визначають просторову РЗ, де МО — мікрооб'єктив

Therefore, the development of a OT new generation should be done by increasing the axial resolution by widening the radiation spectral line.

2. BASIS OF FEMTOSECOND OPTICAL TOMOGRAPHY

Femtosecond laser (FSL) is a laser that radiate the femtosecond duration optical pulses (1 fs = 10^{-15} s) It is a tape of the fiber ultra-speed and ultra-short pulse lasers [3]. FSL can generate such a laser mode as an optical comb (or supercontinuum) (OC). OC is a special type of electromagnetic synchronization in the optical range the frequency spectrum of which loks lake a set of equidistant values with discret value equals f_{rep} (Fig. 3) [4].

The frequency v_m, which corresponds to the OC peak with number m, is determined by the relation:

$$v_{n|} = f_{rep}\cdot m + v_{GEO}. \quad (5)$$

With the help of OC they solve a group of metrological and spectroscopic problems such as measuring of intervals between two optical frequencies or values of frequency in the ranges in which otherwise

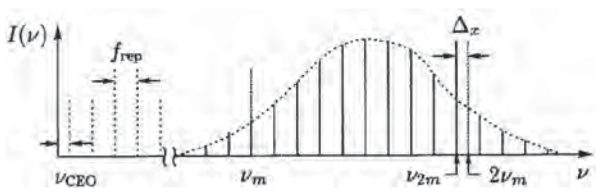

Fig. 3. Spectral characteristics (OC) of femtosecond Ti-Sa laser with passive mode synchronization, where: $I(v)$ is the radiation intensity, v_{GEO} is the offset of the peak with the number $m = 1$ of the «ideal» frequency grid, Δx is the frequency of beat signal between v_{2m} and $2v_m$ signals
Рис. 3. Спектральні характеристики фемтосекундного Ti-Sa лазера з пасивною синхронізацією мод, де: $I(v)$ — інтенсивність випромінювання, v_{GEO} — зміщення піку з номером $m = 1$ «ідеальної» частотної сітки, Δx — частота сигналу биття між сигналом v2m та 2vm

it is difficult to measure them. OC are used in the precision clocks, satellite positioning systems, high resolution laser spectroscopy, for generating of low-noise electromagnetic radiation and analyzing the cold atoms or ions state, and more. [3].

FSL is an effective research tool in biomedicine that is used, for example, for study of suture processes or diagnosis of bio-objects with submicron resolution. FSLs are used as the radiation sources for influencing at the live objects (tissues, cells, cellular organelles) with aim to change theirs structures or functions not only in basic research but also in clinical practice. FSL has been successfully used in ophthalmology for the treatment of cataract and cornea (femto-LASIK method).

Today we propose to use FSL and OC in the OT systems (Fig. 1). First this will allow us to select the scanning frequency v_m (5) depending on the test substance transparency in the OC frequency range. Secondly, the OC broad band radiation $\Delta\lambda$ will increase the OT resolution values (3), (4). Third, the femtosecond interval of pulse effects on live cells does not cause the latter to significantly heat.

Consider some FSLs and their radiation characteristics and consider the characteristics of OTs developed on these lasers basis. When using femtosecond Cr: Forsterite laser with λ_0 = 1250 nm, $\Delta\lambda$ = 125 nm, pulse duration τ = 5,4 fs longitudinal resolution of OT $\delta z \approx 6,2$ µm. When using Ti: Al_2O_3 FSL based on photonic crystall fiber with λ_0 = 1050 nm, $\Delta\lambda$ = 550 nm OT has an axial resolution δz = 1 µm. When using Ti: Al_2O_3 FSL with characteristics: λ_0 = 800 nm, $\Delta\lambda$ = 350 nm, pulse duration τ = 5,4 fs the OT resolution $\delta z \approx 0,91$ µm. The obtained values significantly exceed the resolution level of standard OTs using superluminescent diodes [5] and allow us to predict good prospects for the development of femtosecond optical tomography methods.

CONCLUSIONS

Analysis of literature revealed the main directions for development of optical tomography systems, the main of which is the search for new radiation sources with wide spectrum and small coherence length. Using such sources it will be impossible to increase the resolution of tomography.

For solving this problem in the paper the possibilities and prospects of using femtosecond lasers in optical tomography systems were researched. The obtained analytical and mathematical results show that the use of femtosecond lasers will allow us to choose the frequency of scanning radiation depending on the transparency of investigated substance in the wide frequency range of the optical comb and, due to the broad band of radiation, it becomes possible to increase the resolution value to 1 µm.

The results of the work begin a new direction of femtosecond optical tomography.

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