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Straightforward optical transmission method for visualization of highly-absorbing and scattering objects

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We present technique and initial results of optical screening and imaging of highly scattering and/or absorbing media, including biological objects. The method relies on scanning a weak modulated laser beam across the tested object followed by highly-sensitive lock-in detection, PC-acquisition and data processing. Modulation of laser beam amplitude is synchronized with computer-controlled scanning step and subsequent synchronous detection followed by real-time data processing allowing to enhance the spatial resolution and significantly reduce the overall variation of the transmitted signal. The preliminary studies have shown principal applicability of the suggested technique for medical diagnostics, biology, quality control and homeland security.

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1. Introduction

Screening, imaging and mapping of various objects, including biological, is important problem in different areas of technology, medicine, biology, as well as for security check and other applications. Conventional techniques of screening and tomography are based on the use of nuclear magnetic resonance, X- and γ- rays, terahertz radiation, ultrasonic acoustic waves, etc. It is quite intuitive and natural that visible and near-infrared optical radiation was not seriously considered for this purpose: indeed, the screening problem arises from the necessity to visualize features, which are hidden in the optical domain. Meanwhile optical screening technique, being non-ionizing, and hence harmless for studied substance, could serve as an alternative to known ones, especially in medicine where safety, portability, and low cost are of utmost importance. For biological tissues, optical screening is favored in the near infrared wavelength region (650–1300 nm), centered at 830 nm [1]. This spectral region is out of absorption range for chromophores. Nevertheless, even with optimum wavelength, the direct optical screening is a challenging task: because of strong scattering, the image pattern distorts already at millimeter thickness. Even stronger scattering occurs while passing the skin. The number of photons, which penetrate undeflected through the sample (so called "ballistic photons") decreases exponentially with the tissue thickness. There are yet another (more numerous) channeled groups of photons ("snake light") propagating at small solid angle in forward direction and experiencing less attenuation. But the majority of photons entering tissue contribute to diffused (scattered) light component, which is practically unusable for transmission imaging [1,2]. The characteristic scattering in tissues is commonly expressed in terms of the transport scatter coefficient μ_s with the typical value of ~ 1 mm^{-1} or even higher [2].

Therefore, straightforward optical transmission imaging measurements were found not efficient, and sophisticated techniques have to be implemented to bypass the problems caused by scattering. Thus, the three types of photons (ballistic, snake, and diffused) can be distinguished in imaging through tissue by spatial or temporal filtering. The ballistic light reaches photodetector first, followed by snake light, and finally the diffused component arrives after multiple zigzags in the tissue bulk. Use of picosecond lasers and gated detection technique allows one to selectively record the chosen group, by varying the detection delay [3]. Coherent detection imaging system [4], or heterodyne imaging [5] is successively used to enhance the image contrast in laser computer tomography. It is efficient also to combine optical imaging technique with fluorescence and Raman scattering spectroscopy, to apply radiation modulation and lock-in (phase-sensitive) detection, etc. In spite of these efforts, optical tomography is still too far from being commercially available versatile medical tool.

The present state of the art of optoelectronics allows one to realize both fine spatial resolution (down to ~ 0.1 μm) and high detection sensitivity (several hundreds of photons per μs-range time period) using inexpensive and compact devices. We intend to use this circumstance combining it with lock-in detection for studying the possibility of imaging (mapping) ballistic and least deflected photons transmitted through thick highly scattering/absorbing media.

2. Research method and measurement technique

There are two possible approaches (or their combinations) for solving the optical transmission screening and imaging problem: i) broad-beam illumination and detection of transmitted radiation by a 2D matrix photo-detector; ii) synchronous spatial scanning of

a narrow optical beam and solitary photo-detector. Though the second option implies utilization of mechanical or optoelectronic deflection system, which complicates the device and can slower its operation, it is advantageous because of higher attainable sensitivity. The second approach is chosen as basic one for our studies.

We propose a simple and inexpensive diagnosis technique of direct transmission imaging justified for specific biomedical applications. The method relies on highly-sensitive lock-in detection, acquisition and data processing techniques. We present initial results of optical screening and imaging of highly scattering and/or absorbing media, including biological objects such as human palm and wrist. As is mentioned above, the optimum transmission for biological tissues occurs in the near infrared wavelength region (650–1300 nm); even in this case the direct optical screening is blinded by strong scattering already at millimetre thickness.

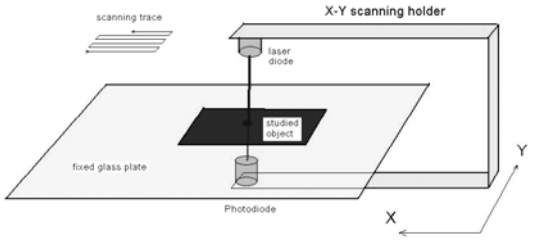

Fig. 1. Schematic drawing of 2D scanning head and unmovable object table.

To overcome this problem, we have used the following experimental approach. The studied object is placed on a flat unmovable object table located between the laser diode (λ = 780 or 850 nm, P ~ 5 mW, Ø 1 mm) and solitary photodiode followed by operational amplifier (see Fig. 1). The laser diode and photodiode are connected rigidly on a movable 2D X-Y scanning holder which is controlled with stepper motors. We have realized computer control and processing of the acquired data, which is an important component for optical transmission imaging. The latter allows to easily adjust the number of X and Y pixels and the scanning rate (linked to sensitivity) depending on particular task. The National Instruments LabPC-1200 DAQ card controls X and Y translations of the holder with a code written in LabVIEW language, providing desired number of points and scanning step for the chosen mapping area, with a temporal step starting from 0.01 s.

Implementation of modulation of laser diode amplitude synchronized with measurement step and synchronous detection of the photodiode signal using lock-in amplifier followed by real-time data processing allowed us to attain the maximum sensitivity determined by noise equivalent power (NEP) of the photodiode, as well as to reduce the hindering contribution from the background illumination and gradual overall transmission changes across the object. Phase-sensitive lock-in detection also helps to diminish multiply scattered (diffused) light component and enhancing the contribution of the signal originated by ballistic and least-deflected photons. In our studies we have used Stanford Instruments SR5100 analog lock-in amplifier.

At each step, the DAQ card averages specified number of measurements of lock-in amplifier voltage, storing this value in a resulting data file. The latter is then presented graphically as a grayscale graph or 3D image with Z axis showing the intensity of the transmitted radiation.

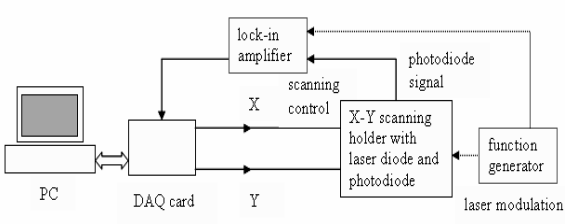

Fig. 2. Block-scheme of the experimental setup.

Assembled and tested experimental prototype device is shown schematically in Fig. 2.

3. Results

Examples of the screening run for flat scattering/absorbing objects at 780 nm wavelength illumination are shown in Fig. 3. The objects we have used are a steel razor (a) and leaf (b), which enclosed between 20 sheets of printer paper, by 10 from each side, combine high scattering of paper sheets with strong absorption of the sandwiched sample. Note that the hidden samples were surely indistinguishable by naked eye when we tried to recognize it shining powerful light (even laser beam) from rear side. Though the paper sandwich causes very strong diffusion, its small and uniform thickness makes impossible generalization of this result to the case of centimeters-thick biological tissue, with inhomogeneous distribution of matter and thickness.

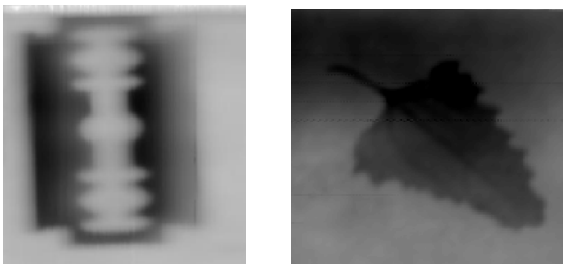

Fig. 3. Images of 2D objects: a steel razor (a), and leaf (b) hidden between layers of scattering media (see text).

Nevertheless, the attained spatial resolution and imaging contrast are shown to be sufficient to distinguish the bone, tendon and vascular structure, which will be useful for revealing fractures, tumors and anomalies. The

preliminary studies have shown principal ability of the suggested technique.

We have tested our setup also for screening of biological objects, such as human hand, shown in Fig. 4 as a grayscale graph showing the transmission signal.

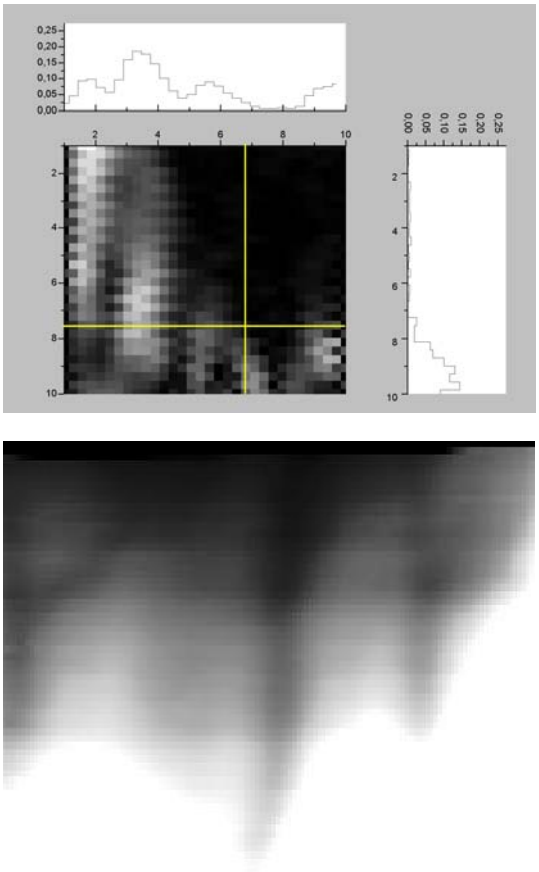

Fig. 4. Images of human hand (fragments of palm area excluded fingers) taken with 30 x 30 (upper picture) and 500x500 (lower picture) X-Y scanning.

4. Discussion

As one can see from Fig. 3, the proposed method is directly applicable for studying thin (~ 1 mm) uniform complex objects such as sandwiched absorbing media enclosed between scattering layers. Similar results have been obtained for the case of several cm-thick uniform macro-homogeneous scattering layers, e.g. foam rubber. Nevertheless, present work was mainly aimed at revealing internal structure of variable Z-profile complex 3D objects such as biological matter.

Summarizing the results of palm screenings, one can state the following. 1) Even for the thickest area of the hand, the transmitted light is still well above the registration noise level. 2) Though the image contrast is rather poor because of remnant diffused light, one can clearly distinguish location and outlines of bones. 3) The overall signal level may vary nearly 2 orders of magnitude while scanning across the hand. The preliminary results confirm potential applicability of the proposed method to reduce the complicating gradual thickness variation contribution. The method does not require complex, bulky and expensive hardware.

We have outlined the following particular tasks for the optimization of system performance: i) enhancement of electronic schemes, optimization of lock-in regime; ii) improvement of the 2D scanning system; iii) use of laser diodes with different wavelengths; iv) implementation of polarization analysis; v) different optical systems for beam formation and collection; vi) development of software support for image.

5. Conclusion

We have studied the possibility to use a simple direct optical transmission technique based on synchronous spatial scanning of a narrow optical beam and solitary photo-detector, for optical screening of some flat and biological objects. The preliminary results confirm potential applicability of the method.

Acknowledgement

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