Optics and Spectroscopy, 2025, Vol. 133, No. 12

Special book „Bio-photonics“ in the memory of Vladimir L. Kuzmin

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DOI: 10.61011/EOS.2025.12.63174.49-25

Special section „Bio-photonics“ of the journal „Optics and spectroscopy“ is dedicated to the memory of Vladimir Leonidovich Kuzmin, an outstanding scientist and leading expert in the field of optics and light scattering physics (1940–2025). On May 7, 2025, Vladimir Leonidovich would have turned 85. For over than fifty years of his

scientific activity, V.L. Kuzmin has made a fundamental contribution to the development of the theory of multiple light scattering, focusing on practical application of his theoretical research to address the current challenges in bio-photonics. Vladimir L. Kuzmin has been widely recognized in the scientific community as one of the leading experts in propagation of electromagnetic radiation in highly scattering media. His fundamental review, co-authored with V.P. Romanov [1], became the basis for a whole generation of researchers in coherent effects of light scattering in disordered systems. V.L. Kuzmin's theoretical studies on propagation and scattering of light in randomly heterogeneous media [2] laid the foundation for modern optical diagnostics methods that are widely used in biomedical applications.

V.L. Kuzmin's contribution to the development of stochastic methods for modeling radiation transport deserves special attention. In 2004, based on combining the Monte Carlo numerical method and an iterative procedure of the solution of the Bethe–Salpeter equation, he jointly with I.V. Meglinski developed a generalized computational approach for modelling the propagation of optical waves in random media [3–5], which laid the foundation for numerous studies of coherent effects in multiple scattering. One of the key features of these works is an ability to model the depolarization of optical radiation in scattering media, which allowed coherent phenomena [6–8] to be described with high accuracy, such as enhancement of coherent backscattering and temporal intensity fluctuations of light.

V.L. Kuzmin made a significant contribution to the development of the theoretical foundations of electrodynamic modelling of scattering media, enabling the transition from a molecular-level description to the macroscopic characteristics of randomly inhomogeneous media and revealing the nature of such phenomena as critical opalescence, coherent backscattering, and depolarization of light in anisotropic media [2,9].

In 2006, V.L. Kuzmin took an active part in organizing a special issue of the journal „Quantum Electronics“ entitled „Problems of Laser Radiation Scattering in Photonics and Biophotonics“ [10]. His review paper, co-authored with I.V. Meglinski, on the fundamental problems of numerical modelling of coherent backscattering effects and temporal intensity correlations [11], as well as the pioneering development of the vector Monte Carlo method for problems of polarization sensitive optical coherence tomography (OCT) [12], became important milestones in the development of biophotonics. The proposed vector method has been actively used to study the interference component of low-coherence backscattering [13,14], to imitate OCT images [15,16], and to study the propagation of light pulses in randomly inhomogeneous media [17].

Particular attention deserves a series of studies by V.L. Kuzmin on the propagation of circularly polarized light in strongly scattering random media, the discovery and comprehensive study of anomalous polarization phenomena, including the polarization memory effect [18,19–21]. These studies made a substantial contribution to the understanding of polarization phenomena in multiple scattering of light in biological tissues.

In 2012, V.L. Kuzmin, together with his students and colleagues, contributed significantly to the theory of propagation of light pulses and elastic waves in semi-infinite elastic media [22]. He derived an exact formulation of the tensor Green's function of a harmonic field, which represented a notable advance in the description of wave phenomena and is of considerable importance for geophysics and seismic monitoring.

Since 2015, V.L. Kuzmin has been actively involved in the study and modeling of photon-density diffuse waves, as well as in the further development of diffusing wave spectroscopy [23–25]. In recent years, he has been interested in the problem of delivering optical radiation deep into the brain for the purposes of laser therapy and optogenetics, including work on optical clearing of biological tissues and optical diffusion tomography [26–28].

This special section brings together works reflecting the development of directions established by Vladimir Leonidovich, and new ideas inspired by his scientific legacy. Publications cover a wide range of issues — from fundamental aspects of light interaction with highly scattering media to the application of modern laser and photonic technologies in biomedicine.

Zhavoronkov et al. performed computational modeling of laser infrared radiation propagation and backscattering in multilayer biological tissues, taking into account the geometry of real curvilinear surfaces, using the example of a human head model. An iterative solution of Bethe-Salpeter equation in the ladder approximation was used in combination with Monte Carlo method to calculate multiple scattering of light in media with different radii of curvature. The results were compared for models with flat and spherical boundaries, and the effect of layers thickness and curvature on the distribution of backscattered radiation intensity was shown. The obtained dependencies allow estimating the errors of approximating flat models and demonstrate the possibilities of using computational modeling for the diagnosis of intracranial injuries and optical tomography of the head.

Doronin et al. propose a new vector-based Monte Carlo algorithm for simulating the propagation of coherent polarized light in scattering media, taking into account interference, phase delay, and polarization rotation during multiple scattering. The method is based on tracking the full electric field vector along the photon trajectory and is realized with some improvements for Apple M energy-efficient processors, ensuring high performance and low power consumption during real-time simulations. The algorithm supports time- and polarization-resolved detection modes, ensuring a precise reproduction of coherent and polarization scattering effects. The results are verified based on analytical solution of Milne problem and demonstrate high precision with a way lesser computational cost, paving the way for a new generation of computational modeling tools in biomedical optics and photonics.

The study by Sergeeva et al. is focused on numerical analysis of boundary conditions and skin structure impact on precision of optical characteristics reconstructed in the method of optical diffusion spectroscopy (ODS). Using Monte Carlo simulation and an analytical signal model, single-layer and double-layer (epidermis + dermis) skin models were studied for contact and non-contact registration of reflected signals. It was highlighted that contact probing provides the absorption and transport scattering coefficients reconstruction with an error of no more than 10%, whereas in case of non-contact registration, the influence of total internal reflection and the surface layer of epidermis leads to a systematic underestimation of the absorption coefficient and an overestimation of the scattering coefficient. The findings demonstrate the need to allow for the boundary effects and skin structure when interpreting ODS data and developing non-invasive optical diagnostic methods.

Kistenev et al. proposed an improved method for decomposing the absorption spectra of gas mixtures of unknown composition with an arbitrary number of components, based on minimizing the „complexity" of the spectrum after removing the contribution of individual components. The complexity criterion is based on the integral area of the module of the spectrum first derivative, which allows for efficient estimation of the concentrations of target gas impurities without prior knowledge of the complete composition of the mixture. The developed multidimensional version of the spectrum reduction method (multiRSC) demonstrated high resistance to noise and accurate recovery of concentrations of small gas components in atmospheric air down to tens of ppb levels, opening up new possibilities for spectral analysis of natural and biological gas samples.

In the work by Berezin et al., the mechanisms of optical clearing of human skin *in vivo* were experimentally and theoretically studied under exposure to a 50% aqueous urea solution. Using the optical coherence tomography method, it has been shown that urea effectively reduces the scattering coefficient in the dermal layer, resulting in significant tissue clearing. Molecular modeling based on methods of quantum chemistry and molecular dynamics confirmed the formation of stable urea complexes with collagen peptides, accompanied by destructed hydrogen structure and water partially displaced from the protein's hydrate shell. A combination of experimental and theoretical data enabled us to refine the correlation between the energy of intermolecular interaction and the efficiency of optical clearing, opening up the prospect of a targeted selection of optical agents in biomedicine.

The work by Umerenkov et al. presents the analysis of nitric oxide (NO) gas transmitter effect on the aggregation activity of human platelets *in vitro* performed by method of turbidimetric laser aggregometry. The dose- and time-dependent effect of a direct NO donor, sodium nitroprusside, on the kinetics of platelet aggregation, assessed by changes in the light transmission of platelet-rich plasma, was studied. It has been shown that nitric oxide has a pronounced inhibitory effect on the aggregation process even at low concentrations, which is associated with the activation of NO/s-GC/cGMP/PKG signaling pathway. The results confirm the potential of using NO donors to correct platelet aggregation disorders and demonstrate the potential of laser aggregometry as a highly sensitive optical method for analyzing the micro-rheological properties of blood.

Platonova et al. proposed an experimental study of diffuse light scattering in double-layer scattering media using a newly designed multi-channel sapphire fiber probe. The method is based on the analysis of a spatially resolved diffuse signal in a stationary mode and allows to find the effective extinction coefficient of heterogeneous biological media. To verify the approach, liquid and polyacrylamide phantoms with different top layer thicknesses and scattering contrasts were fabricated. The probe is highly sensitive to a 1 mm shift in the layers interface and can detect internal inclusions at depths of up to 3 mm. The findings demonstrate high potential of using multi-channel sapphire probes for non-invasive diagnostics and optical monitoring of biological tissues state.

The study of Kasyanenko et al. gives an insight on the interaction of near-infrared laser radiation (1.45 and 1.56 μm) with avascular biological tissues of various thicknesses and modified absorption coefficients due to the diffusion of such clearing agent as glycerol. A comprehensive analysis of the temperature and optical responses of cartilage samples with a thickness of 100 μm to 2 mm, which is comparable to the thickness of the eardrum and articular cartilage, has been conducted. It was found that a thickness of about 500 μm is a threshold value: when this value is exceeded, the dynamics of the transmitted radiation and the thermal response of the tissue change significantly. It has been shown that varying the wavelength and concentration of glycerin allows to control the depth and intensity of heating, as well as the spectral clearing of a biological tissue. The obtained results are of practical importance for optimizing the laser specifications in reconstructive surgery, thermoplasty, and optical therapy of avascular tissues.

The work by Borisov et al. provides a numerical study of the characteristics of resonant optoacoustic detectors (OADs) with variable section cylindrical resonators. Based on a dynamic model, it is shown that higher resonator radius in the region of the standing acoustic wave's antinode leads to a rise of pressure amplitude and, consequently, to an increased detector sensitivity. The findings showed that the traditional analytical sensitivity calculation formulas used for constant-section resonators couldn't adequately describe the behavior of systems with a variable profile. The developed approach gives opportunities for optimizing the design of highly sensitive optoacoustic spectrometers designed for the analysis of volatile molecular markers in exhaled air and for environmental monitoring.

In the study by Kirillin et al. the Monte Carlo method was used to model the optical characteristics of a multilayer medium simulating the biotissue of a human finger at three wavelengths of the green, red and IR ranges; this modeling was used to select the best source-detector distance in the optical layout of a wearable device intended for reflective photoplethysmography and pulse oximetry. This modeling gives new options for improving the design of reflective photoplethysmography and pulse oximetry wearable devices featuring high precision. Vaks et al. are developing a new approach based on THz spectroscopy and metabolomics to identify cancer markers, which is important for early detection of cancer, including urothelial cancer. In this study, the chemical composition of thermal decomposition products of the primary metabolites of bladder tumor tissues was studied for the first time using high-resolution THz spectroscopy methods.

Stepanov et al., assessed the thermal indices of facial skin perfusion using IR thermography method. The impact of anesthesia induction on the kinetics of temperature variation in different facial areas due to changes in microcirculation was studied. This allowed the authors to verify the ability of IR thermography method to quantify local skin blood flow disorders.

The editors express their sincere gratitude to all authors of this collected volume for their active participation, and to the editorial board of the journal „Optics and Spectroscopy" for the opportunity to publish this work and for their assistance in preparing the volume.

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Translated by J.Savelyeva