

Optical properties of polymer-dispersed liquid crystal films as basic elements of imitation measures for calibration of photoplethysmographic devices

© D.G. Lapitan, A.P. Tarasov, L.S. Kapustin, D.A. Rogatkin

Moscow Regional Research and Clinical Institute named after M.F.Vladimirsky (MONIKI), Moscow, Russia

e-mail: lapitandenis@mail.ru

Received November 13, 2025

Revised January 30, 2026

Accepted March 27, 2026

An experimental setup was assembled and the optical properties of two polymer-dispersed liquid crystal films were studied. Transmission spectra of the films were constructed in the UV, visible and near-infrared ranges. Electro-optical curves (transmittance versus applied voltage) were calculated for wavelengths of 515 and 632 nm. Using the two-stream Kubelka-Munk model, the electro-optical curves were then converted into the scattering coefficient of films. At a wavelength of 515 nm, the scattering coefficient of the first film varies in the range of $45\text{--}5\text{ cm}^{-1}$, while the scattering coefficient of the second film varies in the range of $38\text{--}21\text{ cm}^{-1}$ with the applied voltage changing from 0 to 60 V. It was shown that both films can simulate the modulation depth of the photoplethysmographic signal (AC/DC ratio) within the physiological range and, thus, are suitable for use in the developed working simulation measures.

Keywords: polymer-dispersed liquid crystal film, optical properties, transmittance, scattering coefficient, working simulation measure, photoplethysmography.

DOI: 10.61011/EOS.2026.05.63854.62-25

Introduction

Development of optical phantoms simulating the optical properties of real biological tissues is an important task in the field of optical noninvasive diagnostics [1,2]. Such methods as laser Doppler flowmetry, laser doppler imaging, photoplethysmography (PPG), etc., can be specified here with respect to tissue circulation study [3]. Phantoms that mimic tissue circulation are important for such methods. Since, blood flow is a dynamic process, then phantom becomes a measuring tool — a working simulating measure (WSM) designed to store and reproduce a measured quantity, unit of this quantity, mimicking the time-varying behavior of the quantity. For example, for the laser Doppler flowmetry, the best known WSM is the PF 1000 Calibration kit with a Motility standard (Perimed AB, Sweden) [4]. Working principle of this phantom is based on the Brownian motion of polystyrene microspheres in solution and formation of the Doppler frequency shift when light scatters on them.

There are also phantoms made on the basis of photopolymer rubber, gelatin, agar-agar, intralipids, various gels, paraffin, etc., combined with dyes (indocyanine green, Indian ink, etc.) for mimicking optical properties of blood and other tissue components [5,6]. For example, for PPG, there is an optical phantom on the basis of gel with various concentrations of hemoglobin to mimic individual time points on a pulse wave [7]. However, such approach has obvious disadvantages — a new solution shall be prepared for each characteristic point, and the more points are to be simulated, the more solutions are required. There are phantoms in the form of tubes, via which blood is

pumped [8]. Such phantoms also have some disadvantages: first, they are difficult-to-make, second, solutions get dry with time, therefore new solutions shall be prepared each time and, third, repeatability of measurements is low on such phantoms. Thus, there is still an outstanding problem concerning the repeatability of parameters for various liquid, gel and other „hand-made“ phantoms [1].

Meanwhile, there is another technique designed to simulate tissue blood flow parameters. This is a polymer-dispersed liquid-crystal (PDLC) film with electrically controlled optical properties. PDLC consists of liquid crystals that are arranged chaotically when there is no voltage to make the film a heavily scattering medium, and, when a voltage is applied, crystals align along one direction, light scattering by the film decreases and the film becomes more transparent. The film-control voltage varies within 0–110 V, however, a maximum transparency is achieved as early as at 60 V. Therefore, these materials have been recently widely used in various devices — modulators, glasses, smart windows, etc. [9,10].

PDLC films can be also used for simulating circulation processes in tissues and, in particular, the PPG signal. We have earlier patented this idea [11] and proposed a three-layer WSM structure based on such film [12]. A detected PPG signal is known to represent a sum of two components: a variable (AC) component that is formed by arterial blood flow pulsations, and a slowly varying (quasi-constant, DC) component induced by light absorption in fixed tissue structures and by a mean blood volume [13]. AC/DC ratio is often treated as a PPG signal quality indicator. Thus, WSM, despite its structure and operating principle, shall reproduce an AC/DC ratio approximated to real tissues. In

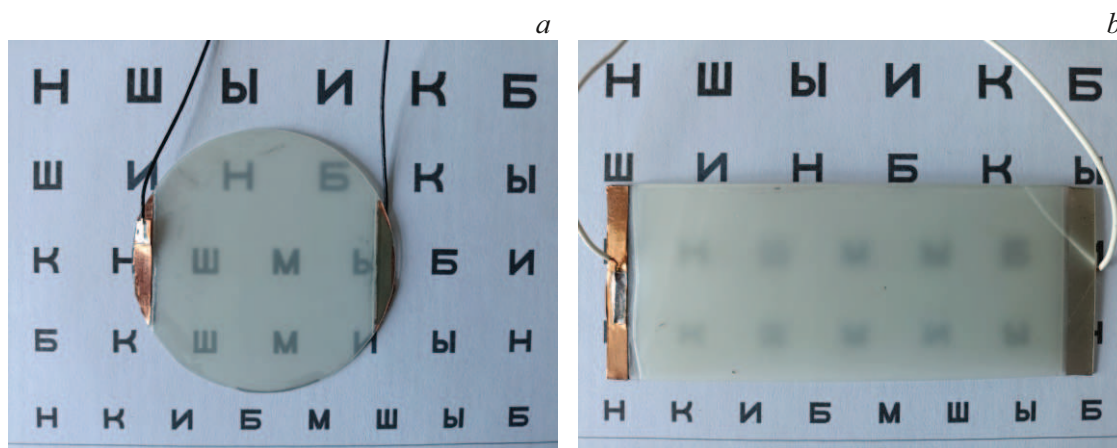


Figure 1. PDLC films used in the study: sample 1 (a) and sample 2 (b).

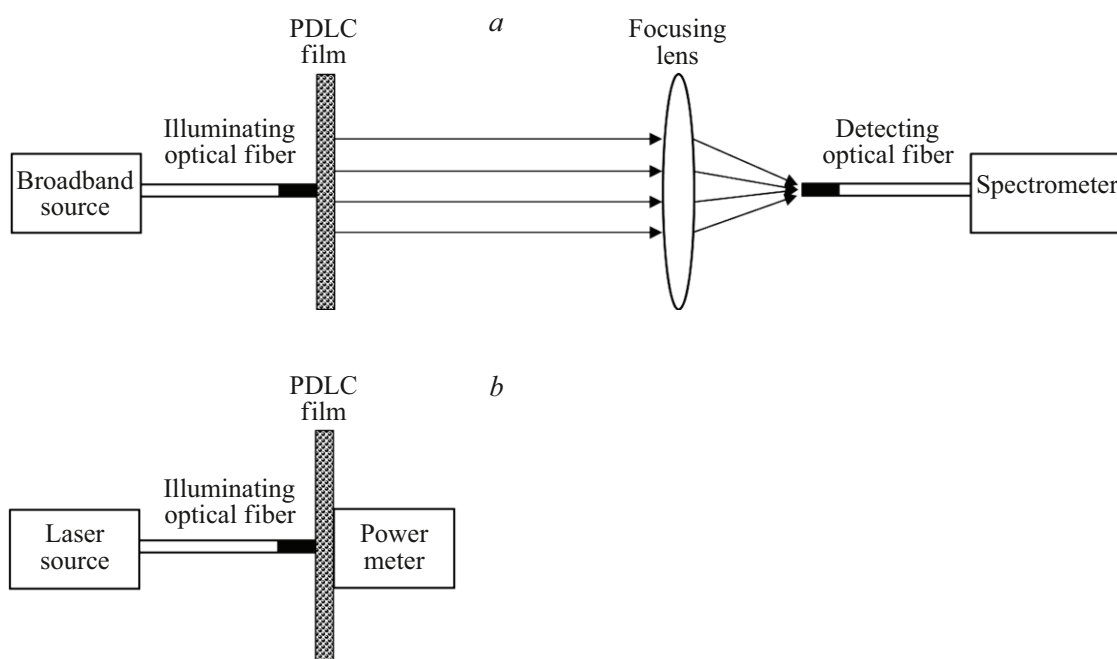


Figure 2. Schematic diagram of the experimental system for examination of optical properties of PDLC films: for measuring transmission spectra (a) and transmittance at a particular wavelength for different applied voltage levels (b).

the proposed three-layer WSM [12], the AC component is simulated by applying an AC voltage to the PDLC film, and the DC component is formed by means of light scattering on a PTFE substrate and absorption on a special optical filter. The measure works in „back scattering“ mode, however, it can also work „transmission“ mode with small layer size modification. Since the AC/DC ratio depends both on blood pulsation amplitude in arteries and on optical properties of tissue, then by varying the modulation depth of an AC signal applied to the PDLC film and by selecting various absorbing optical filters, the AC/DC value can be simulated for various wavelengths.

Optical properties of PDLC films shall be known for precise simulation of optical radiation propagation in such

multilayer WSMs and calculation of a reproducible quantity. However, optical properties of such films are still unknown and depend on many factors (concentration of liquid crystals in the polymer matrix, impurities in the polymer matrix, etc.), and, therefore, can vary between films. The purpose of this work was to measure an optical property variation range for two PDLC film samples depending on the applied voltage to justify the magnitude of AC/DC.

As for optical properties (absorption and scattering coefficients) of materials, full and/or specular transmission and reflection data are often used to determine these properties [14,15]. Then, to evaluate directly absorption and scattering coefficients on the basis of obtained experimental data, various approaches can be used, including *adding-*

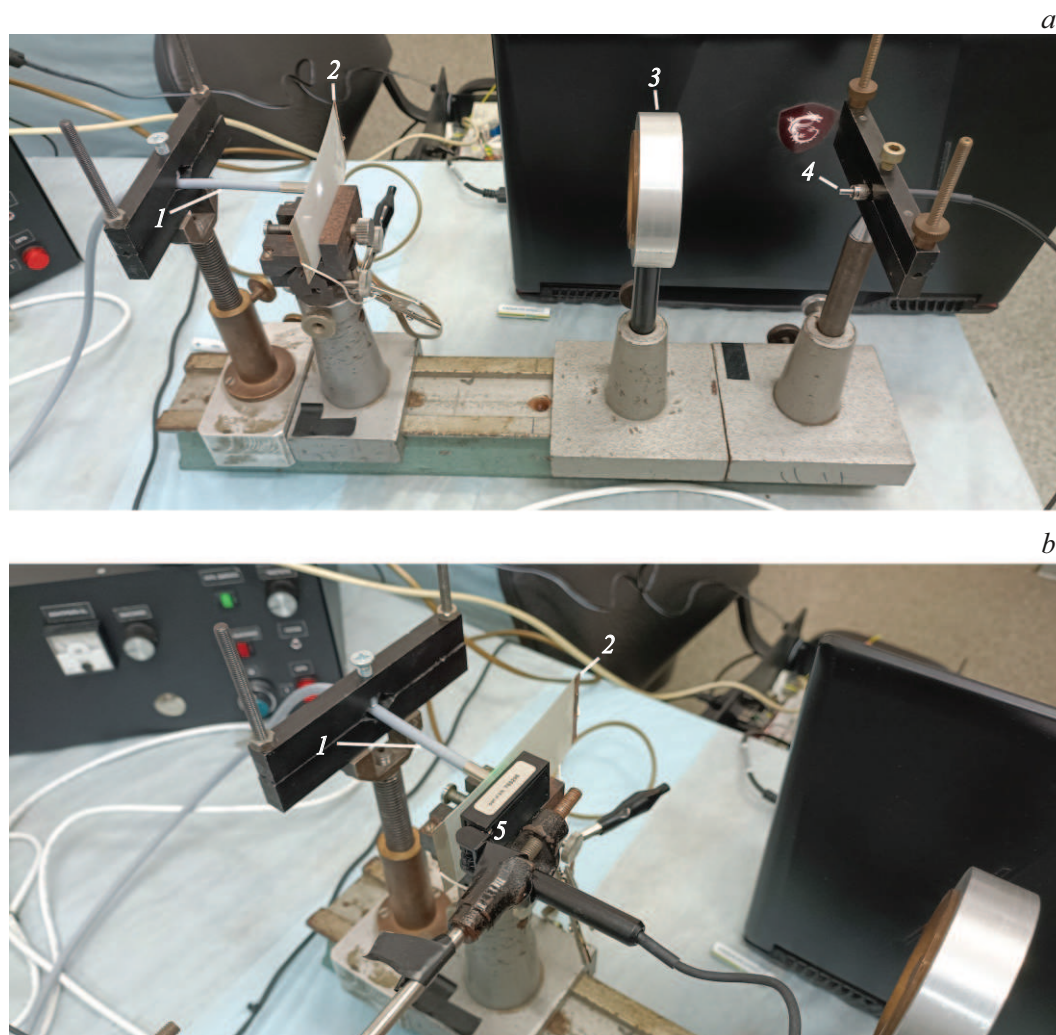


Figure 3. Photographs of the experimental system, (a) and (b) correspond to the system configurations in Figure 2. 1 — illuminating optical fiber, 2 — PDLC film, 3 — focusing lens, 4 — detecting optical fiber, 5 — power meter.

doubling [16], *inverse Monte Carlo method* [17], and *Kubelka-Munk model* [18]. We have used the *Kubelka-Munk model* because it adequately suits a multiple scattering and non-absorbing medium, with the PDLC film being such medium.

Materials and methods

Photographs of the test film samples are shown in Figure 1. Films were custom-made by Inter-systems for research purposes. Films have different shapes due to different structural forms of the developed WSM, but this doesn't influence their optical properties in any way. Thickness of both films is 0.045 cm.

To study optical properties of these film samples, an experimental system was fabricated, see Figure 2 for the schematic diagram. Photographs of the experimental systems are shown in Figure 3. To study spectral properties of films, i.e. for qualitative evaluation of transmission

spectra in different states, the system was assembled in the following configuration (Figure 2, a). Light from a broadband light source — GLORIA-X150A xenon lamp (Zolix Instruments CO., LTD) — strikes the film through 400 μm multimode optical fiber, gets scattered in the film, then is collected by a quartz lens into 600 μm detecting optical fiber and is detected by a spectrometer. The Multikom spectrometer [19] with an operating range of 200–1100 nm was used. Measurement were performed with film in OFF state (zero voltage), film in ON state (60 V) and without film to record a light source spectrum and without a light source to evaluate external background light (noise). Then a noise spectrum was subtracted from spectra obtained on the films, and the calculated values were normalized to the light source spectrum:

$$S_{\text{PDLC,trans}}(\lambda_i) = \frac{S_{\text{PDLC}}(\lambda_i) - S_{\text{noise}}(\lambda_i)}{S_{\text{source}}(\lambda_i)}, \quad (1)$$

where $S_{\text{PDLC,trans}}(\lambda_i)$ is the PDLC film transmission spectrum in arbitrary units, $S_{\text{PDLC}}(\lambda_i)$ is the total PDLC film

spectrum, $S_{\text{noise}}(\lambda_i)$ is the noise spectrum, $S_{\text{source}}(\lambda_i)$ is the light source spectrum.

The second system configuration option was fabricated for measuring film transmittances depending on the applied voltage (Figure 2, *b*). For this, the Multicom 515 nm and 632 nm laser sources were used. The green and red wavelength ranges are actively used in modern PPG measurements [3]. Laser light transmitted through the films was detected using the StarLite power meter (Ophir Optonics Solutions Ltd., Israel), whose sensing head was placed in the immediate proximity to the test film. Instrument error of the power meter is 2%. Coherent laser light made it possible to focus more accurately the light beam scattered by the film into the 1×1 cm power meter head and, thus, to consider side scatter components. During the experiment, voltage applied to the film was varied from 0 V to 60 V at 5 V intervals. For repeatability assessment, measurements were performed 5 times (in different days). Further, a mean value and RMS deviation (RMSD), which reflects a measurement-method error here, were calculated.

Further, the obtained experimental data were used to calculate the scattering coefficient of films. For this, the one-dimensional two-stream Kubelka–Munk model was used. The model takes into account multiple light scattering in the medium, but cannot take anisotropy into account [20]. Since the absorption coefficient of liquid crystals in the polymer matrix is close to zero [21], the film can be represented only as a scattering medium. Optical flux transmitted through such medium can be described by the following equation [22]:

$$F_r = F_0 \frac{1}{1 + SH}, \quad (2)$$

where F_0 is the optical flux that strikes the medium, F_r is the optical flux transmitted through the medium, S is the linear (transport) medium scattering coefficient, $H = 0.045$ cm is the medium thickness. Strictly speaking, S doesn't correspond to classical μ_s in all problems, however, for our idealized one-dimensional problem according to the results of [23], they can be taken as identical. Thus, from knowing the film transmittance F_r/F_0 , the film scattering coefficient can be easily found.

The obtained scattering coefficient was further used to calculate a skin-simulating three-layer measure proposed in [12]. The first layer of such measure is the PDLC film designed to mimic blood pulsations. The second layer is an absorbing optical filter designed to mimic light absorption by blood. And the third layer is PTFE designed to mimic light scattering on fixed tissue structures. According to [12], optical flux back scattered from such measure can be expressed using the following expression:

$$F_{\text{BS,measure}} = F_0 \left[\frac{SH}{1 + SH} + \frac{T_f^2}{(1 + SH(1 - T_f^2))(1 + SH)} \right], \quad (3)$$

where T_f is the transmittance of the absorbing optical filter. Equation (3) is used to calculate the power of signal reproduced by the measure, and the signal modulation depth.

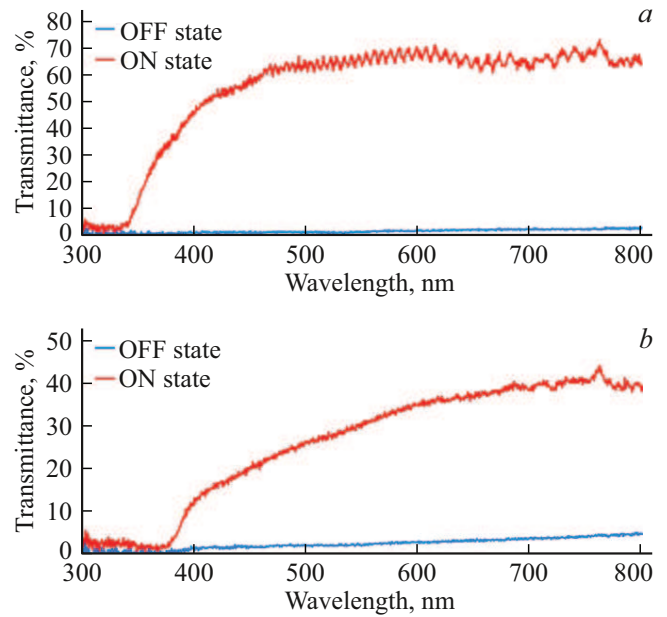


Figure 4. Transmittances of PDLC films in OFF state (0 V) and ON state (60 V) for sample 1 (*a*) and sample 2 (*b*).

For PPG, the modulation depth of the detected signal is the AC/DC ratio and, as mentioned above, is an important signal quality indicator [24].

Results and discussion

Figure 4 shows the measured film transmission spectra. As can be seen, the transmission spectrum for sample 1 is almost uniform to visible and near infrared ranges, while transmission for sample 2 is lower in amplitude and increases linearly as the wavelength grows. Film transmission in OFF state is close to zero throughout the wavelength range.

Figure 5 shows the obtained dependences of the film transmittance on the applied voltage for two wavelengths. Sample 1 has a more abrupt electro-optical curve than sample 2. This suggests that this sample provides a wider variation range of the scattering coefficient and output signal, respectively. The shape of the obtained curves correspond to that in [25], however, certain film transmittances for certain voltages can differ due to a difference in concentration of liquid crystals in copolymer.

The obtained dependences of film transmittance on the applied voltage were further transformed into the dependences of the scattering coefficient ($\mu_s = S$) on the voltage using equation (2). The results are shown in Fig. 6. For sample 1, the scattering coefficient varies from 45 cm^{-1} to approx. 5 cm^{-1} for 515 nm and from 33 cm^{-1} to 5 cm^{-1} for 632 nm. The widest spread of μ_s is observed at low voltages (0–10 V), and the lowest scattering is observed as early as at 15–20 V. For sample 2, electro-optical curve is more gentle and μ_s varies from 38 cm^{-1} to 21 cm^{-1} for 515 nm and from 27 cm^{-1} to 14 cm^{-1} for 632 nm. The obtained

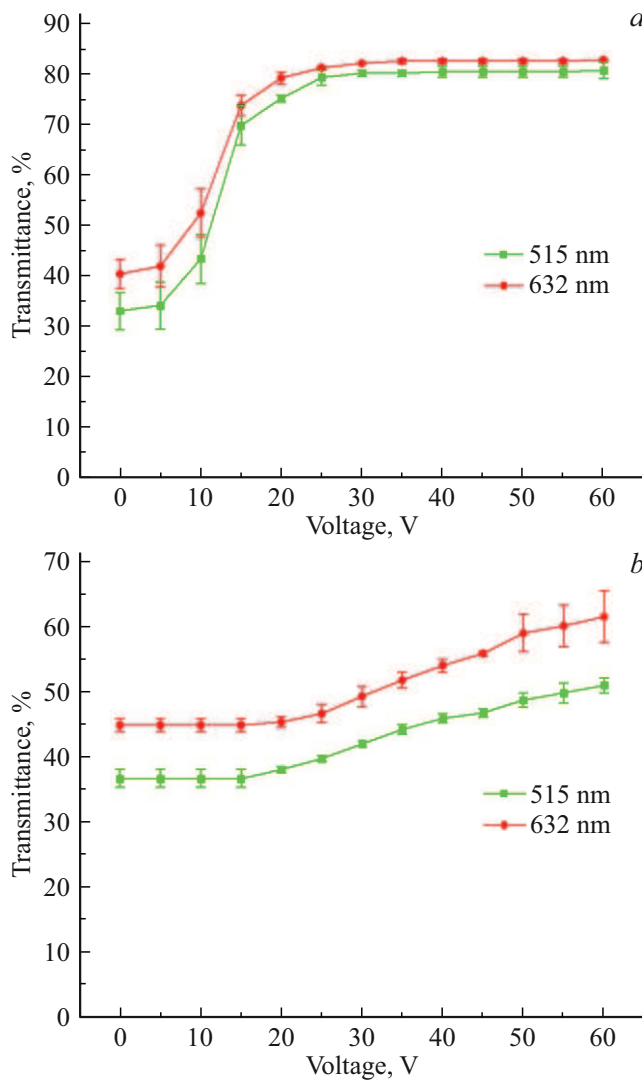


Figure 5. PDLC film transmittance vs. applied voltage for sample 1 (a) and sample 2 (b). Data are shown as a mean value $\pm$ RMSD.

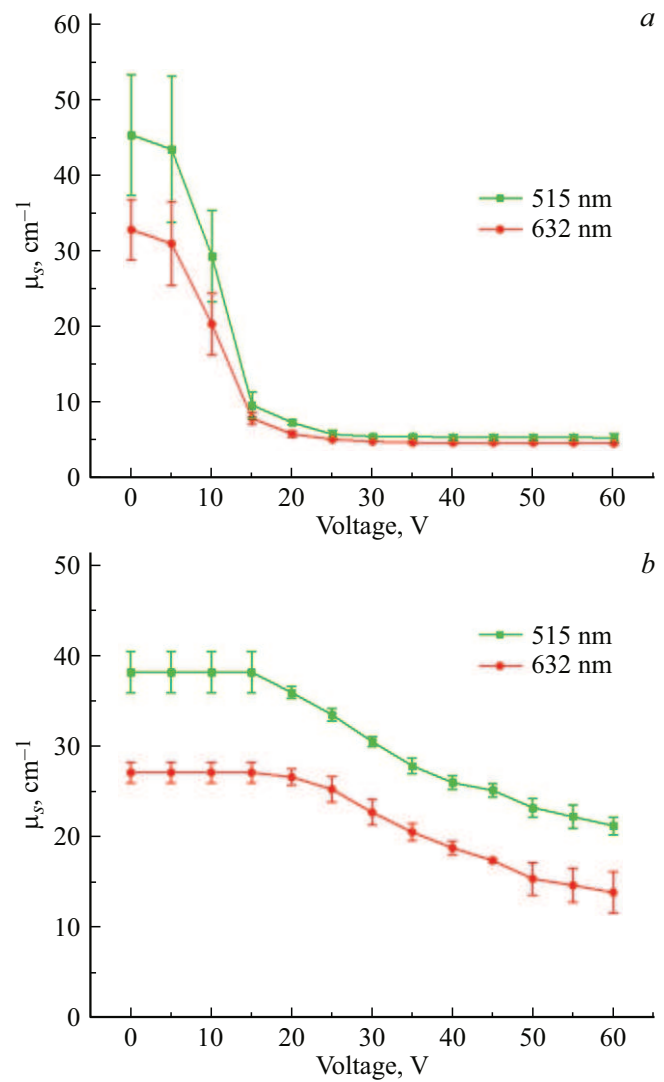


Figure 6. PDLC film scattering coefficient vs. applied voltage for sample 1 (a) and sample 2 (b). Data are shown as a mean value $\pm$ RMSD.

result suggests that film 1 is more sensitive to voltage variation and, consequently, for AC component simulation, a smaller range of control voltages is required.

Calculated scattering coefficients of films made it possible to calculate the optical flux back scattered from the three-layer WSM, i.e. the flux modulation depth (AC/DC). For this a basic optical flux with film in OFF state at $\mu_{s,0} = \mu_s(0\text{ V})$ was first calculated, and then a flux increment induced by the scattering coefficient increment with applied voltage was calculated: $\Delta\mu_s = \mu_s(0\text{ V}) - \mu_s(60\text{ V})$. Final modulation depth of the detected radiation was calculated as:

$$\left(\frac{AC}{DC}\right)_{\text{measure}} = \frac{|\Delta F_{BS, \text{measure}}(\mu_{s,0}, \Delta\mu_s)|}{F_{BS, \text{measure}}(\mu_{s,0})}. \quad (4)$$

AC/DC simulated using (4) depending on the transmittance of the absorbing optical filter T_f (second layer in WSM) are shown in Figure 7. As can be seen, the

modulation depth of the signal reproduced by sample 1 is approximately twice as large as the modulation depth of sample 2. AC/DC for real skin is 3–10% for the green range and 1–5% for the red range [26–28]. Both films exceed these ranges, thus they can be used as the main WSM components.

Conclusion

This study investigated optical properties of two PDLC film samples included in simulation measures for calibration of PPG devices. As a result, film transmittances ranging from 300 to 800 nm and electro-optical curves for 515 nm and 632 nm were obtained. In future, we also plan to study electro-optical properties also for the near infrared range. Scattering coefficient of films was calculated for different levels of applied voltage. Film 1 showed a

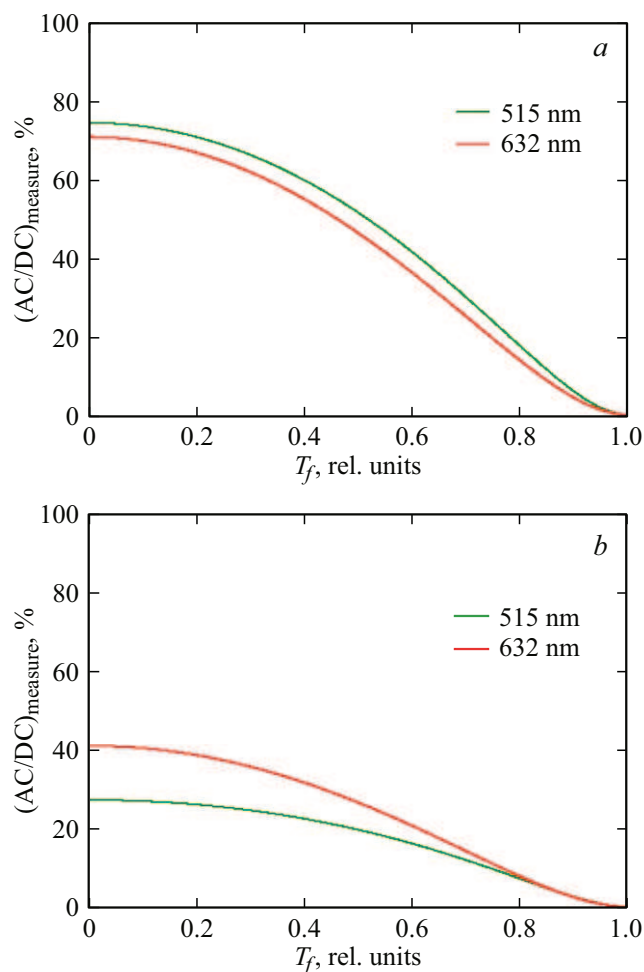


Figure 7. Calculated dependence of the modulation depth of a signal back scattered from the three-layer WSM on the transmittance of the absorbing optical filter T_f for sample 1 (a) and sample 2 (b).

larger scattering coefficient variation range than film 2. Quantitative data for scattering coefficient of film are of critical importance because they ensure more accurate calculations of light propagation in multilayer measures that mimic blood volume pulsations in tissue. In particular, the obtained data were used to calculate AC/DC of the generated signal for the three-layer WSM and it was shown that both films were suitable for such measures.

Conflict of interest

The authors declare no conflict of interest.

References

- [1] L. Hacker, H. Wabnitz, A. Pifferi, S. Di Nardo, A. Farina, M. Pagliazzi, R. Reif, D. Roblyer, I. Schelkanova, Y. Zhao, R.A. Simon, A. Cerussi, B.J. Tromberg. *Nat. Biomed. Eng.*, **6**, 541 (2022). DOI: 10.1038/s41551-022-00890-6
- [2] D.A. Rogatkin, A.V. Dunaev, L.G. Lapaeva. *Meditinskaya tekhnika*, **2** (260), 30 (2010). (in Russian)
- [3] D.A. Rogatkin. *Meditinskaya fizika*, **4**, 75 (2017). (in Russian)
- [4] V. Rajan, B. Varghese, T.G. van Leeuwen, W. Steenbergen. *Lasers Med. Sci.*, **24**, 269 (2009). DOI: 10.1007/s10103-007-0524-0
- [5] A.V. Bykov, A.P. Popov, A.V. Priezhev, R. Myllylä. In: *Optical Coherence Tomography and Coherence Techniques V*, ed. by R. Leitgeb, B. Bouma. *Proc. SPIE*, **8091**, 80911R (2011). DOI: 10.1117/12.889417
- [6] L. Spinelli, M. Botwicz, N. Zolek, M. Kacprzak, A. Durin, P. Sawosz, R. Maniewski, A. Liebert. *Biomed. Opt. Express*, **5** (7), 2037 (2014). DOI: 10.1364/BOE.5.002037
- [7] V.N. Du Le, S. Fronckowiak, E. Badolato. *Sensors*, **25** (7), 2311 (2025). DOI: 10.3390/s25072311
- [8] W.C. Vogt, X. Zhou, R. Andriani, M. Alqassim, P.A. Gourley, P.L. Leu, D.A. Low, H. El-Haddad, Y. Zou, B. Chen, B.A. Moffitt. *Biomed. Opt. Express*, **10**(2), 449 (2019). DOI: 10.1364/BOE.10.000449
- [9] A. Friedman. In: *Mathematics in Industrial Problems*, ed. by A. Friedman. *IMA Vol. Math. Appl.*, **31** (Springer, NY, 1990), p. 89–94. DOI: 10.1007/978-1-4613-9098-5_7
- [10] V.V. Belyaev, V.N. Avdeenkov. *Elektronika: Nauka, tekhnologii, biznes*, **7**, 80 (2023). (in Russian) DOI: 10.22184/1992-4178.2023.228.7.80.90
- [11] D.A. Rogatkin, D.G. Lapitan. Patent RF № 2777514. *Ustroistvo dlya metrologicheskogo kontrolya sostoyaniya priborov opticheskoi floumetrii*. Zayavka № 2021131510 dated 27.10.2021; opubl. 05.08.2022. (in Russian)
- [12] D.G. Lapitan, D.A. Rogatkin, L.S. Kapustin. *Vestnik MGTU im. N.E. Bauman. Ser. Priborostroenie*, **3** (152), 27 (2025). (in Russian)
- [13] J. Allen. *Physiol. Meas.*, **28**, R1 (2007). DOI: 10.1088/0967-3334/28/3/R01
- [14] N. Huber, J. Heitz, D. Bäuerle. *The European Physical Journal-Applied Physics*, **25** (1), 33 (2004). DOI: 10.1051/epjap:2003083
- [15] E. Salomatina, B. Jiang, J. Novak, A.N. Yaroslavsky. *J. Biomedical Optics*, **11** (6), 064026 (2006). DOI: 10.1117/1.2398928
- [16] S.A. Prahl, M.J. van Gemert, A.J. Welch. *Appl. Opt.*, **32** (4), 559 (1993). DOI: 10.1364/AO.32.000559
- [17] I.V. Yaroslavsky, A.N. Yaroslavsky, T. Goldbach, H.J. Schwarzmair. *Appl. Opt.*, **35**, 6797 (1996). DOI: 10.1364/AO.35.006797
- [18] R.R. Anderson, J.A. Parrish. *J. investigative dermatology*, **77** (1), 13 (1981). DOI: 10.1111/1523-1747.ep12479191
- [19] I.A. Raznitsyna, A.P. Tarasov, D.A. Rogatkin. *Instrum. Exp. Tech.*, **63**, 267 (2020). DOI: 10.1134/S0020441220020049
- [20] A. Isimaru. *Rasprostranenie i rasseyaniye voln v sluchaino-neodnorodnykh sredakh*, t. 1 (Mir, M., 1981), 280 s. (in Russian)
- [21] S.T. Wu, K.C. Lim. *Appl. Opt.*, **26** (9), 1722 (1987). DOI: 10.1364/AO.26.001722
- [22] S. Persheyev, D. Rogatkin. *Herald of the Bauman Moscow State Technical University. Ser. Natural Sciences*, **5**, 78 (2017). DOI: 10.18698/1812-3368-2017-5-78-94
- [23] D.A. Rogatkin. *Meditinskaya tekhnika*, **2**, 10 (2007). (in Russian)

- [24] D.G. Lapitan, A.P. Tarasov. In: Proc. of the 2019 IEEE 8th Int. Conf. on Advanced Optoelectronics and Lasers (CAOL) (IEEE, Sozopol, Bulgaria, 2019), p. 103–106. DOI: 10.1109/CAOL46282.2019.9019552
- [25] E.P. Pozhidaev, A.V. Kaznacheev, S.I. Torgova, V.V. Kesaev, V.A. Barbashov. Opt. Mater. Express, **10** (12), 3030–3040 (2020). DOI: 10.1364/OME.410163
- [26] D.G. Lapitan, A.P. Tarasov, D.A. Rogatkin. J. Biomed. Photonics Eng., **8** (3), 030306 (2022). DOI: 10.18287/JPPE22.08.030306
- [27] D.G. Lapitan, A.P. Tarasov, M.E. Shtyflyuk, D.A. Rogatkin. Photonics, **11** (7), 637 (2024). DOI: 10.3390/photonics11070637
- [28] E.F. Pribadi, R.K. Pandey, P.C.P. Chao. Microsystem Technologies, **26**, 3409 (2020). DOI: 10.1007/s00542-020-04895-6

Translated by E.Ilyinskaya