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Measurement of complex refractive index of human blood by low-coherence interferometry

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Abstract. In this article, the usefulness of the optical technique for measurements of blood complex refractive index has been examined. Measurement of optical properties of human blood is difficult to perform because of its nonuniform nature. However, results of my investigation have shown the usefulness of low-coherent interferometry for measurement complex refractive index of human blood. Furthermore, mathematical analysis of spectrum of measured signal have made possible to determined relationship between complex refractive index and hematocrit level in human blood.

1 Introduction

Blood is one of the most important tissues of human body. Its analysis is the most frequently performed procedure in medical diagnosis, because it gives information about patients' condition. Typically, several quantities are measured in a lab. This requires taking a sample, sending it to the lab and performing a series of tests, which may takes even a few hours [1,2]. However, for daily life diagnosis it is often sufficient to measure one or only few parameters in a continuous manner. This creates a demand for specialized measuring devices that can determine the value of one or a few parameters preferably without resorting to laboratory diagnostic and without the need for conventional sample processing, such as centrifuging and adding reagents, in a non- or minimally-invasive way and almost instantly. Optoelectronic measurement methods have gained popularity in medicine, health monitoring and telemedicine because of their unique advantages: good metrological parameters and potentially low cost P[3–5]. However, optical blood measurements are difficult to perform because of the nature of blood. Optical properties of blood can be consider in the micro- and macroscopic way. As a microscopic object, blood can be treated as a medium having scattering centers. It is a heterogeneous medium consists of plasma and blood cells, as shown in Fig.1. Blood plasma contains almost 90% of water and 10% of protein. Blood cells consist primarily of erythrocytes (almost 99%), leukocytes (1%) and platelets. Erythrocytes have the biggest geometrical dimensions, typically: 6.2-8.2 μm [6,7].

The microscopic approach of optical parameters of blood depend mainly on its components' optical properties: the scattering and absorbing capacity of optical radiation, but also on their size and shape. On the other hand, treating blood as a

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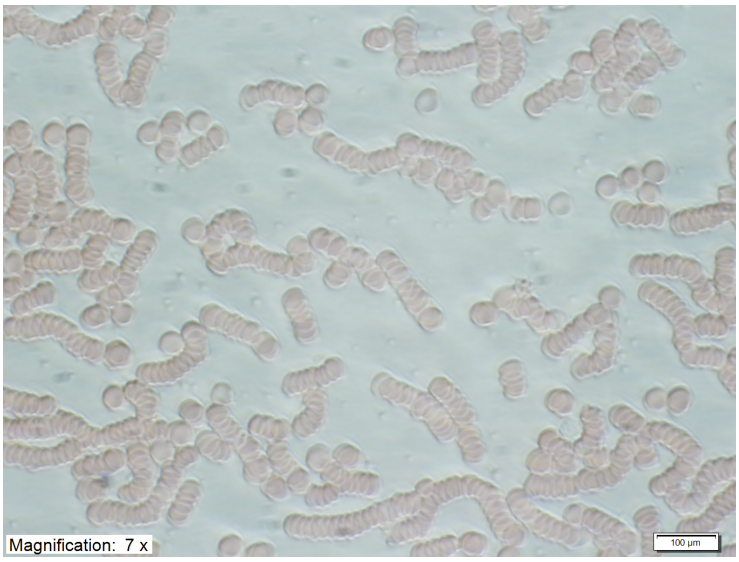


Fig. 1. The picture of human blood sample. Darker areas are blood cells, lighter are plasma.

macroscopic object, its optical properties become those of a homogeneous scattering medium. Mainly: scattering coefficient, absorption coefficient and refractive index. In this case, the complex refractive index can be introduced as [8]:

$$\hat{n} = n(1 + j\kappa) \tag{1}$$

where: n - real part of complex refractive index: $n = c/v$; κ - attenuation index.

The absorption coefficient

$$\chi = \frac{4\pi}{\lambda}\kappa \tag{2}$$

where: λ - wavelength in the medium.

Equations 1 and 2 are correct if the wave equation is shown as:

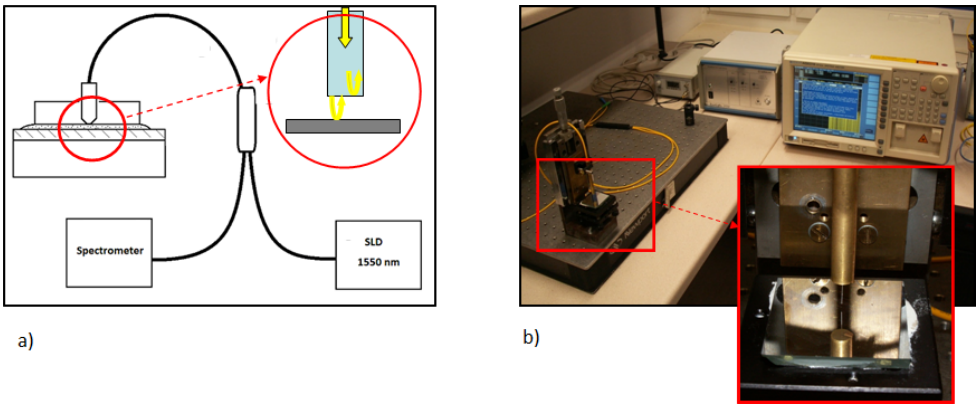
$$\hat{E} = E_0 \exp(kz - \omega t) \tag{3}$$

where: k - the wave vector; t - the phase.

The complex refractive index described by equation 1 is an adequate parameter to characterize blood as a homogeneous dispersion medium.

2 LOW-COHERENT INTERFEROMETRY

The complex refractive index of blood samples has been investigated by means of low-coherence interferometry. The measurement system consists of a broadband source, a sensing interferometer and an optical processor. The light from the broadband source is transmitted to the sensing interferometer where the amplitude of light is divided into two components. An optical path difference (OPD), which depends on the instantaneous value of the measurand, is introduced between them. The measured signal from the sensing interferometer is transmitted back to the optical processor. [10,11]



Because the system works in the phase domain, an optical processor spectral analyser has been used as the detector set-up. Since the spectral signal processing is utilized, the measurement signal can be described as [12]:

$$I_{out}(\nu) = S(\nu)[1 + V_0 \cos(\Delta\Phi(\nu))] \tag{4}$$

where: $S(\nu)$ - the spectral distribution of the light source; V_0 - visibility of interference fringes, $\Delta\Phi(\nu)$ - the phase difference between interfering beams: $\Phi(\nu) = 2\pi\nu\delta/c$, δ - optical path difference, c - velocity of the light in vacuum.

In the spectral domain signal processing the modulation frequency of the measurement signal gives information about the measurand (equation 4) [13]. It occurs in change of modulation frequency of spectrum what can be easily observed by controlling the number of frnges (maximums) in the measured spectrum.

3 MEASUREMENT SET-UP

The measurements have been conducted with the use of a low-coherence optical fibre interferometry set-up developed at our laboratory. As an optical processor Optical Spectrum Analyzer Ando AQ6319 (wavelength resolution of 1 nm, wavelength accuracy of $\pm$50 pm) has been used. As a low-coherence source a super luminescent diode Superlum Broadlighter S1300-G-I-20 with following optical parameters: λ_0= 1290 nm, $\delta\lambda$= 50 nm has been applied. In order to find out whether proposed method has sufficient accuracy to monitor the blood parameters, series of in-vitro measurements were carried out.

During experimental work about 100 samples of the whole human blood has been used for tests. Sets of 2 ml blood samples with various blood parameters, such as hematocrit and hemoglobine, level have been provided by the Gdansk Blood Donor Centre. Samples have been taken from rather healthy volunteers and therefore measurement range of the blood parameters has been limited to the value of blood parameters of healthy persons. However, the use of those samples has allowed me to investigate the relationship between measured quantities and the output of the measurement system.

4 RESULTS

With the use of the low-coherent measurement system, described in the previous section, the complex refractive index of numerous samples have been measured. For

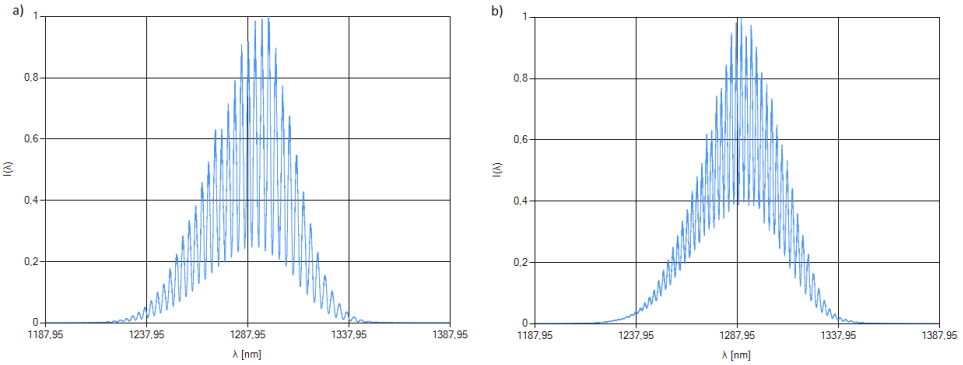


Fig. 2. Measured signal: a) for low complex refractive index, b) for high complex refractive index.

each sample five spectra have been required. In fig.2. the measured signals are shown. In fig.2a signal from sample with low and in fig.2b with higher real part of complex refractive index of human blood are shown.

It can be noted that the change in the real part of complex refractive index of measured sample changes the modulation frequency of measured spectra, which influences the number of fringes in measured spectra. On the other hands, the imaginary part influences the value of visibility of measured signal, what is shown in Fig.2. The analysis of measured signal has been focused on finding correlation between analytic blood parameters used in medicine such as hematocrit and complex refractive index which can be measured by the use of low-coherence methods. Obtained results have been used as an input data to the model that determines the level hematocrit in blood. (Fig.3).

Investigation of this method confirms its ability to determine hematocrit value (defined as the ratio of packed red blood cells volume to whole blood volume [14]) with appropriate measurement parameters. The best configuration of the sensor head has yielded sensitivity of measurement at the value of 2.963 %/nm; and correlation coefficient at the value of 0,98 was obtained from the approximation of the measurement series (fig.3).

5 CONCLUSION

The complex refractive index contains important information about optical properties of investigated object. In this paper low-coherent technique of measurement of complex refractive index of human blood has been described. The low-coherent interferometer, which was designed and elaborated at our laboratory, has been shown. The theoretical analysis and experimental results made it possible to select best construction, which was implemented in low-coherence fibre-optic sensors of refractive index.

Results of investigation showed the usefulness of low-coherence interferometry for measurement of complex refractive index of human blood. Furthermore, mathematical analysis of spectrum of measured signal made possible to determined relationship between complex refractive index and hematocrit of human blood.

This preliminary study can gives opportunity to elaborate non- or minimally-invasive diagnostic method.

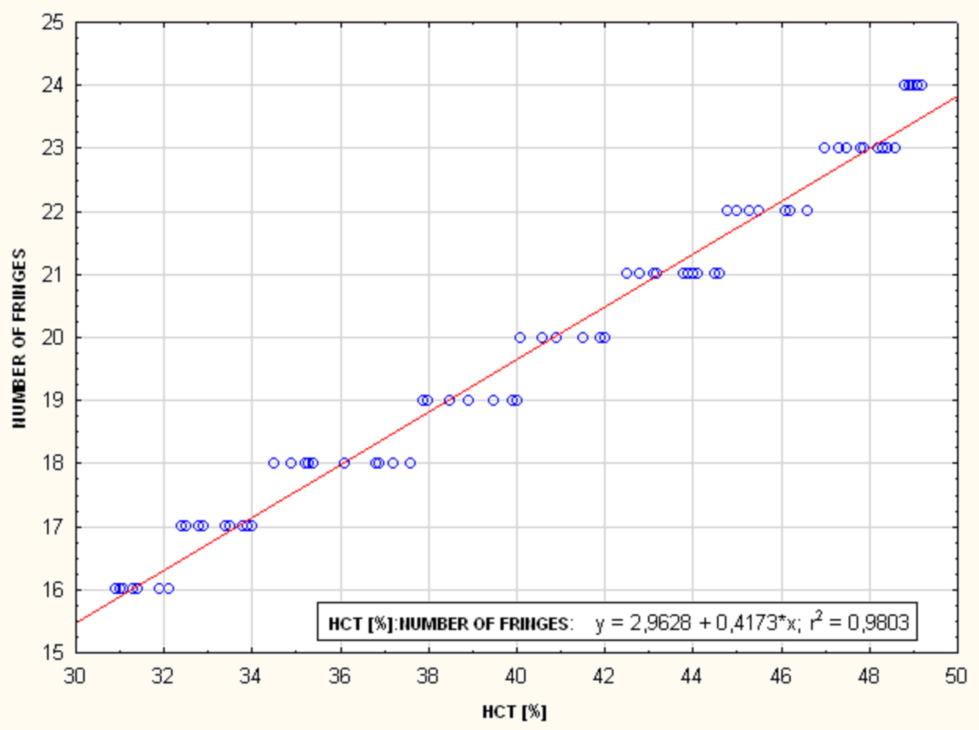


Fig. 3. The change of number of signal spectra fringes vs. HCT (hematocrit value): dots - measured value, line- regression line. (r^2 - determination coefficient of measured value)

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