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Research on the character of laser radiation propagation in a differential Anderson cuvette

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Abstract. The necessity of studying the nature of the propagation of laser radiation in the Anderson differential cuvette is substantiated in order to determine the optimal design parameters of a small-sized differential type refractometer. The construction of the Anderson differential cuvette is considered. A new method for studying the nature of the propagation of laser radiation in the differential Anderson cuvette is proposed. The trajectory of movement of the maximum of the laser radiation directive pattern in the cuvette, as well as beyond it (up to the sensor of the photodiode ruler on which the registration takes place) is plotted. An equation is obtained to study the changes in the nature of the propagation of laser radiation from various parameters of the differential cuvette, the reference liquid medium and the investigated liquid medium. A polynomial of the 12th degree is formed to obtain an analytical solution of the equation from the refractive index of the investigated medium.

Keywords: laser radiation, refraction, liquid, refractive index, Anderson's cuvette, refraction, displacement, polynomial

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Исследование характера распространения лазерного излучения в дифференциальной кювете Андерсона

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Аннотация. Обоснована необходимость исследования характера распространения лазерного излучения в дифференциальной кювете Андерсона для определения оптимальных параметров конструкции малогабаритного рефрактометра дифференциального типа. Рассмотрена конструкция дифференциальной кюветы Андерсона. Предложена новая методика исследования характера распространения лазерного излучения в дифференциальной кювете Андерсона. Построена траектория движения максимума диаграммы направленности лазерного излучения в кювете, а также за её пределами (до сенсора фотодиодной линейки, на котором происходит регистрация). Получено уравнение для исследования изменения характера распространения лазерного излучения от различных параметров дифференциальной кюветы, эталонной и исследуемой жидкой среды. Сформирован полином 12-й степени для получения аналитического решения уравнения относительно показателя преломления исследуемой среды.

Ключевые слова: лазерное излучение, рефракция, жидкость, показатель преломления, кювета Андерсона, преломление, смещение, полином

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Introduction

Reliable express control is becoming an important element in scientific research, industrial production and environmental monitoring [1–7]. The use of express control is necessary to obtain reliable information about the state of the environment at the sampling site in order to make an adequate decision [2, 8–11]. In addition, it is necessary to obtain further confirmation of the detected deviation in the sample on high-resolution devices [10–12]. In this case, the measurements carried out in express mode should not make irreversible changes to the sample of the medium, which will change its composition and physical structure [2, 11–15]. Taking into account these conditions, the number of methods and devices for express control is limited [1, 2, 6, 10–12, 16–18]. One of the devices that allows express control of the state of liquid medium with high precision at the sampling site is a refractometer.

High requirements for conducting experiments, the manufacture of complex mediums, for example, medical suspensions or medicaments for injection into veins, requires measurements of the refractive index n_m of a liquid medium with high precision over a large range of values [17–25]. A differential refractometer based on an Anderson cuvette, for measurements in which a reference liquid is used, is one of the possible solutions of these express control problems. The problem of measuring n_m with an error of 0.0001 over a large range of values is related to the lack of relations between different parameters in the design of the refractometer and the Anderson cuvette. This significantly limits the use of this type of refractometer.

Anderson cuvette design and profile of laser radiation propagation

In the constructions of modern differential refractometers, three types of Anderson cuvettes (in the form of a square and two types in the form of a rectangle), which are made of quartz glass, are mainly used for measurements. On figure 1 is shown the propagation of laser radiation in the Anderson cuvette and after exiting it to the sensor of the photodiode ruler (the sensor is located at a distance *e* from the wall of the cuvette). The use of a photodiode ruler for registering laser radiation in refractometers is currently the most optimal solution [18–25].

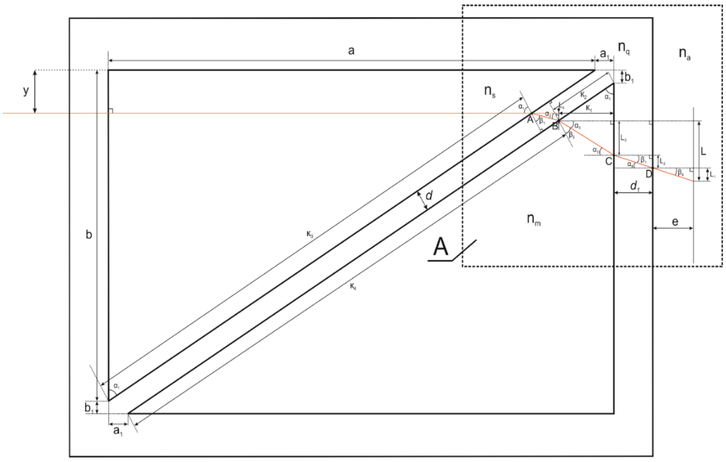

Fig. 1. Anderson cuvette and laser radiation propagation. Fragment A denotes the area for which the equation is derived to determine n_m

In the construction of the differential refractometer designed by us, in contrast to those that were used earlier, it is proposed to use the measured value *L* (by shifting the maximum of laser radiation on the photodiode ruler from the entry point y on the lateral surface of the Anderson cuvette of laser radiation) to determine the n_m value. The measurement error of δn_m in this case will be determined by ensuring that the maximum of laser radiation is registered on one photosensitive sensor. To determine the minimum value δn_m, it is necessary to establish the dependence between the change in the value L on the photodiode ruler on the parameters of the Anderson cuvette, the distance e, and the values n_m and n_s.

The equation for research of laser radiation direction change in the time it dissemination in optical part of refractometer and ratio control

To derive the equation and then verify the mathematical relations at the control points, the description of the nature of the change in the displacement of laser radiation on the photodiode ruler was divided into 4 parts: L_1, L_2, L_3 and L_4 (fragment A, Fig. 1).

For laser radiation in the considered fragment A (Fig. 1), the following relations were written down:

$$\mathrm{A}:\frac{\sin\alpha_1}{\sin\beta_1}=\frac{n_q}{n_s};\ \mathrm{B}:\frac{\sin\alpha_2}{\sin\beta_2}=\frac{n_m}{n_q};\ \mathrm{C}:\frac{\sin\alpha_3}{\sin\beta_3}=\frac{n_q}{n_m};\ \mathrm{D}:\frac{\sin\alpha_4}{\sin\beta_4}=\frac{n_a}{n_q};$$

$$\alpha_1=\alpha_3+\beta_2, L_1=e\,\mathrm{tg}\beta_4, L_2=d_1\mathrm{tg}\beta_3, L_3=K_1\mathrm{tg}\alpha_3, K_1=(y-b_1+L_4)\mathrm{tg}\alpha_1, \mathrm{tg}\alpha_1=\frac{a}{b},$$

$$L_4=|AB|\cdot\sin(\alpha_1-\beta_1)=\frac{d}{\cos\beta_1}\sin(\alpha_1-\beta_1)=d(\sin\alpha_1-\cos\alpha_1\mathrm{tg}\beta_1).$$

These relations allow us to express the values of L_1, L_2, L_3 and L_4 in terms of the parameters of the Anderson cuvette, the distance e, and also the values of the refractive indexes of the reference liquid n_s and the investigated liquid medium n_m.

$$L_4=d\sin\alpha_1\left(1-\frac{n_s\cos\alpha_1}{\sqrt{n_q^2-n_s^2\sin^2\alpha_1}}\right), \mathrm{tg}\alpha_3=\mathrm{tg}\left(\alpha_1-\beta_2\right)=\frac{\mathrm{tg}\alpha_1-\mathrm{tg}\beta_2}{1+\mathrm{tg}\alpha_1\mathrm{tg}\beta_2},$$

$$\frac{L_3}{K_1}=tg\alpha_3=\frac{\mathrm{tg}\alpha_1-\dfrac{n_s\sin\alpha_1}{\sqrt{n_m^2-n_s^2\sin^2\alpha_1}}}{1+\mathrm{tg}\alpha_1\dfrac{n_s\sin\alpha_1}{\sqrt{n_m^2-n_s^2\sin^2\alpha_1}}}=\frac{\sin\alpha_1\sqrt{n_m^2-n_s^2\sin^2\alpha_1}-n_s\sin\alpha_1\cos\alpha_1}{\cos\alpha_1\sqrt{n_m^2-n_s^2\sin^2\alpha_1}+n_s\sin^2\alpha_1},$$

$$\sin\alpha_3=\sin\left(\alpha_1-\beta_2\right)=\sin\alpha_1\cos\beta_2-\sin\beta_2\cos\alpha_1=$$

$$=\sin\alpha_1\sqrt{1-\frac{n_s^2}{n_m^2}\sin^2\alpha_1}-\frac{n_s}{n_m}\sin\alpha_1\cos\alpha_1=\frac{\sin\alpha_1}{n_m}\left(\sqrt{n_m^2-n_s^2\sin^2\alpha_1}-n_s\cos\alpha_1\right),$$

$$\mathrm{tg}\beta_3=\frac{L_2}{d_1}=\frac{\sin\alpha_1\left(\sqrt{n_m^2-n_s^2\sin^2\alpha_1}-n_s\cos\alpha_1\right)}{\sqrt{n_q^2-\sin^2\alpha_1\left(n_m^2+n_s^2\cos^2\alpha_1-n_s^2\sin^2\alpha_1-2n_s\cos\alpha_1\sqrt{n_m^2-n_s^2\sin^2\alpha_1}\right)}},$$

$$L_1=e\mathrm{tg}\beta_4;\ \frac{L_1}{e}=\mathrm{tg}\beta_4=\frac{\dfrac{\sin\alpha_1}{n_a}\left(\sqrt{n_m^2-n_s^2\sin^2\alpha_1}-n_s\cos\alpha_1\right)}{\sqrt{1-\left(\dfrac{\sin\alpha_1}{n_a}\left(\sqrt{n_m^2-n_s^2\sin^2\alpha_1}-n_s\cos\alpha_1\right)\right)^2}}=$$

$$=\frac{\sin\alpha_1\left(\sqrt{n_m^2-n_s^2\sin^2\alpha_1}-n_s\cos\alpha_1\right)}{\sqrt{n_a^2-\sin^2\alpha_1\left(n_m^2-n_s^2\sin^2\alpha_1+n_s^2\cos^2\alpha_1-2n_s\cos\alpha_1\sqrt{n_m^2-n_s^2\sin^2\alpha_1}\right)}}.$$

This allowed us to obtain the following equation for L:

$$\begin{aligned} L = L_1 + L_2 + L_3 + L_4 = \sin\alpha_1 \Bigg(& d\left(1 - \frac{n_s\cos\alpha_1}{\sqrt{n_q^2 - n_s^2\sin^2\alpha_1}}\right) + \left(\sqrt{n_m^2 - n_s^2\sin^2\alpha_1} - n_s\cos\alpha_1\right)\cdot \\ & \cdot\Bigg(\frac{e}{\sqrt{n_a^2 - \sin^2\alpha_1\left(n_m^2 - n_s^2\sin^2\alpha_1 + n_s^2\cos^2\alpha_1 - 2n_s\cos\alpha_1\sqrt{n_m^2 - n_s^2\sin^2\alpha_1}\right)}} + \\ & + \frac{d_1}{\sqrt{n_q^2 - \sin^2\alpha_1\left(n_m^2 + n_s^2\cos^2\alpha_1 - n_s^2\sin^2\alpha_1 - 2n_s\cos\alpha_1\sqrt{n_m^2 - n_s^2\sin^2\alpha_1}\right)}} + \\ & + \frac{K_1}{\cos\alpha_1\sqrt{n_m^2 - n_s^2\sin^2\alpha_1} + n_s\sin^2\alpha_1}\Bigg)\Bigg). \end{aligned} \tag{1}$$

A control check was performed for the obtained equation (1). The refractometers use laser radiation with $\lambda = 632.8$ nm. For $\lambda = 632.8$ nm, the value of $n_q = 1.537826$, $n_a = n_{air} = 1.000273$, $d = 0.5$ mm, $d_1 = 1$ mm, $e = 20$ mm, $y = 4$ mm. The test results are presented in table 1.

Table 1

Calculation results of beam offset distance L

n_s and n_m values ($n_s = n_m$)	Cuvette (size 50 mm × 50 mm)
$n_{air} = 1.000273$	$L = 0.171129$
$n_{water} = 1.327412$	$L = 0.082450$
$n_{ethanol} = 1.361513$	$L = 0.071131$
$n_{petrol} = 1.437762$	$L = 0.043715$

Notations: L – displacement of the laser radiation after leaving the cuvette, n_s – refractive index of the reference liquid, n_m – refractive index of the investigated liquid.

To derive the analytical equation n_m (d, L, n_s, e, K_1, d_1, n_q, α_1), the following notation is introduced:

$$\frac{L_4}{\sin\alpha_1} = d\left(1 - \frac{n_s\cos\alpha_1}{\sqrt{n_q^2 - n_s^2\sin^2\alpha_1}}\right) = L_4', \frac{L}{\sin\alpha_1} - L_4' = \frac{L - L_4}{\sin\alpha_1} = A,$$

$$\sqrt{n_m^2 - n_s^2\sin^2\alpha_1} - n_s\cos\alpha_1 = f_1;\ f_2 = f_1\sin\alpha_1,$$

$$\mathrm{A} = f_1\left(\frac{e}{\sqrt{n_a^2 - f_2^2}} + \frac{d_1}{\sqrt{n_q^2 - f_2^2}} + \frac{K_1}{\cos\alpha_1\left(f_1 + n_s\cos\alpha_1\right) + n_s\sin^2\alpha_1}\right).$$

In this case equation (1) is reduced to the following form.

$$\frac{\mathrm{A}\sin\alpha_1}{f_2} = \frac{e}{\sqrt{n_a^2 - f_2^2}} + \frac{d_1}{\sqrt{n_q^2 - f_2^2}} + \frac{K_1}{f_2\mathrm{tg}\alpha_1 + n_s}. \tag{2}$$

After various conversions equation (2) can be represented as a polynomial $P(f_2)$. The resulting equation (3) is a polynomial of the 12th degree from f_2, in which n_m is located. If we solve it for f_2, we will get an analytical expression for conducting research explicitly and calculating critical points (maximums and boundary conditions). This will be the subject of our further work.

Conclusion

It is worth noting that the obtained equation (1) allows us to evaluate the possibility of measuring the n_m value with an error of 0.0001 when changing the distance L on the photodiode ruler corresponding to the distance between photosensitive sensors (the ruler design contains 1024 sensors). Using equation (1), it is possible to determine experimentally the parameters of the cuvette, the distance e, as well as the value n_s, so that when n_m changes by 0.0001, the maximum of laser radiation moves by one photosensitive sensor. It takes a lot of time and resources. There will also be difficulties when switching from one n_m measurement range to another (for example, from the range from 1.34 to 1.35 to the range from 1.52 to 1.53).

In the case of using an analytical solution for n_m, these difficulties can be identified and measurement techniques can be developed to eliminate them.

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