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TUNABLE MATCHING LAYER METHOD FOR IDENTIFYING IMPURITIES IN LIQUIDS AT MICROWAVES

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The work aims to develop a method for contactless identification of impurity concentration in liquids of a given type in the microwave frequencies. The work presents the theoretical analysis of the novel method for identifying impurities in liquids at microwave frequencies, based on the use of a tunable matching layer (a dielectric layer of variable thickness). To find the reflection coefficient of an electromagnetic wave from the layered structure, a technique consisting of determining the electromagnetic fields in each region and imposing continuity conditions for the field components at each boundary of the layer was used. Numerical estimations of the method's sensitivity are provided using the example of determining ethanol impurity concentrations in water. The results are compared with experimental data reported in other publications. It has been shown that this method has a high sensitivity to impurity concentration.

Keywords: *Matching layer; Impurity concentration in liquids; Contactless; Reflection coefficient; Microwave frequencies*
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INTRODUCTION

High-frequency methods for monitoring and characterizing the dielectric properties of liquids remain an active area of research [1-6]. Among the most advanced approaches is the method presented in [1], which enables non-contact, remote measurement of the real and imaginary parts of a liquid's permittivity in the microwave frequency range. The authors of [1] employed a specially designed cylindrical dielectric resonator as the measurement cell.

We subsequently developed the method proposed in [1] in works [7–10]. In our studies, instead of the traditional dielectric resonator (which operates in a narrow frequency range), a so-called one-dimensional photonic crystal [7] was used. This made it possible to identify liquids over a relatively wide frequency range. The use of a one-dimensional photonic crystal with a defect in a microstrip implementation improved the accuracy of liquid identification and enhanced the technical capabilities of the method described in [1]. It should be noted, however, that the method described in [7–10] exhibits several limitations. Despite being well-suited for liquid identification, it is poorly suited for high-precision tuning of sensitivity to specific types of liquids. In the given paper, we propose a method for relatively accurate non-contact measurement of impurity concentrations in specific types of liquids (e.g., aqueous alcohol solutions) in the microwave wavelength range. This approach provides comparatively high accuracy in measuring impurity concentrations in liquids due to the use of a tunable matching layer.

PROBLEM FORMULATION AND RESULTS DISCUSSION

In this work, the reflection coefficient *R* of the electromagnetic wave from a layered structure (shown in Fig. 1) is calculated.

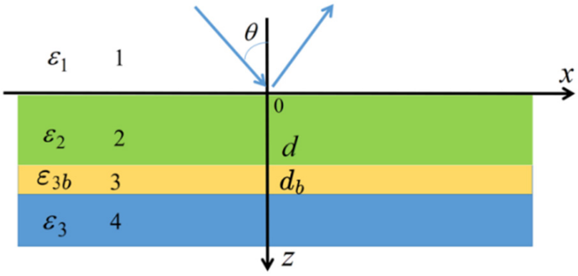

Figure 1. Geometry of the problem: 1 – the free space; 2 – the tunable matching layer; 3 – the wall of the container with the test liquid; 4 – the liquid under test.

It is assumed that the electromagnetic wave is incident from medium (1), with permittivity ε_1, at normal incidence $\theta = 0°$ on the boundary at $z = 0$. The region $0 < z < d$ is occupied by a dielectric layer with permittivity ε_2. This layer

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(referred to as the tunable matching layer) (2) is used to control the reflection coefficient of the electromagnetic wave from the whole layered structure by varying its thickness.

The test liquid is assumed to be placed in a flat container. The container wall (3) has a thickness of d_b and the permittivity ε_{3b}. The spatial region $z > d + d_b$ is occupied by the test liquid (4) with permittivity ε_3. The second boundary of the flat container is not considered in our model, since its effect on the reflection coefficient is assumed to be negligible.

To determine the reflection coefficient R of the electromagnetic wave from the considered structure, the known standard approach was used. This approach consists of determining the electromagnetic field components in each region and applying the boundary conditions for the continuity of these field components at each interface of the structure. It is assumed that the permittivity of the test liquid is a complex-valued function, accounting for both its dispersive and absorptive properties.

Let us consider the components of the electromagnetic fields in each region of the layered structure.

In the region $z < 0$:

$$H_{y1}(z) = e^{ik_{z1}z} + r\cdot e^{-ik_{z1}z},$$

$$E_{y1}(z) = \frac{ck_{z1}}{\omega\varepsilon_1}\left(e^{ik_{z1}z} - r\cdot e^{-ik_{z1}z}\right).$$

In the region $0 < z < d$:

$$H_{y2}(z) = H_2^+ e^{ik_{z2}z} + H_2^- e^{-ik_{z2}z},$$

$$E_{y2}(z) = \frac{ck_{z2}}{\omega\varepsilon_2}\left(H_2^+ e^{ik_{z2}z} - H_2^- e^{-ik_{z2}z}\right).$$

In the region $d < z < d + d_b$:

$$H_{y3b}(z) = H_{3b}^+ e^{ik_{z3b}(z-d)} + H_{3b}^- e^{-ik_{z3b}(z-d)},$$

$$E_{y3b}(z) = \frac{ck_{z3b}}{\omega\varepsilon_{3b}}\left(H_{3b}^+ e^{ik_{z3b}(z-d)} - H_{3b}^- e^{-ik_{z3b}(z-d)}\right).$$

In the region $z > d + d_b$:

$$H_{y3}(z) = t\cdot e^{ik_{z3}(z-d-d_b)},$$

$$E_{y3}(z) = \frac{ck_{z3}}{\omega\varepsilon_3} t\cdot e^{ik_{z3}(z-d-d_b)}.$$

Here, r, t are amplitudes of the reflected and transmitted electromagnetic waves, respectively. The values H_2^+, H_{3b}^+ represent the amplitudes of the forward-propagating electromagnetic waves, while H_2^-, H_{3b}^- denote the amplitudes of the backward-propagating waves in media with permittivity ε_2 and ε_{3b}, respectively. The wave numbers are given by $k_{z1,2,3b,3} = \frac{\omega}{c}\sqrt{\varepsilon_{1,2,3b,3}}$, where ω is the angular frequency and c is the speed of light in vacuum.

From the continuity conditions of the tangential field components at each interface of the considered structure, we determine the amplitude r of the reflected electromagnetic wave. The reflection coefficient R of the electromagnetic wave at the boundary $z = 0$ is defined as follows:

$$R = |r|^2.$$

The amplitude of the reflected electromagnetic wave r should be determined by the following expression:

$$r = \frac{x_2 p_- \cos(k_{z2}d) - i\cdot s_- \sin(k_{z2}d)}{x_2 p_+ \cos(k_{z2}d) - i\cdot s_+ \sin(k_{z2}d)},$$

where

$$p_\pm = x_1 y_+ \pm x_{3b} y_-,$$

$$s_\pm = x_1 x_{3b} y_- \pm x_2^2 y_+,$$

$$y_+ = x_{3b}\cos(k_{z3b}d_b) - i\cdot x_3 \sin(k_{z3b}d_b),$$

$$y_- = x_3\cos(k_{z3b}d_b) - i\cdot x_{3b} \sin(k_{z3b}d_b),$$

$$x_{z1,2,3b,3} = 1\Big/\sqrt{\varepsilon_{1,2,3b,3}}.$$

Let the investigated liquid be contained in a dielectric (plastic) container with thickness d_b = 0.05 cm and the permittivity ε_{3b} = 2.4. We assume that the thickness d of the tunable matching dielectric layer can vary, and its permittivity is ε_2 = 5.5. We also assume ε_1 = 1.0.

Let introduce the dimensionless thickness of the tunable matching dielectric layer as $\delta = 2\pi d/\lambda$, where λ is the wavelength of the electromagnetic wave in free space. The value of λ is taken as $\lambda = 3$ cm. Figure 2 shows the dependence of the reflection coefficient $R(\delta)$ for the water, with the real part of its permittivity $\varepsilon_3' = 62.6$ and the imaginary part $\varepsilon_3'' = 29.4$ at the chosen wavelength. It can be seen from Fig. 2 that obtained dependence is a periodic function of δ.

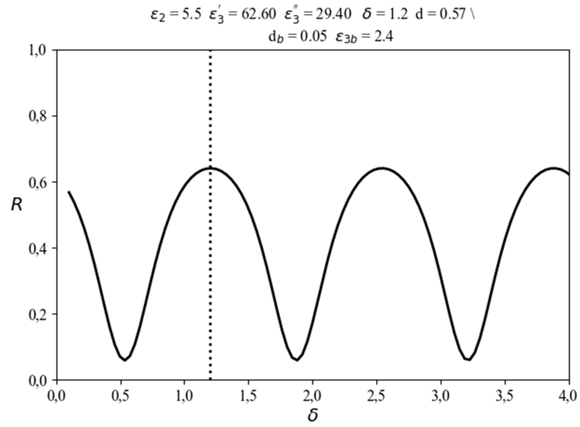

Figure 2. Dependence of reflection coefficient $R(\delta)$ on the dimensionless thickness of the tunable matching layer for pure water

Let's δ = 1.2. This value corresponds to the maximum reflection coefficient R. The chosen value of δ is indicated by a dashed line in Fig. 2. For the selected values of λ and δ, the thickness is d = 0.57 cm.

Now, let us consider how the reflection coefficient R changes in the presence of ethanol impurities in water. The results of the performed calculations are presented in Table 1.

Table 1. Reflection coefficient R from the layered structure (Fig. 1) for ethanol-water solutions of varying concentration.

#1	#2	#3	#4
Concentration of ethanol in water, %	Real part of permittivity ε_3' (λ = 3 cm, experiment [11])	Imaginary part of permittivity ε_3'' (λ = 3 cm, experiment [11])	R (d = 0.57 cm)
0	62.5	30.0	0.641
1	61.0	30.8	0.640
5	55.8	32.0	0.634
10	49.5	33.0	0.627
20	37.5	32.2	0.609
40	21.0	24.5	0.560

The first column of Table 1 shows the percentage concentration of ethanol in water. The next two columns list the real and imaginary parts of the permittivity of water containing ethanol impurities. These data are taken from reference [11]. The fourth column of the table presents the calculated values of the reflection coefficient R of the electromagnetic wave from the structure shown in Fig. 1.

From Table 1, it is evident that the presence of ethanol in water significantly affects the reflection coefficient of the electromagnetic wave. As the ethanol concentration in water increases, the reflection coefficient R decreases. This very fact forms the basis of the novel non-contact method we propose for determining impurity concentration (using ethanol as an example) in water.

Let us estimate now the sensitivity of the given method from Table 1 as the minimal measurable increment in ethanol concentration in water for the two cases described below.

In the first case, we consider pure water with low ethanol impurity concentrations ranging from 0% to 5%. It is known that in typical experiments using the standard vector network analyzer N5230A [7–10, 12], a measurement accuracy of the reflection coefficient R for the layered structure on the order of $\Delta R_{\text{exp}} = 0.1\%$ can be easily achieved. With this method, it is experimentally possible to measure such an increment in ethanol concentration that corresponds to a change in R no smaller than the aforementioned accuracy. From Table 1, it follows that R changes by $\Delta R_1 = 1.1\%$ when ethanol concentration varies from 0% to 5%. Thus, for small ethanol concentrations in water, the accuracy of determining its concentration by the new method is approximately $\Delta R_{\text{exp}} / \Delta R_1 \cdot 5\% = 0.45\%$. In the second case, when the ethanol concentration changes from 20% to 40%, the reflection coefficient varies by $\Delta R_2 = 8.75\%$. For this diapason of impurities, the accuracy of determining ethanol concentration in water is approximately $\Delta R_{\text{exp}} / \Delta R_2 \cdot 20\% = 0.23\%$.

For comparison, in reference [12], the accuracy of the method for determining the dielectric permittivity of liquids in a coaxial cell was significantly lower (the errors in determining the dielectric permittivity of water were no better than 5%).

CONCLUSIONS

Thus, in this work:

1. The new remote method for determining impurities concentration in liquids has been developed. The method is based on measuring the reflection coefficient of the electromagnetic wave from a flat plastic container with liquid, using a tunable matching dielectric layer of adjustable thickness.
2. It is demonstrated that, compared to established methods based on permittivity measurements using coaxial line or photonic crystals, the proposed method offers substantially higher sensitivity to impurities. This enhanced sensitivity arises from the implementation of a tunable matching layer with adjustable thickness.

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МЕТОД РЕГУЛЮВАЛЬНОГО УЗГОДЖУВАЛЬНОГО ШАРУ ДЛЯ ІДЕНТИФІКАЦІЇ ДОМІШОК У РІДИНАХ НА МІКРОХВИЛЬОВИХ ЧАСТОТАХ

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Метою роботи є розробка методу безконтактної ідентифікації концентрації домішок у рідинах заданого типу на мікрохвильових частотах. У роботі представлено теоретичний аналіз нового методу ідентифікації домішок у рідинах на мікрохвильових частотах, заснованого на використанні регульованого узгоджувального шару (діелектричного шару змінної товщини). Для визначення коефіцієнта відбиття електромагнітної хвилі від шаруватої структури була використана методика, яка полягає у визначенні електромагнітних полів у кожній області та накладенні умов безперервності для компонент поля на кожній межі шару. Наведено чисельні оцінки чутливості методу на прикладі визначення концентрації домішок етанолу у воді. Результати порівняно з експериментальними даними в інших публікаціях. Показано, що цей метод має високу чутливість до концентрації домішок.

Ключові слова: *узгоджувальний шар; концентрація домішок у рідинах; безконтактний; коефіцієнт відбиття; мікрохвильові частоти*