DETERMINATION OF ELECTROMAGNETIC PARAMETERS OF LIQUID SUBSTANCES IN THE MICROWAVE RANGE

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The experimental researches of the electrodynamic properties of liquids in the microwave range is described in this work. The calculation formulas within the framework of a single-wave model and the results of trial experiments are presented. Currently, the study of the use of electromagnetic waves in the microwave range (from 0.3 GHz to 30 GHz – UHF (ultra-high frequencies) and SHF (super-high frequencies)) for heating various substances with suitable electrodynamic properties is continuing. Liquid substances are of particular interest in this field. Microwave radiation treatment can be used to solve the problems of disinfection of water, milk, and so on. Microwave heating can be used in the oil industry. An experimental measuring device was assembled to determine the electrodynamic properties of liquid substances. To measure the electrodynamic parameters of substances, a hollow segment of a coaxial line was constructed, which has a disassembly structure and can be completely filled with the test substance before measurements. The dimensions of the coaxial segment are chosen so that, in the absence of filling, its characteristic resistance (impedance) would be 50 ohms, which corresponds to the characteristic resistance (impedance) of the connecting segments of the coaxial lines, and at the same time higher types of waves would be absent in the transmission line. After calibration the measuring object was connected to the system. The frequency characteristics of the VSWR (voltage standing wave ratio) and attenuation were measured using a measuring system. In the absence of filling, the segment is coordinated with the cables of the measuring system, therefore, the reflected wave will be practically absent, and the signal attenuation will be determined by losses in the conductors and contact connections of the segment. When filling the line segment with the liquid substance under testing, both the VSWR and the attenuation will change. From this information, it is possible to determine the electrodynamic characteristics of the filling: the tangent of the dielectric loss angle and the complex relative permittivity. To obtain quantitative characteristics, it is convenient to use the D-matrix method. A scheme of the measuring installation, devices and their connections for experimental research is presented. In the range from 2 GHz to 18 GHz, experimental studies of two segments in waveguide and coaxial designs without filling with dielectrics, as well as with water filling, were carried out. The paper presents the frequency dependences of VSWR, reflection coefficient, attenuation averaged for two line segments without filling. These data allow us to identify the systematic error of the experiment, which will allow us to correct the result for the filled segment. The analysis shows that in the unfilled segment, losses in contact connections prevail over losses in conductors. The frequency dependences of the reflection coefficient, the relative absorption power in the dielectric and the tangent of the dielectric loss angle for the experiment with water are presented. The results obtained are consistent with those published. Thus, using the considered technique, it is possible to determine the electromagnetic parameters of various liquid substances in the microwave range. Currently, the study of the use of electromagnetic waves in the microwave range (UHF (ultra-high frequencies) – 0.3-3 GHz, SHF (super-high frequencies) – 3-30 GHz) for heating various substances with suitable electrodynamic properties is continuing [1-3]. Liquid substances are of particular interest in this field. Microwave radiation treatment can be used to solve the problems of disinfection of water, milk, and so on. Microwave heating can be used in the oil industry (reducing the viscosity of oily materials when pumping through pipes, melting asphalt-paraffin plugs and polluting deposits in the pipes of oil wells, and so on) [2-6]. Most often, to determine the electrodynamic parameters of substances, a method of measuring characteristics is used when the substances under study are located inside a volumetric resonator. Despite the good accuracy, the disadvantage of this approach is obvious - it is impossible to adjust the measurement frequency parameters in a sufficiently wide operating range during experimental studies.

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Description of the experimental research scheme

An experimental measuring device was assembled to determine the electrodynamic properties of liquid substances. To measure the electrodynamic parameters of substances, a hollow segment of a coaxial line was constructed, which has a disassembly structure and can be completely filled with the test substance before measurements.

Figure 1 shows a scheme of the experimental set.

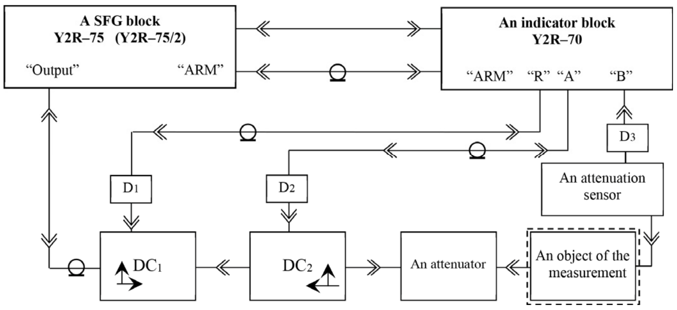

Fig. 1. A scheme of the experimental set with VSWR measuring instrument R2–103 (R2-104)

D1, D2 and D3 are detector heads, DC_1 and DC_2 are directional couplers (forward and reflected waves respectively).

The VSWR-R2-103 measuring instrument was used for measurements in the range from 2 to 8 GHz, and the VSWR-R2-104 measuring instrument was used in the range from 8 to 18 GHz.

The characteristic resistance (impedance) Z_c of the connecting segments of coaxial lines is 50 Ohm.

The dimensions of the coaxial segment are chosen so that, in the absence of filling, its characteristic resistance (impedance) Z_c = 50 Ohm, and higher types of waves would be absent in the line. As is known, the lowest critical frequency of which ($f_{cr}^{H_{11}}$) is the H_{11} mode [7-9].

Thus, the single-mode mode will be achieved in the coaxial segment under the following conditions:

$$f < f_{cr}^{H_{11}}\sqrt{\varepsilon} = \frac{c}{\pi\left(a+b\right)}, \tag{1}$$

where c is the speed of light in vacuum, ε is the relative dielectric constant of the line segment filling, a is the inner radius of the measuring coaxial segment, and b is the external radius, respectively.

After calibration (instead of the measuring object, the reference resistance was connected), the measuring object was connected to the system, which was a piece of coaxial line with a length of l = 9 cm with the diameter of the inner conductor $D_a = 2a$ = 3 mm, and the diameter of the outer conductor is $D_b = 2b$ = 7 mm ($f_{cr}^{H_{11}}\sqrt{\varepsilon}$ = = 19.1 GHz).

The frequency characteristics of the VSWR (voltage standing wave ratio) and attenuation were measured using a measuring system.

In the absence of filling, the segment is coordinated with the cables of the measuring system, therefore, the reflected wave will be practically absent, and the signal attenuation will be determined by losses in the conductors and contact connections of the segment [10-12].

The relationship of the electrodynamic parameters of the filling dielectric with the measurement results of the transmission line segment

When filling a line segment with a substance, both the VSWR and the attenuation will change. From this information, it is possible to determine the electrodynamic characteristics of the filling: ε, tgδ (tangent of the dielectric loss angle), $\tilde{\varepsilon}$ (complex relative permittivity), $\varepsilon^{/}$ is real part of $\tilde{\varepsilon}$: $\varepsilon^{/} = \varepsilon$, $\varepsilon^{//}$ (the imaginary $\tilde{\varepsilon}$ part associated with losses in the dielectric).

$$\tilde{\varepsilon} = \varepsilon' - i\varepsilon'' = \varepsilon\left(1 - i\,\mathrm{tg}\,\delta\right) = \varepsilon\sqrt{1+(\mathrm{tg}\,\delta)^2}\,\exp\left(-i\delta\right), \tag{2}$$

where $\mathrm{tg}\,\delta = \mathrm{tg}\,\delta_{pol} + \mathrm{tg}\,\delta_c \approx \mathrm{tg}\,\delta_{pol}$, $\mathrm{tg}\,\delta_{pol}$ – tangent of the angle of polarization losses, $\mathrm{tg}\,\delta_c = \dfrac{\sigma}{\omega\varepsilon\varepsilon_0}$ – conduction loss angle tangent, i is "imaginary" unit, σ is specific conductivity, $\omega = 2\pi f$ is cyclic frequency (f is frequency), ε_0 is the dielectric constant.

As is known, even at low frequencies (LF), oil, water, milk, etc. are dielectrics (conductivity σ is practically zero), therefore, in the microwave range (UHF and SHF), electromagnetic losses in oil are determined only by polarization effects ($\mathrm{tg}\,\delta_{pol}$). In the future, we will assume that oil does not have magnetic properties ($\mu = 1$).

By measuring the SWR (standing wave ratio), you can determine R (reflection coefficient), and then calculate the substance filling the segment.

At the input of the measurement object, there is a boundary between the media (Z_c jump).

$$|R| = \frac{\mathrm{SWR}-1}{\mathrm{SWR}+1} = \left|\frac{Z_c/\sqrt{\tilde{\varepsilon}} - Z_c}{Z_c/\sqrt{\tilde{\varepsilon}} + Z_c}\right| = \left|\frac{1-\sqrt{\tilde{\varepsilon}}}{1+\sqrt{\tilde{\varepsilon}}}\right| = \left|\frac{1-\sqrt{\varepsilon\sqrt{1+(\mathrm{tg}\,\delta)^2}}\,\mathrm{e}^{-i\delta/2}}{1+\sqrt{\varepsilon\sqrt{1+(\mathrm{tg}\,\delta)^2}}\,\mathrm{e}^{-i\delta/2}}\right|, \tag{3}$$

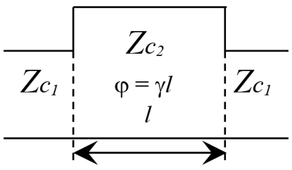

Fig. 2

At the output of the measuring object there will be a reverse jump of Z_c, which gives modulo the same reflection coefficient as formula (3), but with the opposite sign.

The total reflection coefficient (R) at the input (R_{in}) is determined by the superposition of waves reflected from the input and output.

It is convenient to use models and techniques to obtain quantitative characteristics [7–9].

After transformations of the scattering matrices of the basic elements (in Fig. 2: Zc jump ($Zc_1 - Zc_2$), a segment of the matched line with losses, and the reverse Zc jump is the load of the device ($Zc_2 - Zc_1$) with $R_l = -R$) we get the final scattering matrix (S-matrix) of the device:

$$S = \begin{bmatrix} R & T\,\mathrm{e}^{-\gamma l} \\ T\,\mathrm{e}^{-\gamma l} & -R\,\mathrm{e}^{-2\gamma l} \end{bmatrix}, \tag{4}$$

where $T = \sqrt{1-R^2} = \dfrac{2\sqrt[4]{\tilde{\varepsilon}}}{1+\sqrt{\tilde{\varepsilon}}}$ is the transmission coefficient of the reduced voltage, γ (longitudinal wave propagation coefficient) = $\alpha + i\beta$, α and β are attenuation and phase coefficients, respectively [7-9]:

$$\alpha = \frac{\pi f \sqrt{\varepsilon}\sqrt{2}}{c}\sqrt{\left(\sqrt{(\mathrm{tg}\,\delta)^2+1}-1\right)} \approx \frac{\pi f\sqrt{\varepsilon}}{c}\mathrm{tg}\,\delta, \tag{5}$$

$$\beta = \frac{\pi f \sqrt{\varepsilon}\sqrt{2}}{c}\sqrt{\left(\sqrt{(\mathrm{tg}\delta)^2+1}+1\right)} \approx \frac{2\pi f\sqrt{\varepsilon}}{c}\left(1+\frac{(\mathrm{tg}\delta)^2}{8}\right). \tag{6}$$

If the losses are small ($\mathrm{tg}\,\delta << 1$), then formulas (5-6) are simplified:

$$\alpha \approx \frac{\pi f\sqrt{\varepsilon}}{c}\mathrm{tg}\,\delta, \tag{7}$$

$$\beta \approx \frac{2\pi f\sqrt{\varepsilon}}{c}\left(1+\frac{(\mathrm{tg}\,\delta)^2}{8}\right). \tag{8}$$

Using the *D*-matrix method [7, 8], we obtain the reflection coefficient at the input (R_{in}) and the transmission coefficient at the output (T_{21}):

$$R_{in} = \frac{R - R(R^2+T^2)\mathrm{e}^{-2\gamma l}}{1-R^2\mathrm{e}^{-2\gamma l}} = \frac{R(1-\mathrm{e}^{-2\gamma l})}{1-R^2\mathrm{e}^{-2\gamma l}}, \tag{9}$$

$$T_{21} = \frac{T^2\mathrm{e}^{-\gamma l}}{1-R^2\mathrm{e}^{-2\gamma l}} = \frac{(1-R^2)\mathrm{e}^{-\gamma l}}{1-R^2\mathrm{e}^{-2\gamma}}. \tag{10}$$

Solving equations together (3), (5-10), you can calculate the necessary filling parameters ε and tgδ, and then $\tilde{\varepsilon}$, ε', ε'' using (2).

Analysis (9) shows that the frequency dependence of R_{in} at low R and low losses (α) has a pronounced periodicity.

$$R_{in} \approx R(1-\mathrm{e}^{-2\gamma l}) \to 1-\mathrm{e}^{-2i\beta l}. \tag{11}$$

Minimums will be observed at $\beta l = \pi n$ (n is a natural number):

$$f_{\min} = \frac{cn}{2l\sqrt{\varepsilon\left(1+0.25(\mathrm{tg}\delta)^2\right)}}. \tag{12}$$

The maximums will be observed at $\beta l = \pi(n+0.5)$:

$$f_{\max} = \frac{c(n+0.5)}{2l\sqrt{\varepsilon\left(1+0.25(\mathrm{tg}\,\delta)^2\right)}}. \tag{13}$$

By measuring the distance between two maximum or minimum (as you know, the measurement for minimum is more accurate), you can express the necessary parameters for a certain range ($f \in f_n \ldots f_{n+1}$):

$$\varepsilon\left(1+0.25(\mathrm{tg}\,\delta)^2\right) = \frac{c^2}{4l^2\left(f_{n+1}-f_n\right)^2}. \tag{14}$$

For large R, the denominator (9) begins to manifest itself, and the nature of the dependence of $R_{in}(f)$ becomes more complicated [13-15].

The experimental testing of electrodynamic characteristics of liquid substances

Before starting experiments with oil and other samples, two segments were studied in waveguide and coaxial versions without filling with dielectrics, as well as with water filling.

Figure 3 shows a photograph of a measuring installation, devices and their connections for experimental studies of the electrodynamic characteristics of liquid dielectric media (water, milk, varieties of oil, petroleum products, and so on).

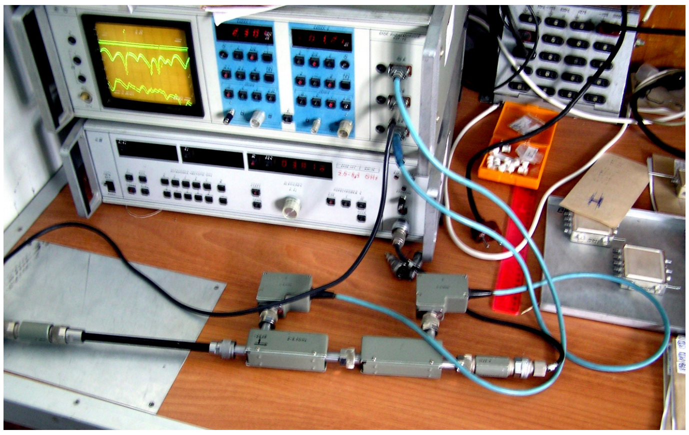

Fig. 3. Photo of connections for the experimental testing of electrodynamic characteristics of liquid substances

Measurement results for the empty segment

Figures 4-6 shows the frequency dependences (VSWR, $|R(f)|$, A in dB) averaged for two segments of the line without filling in the range of 2-18 GHz.

The frequency dependence of the VSWR is presented in Figure 4.

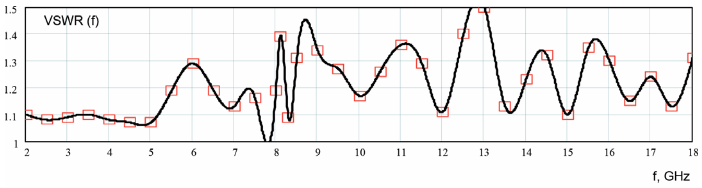

Fig. 4. VSWR (f) dependence of the segment of the coaxial transmission line without filling

It can be seen from Figure 5 ($|R(f)|$) that there is no complete agreement even in an unfilled segment. These data allow us to identify the systematic error of the experiment, which will allow us to correct the result for the filled segment.

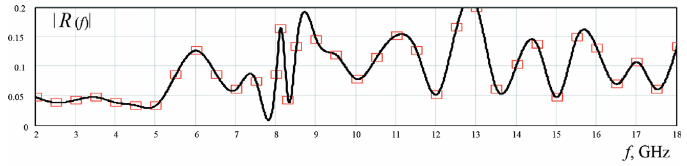

Fig. 5. R (f) dependence of the segment of the coaxial transmission line without filling

The analysis of Figure 6 shows that in the unfilled segment, losses (A in dB) in contact connections prevail over losses in conductors.

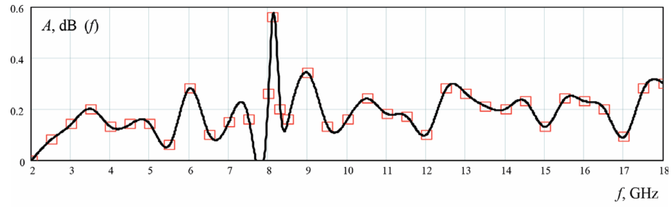

Fig. 6. The dependence of attenuation (in dB) on the frequency of the coaxial transmission line segment without filling

The error can be taken into account by subtracting the results obtained from the dependencies $|R(f)|$ and A(dB) (f) for the filled segment. The most accurate results are obtained by analyzing the relative capacities.

The full power supplied to the input of the measuring object is taken as a "1".

$$P_d + P_0 = 1 - P_{ref} - P_l = 1 - |R_{in}|^2 - |T_{21}|^2 . \quad (15)$$

where P_d is the power of losses in the dielectric, P_0 is the power of losses in the empty segment, P_{ref} is the power of the reflected wave, P_l is the power in the load.

After the transformations, we can express the coefficient of losses in the dielectric (α_d) (16):

$$\alpha_d = \frac{1}{l}\left[\ln\left(\sqrt{1-|R_{in}|^2}\right) - \ln|T_{21}|\right] - \alpha_0 . \quad (16)$$

where α_0 is the coefficient of losses in the empty segment.

After the formula transformations, we get (17):

$$\alpha_d = \frac{1}{l}\left[\ln\left(\sqrt{1-|R_{in}|^2}\right) - \ln|T_{21}| - \ln\left(\sqrt{1-|R_0|^2}\right) + \ln|T_0|\right] . \quad (17)$$

where R_0 is the reflection factor of the empty segment, T_0 is the transmission coefficient of the empty segment.

After calculating the α_d by the formula (7), we determine $\sqrt{\varepsilon}\ \mathrm{tg}\,\delta$.

Measurement results for the segment filled with water

Figures 7-9 shows the frequency dependences of the trial experiment with coaxial segment filled with water from an ordinary water pipe.

A dependence of the reflection factor ($|R(f)|$) of the segment of the coaxial transmission line with water is presented in Figure 7. (The dashed line at the bottom of the graph marks the graph for the unfilled segment which has shown in Figure 5).

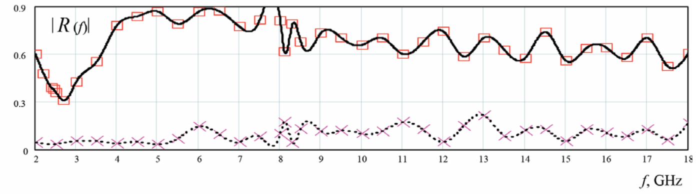

Fig. 7. Dependence of the module $R(f)$ of the segment of the coaxial transmission line with water

A dependence of the relative power of losses in the dielectric in the coaxial transmission line segment filled with water is presented in Figure 8.

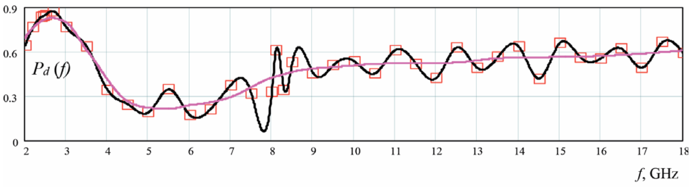

Fig. 8. Dependence of the relative power of polarization losses in a segment of a coaxial transmission line with water

A dependence of tgδ (f) for the coaxial transmission line segment filled with water shown in Figure 9.

Figures 7-9 shows an obvious loss resonance in the 2.4-2.8 GHz frequency range, which is known to be used in microwave heating of water-containing products (f = 2.45 GHz).

When calculating the electromagnetic parameters of water, it turned out that there are two solutions that differ as ε and $1/\varepsilon$ (this follows from the analysis of Figure 2 and formulas (3)). Obviously, solutions with $\varepsilon < 1$ should be excluded.

Conclusions

The results obtained are consistent with those published [1-6].

It is assumed that the losses in the test substance will be insignificant. If $\mathrm{tg}\,\delta > 0.1$, then formulas (5-6) should be used to calculate α and β.

Thus, using the considered technique, it is possible to determine the electromagnetic parameters of various liquid substances in the microwave range.

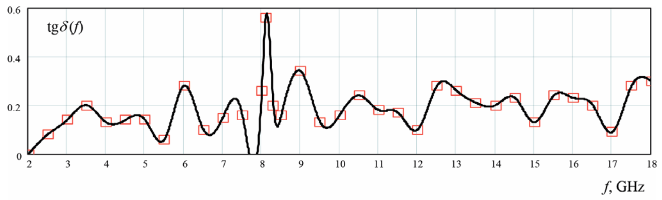

Fig. 9. Dependence of tgδ (f) of the coaxial transmission line segment with water

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ОПРЕДЕЛЕНИЕ ЭЛЕКТРОМАГНИТНЫХ ПАРАМЕТРОВ ЖИДКИХ ВЕЩЕСТВ В МИКРОВОЛНОВОМ ДИАПАЗОНЕ

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Аннотация

В этой работе описана схема эксперимента для исследований электродинамических свойств жидкостей в микроволновом диапазоне, приведены расчетные формулы в рамках одноволновой модели и результаты пробных экспериментов. В настоящее время продолжается изучение применения электромагнитных волн микроволнового диапазона (0.3-30 ГГц - УВЧ и СВЧ) для нагрева различных веществ, имеющих подходящие для этого электродинамические свойства. Особый интерес в этой области представляют жидкие вещества. Обработка микроволновым излучением может применяться для решения задач обеззараживания воды, молока и т. п. Микроволновый нагрев может использоваться в нефтедобывающей промышленности. Для определения электродинамических свойств жидких веществ была собрана экспериментальная измерительная установка. Для измерений электродинамических параметров веществ был сконструирован полый отрезок коаксиальной линии, который имеет разбираемую конструкцию и перед измерениями может быть полностью заполнен исследуемым веществом. Размеры коаксиального отрезка выбраны так, чтобы при отсутствии заполнения его характеристическое сопротивление составляло бы 50 Ом, что соответствует характеристическому сопротивлению соединительных отрезков коаксиальных линий, и при этом в линии передачи отсутствовали бы высшие типы волн. После калибровки в экспериментальную систему подключался объект измерения. С помощью измерительной системы измерялись частотные характеристики КСВН (коэффициента стоячей волны по напряжению) и затухания. При отсутствии заполнения отрезок отраженная волна будет практически отсутствовать, а ослабление сигнала будет определяться потерями в проводниках и контактных соединениях отрезка. При заполнении отрезка линии исследуемым жидким веществом изменится и КСВН, и затухание. Из этой информации можно определить электродинамические характеристики заполнения: тангенс угла диэлектрических потерь и комплексную относительную диэлектрическую проницаемость. Для получения количественных характеристик удобно воспользоваться методом D-матриц. Представлена схема измерительной установки, устройств и их соединений для экспериментальных исследований. В диапазоне от 2 ГГц до 18 ГГц были проведены экспериментальные исследования двух отрезков в волноводном и коаксиальном исполнении без заполнения диэлектриками, а также с заполнением водой. В работе приведены частотные

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зависимости КСВН, коэффициента отражения, затухания усредненные для двух отрезков линии без заполнения. Эти данные позволяют выделить систематическую погрешность эксперимента, что позволит скорректировать результат для заполненного отрезка. Анализ показывает, что в незаполненном отрезке преобладают потери в контактных соединениях над потерями в проводниках. Представлены частотные зависимости коэффициента отражения, относительной мощности поглощения в диэлектрике и тангенса угла диэлектрических потерь для эксперимента с водой. Полученные результаты согласуются с опубликованными. Таким образом, с помощью рассмотренной методики можно определять электромагнитные параметры различных жидких веществ в микроволновом диапазоне.

Ключевые слова: *микроволновый нагрев, жидкие диэлектрические среды, коэффициент отражения, коэффициент потерь, микроволновый диапазон, метод D-матриц.*

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