

A Technique for Non-Contact Identification of Liquids in Closed Containers Using Microwave Planar Metamaterial

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Abstract

At present, the fast non-contact identification of liquids is a real-life task for security systems and quality testing of various drinks. The possibility of identifying liquids in containers using a technique based on two oppositely connected planar photonic crystals (PPCs) with microwaves was experimentally demonstrated. The influence of the thickness of the container's walls, the container's diameter, and the inclination angle of the container axis relative to the plane of the planar photonic crystal on the reliability of the non-contact identification of liquids was experimentally investigated. The minimum change in the concentration of aqueous solutions of ethyl alcohol, sugar, and food salt that could be reliably distinguished in solutions was defined. For liquids containing water in thin plastic containers, the optimum operating frequency band (about 2 GHz to 4 GHz) of the experimental setup for their identification was found. The maximum thickness of the container wall at which the required reliability of the identification of liquids was achieved was evaluated for several selected operating frequencies. The possibility of non-contact analysis of not only aqueous solutions of ethyl and methyl alcohol, but also of their mixes, was experimentally shown. The developed technique for fast non-contact identification of liquids can be applied for food quality control, security systems, and chemical technologies.

1. Introduction

Today, there is an intensive search for techniques for the non-contact identification of liquids in non-conducting containers. Such tasks are real for security systems (for example, at airports) in order to prevent illicit liquids from getting onboard, as well as for systems that control the composition of the liquids, for example, in food-production technologies. There are several ways to solve such tasks by electromagnetic methods.

For example, the method of analyzing the reflection coefficient from the open end of a waveguide to measure the complex permittivity is known [1]. However, not only the amplitude, but also the phase of the reflection coefficient, must necessarily be measured in this method. In addition, a technique for measuring the transmission coefficient of waves passing through a dielectric waveguide with a container placed nearby [2] was developed. The disadvantage of this method was that the results were too highly sensitive to the distance from the container. The method described in [3] was based on measuring the self-resonance frequency of a solenoid with a cylindrical container placed inside it.

The method described in [4] was based on measuring the parameters of the modes of the spectrum of an open-

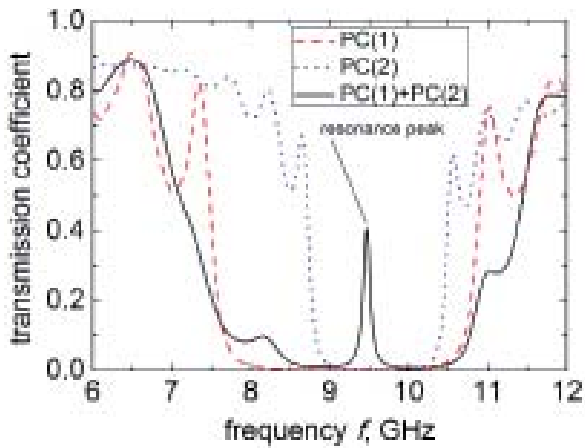


Figure 1a. The calculated spectrum of the transmission coefficient of waves passed through the different photonic crystals in a microstrip design (PPC(1) and PPC(2) curves), as well as for their serial connection (solid line).

ended waveguide with a container placed inside it. However, these methods were only suitable for analysis of containers of a fixed size. Another method was based on ultra-wideband measurement of S parameters of the open space with a container in the centimeter-wavelength range [5]. A similar method [6] used ground-penetrating radar for non-destructive analysis of the permittivity and conductivity of liquids in containers. The disadvantage of this technique was a very complicated method for measuring and processing the experimental data obtained.

A more promising technique used the measurement of parameters of resonator modes with a container that perturbed the resonator [7, 8]. For this technique, the principle of operation was based on the small-perturbation theory [9]. One such device using this technique has been successfully implemented in practice [8]. It used a radio-spectroscopic method, which used a combined dual-mode cylindrical resonator operating at frequencies less than 2 GHz. However, the devices based on this technique are not in widespread use because of the design complexity, the high cost, and the relatively large size. The development of a simple technique for the analysis and identification of liquids is therefore now an unsolved task.

For the technique developed by us, a structure based on a metamaterial such as the planar photonic crystal (PPC) [10, 11] was applied as an alternative to the dual-mode resonator. The suggested technique used low-cost materials and microwave components. The technique demonstrated manufacturing simplicity as well. Despite being inexpensive, the proposed method demonstrated the ability to identify liquids no worse than in [8]. Comparing the two methods presented in [8] and in the present work, we could conclude that the distinctive feature of the latter is the possibility of implementation of the final device in a more compact size.

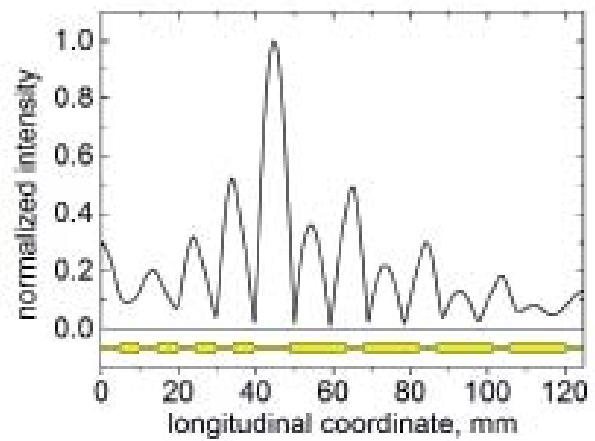


Figure 1b. The calculated distribution of the E field component normal to the planar photonic crystal plane along the planar photonic crystal at the frequency of the resonance peak, $f_1 = 9.5$ GHz.

We earlier proved the efficiency of the planar-photonic-crystal-based technique at frequencies of the order of 9.5 GHz [12-14]. At such frequencies, despite the influence of the constitutive parameters of liquids (the real and imaginary parts of the permittivity) on the microwave field in the planar photonic crystal, the parasitic effect of the container in which the liquid is placed should be taken into account [13]. By decreasing the operating frequencies to 2 GHz one could reduce the influence of the container, but this led to the unjustified increase in the size of the planar photonic crystal [14]. In addition, the influence of the diameter of the container where the liquid was placed increased. In [15], a special modification of a planar photonic crystal, which provided a reduced influence of this diameter, was proposed.

An important task is therefore to determine the influence of such container parameters as its material, diameter, and wall thickness on the reliability of non-contact identification of liquids. The aim of this paper is thus to experimentally determine the influence of structural features of planar photonic crystals and container parameters (material, diameter, wall thickness) on the reliability of the express analysis of liquids in non-conducting containers using the planar-photonic-crystal-based technique in the microwave frequency band.

2. Technique for Fast Non-Contact Identification of Liquids in the Microwave Band

As was shown in [10, 11], passing and blocking areas (pass and stop bands, Figure 1a) appear in the transmission spectrum of the planar photonic crystal (PPC) in the microstrip design. The photonic crystal is presented by alternating sections of microstrip lines of different widths.

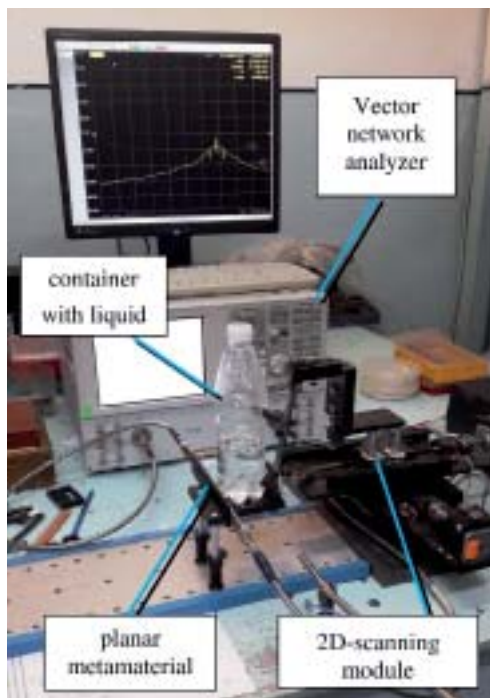


Figure 2a. A photo of the experimental setup for non-contact identification of liquids.

Figure 1a shows the calculated transmission-coefficient spectra of waves passed through the various photonic crystals in the microstrip design. The middle of the stop band for these photonic crystals was placed near the selected frequency of $f_1 = 9.5$ GHz. When some special parameters of two different opposite connected photonic crystals were defined, a narrow transmission resonance peak appeared in the stop band (Figure 1a, the peak near the frequency of $f_1 = 9.5$ GHz). Depending on the abovementioned type of metamaterial design, this peak can be considered as an electrodynamic analog of the “Tamm” state [10] or as a defect mode/oscillation. To form a peak in the transmission spectrum, its frequency had to lie within the boundaries of stop bands for both photonic crystals, and the effective wave impedances for both contacting photonic crystals at this frequency had to be equal. In this case, a concentration of electromagnetic energy was observed [10] (Figure 1b) at the interface between the two photonic crystals. In this figure, the calculated distribution of the component of the E -field normal to the planar photonic crystal plane along the planar photonic crystal symmetry plane at a distance of 0.5 mm from the planar photonic crystal’s surface at the frequency of the resonance peak, $f_1 = 9.5$ GHz, is shown. It is easy to see the field maximum near the interface of the two photonic crystals that is schematically shown in Figure 1b.

The experimental setup for non-contact identification of liquids using metamaterial based on planar photonic crystals in microstrip design is shown in Figure 2a [12]. It consisted of a metamaterial connected with coaxial-microstrip adapters and coaxial cables with a vector network analyzer, N5230A, which was used to measure



Figure 2 b. Various experimental modules based on planar photonic crystals used at the operating frequencies: $f_1 = 9.5$ GHz (1), $f_2 = 3.2$ GHz (2), and $f_3 = 1.0$ GHz (3).

the transmittance of electromagnetic waves in a selected frequency band. For an accurate (about 0.1 mm) positioning of the container with the measured liquid relative to the interface between the two photonic crystals, a two-coordinate scanning device was used [16].

During the experiment, certain parameters of the resonance peak were determined [12]. In particular, the measured spectrum of the transmission coefficient of the electromagnetic wave that passed through the metamaterial based on the planar photonic crystals was approximated by the Lorentz curve, using the least-squares method with fitting parameters a , b , c and f_{res} :

$$T = c + \frac{a}{1 + b(f - f_{res})^2}. \quad (1)$$

Based on the obtained approximation dependence, such parameters of the resonance peak as the resonance frequency, f_{res} , and the quality factor, $Q = f_{res} \sqrt{b(1 + \sqrt{2})} / 2$, for the width at the level $1/\sqrt{2}$ of the maximum value, are then determined [12].

It was experimentally shown [12-14] that when a container with a liquid is placed at a small enough distance from the interface/boundary between two planar photonic crystals (the planar-photonic-crystal working area), the parameters of the resonance peak change. For a visual representation of these parameters, the graphic format was chosen in coordinates $1/Q = f(f_{res})$ on the distance to the planar photonic crystal’s interface, h_{var} , where $1/Q$ is the

inverse Q factor, and f_{res} is the resonant frequency of the peak [8]. Note that according to the small-perturbations theory [8, 9], the resonant frequency is mainly affected by the real part of the permittivity, and therefore the inverse Q factor is mainly affected by the imaginary part of the permittivity. For a fixed distance h_{var} from the planar photonic crystal's interface to the container with the liquid, measured normally to the metamaterial plane, we have one point on the graph in these coordinates. By changing the distance h_{var} , we obtain a set of values for the parameters f_{res} and $1/Q$, which is conveniently represented as a curve on the graph (Figure 3). In this case, it is convenient to normalize the values of the resonance frequency and the inverse quality factor to those values that are observed when the container with the liquid is removed from the working area in the vicinity of the planar photonic crystal's interface.

The next step is to compare the measured curve for the liquid under test with the already existing set of curves for known liquids. After the comparison, the curve from the set that lies most closely to the measured curve for the unknown liquid is selected. This leads to its identification [12].

Naturally, when the values of complex permittivity of several different liquids coincide at a given operating frequency, we obtain the same curves. It is also possible that liquids with different permittivity will give similar points on the curve at different distances h_{var} from the planar photonic crystal's interface. This can happen because each liquid does not correspond to one point on the graph, but corresponds to some curve for different distances. In rare cases, this curve may intersect with the curve for another liquid. For the real liquid identification process, it is therefore recommended to measure the f_{res} and $1/Q$ at several distances, h_{var} , and not at one fixed distance. In order to increase the reliability of liquid identification, it is also possible to carry out measurements at different frequencies using the same planar-photonic-crystal-based setup, since it can have several resonant frequencies [10, 11].

3. Definition of the Optimal Parameters of the Experimental Technique for Fast Non-Contact Identification of Liquids in the Microwave Band

To define the influence of the operating frequency on the reliability of identification of a liquid in a container, the following studies were carried out. During the measurements of parameters of various liquids in the thin polystyrene container, the different characteristics of the dependence of the inverse quality factor, $1/Q$, and the resonance frequency, f_{res} , on the distance h_{var} was experimentally shown (Figure 3) [12-14]. Three different frequencies were chosen for the study: $f_1 = 9.5$ GHz (Figure 3a), $f_2 = 3.2$ GHz (Figure 3b), and $f_3 = 1.0$ GHz

(Figure 3c). The metamaterials based on planar photonic crystals with these operating frequencies were designed and manufactured (Figure 2b). To reduce the size of the planar photonic crystal with the operating frequency of 1.0 GHz (Figure 2b, item 3), areas with different widths of the microstrip line were laid in meander-like style.

Note that with increasing of an electromagnetic wave absorption in liquid, the Q factor of the peak decreased with fixed h_{var} . This led to the shift of the abovementioned curve upwards. For three selected liquids, water had the greatest absorption for the operating frequencies of $f_1 = 9.5$ GHz and $f_2 = 3.2$ GHz, and therefore had the greatest value of the inverse quality factor. Ethyl alcohol had the highest absorption at the operating frequency of $f_3 = 1.0$ GHz, which was caused by its own resonant absorption frequency near 1 GHz. However, the liquids having low losses at microwave frequencies (such as vacuum oil – BM-6), have relatively small effects on the inverse Q factor of the peak. This latest fact is to be expected. As can be seen from Figure 3, the working distance at which the highest reliability of liquid identification was achieved did not exceed approximately 2 mm for the frequency of $f_1 = 9.5$ GHz, and 3 mm for the frequencies of $f_2 = 3.2$ GHz and $f_3 = 1.0$ GHz. This distance is defined not only by the operating frequency, but also by the accuracy of the determination of the resonant frequency and inverse Q factor of the peak.

To define the reliability of the liquid identification using a planar-photonic-crystal-based technique at the operating frequency of $f_1 = 9.5$ GHz, a study of aqueous solutions of ethyl alcohol, salt, and sugar was carried out [12, 13]. The influence of the concentrations of ethyl alcohol (Figure 4a), food salt (Figure 4b), and sugar (Figure 4c) in a water solution in a thin polystyrene container on the form of the dependence of $1/Q$ and f_{res} on the distance, h_{var} , to the container containing the liquid was studied. In more detail, the mass concentration of salt in a saturated solution was taken as 100%. Additionally, a study of the influence of water temperature on the dependence of the peak parameters on the distance h_{var} (Figure 4d) was carried out.

From Figure 4, it could be seen that increasing the concentration of some selected additions to aqueous solutions led to the decrease of the inverse Q factor because of the reduction of the imaginary part of the solution's permittivity. All dependencies in the figures were clearly distinguishable. For example, the minimum distinguishable concentration increment of ethanol (or sugar) in solutions was about 10%, and for salt solutions it was about 20%. It could be seen from Figure 4d that a change of the water temperature of approximately 5° led to noticeable changes (which exceeded the experimental error) in the curve. This made it possible to thus estimate the temperature of water-based solutions.

To define the influence of the container's position relative to the interface of the planar photonic crystals on the reliability of the identification of liquids, the influence

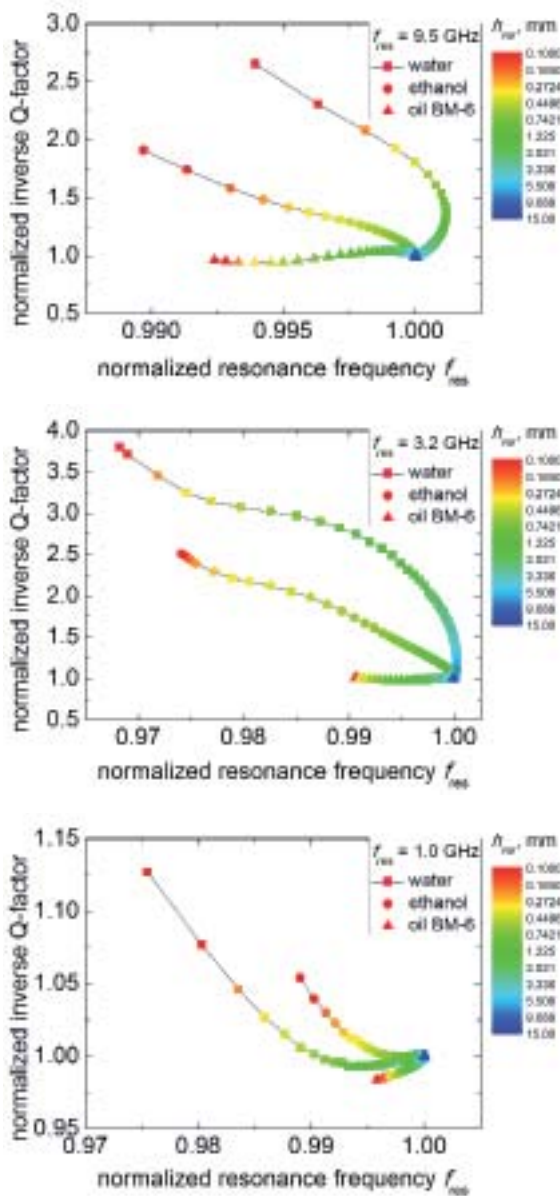


Figure 3. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res} , for different distances h_{var} from the interface of the photonic crystals to the polystyrene container with different liquids for the operating frequencies of the planar photonic crystal: (a) $f_1 = 9.5$ GHz, (b) $f_2 = 3.2$ GHz and (c) $f_3 = 1.0$ GHz.

of the vertical inclination angle of the container with water on the transmission peak parameters was studied. The change in the shape of the dependence of $1/Q$ and f_{res} on the distance h_{var} was analyzed for two cases (Figure 5) [13]. In the first case, the slope of the symmetry axis of the cylindrical PET (polyethylene terephthalate) container varied in the plane normal to the planar photonic crystal's plane (Figure 5a). In the second case, this axis laid in a plane parallel to the planar photonic crystal's plane (Figure 5b). In both cases, as the inclination angle of the container axis increased, the resonance frequency, f_{res} , shifted toward higher frequencies by a value of about 5×10^{-5} with a

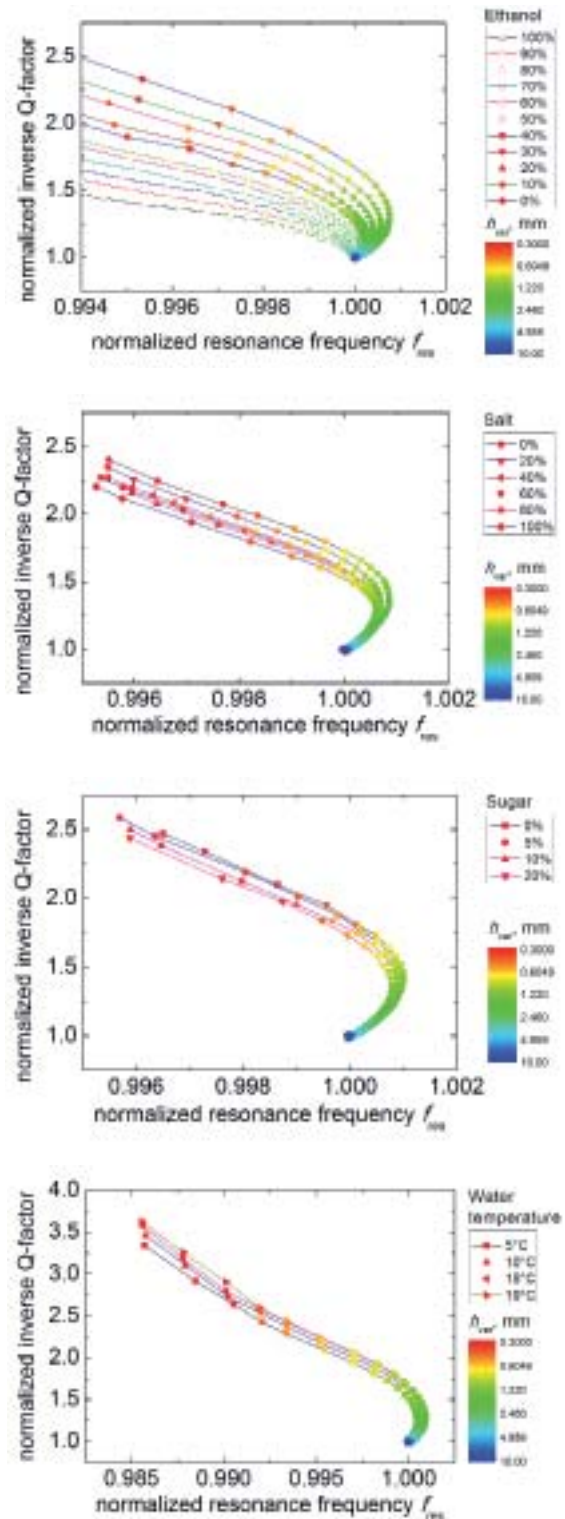


Figure 4. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res} , for different distances h_{var} from the interface of the photonic crystals to the container with liquids: (a) for various concentrations of ethyl alcohol in water; (b) for various concentrations of food salt in water (relatively to the concentrated solution); (c) for various concentrations of sugar in water; (d) for different water temperatures.

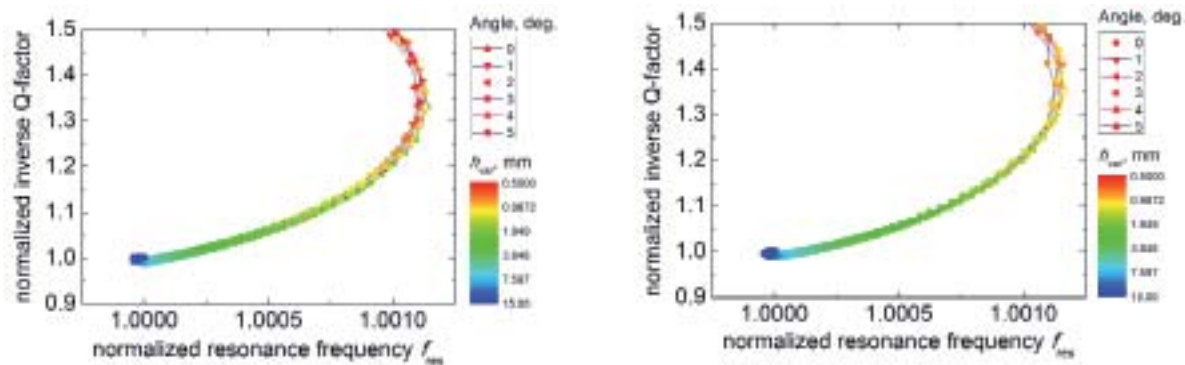


Figure 5. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res} , for different distances h_{var} from the interface of the photonic crystals to the container with water and for various values of the vertical inclination angle of the axis of symmetry of the PET container in the plane: (a) normal to the plane of the planar photonic crystal; (b) parallel to the plane of the planar photonic crystal.

inclination of 1° . At the same time, the values of frequency shift that were observed when the additions to the liquid reached the concentration of about 10% (Figures 4a-4c) or values of frequency shift that were observed with a liquid temperature variation of 5°C (Figure 4d) appeared much greater than frequency shifts caused by the slope of the container's axis.

The next stage of the work was to determine the influence of the container's wall thickness on the reliability of identification of liquids at various frequencies ($f_1 = 9.5\text{ GHz}$, $f_2 = 3.2\text{ GHz}$, and $f_3 = 1.0\text{ GHz}$) [14]. The dependencies of the values $1/Q$ and f_{res} on the distance, h_{var} , for water in cylindrical polyethylene terephthalate copolymer (coPET) containers with wall thicknesses from $h = 0.4\text{ mm}$ to $h = 1.6\text{ mm}$ were experimentally measured (Figure 6).

It was easy to see (Figure 6) that as the operating frequency of the planar photonic crystals increases, the wall thickness of the container had an increasing influence on the measurement results. This could be explained by the fact that as the operating frequency of the planar photonic crystals increases, the ratio of wall thickness to wavelength increases.

In order to determine the reliability of the planar-photonic-crystal-based technique at various frequencies ($f_1 = 9.5\text{ GHz}$, $f_2 = 3.2\text{ GHz}$, and $f_3 = 1.0\text{ GHz}$), a series of measurements of mixed solutions of sugar and ethyl alcohol in water in containers made of the same material, but with different wall thicknesses, was carried out [14]. The concentration of ethyl alcohol in water was chosen to be 25% (a widespread value for alcoholic drinks). Mixed solutions (Figure 7) were studied at three operating frequencies in coPET containers with wall thicknesses of 0.4 mm and 1.6 mm. The sugar content varied in the range of 0 ml to 30 ml for 66 ml of a 25% solution of ethyl alcohol in water.

As could be seen from Figure 7, at the frequency of $f_1 = 9.5\text{ GHz}$ (Figure 7a), the growth of the thickness of

the container walls, h , led to a change of values $1/Q$ and f_{res} of an order of magnitude greater than the result of adding sugar to the solution. Note that at the frequency of $f_3 = 1.0\text{ GHz}$ (Figure 7c), the effect of adding sugar became approximately twice as large as the effect of increasing h .

It could be seen that at the frequency of $f_1 = 9.5\text{ GHz}$, a significant negative effect of an increase in the container wall thickness on the reliability of the definite identification of the studied solutions was observed. To the contrary, at the frequency of $f_3 = 1.0\text{ GHz}$, the influence of the container wall thickness on $1/Q$ and f_{res} was minimal. However, at this frequency, the overall reliability of the method was minimal. This could be explained by the smallness of the container size (the diameter, d , was about 60 mm) in comparison with the wavelength and size of the working area of the planar photonic crystal used in the measurements.

To thus identify aqueous solutions it is reasonable to use operating frequencies in the 2 GHz to 4 GHz band [14]. In this case, the method demonstrated sufficient reliability for liquids, identifying the liquid with a sufficiently small influence of the wall thickness of the container. For the case of other operating frequencies, the following disadvantages were observed. At the operating frequency of $f_1 = 9.5\text{ GHz}$ despite the higher sensitivity, the negative influence of the thickness of container walls (critically reducing the reliability of identification) was clearly observed. At the frequency of $f_3 = 1.0\text{ GHz}$, too small a reliability was demonstrated for the case of small container sizes (with a diameter of less than 60 mm).

It was experimentally obtained that for accurate and reliable identification of aqueous solutions, the maximum wall thickness of a coPET container for the case of an operating frequency of $f_1 = 9.5\text{ GHz}$ should not exceed $h = 0.4\text{ mm}$, and for a frequency of $f_2 = 3.2\text{ GHz}$ should not be more than $h = 1.6\text{ mm}$. For measuring liquids in containers with wall thicknesses $h > 1.6\text{ mm}$ (for example, a glass bottle), the identification of liquids is effectively carried out at frequencies $f_{res} < 3.2\text{ GHz}$. With a small

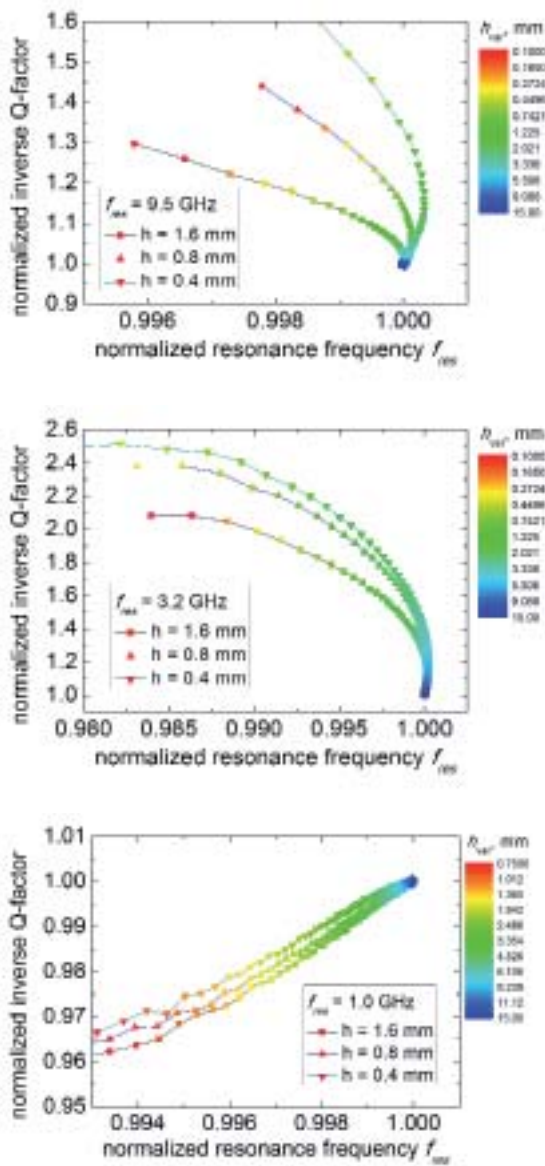


Figure 6. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res} , for different distances h_{var} from the interface of the photonic crystals to the coPET container with water and various wall thicknesses, h , for the operating frequencies of the planar photonic crystal: (a) $f_1 = 9.5$ GHz, (b) $f_2 = 3.2$ GHz, and (c) $f_3 = 1.0$ GHz.

thickness of the container wall (for example, a PET bottle), the highest identification reliability is achieved at frequencies $f_{res} \geq 9.5$ GHz.

Note that the shape of the container also affects the reliability of liquid identification. A small influence of the container shape (for example, wall irregularities) was observed only for the operating frequencies of $f_2 = 3.2$ GHz and $f_3 = 1.0$ GHz, while for the frequency $f_1 = 9.5$ GHz the effect can be too large. In general, the characteristic size of the container's shape irregularities should be much less than the wavelength at the selected operating frequency.

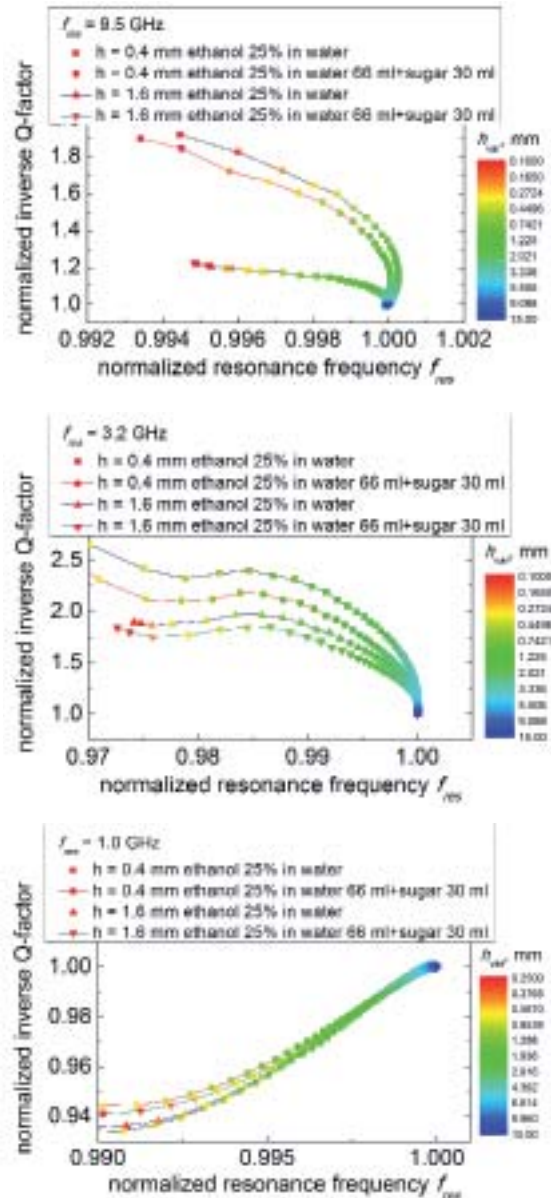


Figure 7. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res} , for different distances h_{var} from the interface of the photonic crystals to the coPET container with sugar solutions in a 25% solution of ethyl alcohol in water and various wall thicknesses, h , for the operating frequencies of the planar photonic crystal: (a) $f_1 = 9.5$ GHz, (b) $f_2 = 3.2$ GHz, and (c) $f_3 = 1.0$ GHz.

In order to determine the effect of container diameter on the reliability of identifying liquids for the technique based on a planar photonic crystal, an additional study was carried out. A series of measurements of water in cylindrical coPET containers with wall thicknesses of $h = 0.8$ mm at the operating frequency $f_4 = 2.5$ GHz, but with different diameters, d , of the container (Figure 8) were obtained.

As could be seen from Figure 8, an increase of the container diameter, d , leads to approximately the same changes in values of $1/Q$ and f_{res} as the change of the container's wall thickness at the frequency of $f_3 = 1.0$ GHz

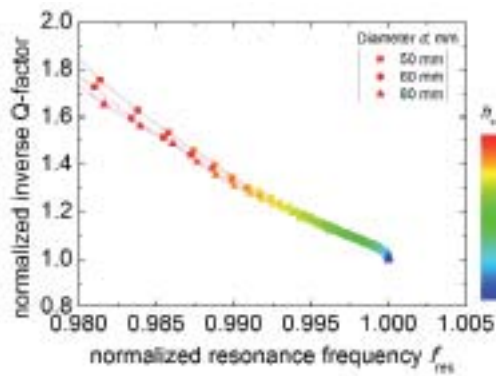


Figure 8. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res} , for different distances h_{var} from the interface of the photonic crystals to the coPET container with water with different diameters of container, d , for the operating frequency of the planar photonic crystal $f_0 = 2.15$ GHz .

(Figure 7c). The diameter of the container thus has a sufficiently small influence on the reliability of identification in this case.

4. Non-Contact Identification of Aqueous Solutions of Ethyl and Methyl Alcohol Using A Technique Based on a Planar Photonic Crystal

Non-contact monitoring of the presence of hazardous methanol in alcoholic drinks is a rather real task [14]. For this purpose, the possibility of distinguishing between aqueous solutions of ethyl and methyl alcohol was investigated. The measurements were carried out in a thin polypropylene container using a metamaterial based on the planar photonic crystal (PPC). The dependencies of $1/Q$ and f_{res} on the distance, h_{var} , to the interface of the planar photonic crystals were experimentally measured at the operating frequencies of $f_2 = 3.2$ GHz and $f_1 = 9.5$ GHz (Figure 9) for three aqueous solutions: 40% ethanol (a traditional solution of strong alcoholic drinks), 20% ethanol mixtures with 20% methanol, and for 40% methanol (in this case, ethanol was completely replaced by methanol).

As could be seen from Figure 9, for the frequency $f_2 = 3.2$ GHz, a larger difference in the measured values of $1/Q$ and f_{res} for selected alcohol solutions than for the frequency $f_1 = 9.5$ GHz was obtained. This can be explained by a significant difference in the specific natural (eigen) resonant frequencies for these two alcohols. As is known, many liquids have their own resonant absorption frequencies in the microwave band. In the Cole-Cole model of permittivity, this frequency for water is about 19.7 GHz, for methanol it is about 3.2 GHz, and for ethanol is about 1.1 GHz [17]. That is, the absorption in water at the frequency of $f_1 = 9.5$ GHz significantly exceeds the absorption in alcohols. However, at the frequency of

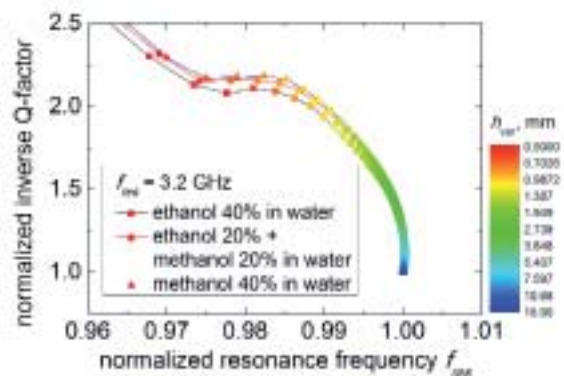
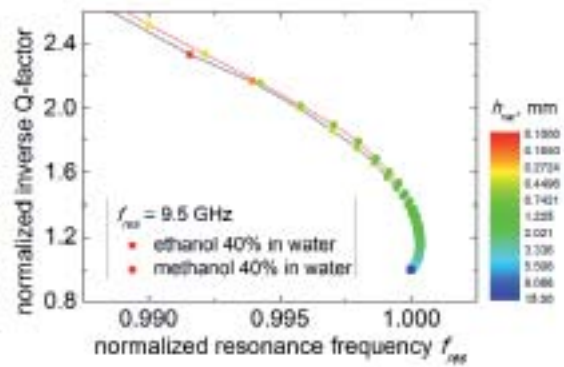


Figure 9. The inverse Q factor, $1/Q$, and the resonant frequency, f_{res} , for different distances h_{var} from the interface of the photonic crystals to the container with ethyl and methyl alcohol solutions in water for the operating frequencies of the planar photonic crystal: (a) $f_1 = 9.5$ GHz, and (b) $f_2 = 3.2$ GHz .

$f_2 = 3.2$ GHz, methanol makes a significant contribution to the total absorption, since its resonant frequency is close to 3.2 GHz. At the same time, the absorption in ethanol and in water is less at this frequency. This leads to a greater shift of inverse Q factor, $1/Q$, at the frequency of $f_2 = 3.2$ GHz (Figure 9b) when ethanol is replaced by methanol in aqueous solutions as compared to that observed at the frequency of $f_1 = 9.5$ GHz (Figure 9a). At the frequency of $f_2 = 3.2$ GHz it is therefore possible to distinguish not only pure alcohol solutions in water, but also their mixtures. This frequency is the best one for identification and recognition of these types of liquids among the two operating frequencies selected here.

5. The Design of a Portable Setup for Non-Contact Identification of Liquids

As a practical implementation of the above-mentioned techniques, a laboratory prototype of a portable setup for the identification of liquids was developed. In such a device, the planar photonic crystal of a special (finger-shaped) form was applied as a measuring element [15] (Figure 10). Giving such a form to the planar photonic crystal allowed us to locate the working area of the planar photonic crystal in

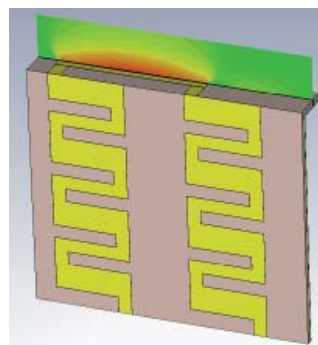
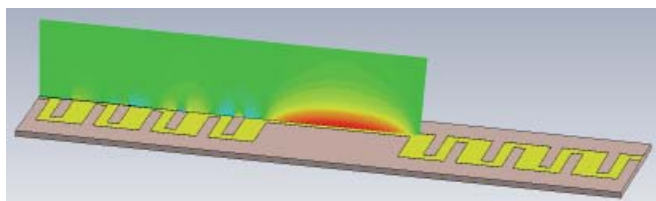


Figure 10. The spatial electromagnetic field distribution for the planar photonic crystal-based metamaterial (the normal component of the electric field): (a) “linear” planar photonic crystal and (b) “finger-shaped” planar photonic crystal.

the plane perpendicular to the plane of the rest of the planar photonic crystal, as shown in Figure 11a. This led to such a positive effect that containers (in particular, of especially large diameters) with liquids under study did not perturb the microwave field of the planar photonic crystal outside its working/resonant area (Figure 10b). This allowed us to avoid additional interaction of the microwave field with the container under study. Naturally, this positively affected the reliability of the identification of liquids.

The portable laboratory prototype (Figure 11b) for the operating frequency of $f_4 = 2.15$ GHz functionally consisted of the transceiver module, the interface and conversion module, the planar photonic crystal module, and the laptop. The overall control of the prototype device was realized by using specially designed software. At a command from the software, the oscillator in the transceiver module started to sweep the frequency in the 2.0 GHz to 2.4 GHz band. Synchronously with the process of frequency tuning, the interface and conversion module digitized the analog signal from the microwave detector located in the transceiver module. In the software window on the laptop, the spectrum of the transmission coefficient of electromagnetic waves passed through the planar photonic crystal module was presented. Note that the system operated in real time.

By locating the container with a liquid under test in the planar photonic crystal working area (Figure 10b), we could get graphs similar to those shown in Figure 8.

The dimensions of the device shown in Figure 11 were not limited from the smallest side. In the future, the device could generally be designed as a single circuit board with the oscillator, planar photonic crystal module, microwave detector, microcontroller, interface and conversion module.

It should be noted as well that all the components of the developed prototype device used were relatively inexpensive, which was undoubtedly a positive factor for considering the question of the device’s serial production.

6. Conclusions

The possibility of identifying liquids in containers using the technique based on two subsequently fitted planar photonic crystals (PPCs) in the microwave band has thus been experimentally demonstrated.

It was shown that in the process of the non-contact identification of liquids, it is necessary to take into account certain characteristics of the container in which the liquid is placed. The influence of the container on the reliability of non-contact identification of liquids using planar photonic crystals was studied. Namely, the influence of the thickness of the container’s walls, the container’s diameter, and the inclination angle of its axis relative to the plane of the planar photonic crystal on the parameters of the resonant transmission peak in the planar photonic crystal-spectrum were experimentally investigated.

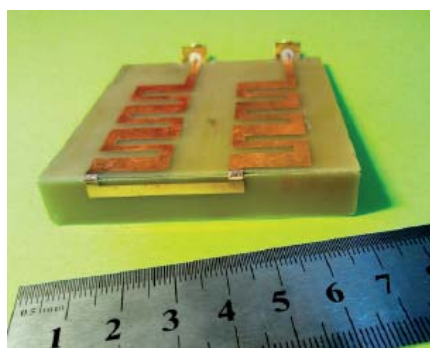


Figure 11. A photo of the (a) finger-shaped module based on planar photonic crystals; (b) portable laboratory prototype for identification and recognition of liquids in closed containers.

The minimum increment of the concentration of aqueous solutions of ethyl alcohol and sugar (10%), as well as food salt (20%), that resulted in reliable distinction of solutions was defined. For water-containing liquids in thin plastic containers, the optimal operating frequency band (of about 2 GHz to 4 GHz) of the experimental setup for their identification was found. The maximum thickness of the container's wall was evaluated for several selected operating frequencies of the setup at which the required reliability of identifying liquids was achieved. It was shown that the influence of the container's wall thickness on the identification results was minimal at an operating frequency of about 1 GHz.

By using the planar-photonic-crystal-based setup, the possibility of non-contact recognition of not only aqueous solutions of ethyl and methyl alcohol, but also of their mixed solutions, was experimentally shown at microwave frequencies.

Note that the use of the principles developed and the techniques based on them for non-contact fast identification of liquids and their analysis can be applied as well to various fields of food quality-control technology, chemical technologies, etc.

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8. References

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