Means for monitoring the dielectric parameters of liquid media based on quasiperiodic Bragg microwave structures in a coaxial waveguide

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Abstract. The main characteristic of the converter element in resonant microwave sensors that determines the sensitivity of the conversion is the quality factor of the resonance line. In structures with periodic inhomogeneity of the classical topology, the quality factor of the circuit at high values of the signal-to-noise ratio may turn out to be low, which entails the emergence of restrictions on the maximum achievable conversion parameters. One of the ways to increase both the Q factor and the modification of other properties of the microwave structure that affect the overall efficiency of the converter element is the use of quasiperiodic elements. The coaxial cable, where the holes in the dielectric act as inhomogeneity, is presented, forming structure with phase shift. Using the method of flow graphs, we obtained the analytical dependence of the reflection coefficient for this structure. The analysis of the frequency response of the microwave reflection coefficient was carried out for different values of the phase shift and the location of the phase shift section along the length of the cable. A numerical and physical experiments were carried out to determine the frequency dependence of the microwave reflection coefficient with a π-phase shift for various values of the automobile fuel permittivity introduced into the cells.

1. Introduction

In the fiber Bragg optic grating technique, high-Q structures with a π-phase shift are actively used [1–7]. Such structures are analogs of resonators based on microwave Bragg structures in a coaxial waveguide (BSCW), which we described in [8–9].

A microwave BSCW with a π-phase shift (Figure 1) is characterized by the presence of a section with a distance between adjacent inhomogeneities equal to kΛ/2, where k is an odd integer, Λ is the period of the Bragg structure (distance between periodic inhomogeneities).

![Figure 1. Bragg microwave structure in a coaxial waveguide with a π-phase shift](image-url)
In Figure 1, the configuration of the coaxial cable is shown for the case $k=1$, where the holes in the dielectric of the coaxial cable or waveguide act as inhomogeneities. Other types can also serve as inhomogeneities, for example, a stepwise change in the internal or external conductors, alternation of various dielectrics. Using the method of flow graphs, we can obtain the analytical dependence of the reflection coefficient for this structure.

2. The analytical dependence of the BSCW reflection coefficient
The flow graph for the case when the phase shift is in the middle of the waveguide will have the form shown in Figure 2.

\[
\Gamma_{\text{BSCW}} = \frac{b}{a} = \frac{\Gamma e^{-2j\beta A} + \frac{K^2 e^{-2j\beta L}(\Gamma - \Gamma_1 e^{-2j\beta A}(1 - \Gamma_1^2))}{1 - \Gamma e^{-2j\beta L}(\Gamma + \Gamma_1)} - \Gamma_1^2 e^{-2j\beta L}(\Gamma^2 + K^2 \Gamma_1)}{1 - \Gamma e^{-2j\beta L}(\Gamma + \Gamma_1)}
\]

where $\beta$ is the propagation constant in the waveguide.

Reflection coefficients $\Gamma$ and transmission $K$ without taking into account more than second-order contours, the description of which contains the reflection coefficient of a single inhomogeneity of $\Gamma$ in the fourth or more degrees, looks like

\[
\Gamma = \frac{\sum_{i=1}^{N} [(1 + \Gamma_i)^2 e^{2(1+i-1)} e^{-2j\beta A}] - \sum_{i=1}^{N} (N - k - i + 1)(1 + \Gamma_i)^2 e^{2(k-1)} e^{-2j\beta A}}{1 - \Gamma e^{-2j\beta L}(\Gamma + \Gamma_1)}
\]

\[
K = \frac{(1 + \Gamma_i)^N e^{N(1+i)} e^{-2j\beta A}}{1 - \Gamma e^{-2j\beta L}(\Gamma + \Gamma_1)}
\]

where $N$ is the number of cascade-connected inhomogeneities.

3. The analysis of the frequency response of the BSCW reflection coefficient
The analysis of the frequency response of the BSCW microwave reflection coefficient was carried out for different values of the phase shift and the location of the phase shift section along the length of the cable or waveguide.

Figure 3a shows the nature of the resonance curve when the distance between the central inhomogeneities changes for three values of the phase shift - $\pi$, $\pi/2$ and $3\pi/2$. Figure 3b shows the resonance curve when changing the location of the section with a $\pi$-phase shift for three location options: in the center of the cable, at a distance from the cable end by 0.2 and 0.3 parts of the total cable length.

Consider a method based on introducing the fluid under study into the cells of the structure formed by periodic holes in the external conductor and the internal dielectric of the cable or waveguide. A change in the effective permittivity of the inhomogeneity leads to a transformation of the shape of the characteristic from which information about the initial properties of the liquid medium can be extracted. Monitoring devices based on microwave BSCW can be used in various automated technological processes. A structure with an equidistant distribution of inhomogeneities has some disadvantages of using dielectric parameters as sensors, one of which is low sensitivity. The sensitivity of the measuring system can be increased by the configuration of the microwave BSCW with a phase $\pi$-shift. Due to the high quality factor of the circuit, the shift of the resonant frequency depending on the dielectric
properties of the liquid is determined with greater accuracy than in the case with an equidistant periodic structure [10, 11].

4. Results of a numerical experiment

A numerical experiment was carried out to determine the frequency dependence of the reflection coefficient of the microwave BSCW with a $\pi$-phase shift for various values of the substance permittivity introduced into the cells.

Figure 3. Frequency response of the microwave BSCW reflection coefficient:

- $a$ – different phase shifts ($1 - \pi$, $2 - \pi/2$, $3 - 3\pi/2$);
- $b$ – different locations of the $\pi$-phase shift from the end of the cable ($1 - 0.2$ cable lengths, $2 - 0.3$ cable lengths, $3 - 0.5$ cable lengths)

The calculation was performed by the flow graph method with preliminary obtaining the scattering matrix of an inhomogeneous region with the test fluid in the electromagnetic simulation program Microwave CST Studio. The permittivity ($\varepsilon$) lay in the range from 3 to 20, and the dielectric loss tangent ($\tan\delta$) in the range from 0.1 to 0.9. Figure 4a shows the reflection coefficient of a structure with 10 holes for a matter with $\tan\delta = 0.1$ for various values of $\varepsilon$, Figure 4b – for $\tan\delta = 0.9$.

Figure 4. Frequency dependences of the reflection coefficient of a microwave BSCW with a $\pi$-phase shift when the cable cells are filled with a matter $\tan\delta = 0.1$ ($a$) and $\tan\delta = 0.9$ ($b$)

Analyzing the obtained dependences, it can be observed that the dependence of the central frequency of the narrow resonance on $\varepsilon$ is linear, and the dependence of the resonance amplitude on $\varepsilon$ has the form $y(x) = 1/(1 + \exp(-k\cdot x))$. In this case, the resolution of determining the resonance deteriorates at large values of $\varepsilon$ and $\tan\delta$. By reducing the number of holes in the structure, this drawback can be somewhat corrected, but this approach entails an increase in the band of the resonance characteristic. Therefore to improve the measurement parameters it is necessary to search for other solutions.
One of these approaches is to reduce the effective dielectric constant of the inhomogeneous region for the case of high values of $\varepsilon$ and $\tan\delta$ of the medium under study, which is ensured by a decrease in the depth of the hole in the coaxial cable. Figure 5 illustrates the result of decreasing the cell depth by 0.25 from the maximum value, where one can observe the achieved expansion of the range of monitoring parameters $\varepsilon$ and $\tan\delta$. To increase the measurement range and reduce the influence of side resonances, the apodization method known in optical technology is used. A smooth change in the cell depth at the beginning and end of the waveguide is introduced (Figure 6).

![Figure 5](image)

**Figure 5.** Frequency dependences of the reflection coefficient of a microwave BSCW with a $\pi$-phase shift when cells reduced in depth for $\tan\delta = 0.1$ (a) and $\tan\delta = 0.9$ (b)

![Figure 6](image)

**Figure 6.** Apodization of the microwave BSCW profile

Figure 7 shows the result of the analysis of various forms of apodization: Gaussian contour (a), Lorentz contour (b), contour in the form of hyperbolic tangent (c) in comparison with the characteristic without apodization (d). From the analysis of Figures 7a-d we can see that the best suppression of the side lobes is shown by apodization by the Gaussian contour, in which there is less distortion of the main resonance shape with an average suppression of the side lobe level.

5. **Results of physical experiment**

An experimental verification of the developed microwave BSCW for use as a sensitive element for monitoring the dielectric parameters of a fluid was carried out using an example of an analysis of the properties of automobile fuel.

Due to the weak absorption of microwave waves by these liquids, that is, having a low loss factor, a variant of the sensitive element was chosen in the form of an air coaxial line with a periodic stepwise disturbance of the inner conductor.
The experimental setup consisted of an Agilent E5071C vector network analyzer with a frequency range of up to 20 GHz, connected via a connecting cable to a vertically located sensor. The measured samples were: “92 ecto” gasoline; “95 regular” gasoline; “95 ecto” gasoline; “100 ecto” gasoline. Figure 8 shows the measured frequency response of the sensor for all sample variants.

As can be seen from the graphs, the results for “92 ecto” and “95 ecto” gasolines are closest to each other, which indicates the proximity of their dielectric properties, which are apparently determined to a greater extent by additives. Table 1 shows the measured values of $\varepsilon'$ and $\varepsilon''$ for various grades of gasoline.

![Figure 7](image7.png)

**Figure 7.** Characteristics of microwave BSCW during apodization by a Gaussian contour (a), Lorentz contour (b), contour in the form of hyperbolic tangent (c) in comparison with the characteristic without apodization (d)

![Figure 8](image8.png)

**Figure 8.** Measurements for automotive fuels: amplitude (a) and phase (b) characteristics
Table 1. Measured values of $\epsilon'$ and $\epsilon''$ for various grades of gasoline

| Gasoline | $\epsilon'$ | $\epsilon''$ |
|----------|-------------|-------------|
| 92 ecto  | 2.146       | 0.023       |
| 95 ecto  | 2.158       | 0.022       |
| 95 regular | 2.197   | 0.029       |
| 100 regular | 2.283  | 0.017       |

6. Summary
We propose scientific and technical foundations for the use of periodic and quasiperiodic Bragg microwave structures in coaxial waveguide systems in the problems of measuring control of the complex dielectric constant of liquid media.

In particular, the following tasks were solved:

1. Models of dielectric permittivity measurements based on mathematical models of Bragg microwave structures in a coaxial waveguide are developed, achievable metrological characteristics are analysed for various configurations of sensitive elements;

2. Quasiperiodic Bragg microwave structures in a coaxial waveguide have been developed, which make it possible to improve certain characteristics and expand the functionality of measuring control devices based on them.

3. Experimental verification of sensitive elements to determine the complex dielectric constant of liquids, experimental studies to measure the properties of automotive fuels of various grades, recommendations for the creation of measuring equipment for dielectric control are got.

The error values obtained are on average ten times less than the values characteristic of existing methods for measuring the complex permittivity. The found solutions can find some special applying in various sensor applications.

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