ISSN 1063-7826, Semiconductors, 2009, Vol. 43, No. 13, pp. 1677–1681. © Pleiades Publishing, Ltd., 2009.
Original Russian Text © D.A. Usanov, A.V. Skripal', A.V. Abramov, A.S. Bogolyubov, M.Yu. Kulikov, 2009, published in Izvestiya vysshikh uchebnykh zavedenii. Elektronika, 2009, Vol. 43, No. 13.

MICROELECTRONIC DEVICES AND SYSTEMS

Photonic Structures and Their Application for Measuring Material Parameters

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Submitted April 7, 2008

Abstract—A computer simulation and an experimental study of the frequency dependences of the transmission coefficients of photonic crystals are carried out on the basis of microstrip lines with distortion in their periodicity in the form of change in the microstrip dimensions and the permittivity of a substrate of one of the alternate pieces of the microstrip line in the range of 0–20 GHz. Good quantitative agreement between the results of calculations and experimental data is obtained. It is shown that there is a possibility of using open microwave transmission lines, namely, microstrip photonic structures, to implement a method for measuring the parameters of material samples with the specified geometrical shape and a certain size that perform a function of nonuniformity in the photonic structure.

PACS numbers: 52.70.Gw, 42.70.Qs

DOI: 10.1134/S1063782609130132

1. INTRODUCTION

Intensive development of nanotechnologies has stimulated the development of a new class of periodic structures that are called photonic structures [1]. These structures consist of alternate layers whose sizes are comparable with the wavelength of electromagnetic irradiation propagating in them. In the transmission spectrum of such a structure, there is some region inhibited for propagating an electromagnetic wave that is an analog of the band gap in crystals. By analogy with real crystals, with distortion in the periodicity of the layer structure in the band gap of a photonic structure, narrow windows of transparency can appear [2, 3]. They are "donor" windows located near the upper frequency's boundary of the band gap or "acceptor" windows located near its lower frequency's boundary [2].

In the microwave range, a one-dimensional photonic crystal can be implemented by both dielectric-filled waveguides [4, 5] and planar transmission with an alternate structure [6–8]. Band filters, variable cavities, and miniature antennas are created on the basis of microwave-photonic crystals [4, 9–11]. A high sensitivity of the frequency dependence of transparency windows in the band gap of a photonic crystal on distortion in periodicity in the layer structure is known. In [5, 12], the possible use of this property of photonic crystals based on the waveguide construction is shown to control the permittivity of layered dielectrics and the parameters of nanometer metallic layers on insulated substrates.

In this publication, we report the results of a computer simulation and an experimental study of the frequency characteristics of open microwave transmission lines, namely photonic structures, in the range of 0–20 GHz. The possibility of their use to realize a method for measuring the parameters of the material that performs a function of nonuniformity in a photonic structure is discussed.

2. THEORETICAL DESCRIPTION

The photonic structure realized in the form of series-connected sections of a microstrip transmission line where the alternate width of the upper strip (Fig. 1) is considered. The photonic crystal on the basis of a microstrip line, which is a complex-structure four-pole circuit, can be presented by a cascade connection of elementary four-pole circuits with the known transmission matrixes, each of which describes a single section of the microstrip transmission line and the direct connection of each pair of the pieces with a different width of the upper strip.

To calculate the reflection and transmission coefficients of an electromagnetic wave through a crystal based on a microstrip line in a quasi-static approximation, the transmission matrix **T** of a complex-structure four-pole circuit was used with the following form

$$\mathbf{T} = \begin{pmatrix} T[1,1] & T[1,2] \\ T[2,1] & T[2,2] \end{pmatrix} = \mathbf{T}'_N \prod_{i=1}^{N-1} (\mathbf{T}''_{i,i+1} \mathbf{T}'_i), \quad (1)$$

where $\mathbf{T}'_i$ is the transmission matrix of the four-pole circuit describing the ith piece of a microstrip transmission line, and $\mathbf{T}''_{i,i+1}$ is the transmission matrix of the four-pole circuit describing the direct connection between its ith and $i+1$ pieces.

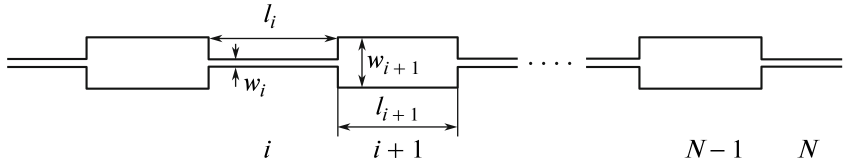

Fig. 1. Structure of a photonic crystal based on a microstrip line: w_i is the width of the upper ith strip, l_i is the length of the ith section of the upper strip.

The expressions for transmission matrixes $\mathbf{T}'_i$ and $\mathbf{T}''_{i,j}$ of the corresponding elementary four-pole circuits have the following form [13]

$$\mathbf{T}'_i = \begin{pmatrix} e^{\gamma_i l_i} & 0 \\ 0 & e^{-\gamma_i l_i} \end{pmatrix}, \quad (2)$$

$$\mathbf{T}''_{i,i+1} = \begin{pmatrix} \frac{R_{i,i+1}+1}{2\sqrt{R_{i,i+1}}} & \frac{R_{i,i+1}-1}{2\sqrt{R_{i,i+1}}} \\ \frac{R_{i,i+1}-1}{2\sqrt{R_{i,i+1}}} & \frac{R_{i,i+1}+1}{2\sqrt{R_{i,i+1}}} \end{pmatrix}. \quad (3)$$

Here, l_i is the length of the i-th piece, γ_i is the propagation constant of an electromagnetic wave in the ith piece, $R_{i,i+1} = \frac{\rho_{i+1}}{\rho_i}$, ρ_i is the shock-wave drag (wave resistance) of the ith piece of a microstrip.

After calculating the transmission matrices **T** of a photonic structure, which is a four-pole circuit, we determine the propagation coefficient of microwave power through the element $T[1, 1]$ of the transmission matrix using expressions (1)–(3)

$$t = \frac{1}{|T[1,1]|^2}. \quad (4)$$

The coefficient of reflection of microwave power from a photonic structure is determined by the squared absolute value of the element $S[1, 1]$ of the scattering matrix

$$r = |S[1,1]|, \quad (5)$$

whose elements are connected with the elements of the transmission matrix **T** by the relationship

$$\mathbf{S} = \begin{pmatrix} S[1,1] & S[1,2] \\ S[2,1] & S[2,2] \end{pmatrix}$$

$$= \begin{pmatrix} \frac{T[2,1]}{T[1,1]} & \frac{T[1,1]T[2,2]-T[1,2]T[2,1]}{T[1,1]} \\ \frac{1}{T[1,1]} & -\frac{T[1,2]}{T[1,1]} \end{pmatrix}.$$

We note that elementary four-pole circuits (2) and (3) are invertible and, between the scattering matrices' elements of these four-pole circuits, the relationship $S[1, 2] = S[2, 1]$ is valid and the determinant of the transmission matrix, $|T| = T[1, 1]T[2, 2] - T[1, 2]T[2, 1] = 1$.

3. COMPUTER SIMULATION

During the computer modeling, a photonic structure was considered that consisted of seven series-connected alternate pieces of a microstrip transmission line with a small and large width of the upper strip, which is involved in a 50-ohm transmission line. The width of the upper strip of the photonic structure of the first, third, fifth, and seventh pieces were 2.5 mm; and the second, fourth, and sixth were 0.5 mm. The length of wide pieces was 7 mm, and the length of narrow pieces was 7.6 mm. The permittivity of the substrate $\varepsilon = 9.6$.

The frequency dependence of the transmission coefficient of the photonic structure simulated in the range from 0 to 27 GHz, which was obtained by the above model and the calculation technique in a quasi-static approximation [13] (Fig. 2, curve *1*), is characterized by the presence of the frequency region inhibited for propagating an electromagnetic wave, that is an analog of the band gap in crystals.

Figure 2 also shows the calculated frequency dependence of the transmission coefficient of the photonic structure $|T|^2$ with their distortion in the form of one (the fourth) shorter section l_4 (curves *2*, *3*, and *4*). In this case, in the frequency dependence of the transmission coefficient, a narrow "window" of transparency appears in the band gap for propagating in the frequency-domain of electromagnetic wave, the location of which can be regulated by changing the length of this section.

Distortion in the periodicity of a photonic structure can be created by both changing the microstrip length and changing the permittivity of the substrate of one from alternate pieces of the microstrip line that results in changing the propagation constant of a wave.

If a photonic structure includes the area with the substrate permittivity ε different from the permittivity of the rest areas, in the dependence $|T(f)|^2$, a narrow transparency window appears in the zone (band gap)

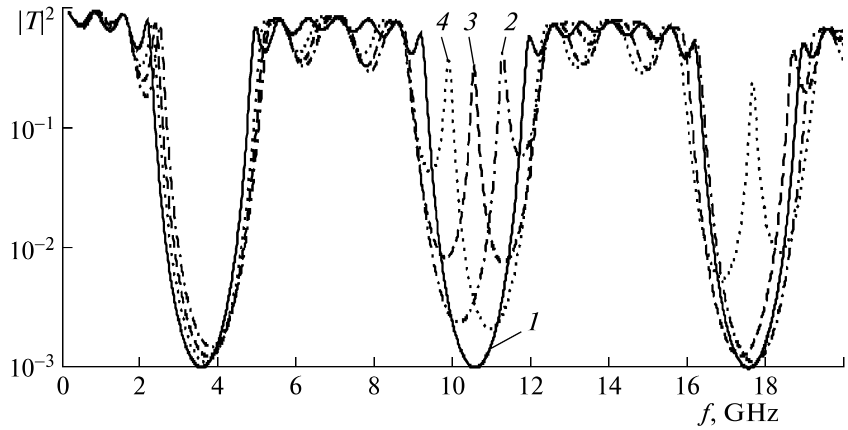

Fig. 2. Frequency dependences of the squared absolute value of the transmission coefficient of a photonic structure with distortion in the periodicity for different lengths l_4 of the forth peace (lesser-width piece): curve *1* corresponds to the photonic crystal without distortions, curve *2*—$l_4 = 4.2$ mm, curve *3*—$l_4 = 5.1$ mm, and curve *4*—$l_4 = 6.0$ mm.

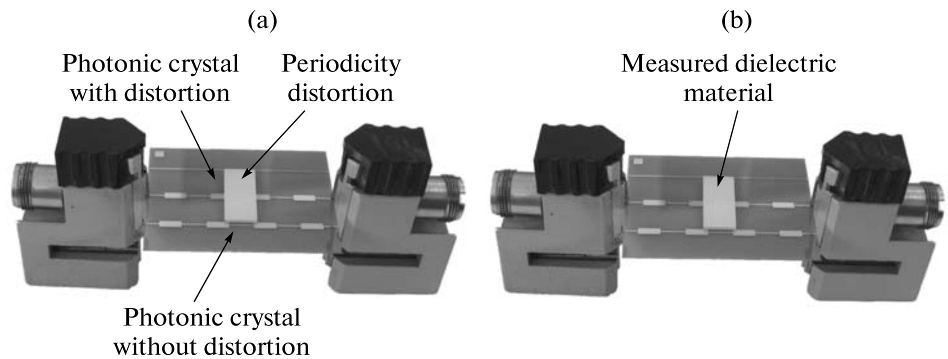

Fig. 3. Photonic structures in a coaxial-to-microstrip adapter (a) and location of the measured dielectric specimen (b).

inhibited for propagating a frequency-domain electromagnetic wave and its location depends on the value of ε.

The calculated dependences $|T(f)|^2$ for the photonic structure with the transparency window at different values of the permittivity ε_4 of one of the layers are similar to that presented in Fig. 2.

By analogy with real crystals, creating the above distortions in photonic structures also results in donor transparency windows appearing in the band gap located near the upper frequency's boundary of the band gap (Fig. 2, curve *2*) or the "acceptor" windows located near the lower frequency's boundary of the band gap (Fig. 2, curve *4*).

4. RESULTS

One-dimensional photonic structures with a polycor (Al_2O_3) substrate were studied experimentally; these structures are represented by a series of connected alternate sections of a microstrip transmission line with a large and small width of the strip conductor and are made according to the parameters specified in the theoretical model. In the experiment, a coaxial-to-microstrip adapter was used (Fig. 3a). The measurements were performed using an Agilent PNA-L Network Analyzer N5230A vector analyzer of circuits.

In the frequency range 0–20 GHz, the frequency dependence of the module of the transmission coefficient $|T(f)|^2$ of an electromagnetic wave interacting with the studied photonic structure based on a seven-layer microstrip line was measured; this dependence is characterized by the presence of frequency regions inhibited for propagating the electromagnetic wave (Fig. 4, curve *1*). The calculated dependence $|T(f)|^2$ is given (Fig. 4, curve *2*) and was obtained by the above model and the calculation technique in a quasi-static approximation.

In the studied structure, the periodicity was distorted in the form of the shorter length l_4 of the fourth high-resistance section of the microstrip transmission line ($l_4 = 5.1$ mm). The presence of such a distortion resulted in the appearance of a transparency window in the band gap of the photonic structure with a central frequency of 10.5 GHZ. Figure 5 shows the experimental and calculated (obtained by the above model and calculation technique in a quasi-static approxima-

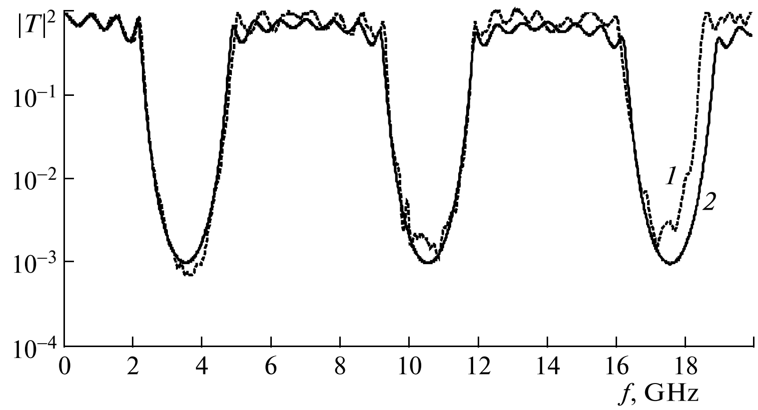

Fig. 4. Experimental (curve *1*) and calculated (curve *2*) dependences $|T(f)|^2$ of a photonic structure based on a seven-layered microstrip line.

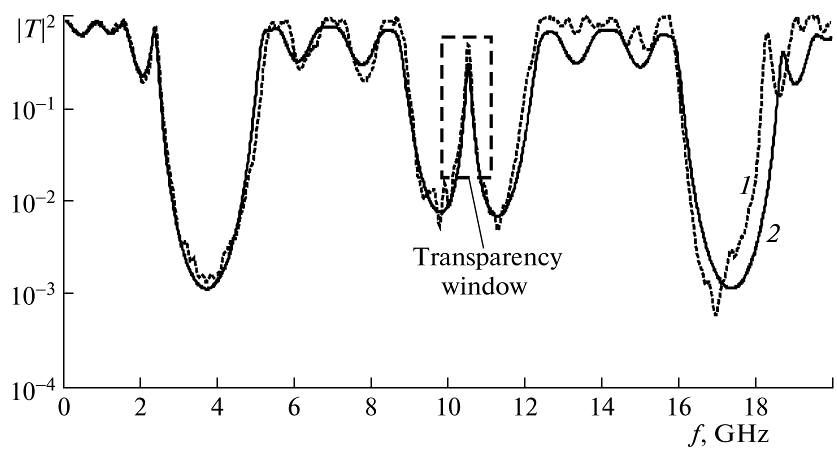

Fig. 5. Experimental (curve *1*) and calculated (curve *2*) dependences $|T(f)|^2$ of a photonic structure based on a seven-layered microstrip line with the presence of the distortion in its periodicity.

tion) frequency dependences of the transmission coefficient of the photonic crystal based on a seven-layer microstrip structure with distortion in its periodicity.

Since distortion in periodicity in a photonic structure can be created by implementation of any situation under which the propagation constant of an electromagnetic wave changes in a single part of the photonic structure due to change in the effective permittivity of the substrate on this piece, the possibility to implement a sufficiently simple technique for controlling the location of the transparency window in the band gap of the photonic structure was studied. We studied the frequency dependence of the transparency window in the band gap (frequency range 9–12 GHz) of the photonic structure when locating the specimens with fixed sizes of 23 × 10 × 2 mm and different permittivity ε above the forth high-resistance piece of the microstrip lines and symmetrically with respect to the strip that results in change in the propagation constant of the electromagnetic wave in the single section of the photonic structure.

Figure 6 shows the results of measuring the frequency dependences of the transparency window in the band gap of the photonic structure on the permittivity ε of the specimens with a fixed size of 23 × 10 × 2 mm, which are located symmetrically relative to the strip, above the fourth high-resistance section of the microstrip line.

The comparison of the calculated results and experimental data exhibits their good quantitative agreement. This allows photonic structures to be used to measure the parameters of a material performing a function of non-uniformity in a photonic structure by solving the corresponding inverse problem just as described in [14, 15]. In this study, in contrast to [14, 15], the material under investigation is in a system open for external effects that can be used to measure the response of this material on these effects.

As suggested, the form of the frequency dependence of the transparency window in the band gap of a photonic structure with the periodicity distortion

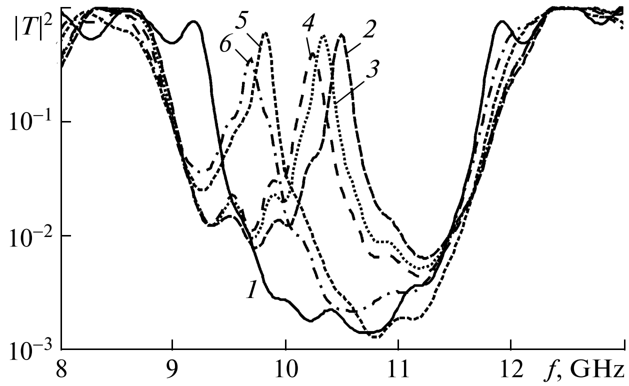

Fig. 6. Experimental dependences $|T(f)|^2$ of photonic structures with the presence of the distortion of its periodicity in the form of change in the length of the fourth layer l_4 = 5.1 mm for different values of ε for the specimens located above the fourth high-resistance section of a microstrip line: curve *3*—ε = 2.1, curve *4*—ε = 2.5, curve *5*—ε = 9.6, curve *6*—ε = 11.8. Curve *1* corresponds to the photonic structure without distortions; curve *2*, with distortion when the measured specimen is absent.

strongly depends on the permittivity of the studied specimens with the specified geometrical dimensions and the certain size (Fig. 6).

As a result of the studies performed, a good quantitative agreement is obtained between the results of the computer simulation of the microwave characteristics of photonic structures using the calculation technique based on the description of these characteristics in a quasi-static approximation by the transmission matrix of a complex-structure four-pole circuit and the results of experimental studies of the frequency characteristic of open microwave transmission lines, i.e., photonic structures within the range 0–16 GHz. The features of the frequency dependences of the transmission coefficients of photonic structures (based on a microstrip structure with distortion in their periodicity in the form of the dimensions of the microstrip) and the substrate permittivity of one of the alternate sections of the microstrip line were studied theoretically and experimentally. It is shown that open microwave transmission lines, namely, microstrip photonic structures, are capable of realizing the method for measuring the parameters of material specimens with the specified geometric shape and a certain size that perform a function of the non-uniformity in a single section of the photonic structure.

ACKNOWLEDGMENTS

The study was supported by the Russian Federation Ministry of Education and Science (project no. 1.4.08, state registration no. 0120.0801702), and a grant of the Russian Federation President for supporting young Russian scientists (MK-2083.2007.8 and MK-2205.2008.8).

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