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ELECTRODYNAMICS AND WAVE PROPAGATION

Bragg Microwave Structures Based on Waveguide-Slot Lines

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Abstract—It is shown that a new type of the Bragg structure based on pieces of a waveguide-slot line can be created in the microwave band. The amplitude-frequency characteristics of such a structure are described theoretically and investigated experimentally in the frequency range 8–12 GHz. The regularities in the distribution of the electric field intensity in a standing wave appearing in the investigated Bragg structure are established. It is found that a resonance singularity appears in the forbidden zone of the investigated Bragg structure when a defect in the form of the changed length of the central section of a regular waveguide is made.

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INTRODUCTION

As far back as at the beginning of the sixties of the twentieth century creators of slow-wave systems for vacuum microwave instruments, who investigated the energy zones of these instruments, noticed the analogy of periodic structure properties in the microwave range and the properties of crystals [1].

Later, in the nineties, the authors of work [2] found an analogy between electron waves in a crystal and light waves in the periodic structure that is called a Bragg structure or a photon crystal and has a permittivity periodically changing in the space. In the microwave range, these structures are realized in waveguides and microstrips with the use of coaxial lines [3–8].

As a Bragg structure, the slotline is interesting by the fact that its application makes it possible to create integral microwave circuits having unique characteristics related to the properties of Bragg structures [9].

1. A MODEL OF A BRAGG MICROWAVE STRUCTURE BASED ON WAVEGUIDE-SLOT LINES

The general view of the Bragg microwave structure based on slotlines is shown in Fig. 1. A waveguide-slot line section is placed in the E plane in the center of the cross-section of a rectangular waveguide (22.86 mm × 10.16 mm). The slotline is made on an alumina (Al_2O_3, $\varepsilon = 9.6$) plate that has the length of 23 mm, the width of 10.16 mm, and the thickness of 1 mm. One side of the plate is covered with the aluminum. The thickness of the aluminum covering is 0.012 mm, and the width of the slot in the covering is 4.0 mm. The sections of a regular waveguide are between the sections of the slotline. This Bragg structure is investigated in the frequency range 8–12 GHz.

The length of regular sections of the waveguide is varied in the range 2–10 mm. The periodicity is violated by changing the length of central regular section l of the waveguide in the range 14–20 mm.

2. COMPUTER MODELING OF THE CHARACTERISTICS OF A BRAGG MICROWAVE STRUCTURE BUILT ON WAVEGUIDE-SLOT LINES

It is known that, in a periodic structure, forbidden and allowed zones appear for certain relationships between the parameters of elements forming this structure. Then, the Bragg condition is fulfilled at the

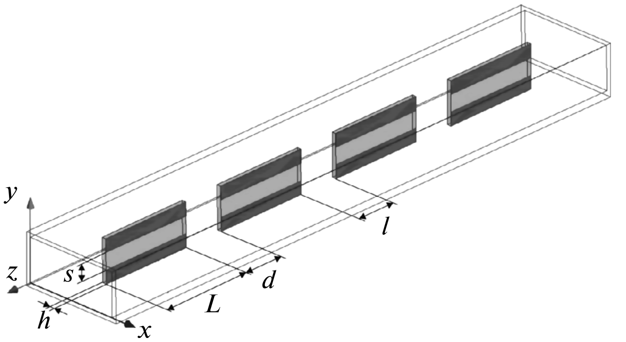

Fig. 1. Model of a photon crystal based on waveguide-slot lines: L is the length of the waveguide-slot line section, d is the length of the regular section of a waveguide, h is the thickness of slotline substrate, s is the slot width, and l is the length of the central regular waveguide section.

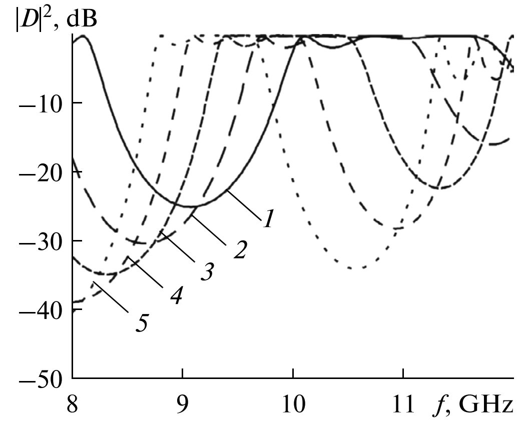

Fig. 2. Frequency dependences of the transmission coefficient of a photon crystal for various thicknesses of the substrate h = (*1*) 0.2, (*2*) 0.3, (*3*) 0.4, (*4*) 0.5, (*5*) 0.6 mm; L = 23 mm; d = 10 mm; s = 4.0 mm; and $\varepsilon = 9.6$.

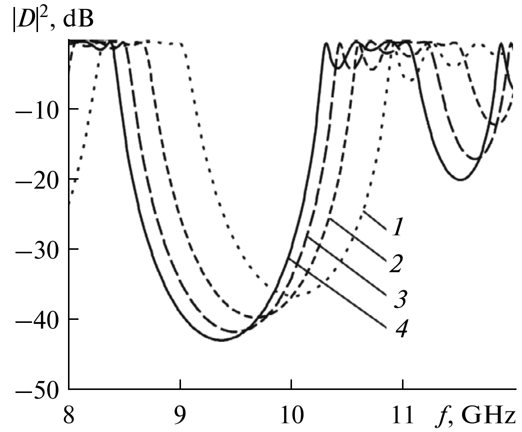

Fig. 3. Frequency dependences of the transmission coefficient of a photon crystal for various permittivities of the substrate ε = (*1*) 8, (*2*) 9, (*3*) 9.6, (*4*) 10; L = 23 mm; d = 10 mm; s = 4.0 mm; and h = 1.0 mm.

frequencies corresponding to middles of forbidden zones ω_B. For a structure consisting of periodically recurring elements of the two types, this condition can be represented in the form

$$\beta_1(\omega_B)d + \beta_2(\omega_B)L = n\pi, \qquad (1)$$

where $d + L$ is the period of the structure with the photon forbidden zone, β_1 is the phase component of the wave propagation constant on the regular waveguide section and this phase component is a function of ω_B, β_2 is the phase component of the wave propagation constant on the section of the waveguide-slot line, and n is the number of a forbidden zone. Note that β_2 is determined by the geometric dimensions of the slotline.

It follows from relationship (1) that the change of the phase propagation constants both on the sections of the waveguide-slot line and on the regular waveguide sections has to shift ω_B. The change of the phase constant on the sections of the waveguide-slot line can be realized by the change of the thickness and permittivity of the substrate and by the change of the slot width [10]. The phase constant can be changed on the sections of the regular waveguide by the change of the permittivity of the medium that fills these sections.

The microwave amplitude-frequency characteristics (AFCs) of a photon crystal created on the basis of alternating sections of the waveguide-slot line and regular waveguide sections is modeled on a computer using system HFSS of electromagnetic modeling and projection.

Figures 2 and 3 show the results of calculation of the frequency dependences of the squared absolute values of transmission coefficient $|D|^2$ of a microwave wave passing a Bragg structure. The structure consists of four sections of a waveguide-slot line. The results are obtained for various thicknesses and permittivities of the substrate of the slotline, respectively.

It follows from the results presented in these figures that the increase of the thickness and permittivity of the substrate in the above ranges shifts the AFCs to the low frequency region and increases the depth of the forbidden zone.

This behavior of the AFC is due to the fact that the increase of the thickness and permittivity of the slotline substrate increases phase constant β_2 of the waveguide-slot line section.

Figures 4 and 5 show the results of calculation of the electric field of the electromagnetic wave inside a photon crystal along the direction of the wave propagation (along the z axis, see Fig. 1) in the plane passing through the center of the waveguide wide wall and in the plane of the waveguide cross-section passing through the standing wave antinode on a section of the waveguide-slot line (along the x axis, see Fig. 1) for various thicknesses of the substrate.

The analysis of distributions of the electric field intensity of the electromagnetic wave inside a photon crystal along the direction of the wave propagation and in the transverse plane of the waveguide makes it possible to conclude that the regime of a standing wave with pronounced nodes and antinodes is realized at the transparency frequencies of the photon crystal inside its structure. As the thickness and permittivity of the substrate of the waveguide-slot line grow, the electric field intensity increases in antinodes and decreases in the nodes. Note that the maximum electric field intensity in the plane of the waveguide cross-section is inside in the center of the substrate. However, the character of dependence $E(x)$ substantially differs from the sinusoidal one that is typical of wave H_{10}.

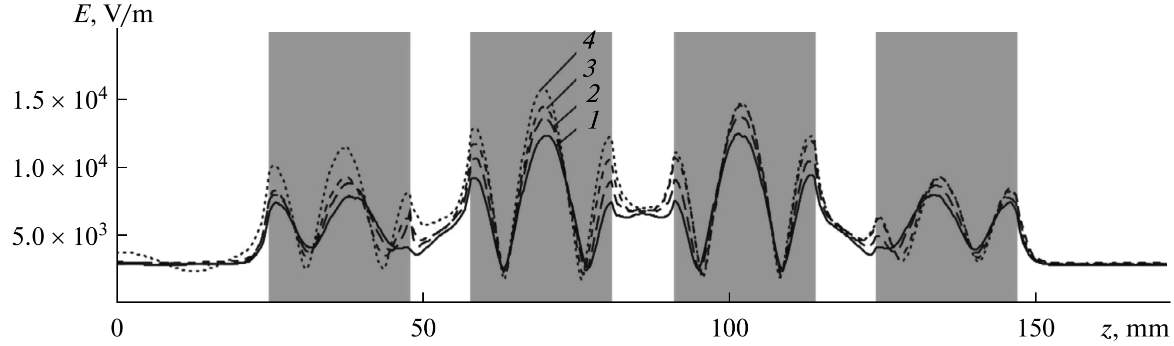

Fig. 4. Distribution of the electric field intensity of the electromagnetic wave in a photon crystal along the direction of the wave propagation h = (*1*) 0.2, (*2*) 0.3, (*3*) 0.5, (*4*) 0.6 mm, x = 11.5 mm, and s = 4.0 mm. The regions that are occupied by sections of the waveguide-slot line are painted gray. The regions occupied by regular waveguide sections are painted light.

As has been note above, a change of the slot width also causes a change of phase constant β_2 of the section of the waveguide-slot line, namely: β_2 grows as the slot width decreases [10]. The results of calculation of the AFC of the investigated structure that are shown in Fig. 6 show that the AFC shifts into the low frequency region as the slot width decreases.

Figure 7 shows the results of calculation of the electric field intensity of the electromagnetic wave inside a photon crystal along the direction of the wave propagation for different widths of the slot on the section of the waveguide-slot line. The analysis of the dependences shown in Fig. 7 indicates that, at the frequencies of the photon crystal transparency, the standing wave behavior is realized inside the crystal structure. As the width of the slot on the section of the waveguide-slot line decreases from 4.0 to 2.0 mm, the antinode intensity increases by two times. Additional investigations have shown that the increase of lengths of regular sections of waveguide d shifts the AFC of the structure to the region of low frequencies (Fig. 8) as it follows from relationship (1).

The results of investigations of the influence of quantity N of periodically recurring elements in the Bragg structure based on alternating sections of the waveguide-slot line and sections of the regular waveguide have shown the following. The increase of these sections causes the decrease of the minimal value of transmission coefficient $|D|^2$ of a photon crystal in a forbidden zone and an increase of number M of resonances forming an allowed zone according to the relationship $M = N - 1$ [11]. When the number of sections of the waveguide-slot line changes in the Bragg structure (see Fig. 1) from four to six, transmission coefficient $|D|^2$ of the photon crystal in the forbidden zone decreases from –40 to –65 dB.

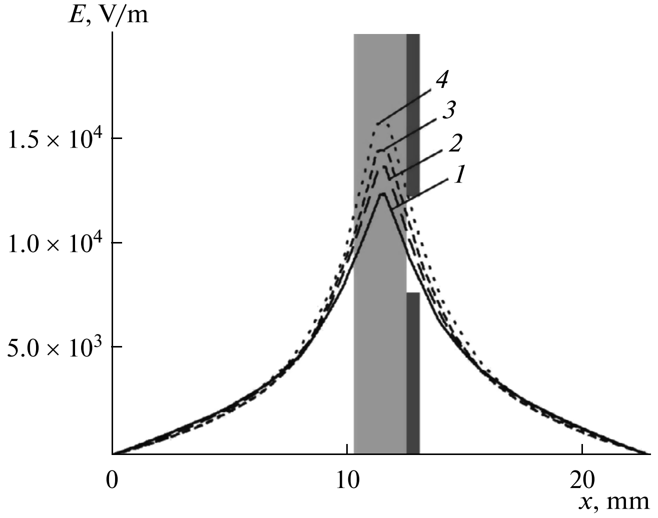

Fig. 5. Distribution of the electric field intensity of the electromagnetic wave in a photon crystal in the transverse waveguide plane h = (*1*) 0.2, (*2*) 0.3, (*3*) 0.5, (*4*) 0.6 mm, z = 69.7 mm, and s = 4.0 mm.

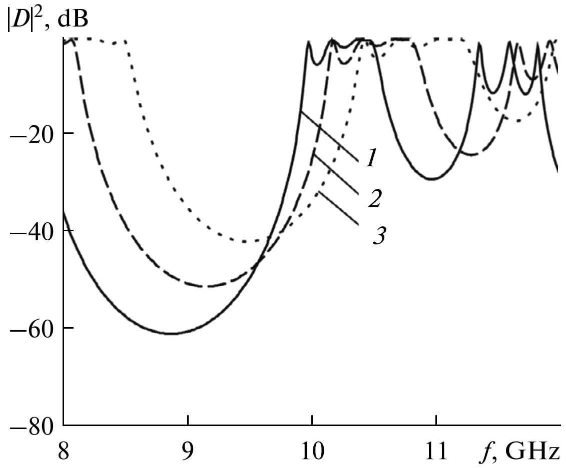

Fig. 6. Frequency dependences of transmission coefficient $|D|^2$ of a photon crystal for various widths of the sections of a slotline s = (*1*) 2.0, (*2*) 3.0, (*3*) 4.0 mm; L = 23 mm; d = 10 mm; h = 1.0 mm; and ε = 9.6.

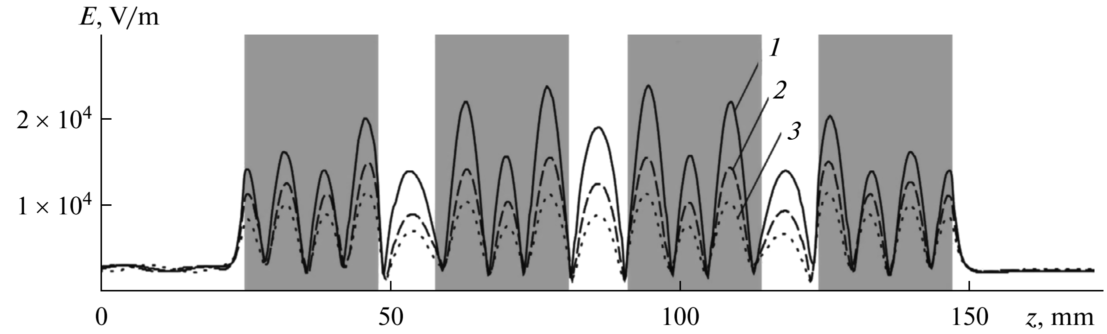

Fig. 7. Distribution of the electric field intensity of the electromagnetic wave in a photon crystal along the direction of the wave propagation s = (*1*) 2.0, (*2*) 3.0, (*3*) 4.0 mm; x = 11.5 mm, and h = 1.0 mm. The regions that are occupied by sections of the waveguide-slot line are painted gray. The regions occupied by regular waveguide sections are painted light.

It is known that, in classic 1D Bragg structures containing alternating layers with different values of permittivity, the presence of a defect that disturbs the periodicity and is a changed thickness or permittivity of one of the layers may cause the resonance singularity in a photon forbidden zone [12]. This singularity, which is called an impurity oscillation mode [4], is highly sensible to the defect parameters.

To clarify the peculiarities of admixture (defect) oscillation mode development in the suggested Bragg structure, the AFC of a defect microwave photon crystal with changed length l of the central section of a regular waveguide is investigated.

Figure 9 shows the results of calculation of the frequency dependences of transmission coefficient $|D|^2$ of a microwave wave passing through a Bragg structure. This structure consists of four sections of a waveguide-slot line of the length 23 mm (curves *1*–*4*). The calculation is performed for various lengths l of the violation and in the absence of a violation. Length l of the violated layer is varied from 14 to 20 mm.

It follows from the results presented in Fig. 9 that the presence of a periodicity violation in the Bragg structure in the form of the changed length of the central section of the regular waveguide causes an impurity oscillation mode (transparency window) appearing in the forbidden zone. The position of this oscillation mode shifts to the low-frequency region when length l of the disturbed layer is increased in the range 14–20 mm.

3. EXPERIMENTAL INVESTIGATION OF THE BRAGG MICROWAVE STRUCTURE BASED ON WAVEGUIDE-SLOT LINES

A Bragg structure is created with the correspondence of the model described above. The experimental AFCs of the considered Bragg structure with different lengths of the regular waveguide sections are measured

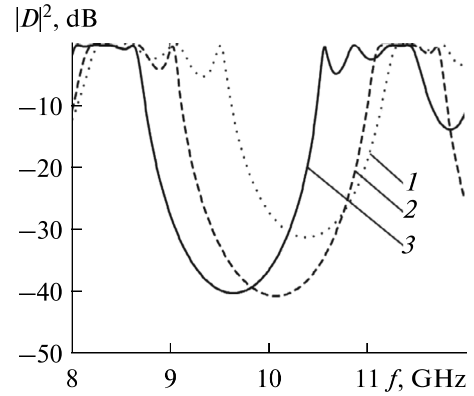

Fig. 8. Frequency dependences of transmission coefficient $|D|^2$ of a photon crystal for various lengths of the regular waveguide sections d = (*1*) 2, (*2*) 5, (*3*) 10 mm; L = 23 mm; s = 4.0 mm; h = 1.0 mm; and ε = 9.6.

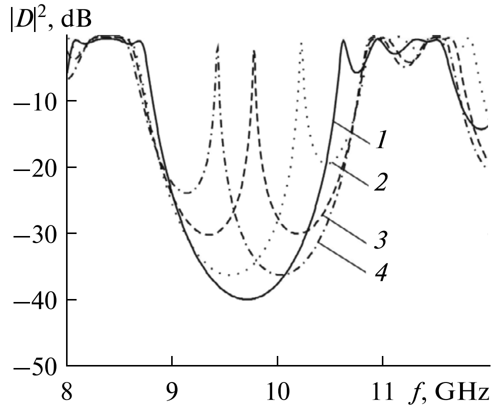

Fig. 9. Frequency dependences of the transmission coefficient of a photon crystal (*1*) without violation and for various lengths of the violated layer l = (*2*) 14, (*3*) 17, (*4*) 20 mm; L = 23 mm; d = 10 mm; s = 4.0 mm; h = 1.0 mm; and ε = 9.6.

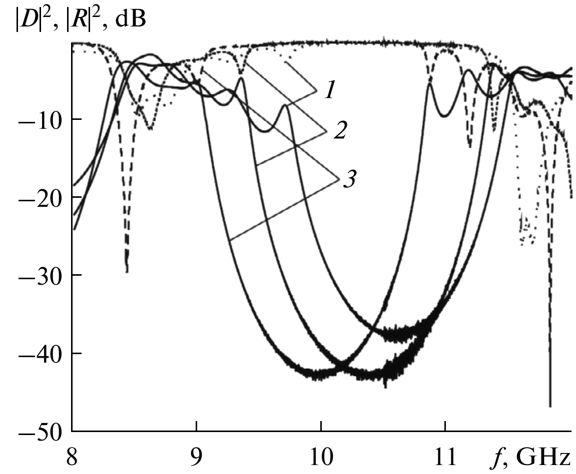

Fig. 10. Experimental frequency dependences of the (dashed, dotted, and dashed-and-dotted curves) reflection ($|R|^2$) and (solid curves) transmission ($|D|^2$) coefficients of a Bragg structure for various lengths of regular waveguide sections d = (*1*) 2, (*2*) 5, (*3*) 10 mm; L = 23 mm; s = 4.0 mm; h = 1.0 mm; and $\varepsilon = 9.6$.

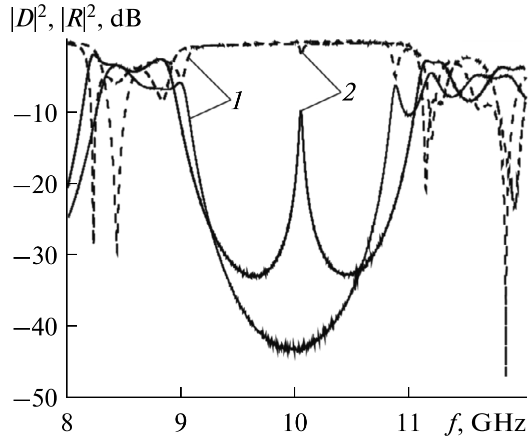

Fig. 11. Experimental frequency dependences of the (dashed curves) reflection ($|R|^2$) and (solid curves) transmission ($|D|^2$) coefficients of a Bragg structure (*1*) without violation and in presence of violation in the form of the changed length of the central regular waveguide section l = (*2*) 17 mm; L = 23 mm; d = 10 mm; s = 4.0 mm; h = 1.0 mm; and $\varepsilon = 9.6$.

with the help of an Agilent PNA-L Network Analyzer N5230A vector circuit analyzer. These data are shown in Fig. 10.

The experimental results show that a photon crystal created on the basis of waveguide-slot lines forms allowed and forbidden zones in the frequency range 8–12 GHz.

The AFCs of a Bragg structure based on sections of a waveguide-slot line having a defect in the form of changed length l of the central regular waveguide section are experimentally investigated. It follows from the experiment that creating in a photon crystal a defect in the form of the central section of a regular waveguide having an increased length results in the appearance of a transmission peak in the forbidden zone and increases the zone width (Fig. 11, curves *2*). Figure 11 also shows the AFCs of the Bragg structure without violations (curves *1*).

The comparison of the experimental results presented in Figs. 10 and 11 and the calculation results presented in Figs. 8 and 9 witness their good qualitative correspondence.

CONCLUSIONS

Thus, in this work, the possibility of creating a new type of a Bragg structure in the microwave range has been theoretically substantiated and experimentally shown. This Bragg structure is based on alternating sections of a waveguide-slot line and regular waveguide sections.

It has been shown that the AFCs of the Bragg structure in the frequency range 8–12 GHz, that are characterized by the presence of allowed and forbidden zones in this frequency range shift to the region of low frequencies as the thickness and permittivity of the substrate grow and as the slot width decreases.

The character of the electric field intensity distribution in the standing wave appearing in a Bragg structure with elements being sections of a waveguide-slot line has been determined.

The appearance of a resonance singularity has been described theoretically and determined experimentally. This singularity is the transparency window in the forbidden zone of the investigated Bragg structure formed when a defect that is the changed length of the central segment in a regular waveguide is formed.

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REFERENCES

1. R. A. Silin and V. P. Sazonov, *Retarding Systems* (Sovetskoe Radio, Moscow, 1966) [in Russian].
2. E. Yablonovitch, T. J. Gmitter, and K. M. Leung, Phys. Rev. Lett. **67**, 2295 (1991).
3. C. A. Kuriazidou, H. F. Contopanagos, and N. G. Alexopolos, IEEE Trans. Microwave Theory Tech. **49**, 297 (2001).

4. B. A. Belyaev, A. S. Voloshin, and V. F. Shabanov, Dokl. Akad. Nauk **50**, 337 (2005).
5. V. M. Mukhortov, S. I. Masychev, A. A. Mamatov, and Vas. M. Mukhortov, Tech. Phys. Lett. **39**, 921 (2013).
6. D. A. Usanov, S. A. Nikitov, A. V. Skripal', A. P. Frolov, and V. E. Orlov, J. Commun. Technol. Electron. **59**, 1101 (2014).
7. D. A. Usanov, A. V. Skripal, A. V. Abramov, A. S. Bogolyubov, M. Yu. Kulikov, and D. V. Ponomarev, Tech. Phys. **80**, 1216 (2010).
8. G. A. Morozov, O. G. Morozov, A. R. Nasybulin, et al., Fiz. Voln. Protsessov Radiotekh. Sist. **17** (3), 65 (2014).
9. V. G. Vinenko and D. A. Usanov, Copyright Certificate, No. 1283878 МКИ4 H01P 1/22, Byull. Izobret. No. 2, 248 (1987).
10. V. G. Vinenko, L. A. Fedoseeva, and D. A. Usanov, Elektron. Tekh., Ser. Elektronika SVCh, No. 3, 81 (1979).
11. D. A. Usanov, S. A. Nikitov, A. V. Skripal', and D. V. Ponomarev, J. Commun. Technol. Electron. **58**, 1035 (2013).
12. E. Yablonovitch, T. J. Gimitter, R. D. Meade, et al., Phys. Rev. Lett. **67**, 3380 (1991).

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