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SHORT COMMUNICATION

Control of the frequency response of a narrow-band filter for the X-band frequency based on a photonic crystal with a movable cylindrical defect

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Abstract
Objectives. The work set out to investigate the possibility and effectivity of using a movable cylindrical defect with metal pins in the design of a photonic crystal to control the frequency response of a narrow-band filter in a rectangular waveguide having a cross-section of 23 × 10 mm in the X-band, as well as to determine the most effective methods for controlling frequency response.
Methods. A numerical simulation of the frequency response of the filter was carried out using the *openEMS* software package, which is based on Maxwell's equations solved by the finite-difference time-domain method. The frequency response of the currently proposed and implemented filter construction in the X-band was further investigated in an experimental study.
Results. Numerical simulation shows that a resonant transmission peak in the stopband of the frequency response can be caused to appear by introducing a movable cylindrical defect having two metal pins into the center of a photonic crystal structure. In addition, the position of this peak on the frequency response can be effectively controlled by rotating the cylindrical defect around its axis. If the position of the defect remains unchanged, an increase in the frequency of the transmission peak occurs as a result of decreasing the period of the photonic crystal. However, the frequency of this resonant transmission peak is most strongly influenced by changes in the size of holes in the photonic structure. These changes can be used to control both the position and shape of the transmission peak, as well as the overall frequency response. At the same time, the difference in transmission remains practically unchanged when the cylinder rotates around its axis. The simulation results were confirmed by the data of an experimental study of the frequency response of photonic crystals made from PETG plastic using 3D printing technology.
Conclusions. The proposed, designed, and manufactured experimental samples of narrow-band filters in the X-band based on a photonic crystal demonstrated reliably variable transmission values and the possibility of controlling the resonant peak frequency and thus the entire frequency response, including operational control. This makes them very promising for practical use in radio-electronic equipment.

Keywords: narrow-band filter, resonant filter, microwave range, photonic crystal, 3D printing, openEMS

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КРАТКОЕ СООБЩЕНИЕ

Управление амплитудно-частотной характеристикой узкополосного фильтра для X-диапазона частот на основе фотонного кристалла с подвижным цилиндрическим дефектом

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Резюме
Цели. Цель работы – исследовать возможность и эффективность использования в конструкции фотонного кристалла подвижного цилиндрического дефекта с металлическими штырями для управления амплитудно-частотной характеристикой (АЧХ) узкополосного фильтра на прямоугольном волноводе с сечением 23 × 10 мм в трехсантиметровом диапазоне (X-диапазоне), определить способы наиболее эффективного управления АЧХ.
Методы. Для численного моделирования АЧХ фильтра используется программный пакет *openEMS*, в основе которого лежит система уравнений Максвелла, решаемая методом конечных разностей во временной области. Проведено также экспериментальное исследование АЧХ действующего макета предложенной и созданной конструкции фильтра в трехсантиметровом диапазоне (X-диапазоне).
Результаты. Результаты численного моделирования показывают, что введение в центр конструкции фотонного кристалла подвижного цилиндрического дефекта с двумя металлическими штырями приводит к появлению в полосе запирания на АЧХ фильтра резонансного пика пропускания, положение которого эффективно управляется поворотом цилиндрического дефекта вокруг его оси. При неизменном положении цилиндрического дефекта уменьшение периода фотонного кристалла приводит к увеличению частоты пика пропускания. На частоту резонансного пика пропускания наиболее сильное влияние оказывает изменение размера отверстий в конструкции фотонного кристалла, что может использоваться как эффективный фактор для управления положением пика пропускания и формой всей АЧХ; при этом значение коэффициента пропускания при повороте цилиндрического дефекта вокруг его оси практически не изменяется. Проведены также экспериментальные исследования АЧХ фотонных кристаллов, изготовленных с использованием технологии 3D-печати из пластика PETG (полиэтилентерефталатгликоль), данные которых согласуются с результатами моделирования.

Выводы. Предложенные спроектированные и изготовленные экспериментальные модели узкополосных фильтров в трехсантиметровом диапазоне (X-диапазоне) на основе фотонного кристалла показали достаточные для практики изменения значения коэффициента пропускания и возможности эффективного управления частотой резонансного пика и всей формой АЧХ, что делает их весьма перспективными для практических применений в радиоэлектронной аппаратуре.

Ключевые слова: узкополосный фильтр, резонансный фильтр, СВЧ-диапазон, фотонный кристалл, 3D-печать, openEMS

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INTRODUCTION

Electromagnetic waves are widely used in diverse fields of science and technology, including radiolocation and navigation services, as well as information and telecommunications technologies, medical equipment, etc. One of the most common types of transmission lines for microwave electromagnetic waves are rectangular waveguides with so-called partially- and fully-filled waveguides, whose fillable structures are typically comprised of dielectric plates of various shapes and sizes. Artificial materials and structures are used in various waveguide designs, particularly those based on photonic crystals or metamaterials [1–13]. Photonic crystals in the microwave range are based on a section of waveguide whose filling comprises a periodic structure consisting of individual cells made of materials having different refractive indices. This leads to the formation of band gap and allowed photonic bands (frequency ranges) in the transmission spectrum analogous to energy bands in solids [1, 2, 4–9]. Thus, photonic crystals can be used to construct frequency-selective devices, in particular, on the basis of rectangular waveguides [6, 7]. Such devices are capable of isolating microwave radiation both in a specific frequency band (bandpass filter), as well as in the frequency range below (low-pass filter) or above (high-pass filter) a specific cut-off frequency in a given frequency range, and passing it to the output of the device almost without loss.

Adding a single defect to a photonic crystal results in a violation of the periodicity of its structure and the appearance of a resonant transmission peak on its frequency response [10–12]. By controlling the position, shape and size of the defect, resonant (narrow-band) filters, controllable sensors, absorbers, and other useful devices can be created [1–4, 7–10].

This paper presents studies on photonic crystals into which a mobile rotating cylindrical defect has been inserted. In addition, the results of experimental studies into photonic crystal samples fabricated using 3D printing technology are compared with the characteristics of their mathematical models using the specialized *openEMS* software[1].

DESCRIPTION OF THE STRUCTURE

Innovative 3D printing technology is already widely used for the prototyping of products in the microwave range [13–16]. In this paper, fused deposition modeling (FDM), a type of 3D printing technology, is used to fabricate photonic crystals. FDM technology is based around the melting and application of plastic filament to form layers on the surface of previously applied layers to form the structure of a given model. The structure is created by first designing a 3D model, typically in a computer-aided design (CAD) system[2]. The 3D model can be saved in the widely used STL file format as a numerical array. The photonic crystal is designed using the *OpenSCAD* CAD system, which can be used to create complex three-dimensional models with a high degree of parameterization. The design optimization process is greatly simplified by the ability to automatically recalculate the entire geometry by changing one parameter. The resulting photonic crystal comprises a section of a rectangular waveguide having a fully filled cross-section of 23 × 10 mm. Air holes are placed periodically along the waveguide axis. The cross-section of the holes is rectangular. Polyethylene terephthalate glycol (PETG), which has a relative permittivity of $\varepsilon' \approx 2.5$ in the investigated frequency range, is selected as a material for the fabrication of the photonic crystal [15, 16].

A schematic representation of the proposed structure with designations of the main dimensions of the designed

[1] https://www.openems.de. Accessed March 20, 2025.

[2] https://openscad.org. Accessed March 20, 2025.

Table. Main dimensions of the elements of the designed photonic crystal having a rectangular hole shape

Hole shape	Number of holes (i)	Hole period (Λ), mm	Hole size along the waveguide axis (w), mm	Hole spacing (L), mm	Hole size along the wide wall of the waveguide (g), mm
Rectangular	4	24–31	5–9	19–22	18

elements is shown in Fig. 1. The specific values for the dimensions are given in the table. Similar photonic crystal structures have been proposed and analyzed in several works (e.g., [6, 13]).

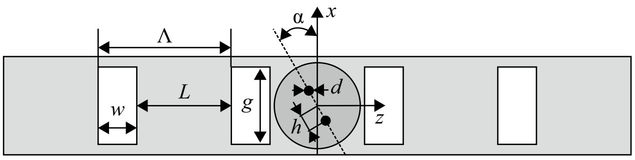

Fig. 1. Schematic representation of the proposed structure for filling a photonic crystal with a mobile rotating defect (viewed from the wide wall side of the waveguide, in the *xz* plane)

A defect located in the center of the designed photonic crystal comprises a movable cylinder rotating around its axis, in which two thin metal rods with a circular cross section and a diameter of $d = 2$ mm are placed symmetrically at a distance of $h = 4$ mm on either side of the axis. The position of the first defect (rotation angle $\alpha = 0°$) corresponds to the position of a pair of defect rods perpendicular to the waveguide axis, along the x-axis. The position of the second defect (rotation angle $\alpha = 90°$) corresponds to the position of a pair of defect rods along the waveguide axis, i.e., along the z-axis.

RESULTS AND DISCUSSION

After determining the optimal structure of the photonic crystal, the stage of numerical modeling of its properties can begin. The *openEMS* software used for this purpose is based on the finite difference time domain method, representing one of the most popular numerical methods in computational electrodynamics [17]. The software supports the import and export of geometric models from various file formats (e.g., PLY, STL), which greatly simplifies the modeling process, especially when CAD is used for design. *openEMS* is integrated with scripting languages such as *MATLAB*[3], *Octave*[4], and *Python*[5] for automating the process of setting model parameters, performing calculations, and processing the obtained data.

Figure 2 depicts 3D printed photonic crystal structures having a cylindrical defect, while the frequency response of the photonic crystals obtained by numerical modeling and experimental studies is shown in Fig. 3. Specific data are given for two defect positions: $\alpha = 0°$ (position *1*) and $\alpha = 90°$ (position *2*). Both numerical simulation and experimental data indicate that a clear resonance peak in transmission can be observed at defect position *2*. At the resonance peak frequency, the change in transmission coefficient (ΔT) exceeds 15 dB when the defect position changes from *1* to *2*.

Fig. 2. General view of the manufactured photonic crystals with defect

The dependence of the transmittance peak position on the photonic crystal period is shown in Fig. 4. As the period of the photonic crystal decreases, the transmittance peak is observed to shift towards high frequency. The change in the hole size w has a stronger effect on the position of the transmission peak frequency compared to the change in the hole spacing L.

The dependence of the change in transmission coefficient ΔT on the period of the photonic crystal Λ is shown in Fig. 5. The change in transmission coefficient ΔT reaches 22 dB at the fixed hole size $w = 5$ mm, and the effect of the hole spacing L is minimal. When the hole size w is increased from 3 mm to 9 mm and the hole spacing L is fixed at 22 mm, the change in the transmission coefficient ΔT for the photonic crystal reaches 14 dB (from 16 dB to 30 dB).

[3] https://www.mathworks.com/products/matlab.html. Accessed March 20, 2025.
[4] https://octave.org/. Accessed March 20, 2025.
[5] https://www.python.org/. Accessed March 20, 2025.

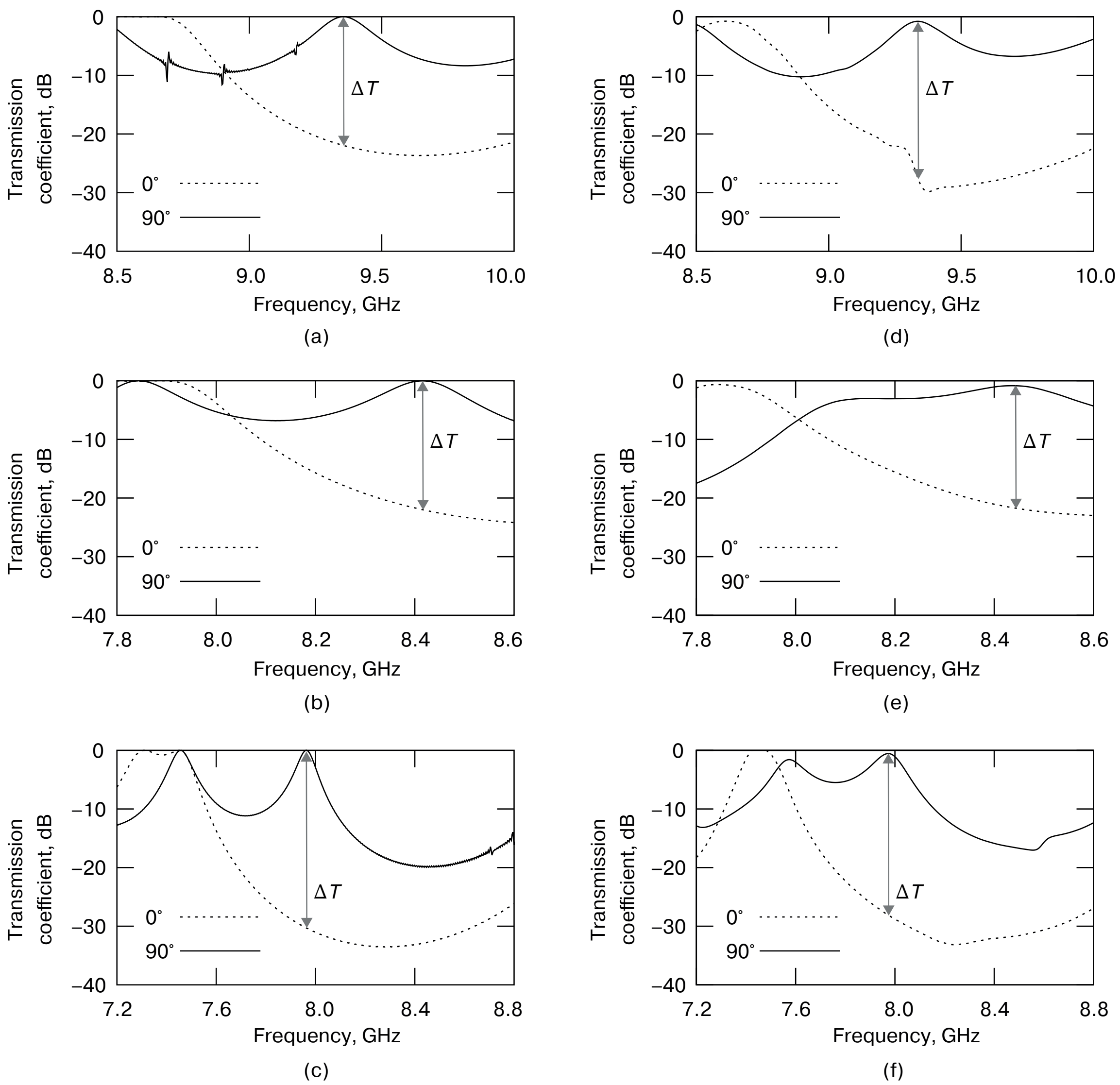

Fig. 3. Frequency response for defect rotation angle α equal to 0° and 90° obtained by numerical modeling (a, b, c) and experimental study (d, e, f) of photonic crystals: *L* = 19 mm, *w* = 5 mm (a, d); *L* = 22 mm, *w* = 5 mm (b, e); and *L* = 22 mm, *w* = 9 mm (c, f)

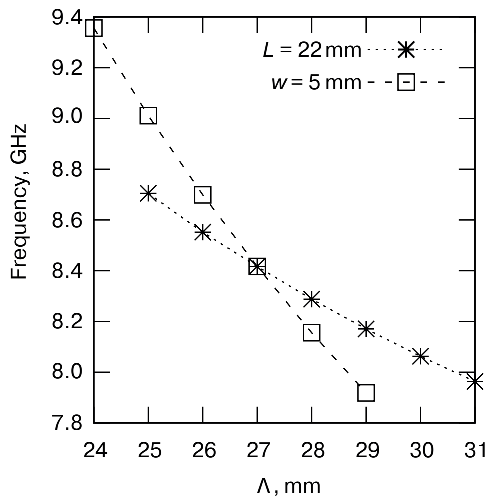

Fig. 4. Dependence of the photonic crystal transmission peak frequency on the period Λ at a fixed hole size *w* (dotted line) and hole spacing *L* (dashed line)

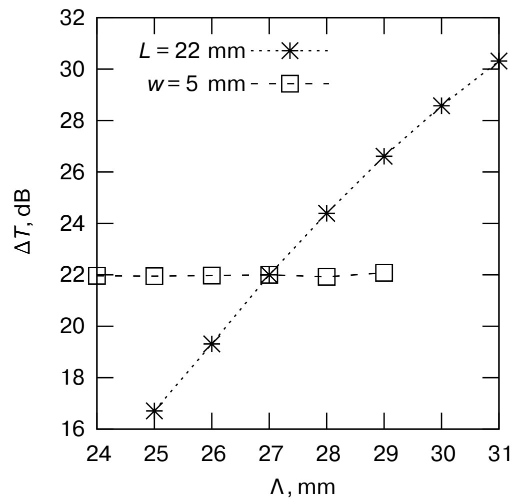

Fig. 5. Dependence of the change in the transmission coefficient (Δ*T*) on the photonic crystal period Λ at a fixed hole size *w* (dotted line) and hole spacing *L* (dashed line)

CONCLUSIONS

The paper demonstrates the possibility of effectively using a mobile cylindrical defect to control the frequency response of a narrow-band filter in a rectangular X-band waveguide having a cross-section of 23 × 10 mm. The defect rotates around its photonic crystal structure axis with respect to which two identical metal pins are symmetrically arranged. Numerical simulation results show that the transmission peak shifts to higher frequencies as the hole period Λ of the photonic crystal decreases. The largest shift in the frequency of the transmission peak with increasing hole period occurs at a fixed hole spacing. At the same time, the minimum change in transmission coefficient is observed for a defect rotation angle of 90° (position *2*). Designed and experimentally developed models of photonic crystal-based narrow-band filters of this structure show a change in the transmission coefficient in the range of 16 dB to 30 dB when the angle of defect rotation is changed from 0° to 90°. The results are promising for use in real technical applications.

Authors' contribution. All authors equally contributed to the research work.

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