Study of a Promising Electrodynamic Photonic Crystal-like Structure inside a Rectangular Waveguide

Andrey Starodubov
Saratov State University
Saratov Branch, V.A. Kotel'nikov Institute of Radio Engineering and Electronics RAS,
Saratov, Russia
StarodubovAV@gmail.com

Artem Badarin
Saratov State University
Yuri Gagarin State Technical University of Saratov
Saratov, Russia
badarin.a.a@mail.ru

Viktor Galushka
Saratov State University
Saratov, Russia
gwiktor@mail.ru

Anton Pavlov
Saratov State University
Saratov, Russia
mr.anton.pavlov@gmail.com

Yurii Kalinin
Saratov State University
Saratov, Russia
noios@sgu.ru

Semen Kurkin
Saratov State University
Yuri Gagarin State Technical University of Saratov
Saratov, Russia
kurkinsa@gmail.com

Alexey Koronovskii
Department of Nonlinear Processes
Saratov State University
Saratov, Russia
alexey.koronovskii@gmail.com

***Abstract* — Here we report on experimental and numerical investigations of an electrodynamic structure assembled according to photonic crystals' principles placed inside a X-band rectangular waveguide which is promising for microwave electronics. The features of dispersion characteristics of photonic crystals can be used for efficient excitation of high-order (and, hence, high-frequency) electromagnetic modes. In this work, the electrodynamic structure is a2D array of thin metal pins . Transmission and reflection of proposed system were measured experimentally and evaluated numerically. The experimental results are in good agreement with the numerical ones.**

Keywords —regular electrodynamic structure, high-power microwaves, vircator, free electron laser, photonic crystal, X-band

I. Introduction

Major challenges for modern microwave electronics include increase of microwave radiation generation and amplification efficiency using existing circuitry (especially for high-power solutions)and their promotion towards THz frequency range [1]. One of possible ways for the solution of the formulated problems is the use of new ideas and approaches for the development and optimization of the "classical" devices of microwave electronics. Such an idea is the use of a photonic crystal (PC) as an electrodynamic structure (slow-wave or output structure) of the device. Recent studies, both theoretical and experimental, demonstrate attractive properties of photonic crystals, namely their ability to concentrate electromagnetic energy and direct its flow [2-4]. The features of dispersion characteristics of such structures (the presence of allowed bands and band gaps) can be used for efficient excitation of high-order (and, hence, high-frequency) electromagnetic modes.

Photonic crystals have demonstrated their efficiency in free electron lasers and vircators [3, 5, 6]. The idea to combine the classical configuration of the axial vircator with the PC system has been proposed by Baryshevsky [5]. The author suggested that the diffraction properties of PC and its high interaction impedance provide an additional generation mechanism in such a system. Later, it has been shown that PC located in the drift tube of the axial vircator allows for significan improvement of microwave generation efficiency due several factors: (i) high interaction impedance with passing relativistic electron beam (REB), (ii) distributed electromagnetic feedback with VC, and (iii) efficient electromagnetic energy output as compared to the traditional cylindrical waveguide [7].

Thus, investigation of photonic crystal structure characteristics in real systems is an actual problem of modern electronics. Current work is devoted to experimental and numerical study of a promising electrodynamic structure in the form of photonic crystal in X-band rectangular waveguide.

II. System under Study

Detailed studies of electrodynamic characteristics of a photonic crystal-like structure in the X-band rectangular waveguide (23x10 mm) were carried out. The photonic crystal is a 2D array of thin metal pins. This three-dimensional structure has two spatial periods (Fig. 1). The photonic crystal has 20 periods in the beam propagation direction (z axis), each consisting of 4 pins. Period length (l_z) was 3.1 mm, pin diameter was 0.1 mm, spacing between rods (l_x) was 3 mm.

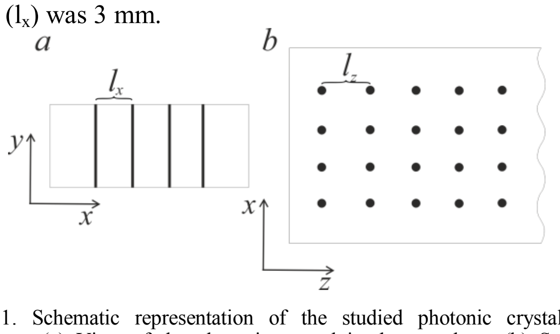

Fig. 1. Schematic representation of the studied photonic crystal-like structure. (a) View of the photonic crystal in the xy plane. (b) Several periods of the photonic crystal in the longitudinal direction. l_z is the longitudinal period; l_x is the transverse period.

The numerical evaluation of scattering parameters (S-parameters) of a rectangular waveguide with a photonic crystal structure was performed. Numerical simulation is based on solving Maxwell's equations in three spatial coordinates using the FDTD method with staircase approximation of boundaries. Gaussian pulse is used as input signal for the simulation. This signal is well suited for the S-parameters calculation because its transformed frequency domain signal is also Gaussian.

To fabricate a photonic crystal-like periodic structure, a 10 cm long section of standard X-band rectangular straight waveguide was used. Holes on the wide sides of straight waveguide section were drilled with CNC milling machine [8]. The diameter of used drilling bits was 0.6 mm. Metal pins were made of copper (oxygen-free) wire with diameter of 0.11 mm.

The experimental setup (Fig. 2,a) is based on a vector network analyzer PNA N5227A (Keysight Technologies). The studied PC was fabricated in X-band (WR-90) straight waveguide section. The waveguide section is connected to the vector network analyzer with waveguide to coax adapters (PE9804, Pasternak, Inc.) and coax cables (SC-35-MF-48, Maury Microwave). The measurements were preceded by a full 2-port type calibration procedure on coaxial ends adapters using E-cal module (N4691B, Keysight Technologies). Experimentally measured return loss (S11) and transmission loss (S21) parameters are presented in Fig. 3.

III. Main Results

Results of numerical simulation of return loss (S11) and transmission loss (S21) parameters of the waveguide section with PC are also shown in Fig. 3.

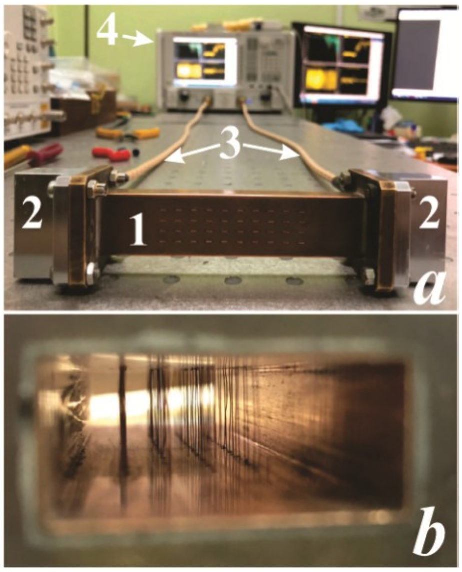

Fig. 2. Photo of the experimental setup (a) and the internal structure of photonic crystal (b). 1 – straight X-band waveguide section with photonic crystal, 2 – PE9804 waveguide to coax adapters, 3 – SC-35-MF-48 coax cables, 4 – PNA N5227A vector network analyzer.

The comparison of experimental and numerical simulations results has shown that developed photonic crystal in straight rectangular waveguide section has acceptable transmission and reflection characteristics in some frequency bands. Analysis of the experimental and numerical obtained results has shown that the bandwidth (we use the S11 level of "minus" 10 dB) does not exceed one hundred megahertz. Future work will be devoted to further improve transmission and reflection characteristics as well as bandwidth extension of developed PC.

IV. Conclusion

A promising photonic crystal-like electrodynamic structure inside a straight rectangular waveguide section was developed, fabricated and studied both numerically and experimentally. The obtained experimental results are in good agreement with the numerical ones.

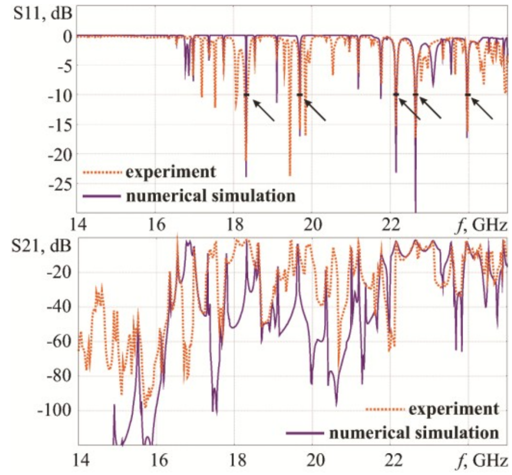

Fig. 3. Results of numerical simulations (solid lines) and experimental measurements (dashed lines). The suitable frequency bands are shown by black arrows.

Acknowledgment

The studies were supported by the Ministry of Education and Science of the Russian Federation (Project 3.859.2017/4.6), the Russian Foundation for Basic Research (Project № 19-02-00757 A).

References

[1] J. Benford, J. A. Swegle, and E. Schamiloglu, High Power Microwaves, 3rd Edition, CRC Press, Taylor and Francis Group, 2016.

[2] K. Yasumoto, Electromagnetic Theory and Applications for Photonic Crystals, CRC Press, 2005.

[3] V. Baryshevsky, "Spontaneous and induced radiation by electrons/positrons in natural and photonic crystals. Volume free electron lasers (VFELs): From microwave and optical to X-ray range," Nucl. Instrum. Methods Phys. Res., Sect. B, vol. 355, pp. 17–23, 2015.

[4] B. Wang and M. A. Cappelli, "A plasma photonic bandgap device," Appl. Phys. Lett., vol. 108, 161101, 2016.

[5] V. G. Baryshevsky and A. A. Gurinovich, "Hybrid systems with virtual cathode for high power microwaves generation," preprint arXiv:0903.0300, 2009.

[6] V. G. Baryshevsky, N. A. Belous, A. A. Gurinovich, E. A. Gurnevich, V. A. Evdokimov, and P. V. Molchanov, "Experimental studies of volume FELS with a photonic crystal made of foils," Proceedings of FEL2010, 2010.

[7] N. S. Frolov, S. A. Kurkin, A. A. Koronovskii, A. E. Hramov, and A. O. Rak, "High-efficiency virtual cathode oscillator with photonic crystal," Appl. Phys. Lett., vol. 113, 023503, 2018.

A. G. Terentyuk, A. G. Rozhnev, N. M. Ryskin, A. V. Starodubov, V. V. Galushka, A. M. Pavlov, "Development and modeling of folded-waveguide slow-wave structures for millimeter-band traveling-wave tubes," 43rd Int. Conference on Infrared, Millimeter, and Terahertz Waves, 2018, pp. 1-2., doi: 10.1109/IRMMW-THz.2018.8510165