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PHOTONICS

DEFECT MODE FORMATION IN THE SPECTRUM OF A SPATIALLY BOUNDED PHOTONIC FINITE-SIZE CRYSTAL

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The present paper discusses the outcome of the experimental and theoretical analysis of transmission spectrum singularities in the one-dimensional spatially bounded dielectric periodic structure, i.e., a photonic crystal (PC). An impact of the defect PC cell thickness upon the formation of the defect mode in the transmission spectrum has been studied. In addition, the scenario of the "defect-free" spectrum to the "defect modes" spectrum transition has been analyzed.

KEY WORDS: *periodic structure, photonic crystal, defect mode, transmission spectrum, band structure, transfer matrix method, the Tamm state*

1. INTRODUCTION

The scientific world has been over many decades focusing its research effort on studying the nature, different properties and feasibility of using spatial-periodic structures (SPS), namely, photonic crystals (PC). The distinguishing feature of these structures is the presence of band structure of their transmission spectrum [1]. One of the fields of SPS application in electronics is the development of electronically controlled microwave filters, couplers, attenuators, etc.

The disturbance of spatial periodicity in structures of these types give rise to a number of singularities in the transmission spectrum: defect modes (DM), surface states (SS). These singularities, which show a high Q-factor, serve to create the necessary conditions for the efficient restructuring of the above microwave elements.

In this paper, we pay attention to the study of such particular mainly occurring in the frequency spectrum of PC as defect mode. Work in this direction for natural crystals being a long time. The concept of "defect state" belongs to the physics of natural crystals. These states are brought about by diverse deformations such as impurities, dislocations. As a consequence, some additional narrow domains, i.e., defect modes/states are brought about in forbidden energy bands of the natural crystal spectrum. Moreover, the research community is now provided with earlier experimental and theoretical evidence that the relative arrangement of atoms at the surface differs from their position in a structure volume [2,3]. In particular, as shown in [4], the dispersal of surface atoms (we mean variations in the behavior of atom periodicity on the surface) in reference to their closest neighbors may be chiefly responsible for the onset of surface states.

Later, these concepts have been applied in electrodynamics. Many experimental [5] and theoretical [5-7] studies were time and again made to get a better insight into the impact of deformation in differently configured PCs (i.e., PC periodicity disturbance) upon the onset of DMs in the PC transmission spectrum. In particular, one of the first studies in which experimentally in the optical range have been registered the field distribution of a periodic structure with a defect, was the work of [8].

However, an issue of whether inhomogeneities, which came to be, inevitably or purposefully, formed in a PC have an impact upon their spectrum, is stile open. Or, to put it in different terms, an issue pertinent to the scenario of the "defect-free" spectrum to the "defect modes" spectrum transition remains unanswered. This particular matter is of prime importance for practical applications in which the PCs have a finite number of elements. The allowed PC transmission spectrum bands with a finite number of elements (N) are the superposition (N-1) of peaks resulting from the Bragg rereflections between elementary cells (here we deal with the simplest case of a 1-D PC). We believe that analyzing the DM formation due to such oscillations will make it possible to make a prognosis about the manner in which the technological flaws in producing any type of a PC are likely to affect the formation of their spectrum. Besides, this analysis will prove to be useful in terms of solving an inverse problem of how to generate a spectrum with preset DMs.

The experimental and theoretical studies on this issue are based upon an example of a one-dimensional PC capable of being operated in the millimeter wave range, and they constitute the subject-matter of this particular work.

2. THE STRUCTURE UNDER DISCUSSION, THEORETICAL MODEL AND THE EXPERIMENTAL SETUP

In this paper the authors are concerned to explore the spectrum of electromagnetic wave transmitted through a finite spatial-periodic structure placed in a waveguide. The elementary cell of this structure consists of two dielectric layers – one is made of quartz ($d_q = 1.5$ mm) and the other one is made of polystyrene ($d_p = 1.2$ mm) (see Fig. 1). The whole structure is composed of 12 elementary cells. In the 6-th period the variation in polystyrene layer thickness is varied between 0.1 mm and 3.5 mm.

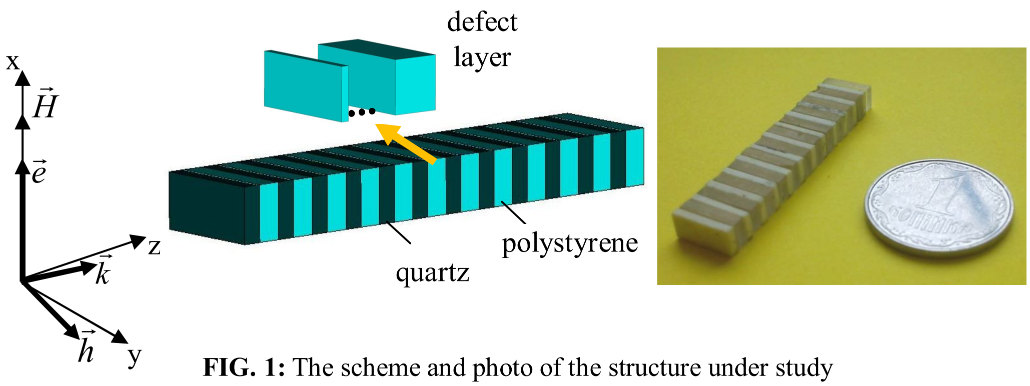

FIG. 1: The scheme and photo of the structure under study

We used of the well-known transfer matrix method [8] for numerical simulation of the spectrum of electromagnetic wave transmission through a structure under study. The numerical experiments that we have carried out allowed us to obtain a series of transmission spectra typical of which are shown in Fig. 2.

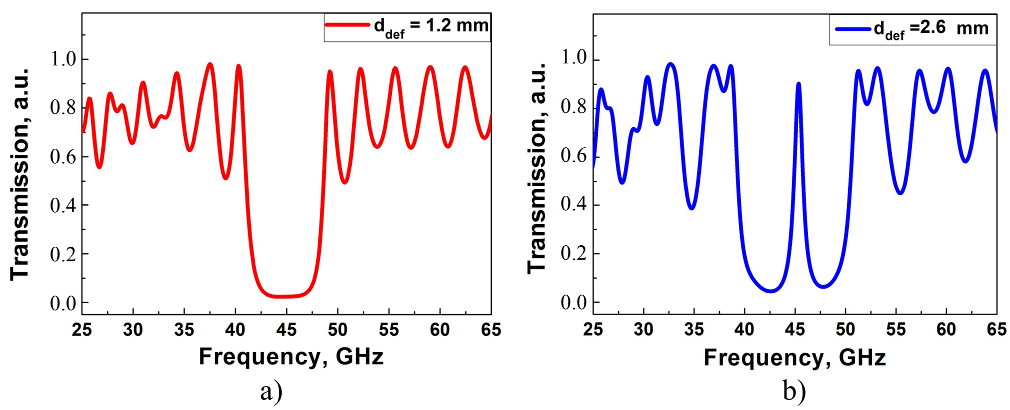

FIG. 2: The typical transmission spectra of the PC being studied: a) defect-free PC ($d_{def} = d_p = 1.2$ mm); b) PC with defect ($d_{def} = 2.6$ mm)

3. COMPUTATIONAL AND EXPERIMENTAL RESULTS AND THEIR COMPARATIVE ANALYSIS

Following experimental and theoretical investigation we have plotted the graph of transmission coefficient versus the frequency and thickness of a defect layer (Fig. 3). The pass bands for the "defect-free" PC (Fig. 3(b)) have the known shape with $(N-1)$ peaks for PC of (N) elements. The graph is color-coded: the intensity of electromagnetic wave transmission factor is marked with the blue (minimum) changing over to the red colors (maximum), respectively. Specifically, the peaks of the interference maxima in pass bands are shown in the dark color. The typical transmission spectra of defect-free PC (Fig. 3(b)) and PC with defect (Fig. 3(a)) see below. Note that, as the frequency increases, the form of pass beads becomes more complicated and shows various patterns. The points relevant to the experimentally obtained DM frequencies in the first (low-frequency) stop band are marked with white asterisks for various thicknesses of a defect layer.

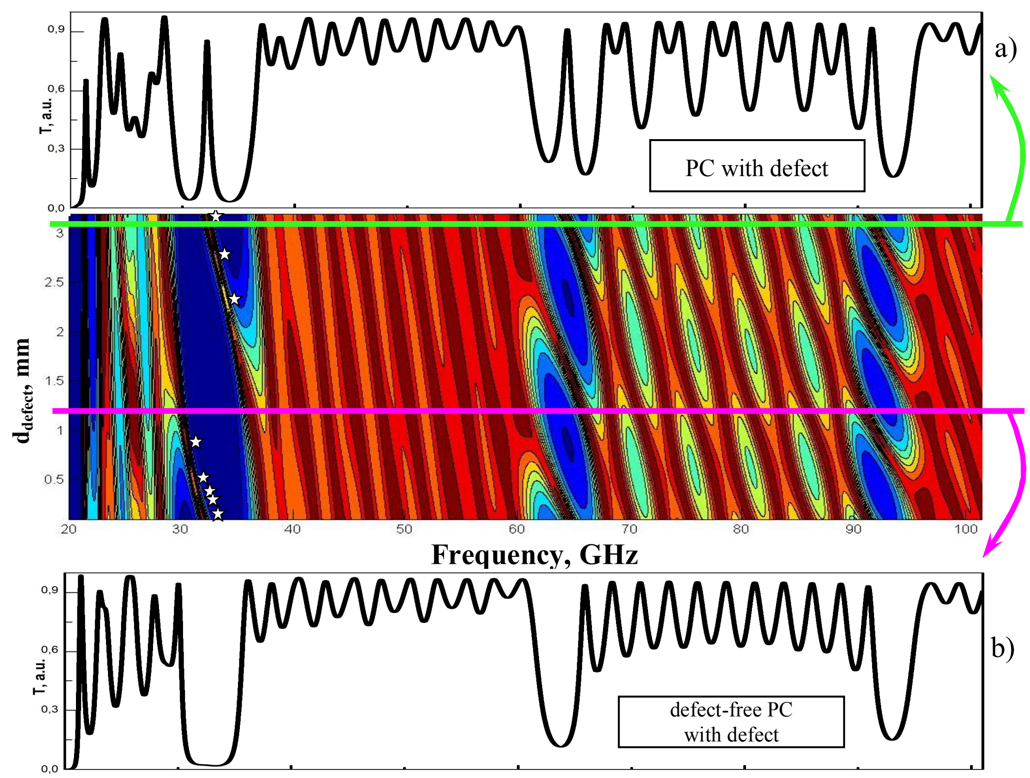

FIG. 3: (color online). Numerically calculated and experimentally measured (asterisks) the PC transmission spectra as a function of the defect layer thickness: a) the PC with defect; b) the "defect-free" PC

The disturbance of translation symmetry in a bounded PC [9] leads us to arrive at new solutions of the Maxwell equations, which, in their turn, manifest themselves as DMs in the PC transmission spectrum (Fig. 2(b)).

In constructing the field distribution for these solutions (at a DM frequency, Fig. 4), as it previously shown for the optical range in [8], we can see that the envelope of the microwave field electric component amplitudes exponentially falls down, as it moves away from the defect layer.

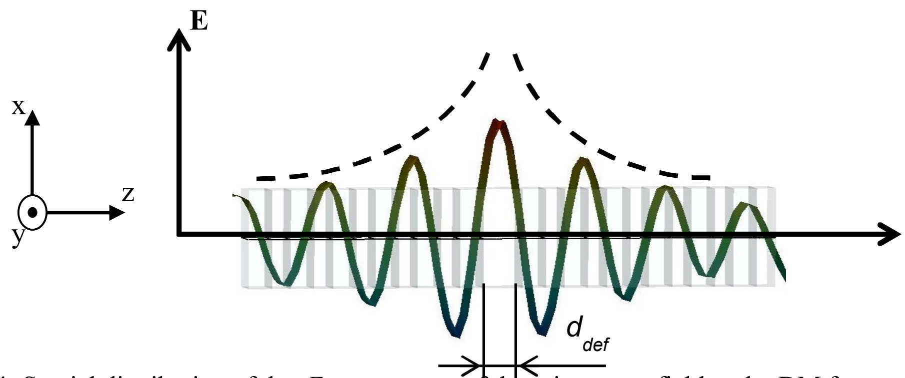

FIG. 4: Spatial distribution of the E -component of the microwave field at the DM frequency

Figure 5 presents the details of the first forbidden band of the PC spectrum. The solid line is theoretical data; the red check marks correspond to experimental points.

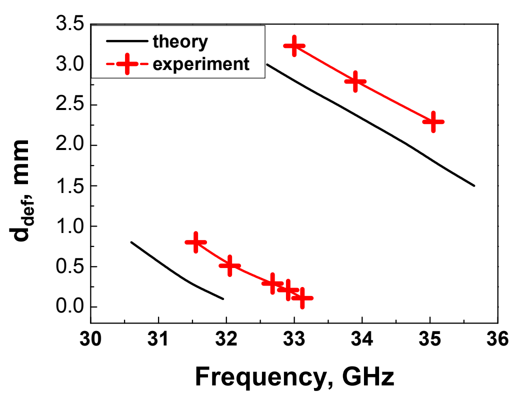

FIG. 5: Theoretical and experimental dependences of DM peak frequencies versus the defect layer thickness

When analyzing Fig. 3 one can show that the slope of derivative $\partial d_{defect} / \partial f_{DM}$ grows, as the band number increases (see Fig. 6). This is due to the fact that, as the band number grows the wavelength tends to decrease, and the "optical length" of the defect (d) will come close to the wavelength. Other words, the impact of the defect layer on the band structure will get stronger with a decrease in the wavelength (with a growth in frequency). The observed difference in DM frequency, from the standpoint of experiment and theory, results from the following: the computations include the oblique incidence of the electromagnetic wave only, and at the same time no account is taken in this computational procedure of the waveguide boundary-value conditions [10].

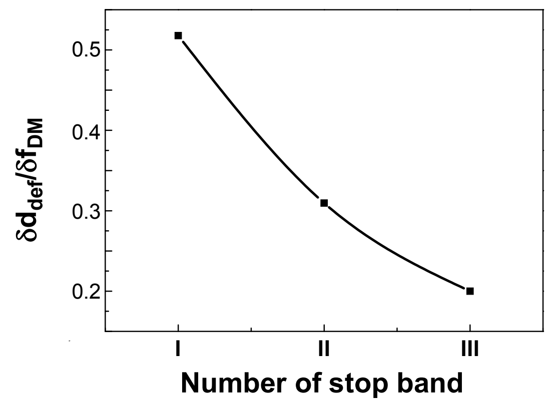

FIG. 6: Variations in the impact of the defect layer thickness upon the DM frequency for different forbidden spectrum bands

Thus, we can say with reasonable confidence that i) the disturbance of periodicity in a one-dimensional PC invariably lead to the DM arising in the stop band; ii) the field amplitude exhibits an exponential drop from the defect layer deep into periodic structures; iii) it is quite an easy thing to reveal the event during which the DM may migrate into an allowed energy band by gradually reducing the thickness of the defect layer to that of an appropriate element in a crystal. As a consequence, the spectrum acquires a typical form for the defect-free PC with a finite number of elements.

Besides, it can be shown that the common known electrodynamic Tamm state [10,11] arising in the one-dimensional PC may be thought of as a particular case for the DM. One of the distinctions in these two spectrum singularities is that an oscillation for the DM is set up in a volume of defect layer, but not at the layer interface as with the Tamm state. Furthermore, the equality of impedances is a necessary condition to form the Tamm state for two media [9]. The necessary condition for three media, namely, PC-defect-PC, is the equality of impedances of all three media.

4. CONCLUSIONS

The research of transmission spectra for the dielectric photonic crystal (PC) having a finite number of elements has been carried out. An impact of the varying the defect thickness on the defect mode formation in the spectrum of PC transmission has been analyzed both theoretically and experimentally.

It is shown that, as the defect layer thickness increases, the extreme maximum in the pass band is continuously migrating into the PC stop band, thereby forming the defect mode peak.

In summary, let note that any disturbance of spatial periodicity in PC structures give rise to a crystal singularity in the PC spectrum, namely, a defect mode. This mode with possessing the predicted Q-factor and the given type of field spatial distribution can be formed purposefully to meet the specific practical requirements. It should be also pointed out that the electrodynamic Tamm state is an important singularity in the PC spectrum. It can be shown that the well-known electrodynamic Tamm state can be considered, to some extent, as a particular case of the defect mode. This question is a subject of a further research.

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