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Selective defect mode amplification in a multi-defect photonic crystal

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Spectral characteristics of one-dimensional photonic structures formed by a sequential combination of Bragg reflectors and dielectric layers are investigated. The formation of one or more frequency combs of defect modes in the photonic bandgap region is shown. The features of optical field distribution over a defect photonic structure make it possible to implement selective amplification of defect modes.

Keywords: defect photonic crystal, defect modes, optical field localization, selective amplification.

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Introduction

In the transmission spectrum of dielectric periodically layered structures with a certain coordinated layer thickness, also known as photonic crystals, there are photonic bandgaps (PBGs) — frequency intervals in which there is no transmission at high reflection coefficient. One or more relatively narrow spectral bandpasses (bands of suppressed reflection) may also be formed in PBG due to violation of strict periodicity of optical path length in the layers of the structure [1]. Such „defect" layers may have a thickness or refractive index different from that of the photonic crystal layers. Modes associated with the presence of defect layers in the photonic crystal structure are also called „defect modes" [2–4]. Various materials and metastructures (liquid crystal materials, nanocomposite materials, two-dimensional structures, graphene, etc. [5–8]), as well as photonic structures of different topology [8–11] are used to control the number and frequencies of defect modes. The specific features of the spectral characteristics of defect photonic crystals are used to develop reflectors, filters, multiplexers, and other photonic and optoelectronic devices [12].

In this paper we propose a design of a one-dimensional photonic crystal structure, the PBG region of which has one or more groups of spectral transmission lines (spectral combs) associated with defect modes. Such a structure is a multidefect photonic crystal (MDPC) — a distributed Bragg reflector divided into parts (domains) by several defect layers.

1. Defect structure design. Spectral line combs of defect modes in PBG

Let us consider an MDPC based on a Bragg reflector with a unit cell $[AB]$, where the layers A and B are made of dielectric materials with refractive indices n_A and n_B respectively. This dielectric reflector is divided by layers $D_1, D_2, \ldots, D_{M-1}$ into M identical domains $[AB]^N$ with the number of binary layers N in each of them. The layered photonic structure is completed by an additional defect layer D_M. The materials of the defect layers D_i $(i = 1, \ldots, M)$ are characterised by the identical refractive indices n_D. Thus, the sequence of dielectric layers of MDPC is described by the formula $[[AB]^N D]^M$. The MDPC design is shown in Fig. 1. We consider the case when the MDPC is immersed in a homogeneous non-absorbing medium (air) and the light wave falls normally on the MDPC from the side of the surface layer A.

The transfer matrix method [13] is used to calculate the spectral characteristics of the periodically layered structure. For the amplifying layers, analytical expressions for the complex reflection and transmission coefficients are given in [14]. The transfer matrix for the whole structure is formed by sequential multiplication of the interface matrices and the transfer matrices through the material layers.

All calculations in the present study are performed for the following fixed parameters: $n_A = 3.35$ (GaAs), $n_B = 2.89$ (AlAs) [15], $N = 10$, thicknesses d_A and d_B of layers A and B correspond to the condition of Bragg resonance reflection at vacuum wavelength $\lambda_{Br} = 1.55\,\mu$m: $d_A n_A = d_B n_B = \lambda_{Br}/4$. In what follows, we also consider the case of MDPC with a single amplifying defect, whose optical characteristics are determined by the complex refractive index $\tilde{n}_D = n_D + ik_D$, where $n_D = 3.35$ and $k_D = -10^{-3}$.

Fig. 2 shows the transmission and reflection spectra of MDPC with the same number of domains $(M = 4)$ and defect layers of different thickness $(d_D = d_A$ and $d_D = 23d_A)$. It can be seen that in contrast to the case of a photonic crystal with a single defect layer, in the PBG of which separate spectral transmission lines are formed, in the

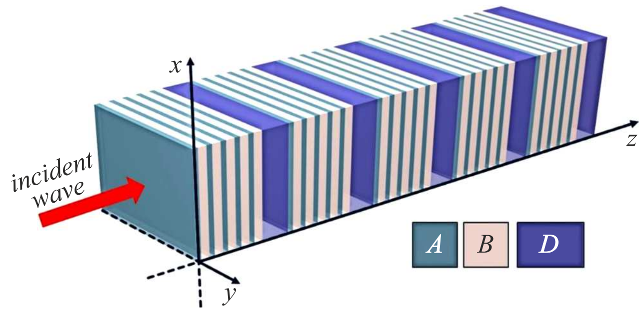

Figure 1. The problem geometry: MDPC has the structural formula $[[AB]^N D]^M$, where $[AB]^N$ are Bragg reflectors (domains) made of layers A and B, N is a number of $[AB]$ periods in the domains, D are defect layers, M is number of domains (coincides with the number of defect layers). The light wave is incident on the MDPC from the side of layer A.

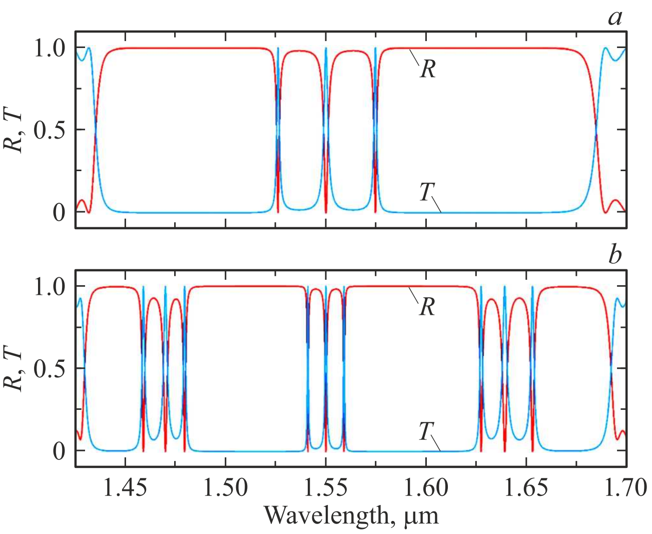

Figure 2. Transmission (blue curves) and reflection (red curves) spectra of MDPC with the number of domains $M = 4$ for different thickness of defect layers: $d_D = d_A$ (a), $23d_A$ (b).

MDPC transmission spectrum the spectral lines of defect modes are grouped into combs. The number of transmission lines in each spectral comb is determined by the number of domains and is equal to $M - 1$. In particular, in the case shown in Fig. 2, for $M = 4$ the number of lines in each comb is 3. The number of spectral combs in the MDPC PBG increases as d_D increases: one comb is observed for $d_D = d_A$ (Fig. 2, a) and for $d_D = 23d_A$ three combs are seen (Fig. 2, b).

Fig. 2 also shows that the spectral width and the distance between the spectral lines of the defect modes in the comb decrease as the total number of defect modes increases. An increase in the number of unit cells N in the domains leads to a similar effect (not shown in Fig. 2).

At frequencies corresponding to the defect modes, the light wave is localised in the region of the MDPC defect layers. However, for different defect modes, the optical field is localised in different layers of the structure. Analysis of the field distribution over the MDPC shows that at the frequencies of the external modes of the comb, all defect layers (except for the outer layer D_m) are the regions of light wave localisation, while for the internal modes the field intensity can differ significantly in different defect layers. In particular, for MDPC with six domains ($M = 6$) the central defect mode (at wavelength $1.55\,\mu$m) is localised in the first, third and fifth defect layers, while the neighbouring defect modes (near wavelengths 1.54 and $1.56\,\mu$m) — mostly in the first, second, fourth and fifth defect layers (hereinafter, the defect layers are numbered in the direction of light wave propagation).

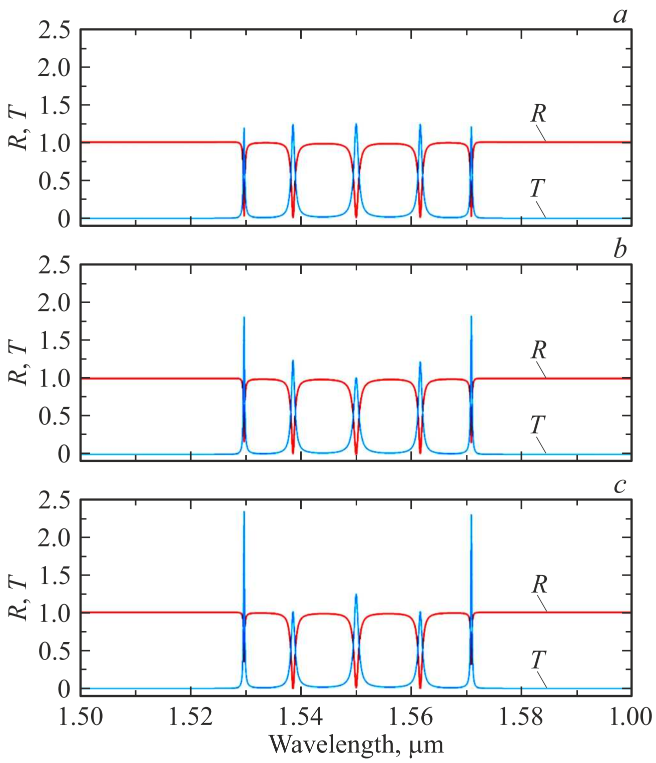

Figure 3. Transmission (blue curves) and reflection (red curves) spectra of MDPC with amplification in the first (a), second (b), third (c) defect layers. The structure parameters are: the number of domains $M = 6$, the thickness of defect layers $d_D = d_A$. The rest of the parameters are the same as in Fig. 2.

The difference in the nature of localisation of optical radiation at different defect modes provides the possibility to selectively control the radiation at different frequencies. To do this, it is necessary to place some medium in defect layers, which fulfils the role of, for example, a polariser, absorber, etc. The possibility of selective amplification of defect modes by using an amplifying medium as a defect layer material is shown below (the optical characteristics of the amplifying material are given above).

The transmission and reflection spectra of MDPC with six domains ($M = 6$), in which one of the defect layers is made of an amplifying material, are shown in Fig. 3.

The presence of the amplifying layer in MDPC results in an increase in the energy coefficients of reflection and transmission at the frequencies of defect modes. In accordance with the above-mentioned specific features of field localisation on the defects of the structure, the presence of amplification in the first defect layer leads to amplification of all defect modes (Fig. 3,*a*), in the second defect layer — peripheral defect modes (Fig. 3,*b*), in the third (central) defect layer — external and to a lesser extent central defect modes (Fig. 3,*c*). In the presence of amplification in the fourth or fifth defect layers, the spectral picture is almost identical to the case of amplification in the second and first defect layers, respectively. If the last (sixth) defect layer is amplifying, the amplification of all defect modes in the comb is observed, but the level of this amplification is the lowest, since this defect is outside the resonators formed by MDPC domains.

Conclusion

Defect structures with a comb-like transmission spectrum in the wide PBG region may be interesting in terms of designing multichannel resonator and laser structures, sensors, and optical filters. The total number and position of spectral combs and separate spectral lines of defect modes in the spectrum of MDPC are determined by the thickness of defect layers, the number of domains (Bragg reflectors) and the number of unit cells in them. The inhomogeneous distribution of the defect mode field in MDPC enables selective suppression or enhancement of reflection and transmittance in narrow spectral bands in the photonic bandgap region.

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Conflict of interest

The authors declare that they have no conflict of interest.

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