Optik 160 (2018) 189–196

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

One-dimensional photonic crystal filter using a gradient-index layer

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A R T I C L E   I N F O

Article history:
Received 6 November 2017
Accepted 31 January 2018

Keywords:
Photonic crystals
GRIN
Monochromatic filter
Defect mode

A B S T R A C T

This work deals with a monochromatic filter which is designed using a symmetrical one-dimensional photonic crystals (1DPC) containing a gradient refractive index (GRIN) defect layer introduced in the center of the system. The results show that, by choosing some appropriate parameters of the defect layer such as the function of the refractive index and its geometric thickness, we are able to determine a high-performance monochromatic filter. The important obtained result is that we can obtain a very large quality factor of this filter by a GRIN function having the sinus form and the position of its transmission peak can be predefined by selecting the geometric thickness of the defect layer.

1. Introduction

Nowadays, the photonic crystals have recently emerged at the forefront of potentials research especially in optoelectronic. With the focus mainly on design, the aspect of efficiency against optical irradiation of such structures has so far not been thoroughly addressed. Particularly, 1D photonic crystal (1DPC) is a one-dimensional binary dielectric material. It has a periodic structure formed by two distinct dielectrics with different refractive indices [1]. Generally, the periodic structures (PCs) are designed to control and to operate the propagation of light [2]. It is called a crystal, because of its periodicity, and photonic because it acts indeed on light. Such a layered structure can possess frequency regions in which the propagation of electromagnetic waves is forbidden [3]. These regions are called photonic band gaps (PBGs) and have been a crucial topic in optical physics over the past two decades [4]. Moreover, PBGs which arise from the structurally periodic property are analogous to the electronic band gaps (EBGs) in solids because the potential energy seen by electrons is also periodic in space [5,6].

The origin of the PBG in the transmitted wave with 1DPC structures results from the destructive interference among the waves scattered by interfaces of the layers in the forward direction. In the normal incident case, the characteristics of the PBGs and defect modes depend closely on the optical properties of the constituted layers and defect layer [7–9].

Different arrangements of 1DPC structures have attracted much attention because they can be easily fabricated by modern experimental techniques. That is why research topics on 1DPCs, including fundamental issues and novel systems for photonic applications have been of much interest to the communities of optics, photonics, materials science, and condensed matter physic [10].

An important issue related to the PBG is the existence of defect modes within this region of frequencies. The defect modes are generally to be generated when in a PC the translational symmetry is broken. This can be done by inserting a defect layer

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https://doi.org/10.1016/j.ijleo.2018.01.129

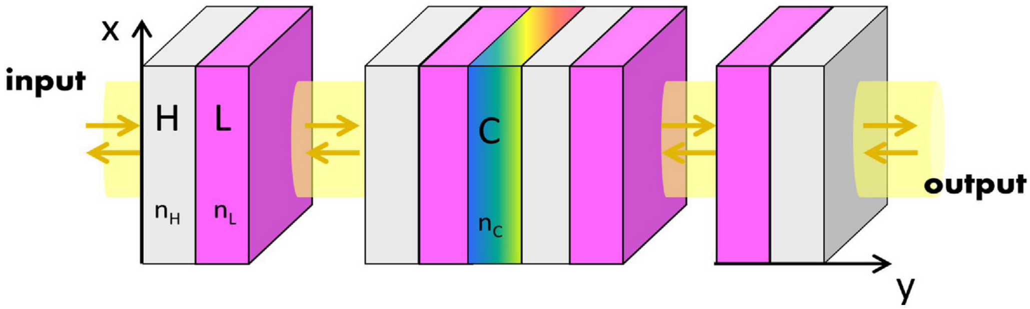

Fig. 1. Binary defective 1DPC structure.

into the PC or removing a single layer from the structure [11]. The defect layer acts in principle as a cavity such that the resonant tunneling mode exists in the PBG.

The presence of defect modes within the PBG is strongly dependent on the considered PC structure, including the material as well as the thickness of defect layer. Thus, the relationship between the defect modes and the PC structure is an important and fundamental issue. Furthermore, the knowledge of the defect modes properties will be informative and it seems in demand to design of a PC-based transmission narrowband filter [11–14].

However, the completely periodic PC can be, also, broken by introducing point defect with a variable refractive index. As a result, artificially created modes can be concentrated in a small area or guide through the waveguides. The ability to control light propagation direction can be improved by introducing this new concept of graded index (GRIN) medium. The term graded index is used for describing an inhomogeneous media in which the refractive index can vary point by point. A GRIN PC structure can be created by gradually varying parameters of the defect layer in the PC. There are several ways to generate an index gradient such as changing lattice constant, radii of the rods or dielectric. An example of such an element is a planar-surface GRIN lens [15].

The aim of this work is to provide a numerical study on the properties of the defect modes, the transmitted properties of a normally incident plane wave beam on a defective symmetrical 1DPC structure with a gradient refractive index (GRIN) defect layer. The transfer matrix method to calculate the numerical evolution of the transmitted wave has been used.

Indeed, three GRIN distribution functions are applied to defect layer in the structure of $(HL)^j C(LH)^j$, where H and L are constant refractive index materials and C stands for GRIN defect layer. The paper is devoted as follow: First, we introduce the proposed PC structure and materials in Section 2. A short brief result of the transfer matrix calculation is also presented. The applied GRIN distribution functions are introduced and illustrated graphically. Second, the behavior of corresponding defect modes in the band gap as well as the properties of the transmitted beam, are presented in Section 3. Finally, the conclusions of the paper are summarized in the Section 4.

2. Model and theory

Consider a binary defective 1DPC structure with arrangement of $(HL)^j C(HL)^j$, as schematically depicted in Fig. 1, where H and L are two kinds of dielectric materials with constant refractive indexes of $n_H = 2.3$ and $n_L = 1.45$, respectively. C stands for the GRIN defect layer.

We used the transfer matrix method to calculate the transmission T. This method is widely used for the description of the properties of stacked layers and it is extensively presented in [16–18]. We implemented such an algorithm in MATLAB and used it to determine the optical transmission of our photonic structures. In our approach, we considered non-absorbing layers, non magnetic and a normal incidence of the incident light.

Let us consider for investigation a stack of m layers as it can be seen in Fig. 1.

Using the notations given in this figure, we have considered known the refractive index of the medium from where the beam of light emerges $n_0 = 1$ (air), the refractive index of the medium in which the beam of light exits $n_S = 1.5$ (glass).

The electric field amplitudes E_m at each side of each layer of the system are related by the 2–2 complex transfer matrix which can be expressed as [19,20].

$$\begin{bmatrix} E_0^+ \\ E_0^- \end{bmatrix} = C_1 C_2 C_3 \ldots C_m \begin{bmatrix} E_{m+1}^+ \\ E_{m+1}^- \end{bmatrix} \tag{1}$$

Here, C_m is the well-known transfer matrix whose elements are:

$$C_m = \begin{pmatrix} \dfrac{e^{-i\phi_m}}{t_m} & \dfrac{r_m e^{i\phi_m}}{t_m} \\ \dfrac{r_m e^{-i\phi_m}}{t_m} & \dfrac{e^{i\phi_m}}{t_m} \end{pmatrix} \tag{2}$$