Design of annular photonic crystal slabs

H. Kurt, R. Hao, Y. Chen, J. Feng, J. Blair, D. P. Gaillot, C. Summers, D. S. Citrin, and Z. Zhou

1Department of Electrical and Electronics Engineering, TOBB University of Economics and Technology, Ankara, 06560 Turkey
2Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan, China
3School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0245, USA
4Institut d’Electronique de Microélectronique et de Nanotechnologie Université des Sciences et technologies de Lille, 59652 Villeneuve d’Ascq Cedex, France
5School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0250, USA
6Unité Mixte Internationale 2958 Georgia Tech-CNRS, Georgia Tech Lorraine, 2, rue Marconi, 57070 Metz, France

Received April 23, 2008; revised May 30, 2008; accepted June 4, 2008; posted June 11, 2008 (Doc. ID 95377); published July 14, 2008

We present the design of realistic annular photonic-crystal (APC) structures of finite thickness aiming to obtain a complete photonic bandgap (PBG). The APC is composed of dielectric rods and circular air holes in a triangular lattice such that each rod is centered within each hole. The optical and geometrical values of the structure are studied, and the interplay between various design parameters is highlighted. The coupled role of the inner-dielectric-rod radius, material types, and slab thickness is investigated. It is shown that the slab thickness is vital to obtain a complete photonic bandgap below the light line, and the specific value of the inner-dielectric-rod radius to sustain the maximum PBG if the hole radius is fixed at proper value is found.

© 2008 Optical Society of America

OCIS codes: 160.5293, 230.5298, 130.3120, 130.5440

Two-dimensional (2D) photonic crystals (PCs) find widespread use in the design of optical devices with wavelength and subwavelength dimensions. The ultimate control of the flow of photons in all possible directions can be attained only with three-dimensional (3D) PCs. However, the fabrication of 3D periodic structures is challenging. 2D PC slabs are relatively easy to manufacture and are compatible with planar lightweight technology. As a result, these considerations have made 2D PCs popular in the research arena [1–6]. The price paid for deployment of PC slabs is the typically pronounced polarization sensitivity of the designed photonic circuitry (TE versus TM). In particular, it is difficult to achieve photonic bandgaps (PBGs) for both TE and TM modes with a large frequency overlap. To provide a solution to obtain polarization-insensitive PCs, Kurt and Citrin proposed and analyzed a novel type of PCs composed of both dielectric pillars and air holes in such a way that the lattice geometry has a ring shape [7]; such structures were named annular PCs (APCs). Other aspects of APCs were studied in a recent paper [8]. A complete bandgap for PC slabs has been found using a triangular lattice of triangular air holes [9,10].

In the earlier study [7], only a 2D analysis was performed. Realistic 2D PCs, however, have finite slab thickness. As a result, the height of the structure should be considered when the plane-wave method (PWM) or finite-difference time-domain method is used. Therefore, in the present Letter, we consider the optimization of the optogeometric parameters subject to physically reasonable constraints employing the 3D PWM to design annular PC slabs providing bandgaps for both TE and TM polarizations [11].

A schematic of the annular PC slab is shown in Fig. 1. The relevant design parameters are the diameters of the dielectric pillars (d1 = 2r1) and holes (d2 = 2r2) and the slab thickness (h). In this Letter, there are four cases of the materials considered: Ge–Ge, Ge–Zr3N4, (a-Si)–(a-Si) and (a-Si)–Zr3N4. The first material designates the background material, and the second one is for the pillars. The refractive index of a-Si is taken as n = 3.73, and the remaining refractive indices are 4.0 for Ge and 3.30 for Zr3N4, aiming to target the optical regime at 1550 nm. The annular PC slab is assumed to lie on top of a SiO2 substrate with n = 1.45. We should note that the annular region r1 < r < r2 is air with n = 1. Since the refractive index

Fig. 1. (Color online) Annular photonic-crystal slab with thickness h and lattice constant a. The air-hole diameter is represented by d2 and pillars composed of either Ge, a-Si, or Zr3N4 have diameter d1. The background material is either Ge or a-Si on top of the SiO2 substrate.

© 2008 Optical Society of America
of each material is fixed based on the selection of the operating frequency, the remaining parameters for the optimization are $r_1$, $r_2$, and $h$.

Fabrication of the annular structure would first consist of patterning air holes into the silicon-on-insulator substrate, most likely through the use of resists and electron-beam lithography, given the requirements for nanoscale dimension precision. The ring structure and the center pillar could then be formed by conformally coating the substrate through the use of a chemical vapor deposition or atomic layer deposition thin-film surface-coating process. Finally, either a wet or dry surface etch could be used to remove the extraneous surface layers, creating the structure as seen in Fig. 1.

The polarization can be classified as TE and TM for a pure 2D system and even and odd modes for symmetric PC slabs, such as a membrane surrounded by air on both sides [12]. If the slab thickness is very thin, allowing for only the fundamental TE and TM modes, then the even and odd modes are called TE- and TM-like. On the other hand, for asymmetric PC slabs, the lack of reflection symmetry mixes the TE and TM modes. It is nonetheless common to call the modes in an asymmetric PC slab as TE- and TM-like [13, 14]. Even though such terminology is not strictly correct, we should note that all six components of the electric and magnetic fields are nonzero.

We will present the 3D PWM results, but it is important first to emphasize the role played by each parameter on the dispersion diagram of the APC slab. The outer radius $r_2$ should be sufficiently large to provide enough space for the inner dielectric pillars, which is expected to lead to a wide bandgap mainly for the TE modes. If the hole diameter, however, is very large, then thin veins between holes may lead to fabrication difficulties and eventually to mechanical instability [7]. Considering these tradeoffs, we can fix $r_2$ at 0.46$a$, providing a large TE-like bandgap such that the TE- and TM-like bandgaps overlap and search for the optimized values of $r_1$ and $h$ for each material type to ensure that the overlap is large. Another $r_2$ value rather than 0.46$a$ could potentially give a slightly larger or smaller PBG than the one we obtain here; however, the main findings of this study will remain the same.

After fixing $r_2$, we have two other parameters to choose, viz., the thickness of the slab $h$ and the inner dielectric-rod radius $r_1$. First, we pick a reasonable $h$ value and scan $r_1$ from 0.15$a$ to 0.25$a$. The gap–midgap ratio defined as $\Delta\omega/\omega$ is then read from the dispersion diagram. Next, $h$ is increased to another value, and the previous procedure is repeated. These steps are carried out for the cases of the four steps of materials. The findings are summarized in Fig. 2.

There are a number of important observations to be made from Fig. 2. First, we can see the role of the slab thickness on providing a complete PBG. To clearly see the interplay between the parameters, it is helpful to fix one of them and change the others. For example, if the slab thickness $h$ is maintained constant at 0.6$a$ (solid curve) and the material is changed from Ge–Ge to Ge–Zr$_3$N$_4$, the value of $r_2$ that provides the maximum PBG shifts to a larger value. This is expected, because when we change the material type of the inner dielectric rod from Ge to Zr$_3$N$_4$, we basically reduce the refractive index from 4.0 to 3.30. Similar variations occur for the (a-Si)–(a-Si) and a-Si–Zr$_3$N$_4$ material combinations. For instance, at $h=0.8a$, maximum PBG occurs for $r_2$ equal to 0.19$a$ and 0.21$a$ if the inner dielectric-rod material is changed from a-Si to Zr$_3$N$_4$, respectively.

![Fig. 2.](https://example.com/fig2.png)

Fig. 2. (Color online) For a given material selection, the gap–midgap ratio is plotted versus the slab thickness $h$ and the rod radius $r_1$. The radius of the hole $r_2$ is taken to be 0.46$a$. The refractive indices of the dielectric materials are given in the text.
Alternatively, one can fix the material and alter the slab thickness $h$. The PBG width variation possesses distinct features. As $h$ is increased, the positions of maximum PBG move to lower $r_2$. This is because the increment in $h$ brings the modes downward in the dispersion diagram. As a result, the overlap of the bandgap region of TE- and TM-like modes is enhanced.

Another feature is that the $h$ should be selected carefully for large PBG. Increasing it beyond a certain value degrades the PBG. Among the presented results, the maximum gap–midgap ratio is around 8.5%, with $h=0.8a$ and $r_1=0.19a$ for material selection of Ge–Zr$_3$N$_4$. Figure 3 shows the dispersion diagram for these specific values, and as can be seen there is a complete bandgap from 0.3657 to 0.3982 in terms of normalized frequency.

Physical devices have finite thickness $h$. For a certain thickness, the useful bandgap region should lay below the light line ($\omega/k = c/n$, where $n=1.0$ for the air cladding in top of the APC and $n=1.45$ for the substrate). Frequencies above this line are leaky modes and are not confined in the APC slab. Therefore, the overlap of TE- and TM-like bandgap frequencies should be optimized with respect to $h$. The portion of the bandgap above the light line can be brought to lower frequencies in two ways. One is to select materials with higher refractive indices, and the other is to increase $h$.

Increasing $h$ has the effect of shifting all the frequencies in the dispersion diagram to lower values. As a result, for an optimum $h$, we should be able to have fairly wide PBG. While optimizing $h$, we should keep also in mind the fabrication limitations of the etching depth. In the study, the optimum $h$ is around $0.80a$, but we should note that a finer tuning of the parameters scan will provide a slightly different value.

In conclusion, we have analyzed the band structure of APC slabs of finite height in order to obtain a complete PBG. The optimum structure parameters, i.e., slab thickness and inner-dielectric-rod radius, are presented subject to certain constraints placed by material availability, fabrication, and operating frequency. The study reveals the importance of the geometrical parameters as well as material types to obtain a full PBG for all polarizations. More specifically, keeping material type and hole radius constant and scanning for either slab thickness or inner-dielectric-rod radius yield maximum PBG at different values. As the slab thickness is increased, the maximum PBG occurs at lower inner-dielectric-rod radius. This behavior scales up or down if the material is changed owing to the different refractive index. Device implementation of this structure for waveguides will be highly desirable owing to the polarization insensitivity nature of the PBG.

The work of D. S. Citrin and J. Feng was supported in part by the National Science Foundation by grant ECCS 0523923. D. S. Citrin would also like to acknowledge the support of the CNRS. The work of Z. Zhou, R. Hao, J. Feng, and Y. Chen was partially supported by the National Basic Research Program of China (2006CB708310), the National Natural Science Foundation of China (60578048), and Natural Science Foundation of Hubei Province, China (2006ABD002).

References

Fig. 3. (Color online) Photonic band diagram of 2D annular PC slabs. The thickness of the slab is $h=0.8a$, $r_1=0.19a$, and $r_2=0.46a$ for the material selection of Ge–Zr$_3$N$_4$. 