Enhanced bandgap in annular photonic-crystal silicon-on-insulator asymmetric slabs

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Photonic band structures of annular photonic-crystal (APC) silicon-on-insulator (SOI) asymmetric slabs with finite thickness were investigated by the three-dimensional plane-wave expansion method. The results show that for a broad range of air-volume filling factors, APC slabs can exhibit a significantly larger bandgap than conventional circular-hole photonic-crystal (PC) slabs. Bandgap enhancements over conventional air hole PC SOI slabs as large as twofold are predicted for low air-volume filling factors below 15%. This desirable behavior suggests a potential for APC SOI slabs to serve as the basis of various optical cavities, waveguides, and mirrors. © 2011 Optical Society of America

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The photonic bandgap (PBG) is a key feature of photonic crystals (PCS) [1–10], and it gives rise to various useful properties, including spatial control of light at point and line defects [6–9,11]. These properties become more pronounced as the PBG is increased, which therefore has been the focus of considerable research [1–9]. Annular PCs (APCs) [3–8,10,11], which combine features of both dielectric-rod and air hole PCs, were first proposed to obtain a complete PBG for both transverse-electric (TE) and transverse-magnetic (TM) modes [3–8]. Such structures have recently been fabricated by electron-beam lithography and reactive ion etching [6], and also by atomic layer deposition and sacrificial etching for a more complex and general type [2]. Moreover, due to the two adjustable geometric parameters associated with the air-ring geometry in APCs, such structures are convenient for providing tailoring of the modes to have specific dispersion properties for self-collimation and slow light [6,10,11].

Our work focuses on the recent observation that APCs can offer larger PBGs for TE modes than conventional circular-hole PCs [6]. However, that result only considered a two-dimensional (2D) PC; further confinement within slabs as encountered in real applications was not addressed. Confinement within the slabs couples with the periodicity of the PC in a nontrivial manner; thus, a fully three-dimensional (3D) approach is warranted. Using a 3D plane-wave expansion method (PWM) [12], this Letter demonstrates theoretically the enhancement of the PBG as a function of the air-volume filling factor (AVF) (ratio of air volume in a PC unit cell to the unit-cell volume) in suitably designed APCs fabricated in silicon-on-insulator (SOI) slabs. It is shown that for a wide range of AVFs, the APC can supply a larger PBG than a conventional circular PC.

Asymmetric SOI slabs provide one of the most popular and promising platforms to implement all-optical integration, and thus this kind of slab is chosen as the focus of our study. The inset in Fig. 1 shows a schematic diagram of the structure; an APC slab based on a triangular lattice is assumed to lie on top of a SiO2 layer of refractive index $n_s = 1.45$. The outer and inner radii of the air rings (annuli) are $R$ and $r$, respectively. The annuli are composed of air with refractive index $n_a = 1$; the remaining portion within the slab is silicon (Si) with refractive index $n = 3.4$; $a$ is the lattice constant and $h = 0.6a$ is the slab thickness. The thickness is taken for comparison with [1] and also to obtain a large PBG. In order to make calculations efficient, the thicknesses for both the SiO2 and air layers are set to 1.5a to confine light vertically in the silicon layer. This value is chosen after comparisons with thicknesses of 2.0a and 2.5a, and almost the same bands below the light line are obtained.

The polarization of modes within the PC can be classified as TE and TM for symmetric PC slabs, such as a...
membrane surrounded by air on both sides [1]. For asymmetric PC slabs, however, the lack of reflection symmetry in the z direction mixes the TE and TM modes. Conventionally, the modes in a PC asymmetric slabs are still called TE- and TM-like [2,4] since these labels may identify the predominant character of the modes, provided that TE–TM mixing is not too severe. To assure this assumption is also sensible for our APC asymmetric slabs, the photonic band structure and the field distributions are investigated. Figure 1 shows the photonic band structure for a typical APC slab, with an AVF of 20% and outer radius \( R = 0.32a \). There is no complete PBG for this APC slab; however, a PBG for TE-like modes is seen. From Fig. 2, the PBG below the SiO\(_2\) light cone is constrained by the parts of the first two TE-like bands. Specifically, the PBG width is determined by the highest point in the first TE-like band and the lowest point in the second TE-like band. There are also two TM-like bands in the PBG. Consequently, investigating these four bands should be sufficient to identify the PBG.

As an example, in the zone below the SiO\(_2\) light cone, the highest points from bands TE1 and TM1 at the \( M \) point, and the lowest points of bands TM2 and TE2 at the \( M \) point are chosen. The normalized \( z \) components of the magnetic field \( H_z \) of these four modes are shown in Fig. 2. In each panel, the left panel is the normalized \( H_z \) distribution in the \( x\)–\( z \) plane when we take the section through the axis of the annulus, and the right panel is the normalized \( H_z \) amplitude along the axis of the annulus. Figures 2(a) and 2(b) show almost symmetric \( H_z \) distributions, meaning that bands TE1 and TE2 are essentially even, which is to say almost entirely TE-like; conversely, Figs. 2(c) and 2(d) show almost entirely odd \( H_z \) distributions, meaning that bands TM1 and TM2 are overwhelmingly TM-like. The field distributions in Fig. 2 penetrate into the two asymmetric layers almost symmetrically, which is mainly due to the refractive index of SiO\(_2\) being close to that of air. We therefore conclude that TE–TM mixing is weak and can be neglected. The field profiles in the \( x\)–\( y \) plane for corresponding TE-like modes also are approximately even. We have also explored the field maps for a range of parameter values and positions in the Brillouin zone and find that this conclusion is upheld.

Having established the validity of the TE and TM labels for the modes even in the APC asymmetric slabs under consideration, we explore the effects of varying the parameters on the PBG. Figure 3 shows the PBG (as the gap-to-midgap ratio) as a function of \( R \) for a series of asymmetric APC slabs with AVFs from 15% to 40% stepped in 5% increments. The labels \( f_{3D}, f_{2DE}, \) and \( f_{2D} \) in Fig. 3 are the AVFs for the 2D APC SOI slabs calculated by the 3D PWM [case (1)], 2D air holes-in-effective-index APCs calculated by the 2D PWM [case (2)], and 2D air holes-in-silicon APCs calculated by the 2D PWM [case (3)], respectively. The PBGs for the lowest and highest AVFs (15% and 40%) obtained in case (1) are also compared with the PBGs in case (2) and case (3).

The conventional effective index method uses the slab effective index (in the absence of the APC structure) as the background index in a 2D simulation to approximate the realistic slab structure to simplify the computation [6, 13, 14]. Typically, for applications based on the SOI platform, the effective index for the PC modes of interest is taken as the fundamental mode effective index of the ideal multilayer slab waveguide for a wavelength of 1550 nm. Here, it is taken to be 2.835, which is the same as in [6], and almost the same curves are obtained. Because of the adopted lower value effective index, a narrower PBG will be obtained with the effective index method. Thus the PBGs obtained in case (2) have narrower PBGs than in case (1). As for the 2D effective index method, it provides approximate band structure in a narrow bandwidth near 1550 nm, where the effective index is computed, but is not sufficient precise for high-index-contrast situations [13]. Therefore, although 2D methods are convenient for obtaining a qualitative understanding, 3D analysis is necessary to arrive at an adequate quantitative result for PBG width.

On the other hand, the results for case (3) are almost the same as those for case (1) for low AVF, but have

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**Fig. 2.** (Color online) Dependence in the \( x\)–\( z \) plane of the \( H_z \) distributions of TE- and TM-like modes within one unit cell at various wave vectors. Field maps are sections taken through the axis of the annulus. (See Fig. 1 for coordinate axes.) The plots of \( H_z \) versus \( x \) are taken along the axis of the annulus. The wave vectors for (a) and (c) are at the \( K \)-point, while the wave vectors for (b) and (d) are at the \( M \)-point.

**Fig. 3.** (Color online) Normalized PBG width of APCs, plotted as the gap-to-midgap ratio, versus the outer radius \( R \) of the annuli; the maximum value of \( R \) taken to be 0.45a. The labels \( f_{3D}, f_{2DE}, \) and \( f_{2D} \) denote the AVFs for the 2D APC SOI slabs, 2D air holes-in-effective-index APCs, assuming that the center wavelength is 1550 nm, and 2D air holes-in-silicon APCs, respectively. Thus, for a given curve, as \( R \) varies, so does \( r \) to preserve the specified AVF. The leftmost points of each curve have zero inner radius \( r \); thus they also correspond to the results for conventional PCs.
wider PBGs for higher values of AVF. In 3D situations of low AVFs, the in-plane dimension for air annuli $R - r$ will have very small values, while $h$ is maintained the same as in high AVFs. Relatively, $h$ is several times larger than $R - r$ in low AVFs. Therefore, the structure comes close to the ideal 2D assumption, which has $h$ infinite. Thus, the PBG curve for case (1) is almost the same as for case (3). However, for a high AVF 3D slab APC, the structure can no longer be approximated by the 2D model. Consequently, substantial deviations of 3D and 2D simulations result for high AVF.

For a given AVF, the PBG as a function of $R$ exhibits a single peak, which means that by adjusting the structural parameters of the APC within a broad range, the band structure in the vicinity of the PBG does not undergo qualitative change with $R$ and also that a maximum PBG can be identified. That is, one can increase the PBG in APCs for a given AVF compared with conventional air hole PCs. As shown in Fig. 3, compared with conventional air hole PCs, which are shown as the leftmost points of the curves, however, only a 1% bandwidth enhancement can be obtained by using the APC for a high AVF of 40%. It is worth noting that as shown in Fig. 3, for a low AVF of 15%, the air hole PC can supply a normalized PBG of 7.8%, while an optimized APC can enhance the PBG to 14.0%—close to a factor of 2. Therefore, APCs are especially useful for applications that require a large PBG, but also where it is desirable to maintain a low AVF, such as in optical cavities. If the AVF, though, is high, the light confinement in the vertical direction becomes weaker, which would restrict the maximum attainable $Q$ of the cavity. Therefore, a tradeoff between the maximum PBG and the minimum AVF must be made [15]. In that situation, the advantages of the APC would be significant, for it can enhance the PBG while maintaining a low AVF, or, to put it another way, the APC can supply the same PBG as a conventional PC but with a lower AVF.

It is also interesting that $R$ to maximize the gap for any AVF increases monotonically with AVF. Let us turn to the field distributions in Figs. 2(a) and 2(b), for they are closely connected to the gap. The fields are mainly localized in the central silicon rod and extend to the surrounding areas in Fig. 2(a). If the silicon rod is not sufficiently large, more fields will leak to the air annuli thus pulling up the mode frequencies in TE1, which will narrow the gap. In contrast, in Fig. 2(b), although the fields have highest amplitude in the silicon surrounding zone, they cannot fill up the entire surrounding silicon zone. Therefore, the change of $R$ does not influence the frequency much. When increasing the AVF, the air annulus is also increased. To obtain a large gap, $r$ of the annuli was restricted, thus resulting in an increase of $R$. Thus, monotonically increasing $R$ versus AVF to maximize the gap can be observed in Fig. 3.

In conclusion, we have analyzed the band structure of asymmetric APC slabs of finite thickness based on SOI in order to enhance the PBG compared to what can be obtained with more conventional PC slabs. Field distributions in the PBG asymmetric slabs show the TE- and TM-like labels for PBG remain meaningful. The study reveals that APCs can significantly increase the PBG for a given AVF. The enhancement is especially distinguished for low AVFs; for example, the APC slabs would enhance the PBG to nearly a factor of 2 in low AVF with 15%. This PBG enhancement is favorable for large-bandwidth devices such as waveguides, sensors, mirrors, and optical microcavities.

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References