Tunable photonic crystal circuits: concepts and designs based on single-pore infiltration

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We demonstrate that the infiltration of individual pores of certain two-dimensional photonic crystals with liquid crystals and (or) polymers provides an efficient platform for the realization of integrated photonic crystal circuitry. As an illustration of this principle, we present designs for monomode photonic crystal waveguides and certain functional elements, such as waveguide bends, beam splitters, and waveguide intersections. These devices exhibit very low reflection over broad frequency ranges. In addition, we discuss the inherent tunability of these devices that originates in the tunability of the infiltrated material.

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One of the most attractive applications of photonic crystals (PCs) is the creation of ultracompact photonic integrated circuits (PICs) that would provide seamless, all-optical signal processing capabilities. This concept rests on the ability of certain PCs to eliminate the propagation of light over extended frequency ranges irrespective of the direction of propagation. When a defect structure is embedded in these PCs, radiation with frequencies in such photonic bandgaps (PBGs) remains trapped at the defect sites and waveguiding applications may be realized as the PBG prevents the leakage of the radiation to the medium surrounding the PC. However, the realization of complex PICs imposes more stringent requirements on the designs: To achieve acceptable performance and a certain robustness with respect to fabrication tolerances, it is imperative to minimize parasitic Fabry–Perot resonances between connecting elements such as waveguide bends, beam splitters, and waveguide intersections. Ideally, all these connecting elements should be nonreflecting over a broad frequency range. In addition, the cross talk between waveguides in an intersection should be strongly suppressed.

As is well known,[1] removing a single row of rods in a two-dimensional (2D) PC consisting of a square lattice of dielectric rods creates a broadband monomode waveguide for E-polarized light (electric field vector parallel to the rods). In addition, reflection from waveguide bends in these systems does not exceed 5% over a wide frequency range[1] and changing the radii of certain rods facilitates the design of relatively broadband low-reflection beam splitters[2] (see Ref. 3 for further references). This is possible because the removal of a single rod in such PCs creates cavity modes with almost circular symmetry, so that the coupling between cavity modes around bends and splitters remains strong for any bend angle. However, there is also a penalty—elimination of parasitic cross talk between the intersecting waveguides requires the use of high-Q resonances. This significantly narrows the free bandwidth for these systems.[4] In addition, any real rod-based structure would consist of finite-height rods so that light propagating in the resulting air waveguide could not be guided in the third dimension. To circumvent these problems, it was recently suggested to sandwich such structures between properly designed three-dimensional (3D) PCs.[5] Clearly, such an approach requires highly advanced 3D fabrication techniques.

As a result, 2D PCs for application at optical wavelengths typically consist of arrays of air pores that have been etched into high-refractive-index materials, such as macroporous silicon, GaAs, or InP, through standard semiconductor processing technologies. The majority of defects studied in such systems consist of missing pores, and therefore guidance in the third direction may be realized. In these PCs, PBGs for H-polarized light are typically larger than PBGs for E-polarized light, and substantial effort has been devoted to the design of efficient functional elements for H-polarized light. However, in this case a single missing pore creates a doubly degenerate dipolelike cavity mode. Consequently, the resulting PC waveguides are intrinsically multimode. Therefore, despite the large PBGs, the frequency regions of monomode operation of straight waveguides are rather narrow. More importantly, guiding light around bends is rather inefficient in the H-polarized case because (i) the waveguides may become multimode in the vicinity of the bends and undesired cross coupling between different modes occurs and (ii) there exists an impedance mismatch between the waveguide modes in the different leads due to their asymmetric coupling to the dipolelike cavity modes of the bend. Nevertheless, we note that this asymmetric p coupling has

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been exploited for the design of relative broadband low-cross-talk waveguide intersections.[6]

In this Letter we suggest a novel platform for tunable PC circuits that combines several attractive advantages: (i) The PC circuits are based on 2D PCs consisting of air pores in high-refractive-index dielectrics and therefore are easily fabricated. (ii) They exploit nondegenerate defect modes created for E-polarized light by infilling individual pores with appropriate low- or moderate-refractive-index materials such as liquid crystals and (or) polymers. By construction, this leads to essentially monomode PC waveguides. Furthermore, a peculiar symmetry of these cavity modes may be exploited to simultaneously obtain designs for broadband nonreflecting waveguide bends and beam splitters as well as broadband low-cross-talk waveguide intersections. (iii) Owing to the tunability of the infilled materials, the resulting circuits will be tunable. Here we note that the idea to infiltrate PCs with liquid crystals to achieve tunable band structures has been suggested theoretically[7] and validated experimentally for 3D[8,9] and 2D[10,11] PCs. In addition, a tunable beam splitter for H-polarized light in 2D PCs with liquid-crystal-infilled pores was recently suggested theoretically.[12] Unfortunately, the corresponding cavity mode remains doubly degenerate and dipolelike. As a result, the PC waveguides are intrinsically multimode, and it remains a challenge to design broadband nonreflecting waveguide bends, beam splitters, and intersections.

Let us consider a 2D PC consisting of a square lattice of cylindrical air pores (radius $r = 0.475a$; lattice constant a) in a silicon matrix with refractive index $n = 3.46$ (macroporous silicon[13]). For E-polarized light this structure exhibits two complete PBGs with the larger, fundamental bandgap, extending from $a/\lambda = 0.238$ to $a/\lambda = 0.291$ (20% of the midgap frequency). Infilling a material with refractive index $n_{\mathrm{def}} = 1.55$ into a single pore gives rise to a nondegenerate monopolelike cavity mode as depicted in Fig. 1. In Fig. 2(a) we display the dispersion relation for the propagating guided modes of a straight PC waveguide created by infilling a material with refractive index $n_{\mathrm{def}} = 1.55$ into a single row of pores. This and all subsequent results were obtained with an accuracy better than 1% through the Wannier function approach[14] using the ten most relevant Wannier functions per unit cell. Since it is based on a nondegenerate cavity mode, this PC waveguide is monomode throughout the entire available frequency range. The bandwidth of this mode can be significantly increased either by increasing the radius of the pores or by increasing the refractive index of the infilled material, as demonstrated in Fig. 2(b).

In Fig. 3 we present the transmission spectra for three different designs of a 90° waveguide bend. The designs that have been successfully used for E-polarized light in rod-based PCs[1] appear to be extremely inefficient in our case. For instance, the transmission through the waveguide bend depicted in Fig. 3(a) is almost zero over the entire frequency range of interest. In fact, our initial attempts at improving these results by rounding the waveguide bend failed completely. However, once we ignored this standard procedure employed in other systems and started to design photon-hopping paths based on the field distribution of the cavity mode displayed in Fig. 1(b), we were able to arrive at successful designs for a broadband low-reflection waveguide bend as illustrated in Figs. 3(b) and 3(c).

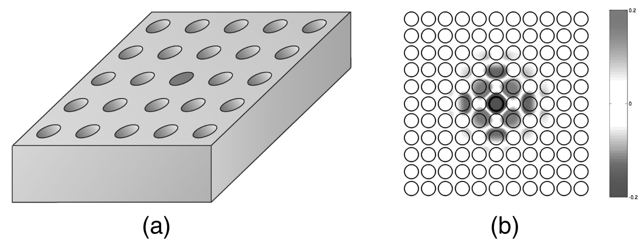

Fig. 1. (a) Schematic of a 2D PC consisting of a square lattice of air pores with a single pore infilled with a liquid crystal or a polymer. (b) Electric field distribution for the corresponding nondegenerate cavity mode for E-polarized light.

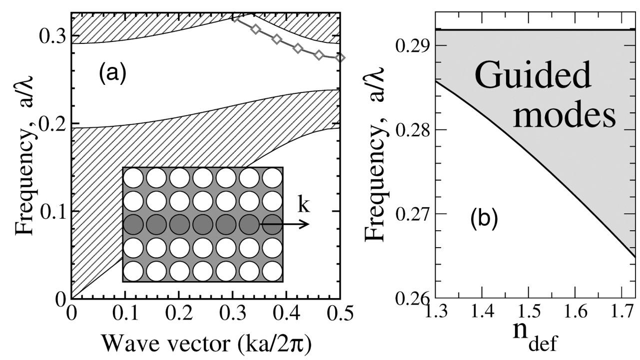

Fig. 2. (a) Dispersion relation for a PC waveguide obtained by infilling a single row of pores with a material with refractive index $n_{\mathrm{def}} = 1.55$. The hatched areas represent the projected band structure of the underlying PC. (b) Bandwidth of the guided modes (shaded area) of the same PC waveguide as a function of refractive index n_{def} of the infilled material.

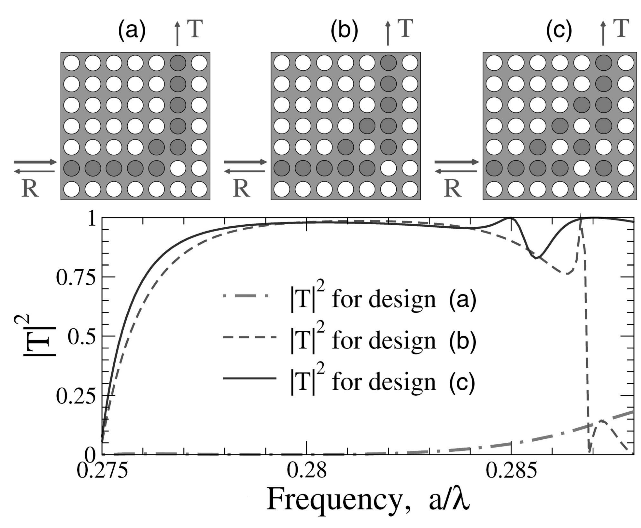

Fig. 3. Transmission spectra for three different designs of waveguide bends as illustrated in the upper drawings.

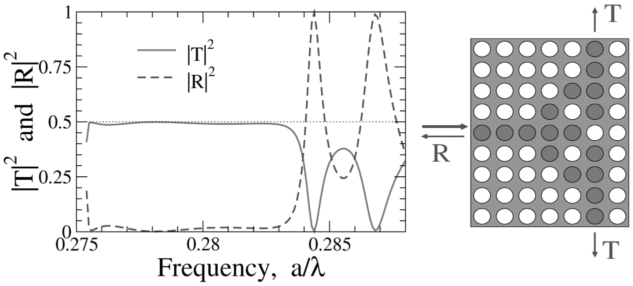

Fig. 4. Transmission and reflection spectra for our optimized design of a beam splitter whose schematic is shown at the right.

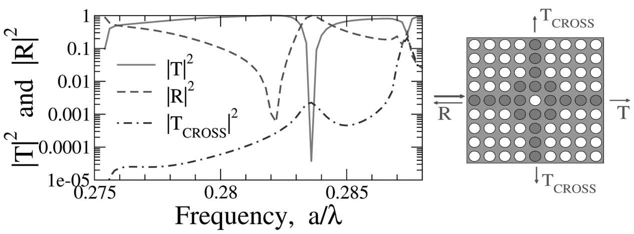

Fig. 5. Transmission and reflection spectra for a broadband low-cross-talk design of a waveguide intersection whose schematic is shown at the right.

As depicted in Fig. 4 for our optimized beam splitter design, the photon-hopping picture is an appropriate description for monomode waveguide systems in PCs.

To design an efficient waveguide intersection, we utilized the inefficient design of a waveguide bend shown in Fig. 3(a). In this case (see Fig. 5) we were able to almost completely eliminate parasitic cross talk between the waveguides without having to take recourse to high-Q resonances as suggested in Ref. 4. As a result, our waveguide intersection operates over a broad range of frequencies. A careful inspection of Fig. 5 reveals that the reflection from the intersection vanishes in only a relatively small frequency range. However, we can easily shift and extend this region by changing the refractive index of the material infiltrated into the four corner pores, either directly by changing the material itself or by locally tuning the material properties through an external control parameter such as tuning an infiltrated ferroelectric liquid crystal through an applied dc electric field. More generally, infilling pores with materials exhibiting different refractive indices allows us to further improve the characteristics of all the devices discussed above.

In conclusion, we have shown that the infiltration of low-refractive-index materials into air pores of bulk high-index 2D PCs provides a novel platform for ultracompact PICs using E-polarized radiation. Owing to a nondegenerate cavity mode with a peculiar field distribution, we have designed monomode PC waveguides and a number of broadband nonreflecting functional elements such as bends, beam splitters, and low-cross-talk waveguide intersections. Further designs (not shown) include a folded directional coupler with a 2D quality factor Q in excess of 40,000. These functional elements may be realized by infiltrating different types of liquid crystals and (or) polymers into appropriate 2D PCs (for a recent overview on the current state of microinfiltration see Ref. 15). We emphasize that many low-refractive-index materials, e.g., photopolymers, can be solidified after the infiltration process, so that this approach allows mechanically stable PC circuits. Our concept opens numerous avenues for tunable PC circuits based on the tunability of the infiltrated materials that can enhance the utility of these composite systems over and above that of conventional PC circuits. The achievable tunability can be estimated from the shift $\Delta\lambda/\lambda$ of the resonance wavelength of the cavity mode generated by a single infilled pore whose index of refraction is changed by Δn. For the system considered in this Letter we obtained $\Delta\lambda/\lambda \approx 0.06\Delta n$, whereas for a corresponding triangular-lattice system we find $\Delta\lambda/\lambda \approx 0.14\Delta n$. (Note that the birefringence of nematic liquid crystals can lead to values for Δn as large as 0.2.)

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