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Properties, applications and fabrication of photonic crystals with ring-shaped holes in silicon-on-insulator

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Abstract

We show that photonic crystals with ring-shaped holes (RPhCs) exhibit superior properties compared to conventional photonic crystals (PhCs). At low air-fill factors RPhCs can have a larger bandgap than conventional PhCs. Moreover, RPhC waveguides with both high group index and small group velocity dispersion can be designed. RPhC waveguides are also more sensitive to external refractive index changes, which is attractive for sensor applications. Finally we set up a procedure to pattern RPhCs in silicon-on-insulator.

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1. Introduction

Planar photonic crystals (PhCs) are structures with a periodic variation of the dielectric constant in two dimensions [1]. From the periodicity, a forbidden wavelength range for photons can arise (i.e., photonic bandgap). PhCs are used to realize various building blocks (e.g. waveguides, cavities or mirrors) that can be functionalized or combined to realize high-performance devices for integrated optics: filters, lasers, splitters or sensors to cite only a few.

Lattices of circular holes are the dominating PhC geometries. We choose to study photonic crystals based on ring-shaped holes (RPhCs). It has been demonstrated earlier that RPhCs possess polarization-independent photonic bandgap [2]. We also have shown that some RPhC waveguides (RPhCWs) exhibit low group velocity dispersion [3,4].

Fig. 1 shows a schematic of an RPhC. The ring is defined by its inner and outer radii R_{in} and R_{out}. Hence two parameters are available for tailoring of the photonic band structure. A circular hole corresponds in fact to the limit case $R_{in} = 0$.

In this paper, we investigate different properties of RPhCs, refine our results on slow light RPhCWs and show that RPhCWs can be used as efficient biosensors. We also demonstrate fabrication of such structures. We

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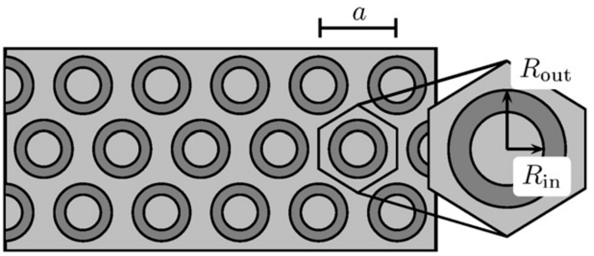

Fig. 1. Sketch of an RPhC.

consider a thin silicon slab (< 500 nm) on silica as material platform. It is commercially available as silicon-on-insulator (SOI) wafers. From the fabrication point of view, thin slabs require only shallow etching, which is convenient in the case of high aspect ratio structures such as RPhCs.

2. Properties and applications

2.1. Bandgap width and frequency

In order to study the bandgap of the RPhCs, their band structures were calculated with the MIT Photonic Bands software, which uses the plane wave expansion (PWE) method [5]. In the 2D simulations of Figs. 2 and 3, we take $n_{eff} = 2.835$ as the background refractive index. This corresponds to the effective index of the fundamental guided TE mode in a 220 nm thick silicon slab on silicon dioxide at a wavelength of 1550 nm. All the simulations were carried out for the TE polarization.

Figs. 2 and 3 show the bandgap edge frequencies and the gap to mid-gap ratio, respectively, as a function of R_{out}. The graphs are plotted for different values of the air-fill factor f_{air}, which is defined as the area of the air hole divided by the area of a primitive cell of the RPhC lattice:

$$f_{air} = \frac{2\pi}{\sqrt{3}a^2}(R_{out}^2 - R_{in}^2), \quad (1)$$

where a is the lattice constant. The dots in Figs. 2 and 3 correspond to the case where $R_{in} = 0$, i.e., where the hole is circular.

When $R_{out} < 0.38a$, the top and bottom edges of the bandgap are at higher frequencies in the RPhC than in the conventional PhC with the same f_{air} (Fig. 2). This means that the eigenmodes above and below the bandgap in the RPhC concentrate more of their energy in the air region, compared to the conventional PhC.

For $f_{air} < 30\%$, it is possible to find values of R_{out} for which the gap width in the RPhC is larger than in the conventional PhC (Fig. 3). The larger bandgap is an advantage in mirrors and cavities, where modes deep inside the bandgap experience higher reflectivity.

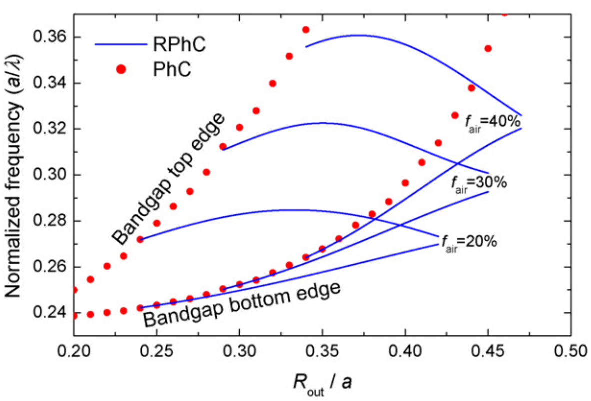

Fig. 2. Bandgap top and bottom edge frequencies for the TE polarization in an RPhC as a function of ring outer radius R_{out} at different air-fill factors. The dots correspond to a conventional PhC with radius R_{out} ($R_{in} = 0$).

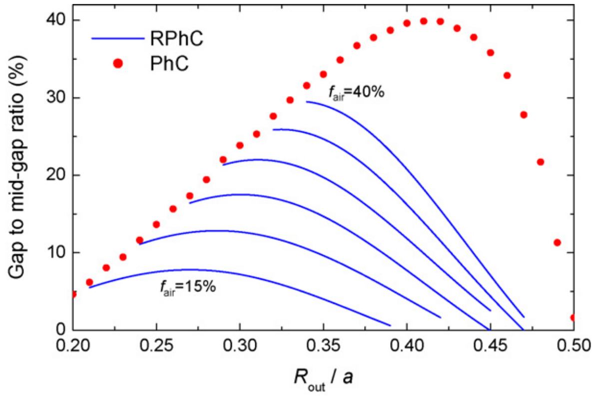

Fig. 3. Gap to mid-gap ratio for the TE polarization in an RPhC as a function of ring outer radius R_{out}. The solid lines correspond to air-fill factors from 15% to 40% with a step of 5% units. The dots correspond to a conventional PhC.

2.2. Slow light in RPhC waveguides

Guided modes in PhC waveguides (PhCWs) exhibit decreased group velocity near the Brillouin zone edge (i.e., when the propagation constant β of the guided mode is close to π/a) [6–10]. This enhances light–matter interaction and nonlinearities, which may be utilized to realize more compact integrated optics devices. However, slow modes usually have a very high group velocity dispersion, which leads to optical signal degradation in telecommunication systems. Therefore, it is necessary to tailor the dispersion properties of the slow mode [11–13].