Photonic Crystals with Split Ring Unit Cells for Subwavelength Light Confinement

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Abstract: We report a split ring photonic crystal that demonstrates an order of magnitude larger peak energy density compared to traditional photonic crystals. The split ring offers highly focused optical energy in an accessible subwavelength gap.
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1. Introduction

The study of photonic crystals (PhCs) has enabled the understanding of micro and nanoscale optical phenomena while at the same time advancing precise control over the modal and dispersive properties of a wide range of optical devices that rely on strong-light matter interaction. Among the notable PhC-based devices that have been demonstrated are PhC lasers, electro-optic modulators, optical biosensors, and solar cells. Recent work has revealed that the specific geometry of a PhC unit cell strongly influences the local electric field and energy distributions. For example, adding dielectric features such as an antislot [1] or a bowtie [2] to a circular unit cell was shown to change the energy distribution from being relatively uniform across the unit cell to becoming highly localized, which can be explained using fundamental electromagnetic interface conditions. Prior work has also shown that a mix and match approach can be applied to PhC design wherein different unit cell shapes (e.g., antislots and bowties) can be combined in a single PhC nanobeam to achieve an even higher level of control of the mode profile without sacrificing the quality factor (Q) of the PhC [3]. Hence, other strategic unit cell shapes could be employed to realize desired field distributions that are favorable for specific applications and fabrication methods. Here, we report on the properties and design flexibility of split ring PhC unit cells. Split ring PhCs support an order of magnitude higher peak electric field energy density as compared to a traditional PhC as well as several subwavelength tuning parameters to adjust the optical energy and frequency of transverse electric (TE) photonic bands. The split ring PhC localizes light inside the low-index split region making for a desirable match to applications including optical biosensing, optical trapping, and enhanced emission from a quantum dot or other nanoscale emitter that could be incorporated in the split void region.

2. Split Ring Photonic Crystal Design, Simulation, and Experimental Results

Fig. 1(a-b) shows an illustration of the split ring PhC field confinement and a schematic of the available subwavelength tuning parameters for adjusting the confinement of the electric field and the frequency of the photonic band edges. For all finite-difference time-domain simulations, the period of the split ring unit cells is 390 nm, the waveguide width is 750 nm, and the split ring parameters are: $r_{C,inner}$ = 50 nm, $r_{C,outer}$ = 70 nm, and r_{air} = 90 nm. The split width (w_s) and split ring rotation angle (θ) are the variable parameters considered in this work. Fig. 1c shows a scanning electron micrograph of a fabricated split ring PhC waveguide. In this case, the split width and the outer airhole radius are approximately 30 nm and 300 nm, respectively.

Fig. 1(d-e) shows the electric field energy density (proportional to E^2) distribution at the air band edge of the R0 (i.e., $\theta = 0^\circ$) and R90 (i.e., $\theta = 90^\circ$) split ring unit cells normalized to the peak energy density in the R0 unit cell (E_{R0}^2). The peak energy density in the unit cell drops by ~40% as the split ring angle is varied from zero to ninety degrees, and the location of peak energy density transitions from being well-confined inside the split to being spread out along the upper and lower air ring regions. For the R0 unit cell, the TE-polarized electric field that oscillates in the plane across the waveguide width (y-direction) directly crosses the vertical silicon-air-silicon interfaces of the split. Electromagnetic interface conditions dictate that the normal component of the electric field is discontinuous across an interface (i.e., scaled by the ratio of the electric permittivities of the two dielectric materials at the interface). Since the electric field is normal to these silicon/air interfaces, the electric field amplitude in the air slot of the R0 split ring PhC unit cell is enhanced by the ratio of the silicon and air permittivities - this effect is known as the slot effect [4]. We note that the lower electric field energy density present in the air regions toward the top and bottom of the unit cell between the outer edge of the silicon ring and silicon region outside the air hole can also be explained by electromagnetic interface conditions; the electric field enhancement in these air regions is much lower than in the split due to their much larger width [4]. Conversely, for the R90 split ring unit cell, TE-polarized light is tangential to the silicon-air-silicon interfaces of the split. Therefore, since electromagnetic interface conditions dictate that the tangential component of the electric field is continuous across an interface, there is no electric field enhancement in the split of the R90 split ring unit cell.

Fig. 1f quantifies the peak energy density in the split as a function of rotation angle normalized to the peak energy density in the R0 unit cell. In comparison to the traditional circular air hole PhC, the peak energy density in the split of the R0 split ring PhC is 10-times higher. Notably, the peak energy density inside the split diminishes by greater than one order of magnitude from R0 to R90, offering tunability of electric field strength and location from inside the well-localized split (R0) to the surrounding airhole (R90). Such tunability could be advantageous for PhC cavity applications for which a large difference in peak energy density is desirable in adjacent unit cells (e.g., optical trapping); prior work demonstrated that PhC cavities can be formed by appropriately rotating asymmetric unit cells to taper the mirror strength along the nanobeam [1]. Fig. 1g shows that as the split width increases, the peak energy density decreases, following from the slot-effect. The peak energy density scales by a factor of nearly four as the split width changes from 5 and 40 nm.

The design degrees of freedom offered by the split ring PhC demonstrate for the first time that it is possible to move an optical “hot spot” at any location within the PhC unit cell, rather than being limited to the center of a waveguide, PhC unit cell, or dielectric region between PhC unit cells. Experimental validation of slow light split ring PhCs will be reported along with straightforward extensions of the design to form split ring PhC nanobeam cavities based on modification of one or more of the subwavelength tuning parameters along the nanobeam. Appropriate selection of the tunable parameters of the split ring PhC make it an attractive option for particle-field interactions in optical trapping or optical sensing platforms. Together with other recently reported subwavelength-engineered PhC unit cell designs such as the bowtie and antislot, split ring unit cells expand the design space options for achieving a highly tailorable mode profile that can be customized for desired guided wave applications.

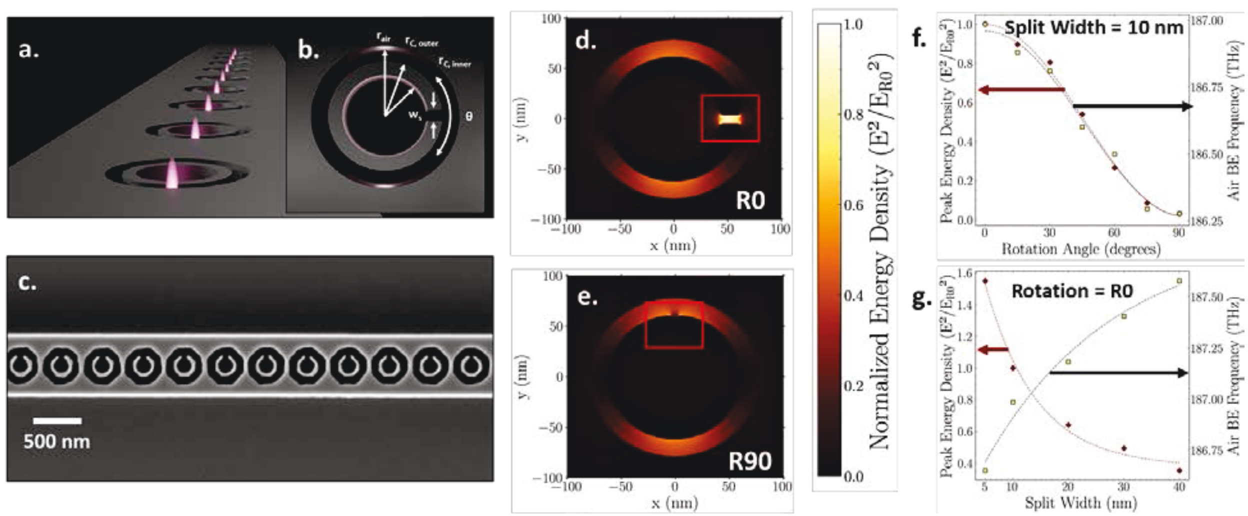

Figure 1. (a) Illustration of split ring PhC waveguide. (b) Schematic of subwavelength tuning parameters. (c) SEM image of split ring PhC waveguide fabricated using electron beam lithography. (d-e) Electric field energy density (i.e., proportional to E^2) distribution at air band edge for (d) R0 and (e) R90 split ring PhC unit cells using a color map normalized to the peak energy density of the R0 unit cell (E^2/E_{R0}^2), allowing direct comparison across unit cells. (f) Rotation angle dependence of peak energy density (normalized to E_{R0}^2) inside split ring PhC unit cell (red diamonds) and air band edge (BE) frequency (yellow squares); the split width is held constant at 10 nm. (f) Split width dependence of peak energy density (normalized to E_{R0}^2) and air band edge frequency; the rotation angle is held constant at zero degrees.

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