

Photonic Metacrystal: Design and Experimental Results

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Abstract: Going beyond the limited design freedoms of traditional photonic crystals, we experimentally show how photonic metacrystals exploit the inclusion of subwavelength dielectric scatterers in the unit cell to deterministically modify k -space and real space profiles.

1. Introduction

The possibility of combining the desirable attributes of low loss, high quality (Q) factor photonic crystals with the unique light-matter interactions achievable with metamaterials is of great interest to expanding the capabilities of photonic systems. In addition, bringing the control of amplitude and phase achievable in metamaterials that are utilized for out-of-plane applications to photonic crystals would enable new design freedoms and capabilities for on-chip, guided-wave photonics. In order to combine the best properties of metamaterials and photonic crystals, subwavelength geometries must be integrated with photonic crystals with sufficient periodicity maintained to allow temporal confinement based on the photonic bandgap. For example, by introducing a subwavelength periodic variation in a hyperbolic medium, one can design a photonic hypercrystal with a unique photonic band structure and light-matter interactions [1]. In this work, we take a different approach and instead introduce deep-subwavelength-sized features inside the unit cells of traditional photonic crystals without a requirement for utilizing a hyperbolic material. Building on our initial work [2,3], we more deeply investigate the broader design methodology involved in adding metamaterial-like geometries to photonic crystals, including many new degrees of design freedom that are enabled. We introduce the name *photonic metacrystal* for structures that combine the concepts and design attributes of both metamaterials and photonic crystals. Here we present new design freedoms enabled by the subwavelength geometries in photonic metacrystal unit cells and experimental results on two photonic metacrystal cavity designs.

2. Photonic metacrystal design methodology

The photonic metacrystal design methodology focuses on engineering the shape of the constituent unit cells. Here we consider air mode operation in which the air mode traps light within the open area of a unit cell, which provides an ideal platform for inserting subwavelength scatterers of interest. Figure 1 shows the uniformly distributed energy within the air hole of a circular unit cell and how inserting different shaped subwavelength scatterers into that unit cell can deterministically modify the mode profile. These types of subwavelength nanoscale shapes have been extensively studied as plasmonic elements and metamaterial building blocks. We note that the modified mode profiles of photonic metacrystals result from redistribution of the electric and displacement fields based on boundary conditions. The ability to engineer the mode profile of photonic metacrystals opens the door to studying light-matter interactions under high Q-factor regimes using in-plane guided waves with modest input light intensity.

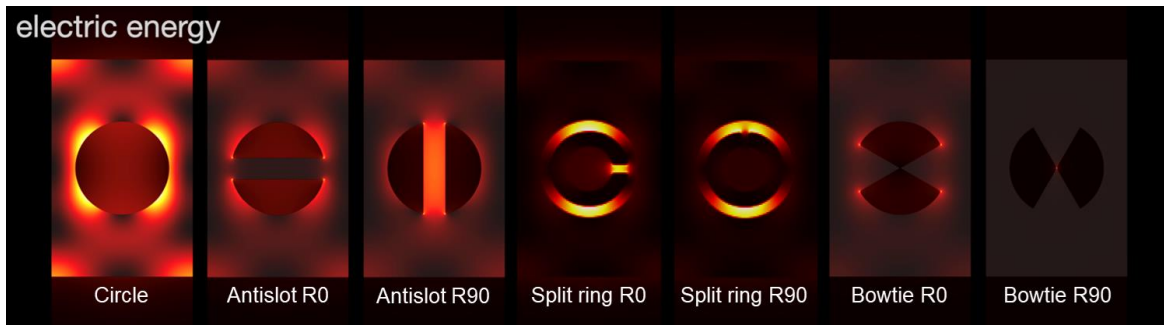


Figure 1. Electric energy distribution in several different photonic metacrystal unit cell designs compared to a traditional circular unit cell.

3. Experimental results

We experimentally investigated new approaches to cavity design enabled by the new degrees of freedom in the unit cell, taking the bowtie as an initial case study. While the degrees of freedom in a traditional circular unit cell photonic crystal include only radius and waveguide width, with a bowtie shaped dielectric block inside the air hole, even more degrees of freedom are enabled, including the bowtie tip angle, bowtie connection width, and bowtie rotation angle. Figure 2 shows scanning electron microscopy images and corresponding measured transmission spectra of bowtie photonic metacrystals exploiting two of these degrees of freedom in cavity design. Figure 1 A-D show the experimental results of a rotation angle modulated bowtie photonic metacrystal. This design was proposed in 2016 but was not previously experimentally verified [3]. The rotational angle of bowtie modulates the upper band edge frequency (air band) of the photonic metacrystal. As the rotational angle changes from 0° (R0) to 90° (R90), the upper band frequency reduces. The R90 unit cell's upper band frequency is nearly at the center of the R0 unit cell's photonic bandgap. Therefore, it is possible to design a photonic cavity with an R90 bowtie unit cell as the central cavity unit cell and R0 unit cells at the two ends as mirrors for optical confinement [3]. The measured Q factor of the fundamental resonance of the rotation angle modulated bowtie photonic metacrystal is $\sim 50,000$. Figure 1 E-H show the experimental results of a bowtie connection width modulated bowtie photonic metacrystal. A bowtie with a 60 nm connection width serves as the central cavity unit cell and the bowtie connection width of adjacent unit cells progressively decreases down to 5 nm at the outer mirror unit cells, causing the necessary change in the air band edge frequency to support resonant modes in the cavity. The fundamental mode of the bowtie connection width modulated photonic metacrystal has a Q-factor $\sim 53,000$.

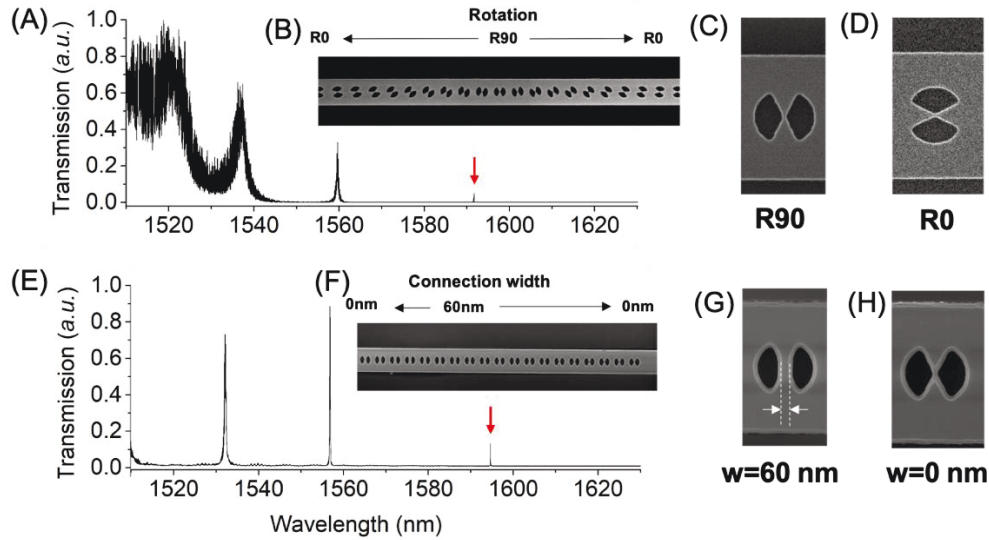


Figure 2. Experimental results of two different bowtie photonic metacrystal cavities: (A-D) rotational angle modulated design and (E-H) bowtie connection width modulated design. Transmission spectra and SEM images are shown.

3. Conclusion

We reported a new class of photonic crystal – the photonic metacrystal – that combines the advantages of photonic crystals and metamaterials by introducing subwavelength scatterers into the photonic crystal unit cell. Light-matter interaction can be tailored through the deterministic design of the subwavelength dielectric features inside the air holes of the photonic metacrystal. We experimentally demonstrated that new unit cell design features, including the rotation angle and connection width of a bowtie-shaped unit cell, can be modified to predictably tune the optical band structure and create high Q cavities. These additional degrees of freedom, which are not present in traditional photonic crystals, provide new ways to simultaneously control the band structure in k space and the mode profile in real space. We believe the continued investigation and utilization of photonic metacrystals will significantly expand the application space of guided wave photonics.

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