Experimental demonstration of guiding, bending, and filtering of electromagnetic wave in disordered photonic band gap materials

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Abstract: We report the first experimental demonstration of guiding, bending, filtering, and splitting of EM wave in 2D disordered PBG materials, along arbitrarily curved paths, around sharp bends of arbitrary angles, and through Y shape junctions.

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Line defects in photonic band gap (PBG) materials can confine and guide light through narrow channels and around sharp corners, which is important for large scale all-optical circuit applications [1]. An enormous range of technological developments in telecommunication industry, laser engineering, optical computing, spectroscopy, and radiation, have been suggested, when light with selected frequencies can be directed along chosen paths or be confined within a specific volume in PBG materials [2]. Conventional PBG materials are periodic structures, in which only limited numbers of rotational symmetries are allowed. Angular differences make it difficult to form a complete PBG in periodic structures without a large dielectric contrast. The orientations of channels cut in photonic crystals for light guiding are also restricted by the crystal symmetries, limiting potential applications.

Contradicting the long standing intuition that periodicity or long-range translational order is required in photonic band gap formation, a new class of disordered hyperuniform (HPU) materials was predicted to possess sizeable and isotropic photonic band gaps [3]. Recently, we have experimentally observed isotropic PBG in these disordered materials [4]. In these isotropic disordered structures there are no preferential symmetry directions; hence it becomes possible to construct wave-guiding and filtering channels with arbitrary bending angles in them.

In this paper, we report the first experimental demonstrations of guiding, bending, filtering, and splitting of electromagnetic wave in 2D isotropic disordered PBG materials, along straight or arbitrarily curved paths, around sharp bends of arbitrary angles, and through Y shape junctions. We demonstrate broad band pass through channels of various shapes, as well as versatile and flexible defect tuning abilities for narrow band filtering, in these disordered PBG materials. In our study, nearly 100 percent transmission of electromagnetic waves around sharp corners of arbitrary angles with bending radii smaller than one wavelength is observed experimentally.

The 2D isotropic HPU disordered PBG material constructed for this study consists of a network of Al_2O_3 cylinders and thin sheets.. Each cylinder has three nearest neighbors to which it is connected by sheets. The cylinders are particularly important for forming PBG for the TM polarization, while the connected sheets are important for the TE polarization. There is neither Bragg scattering nor long range order in this structure. It was argued that hyperuniformity, combined with uniform local topology and short-range geometric order can explain the origin of PBGs in these disordered materials [3]. The PBGs are associated with local resonant scattering instead of Bragg scattering, hence isotropic. Details about designing these 2D HPU PBG materials can be found in Ref. [3].

Experimentally, we used stereolithography to fabricate the bases of the structures at the scale of average spacing a=13.3 mm, and use commercially available 100.0 mm tall Al2O3 cylinders of radius r=2.5 mm and thin sheets of thickness t=0.38 mm of various width to assemble the HPU network structure. A square lattice with the same “lattice spacing” (a=13.3mm) and similar filling fraction (r=0.188a and t=0.029a) was constructed with identical dielectric cylinders and sheets for comparison. Experimentally the photonic properties are measured using a HP-8510C vector network analyzer for microwaves with wavelength comparable to twice the cylinder spacing (7-13 GHz). The dielectric constant of these Al_2O_3 materials was measured to be 8.76 at this frequency range. Both experimentally and numerically this structure is found to possess band gap of relative width respect to center frequency equals to 8.2%, 13.5% and 4.0% for TE polarization, TM polarization, and both polarizations, respectively.

Wave-guiding channels are constructed and modified by removing rows of building blocks and adding individual extra defects cylinders. Transmission through the channels was measured by placing two small microwave horn antennas right next to the channel openings. Absorption materials were placed around the sample to reduce noise. Calibrations were done when no sample is presented between two directly facing horns separated at the distance equal to the length of the channel.

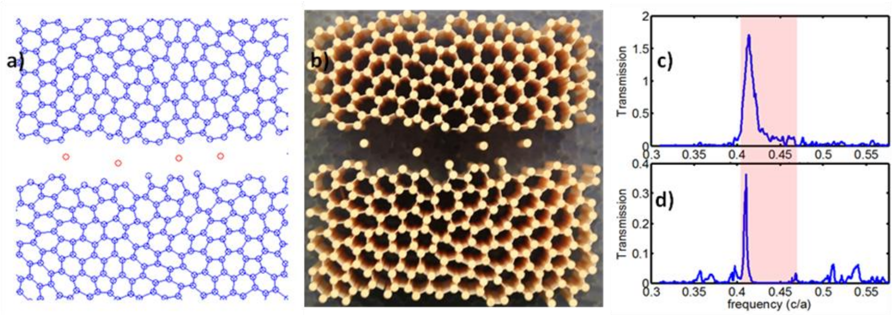

Figure 1. (a) A Sketch and (b) A photo of a straight wave-guiding channel. Measured transmission through the straight channel without (c) and with (d) the four extra defect cylinders marked in red.

Figure 1 shows a sketch (a) and a photograph (b) of a straight wave-guiding channel created by removing two rows of cylinders and sheets along a line. For the completely opened channel, without the 4 extra cylinders marked in red, the TM transmission spectrum is shown in Figure 1c, while the PBG for TM modes is highlighted with the pink shade. A broad band of frequencies are guided through the open channel with very high transmission, compared with the calibration of two facing horns separated by the same distance. When the extra four defect cylinders are placed inside the channel, a resonant transmission peak of a single frequency appears, as shown in Figure 1d. When one more extra cylinder is placed at the center of the existing array of four cylinders, the above resonant peak shown in Figure 1d completely disappear. It is clear that the coupled resonator waveguide can be fine-tuned to serve as a narrow band pass filter with a high Q factor. The propagating mode is strongly related to a resonance built inside the channel, suggesting versatile ability to design local defects for wave-guiding and filtering for various applications.

Figure 2 (a) and (b) show the sketch and transmission through a channel with 50^{o} bending angle. Figure 2 (c) and (d) show the sketch and transmission through an S shape channel. In both cases, broad band passes of high transmission efficiency are obtained, and extra defects can be added to fine-tune the filtering frequencies.

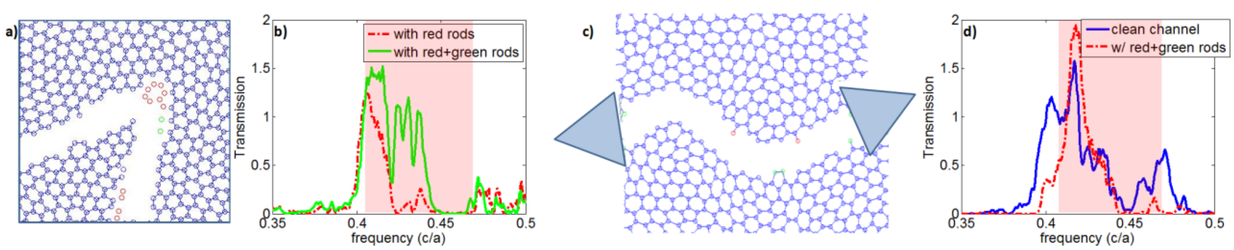

Figure 2. Sketches of a sharp bending channel of 50.º (a) and an S shape channel (c). Measured transmission through the 50.º channel (b) and the S shape channel (d).

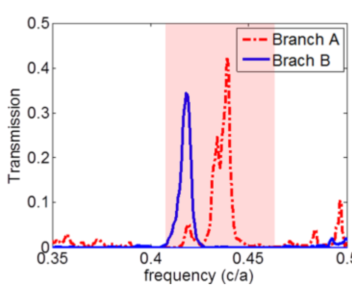

Figure 3. Measured frequency splitting in two branches of a Y junction channel.

More importantly the disordered HPU PBG material offers a very flexible platform for defect design to select tunable frequencies. It is particularly remarkable that we were able to demonstrate that the transmission peaks through two branches of a Y shape junction can be tuned to different frequencies by arranging different distribution of extra defect cylinders in the two output branches. As shown in Figure 3, the transmission peak though branch A (red dash dot) differs by 6.5% from that through branch B (blue solid line).

In summary, for the first time we have experimentally demonstrated the ability and flexibility of a disordered PBG material to guide, bend, filter, and split EM waves along arbitrary paths. We have proven that these PBG materials offer unique advantages over photonic crystals and are ideal for being used in various photonics applications, especially as an optical insulator platform for planar optical circuits.

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