Freeform wave-guiding at infrared regime in two dimensional disordered photonic bandgap materials

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Abstract: We report the first experimental demonstration of guiding, bending and power-splitting of light in 2D disordered photonic bandgap materials at infrared wavelengths, along curved paths, around sharp bends of arbitrary angles, and through Y-shape junctions.

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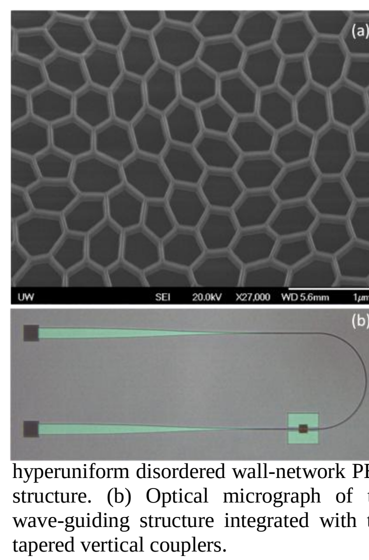
Point defects and line defects in PBG materials can confine light in a small volume and guide light through narrow channels and around sharp corners, which is important for large scale all-optical circuit applications [1] and other photonics technological developments [2]. The intrinsic anisotropy associated with periodicity in photonic crystals can greatly limit the scope of PBG applications and places a major constraint on device design. For example, even though 3D photonic crystals with complete PBGs have been fabricated for two decades [3], “3D wave-guiding” has not been experimentally demonstrated until very recently by Noda et. al. [4]. They also prove that, due to the mismatch of the propagation modes in line defects along various symmetry orientations, vertical-trending waveguides have to follow one particular major symmetry direction to guide waves effectively out of the horizontal symmetry plane in a 3D woodpile photonic crystal [4].

Recently, disordered photonic media and random textured surfaces have attracted increasing attention as strong light diffusers with broadband and wide-angle properties [5]. Contradicting the long-standing intuition that periodicity or long-range translational order is required in photonic band gap (PBG) formation, a novel class of hyperuniform disordered photonic PBG materials was recently designed by a constrained-optimization method, which combines advantages of both isotropy due to disorder and controlled scattering properties due to hyperuniformity and uniform local topology [6,7]. In these isotropic disordered structures, it becomes possible to construct wave-guiding channels with arbitrary bending angles. Recently, in the microwave regime, we have experimentally observed isotropic PBG and demonstrated freeform wave-guiding in centimeter-scale alumina based hyperuniform disordered materials [7, 8].

In this paper, we report the first realization of sub-micron scale hyperuniform disordered wall-network structures and the first experimental demonstrations of guiding, bending, and power-splitting of infrared waves of 1.55 micron wavelength in them, along straight or arbitrarily curved paths, around sharp bends of arbitrary angles, and through Y shape junctions.



he hyperuniform disordered wall-network PBG structure. (b) Optical micrograph of the wave-guiding structure integrated with the tapered vertical couplers.

The hyperuniform disordered wall-network structure was designed by employing a centroidal tessellation of a hyperuniform point pattern to generate a “relaxed” dual lattice, whose vertices are necessarily trihedrally coordinated by construction. The lattice vertex pairs are connected with dielectric walls to trihedral-network photonic architectures, featuring a TE polarization PBG [6]. More details about designing these disordered PBG materials can be found in Ref. [6]. Figure 1a shows a SEM image of such a wall-network hyperuniform disordered structure we fabricated on a Si-on-insulator wafer. The average lattice spacing is a=499 nm and our numerical simulations show that there is a TE polarization PBG with zero density-of-state centered around 1.55 micron, with various widths depending on different choice of wall thicknesses. The wall thickness shown in Fig. 1a is 50 nm. The thickness of the Si slab is 220 nm.

Test structures with various wave-guiding line defects are designed by substituting polygon-shape air cells along desired paths with filled Si. Each device is then integrated with tapered vertical couplers [9] for transmission measurements. We use E-beam lithography and an inductively- coupled plasma reactive ion etching process to fabricate the integrated test structures. Figure 1b shows an optical micrograph of one test structure, including the input/output vertical couplers and the wave-guiding device. Transmission measurements were done in a setup similar to what is described in Ref. [10] without removing the SiO_2 layer underneath.

The insert in Fig. 2 shows a sketch of a straight wave-guiding channel created by removing two rows of air polygons along a line. The wall thickness is 80 nm. The measured transmission spectra, with and without the defect channel, are shown as a blue solid curve and a green dashed curve respectively. The measured transmission through the waveguide defect is about three orders of magnitude higher than that without the waveguide defect.

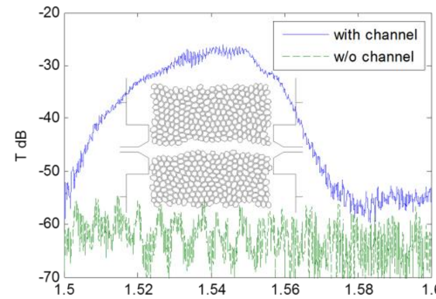


Figure2. A sketch of a straight waveguide channel (insert) and the measured transmission with and without the waveguide channel.

Figure 3 show sketches of channels with a 50^o bending angle with various modifications at the bending corner (a)-(c), and their corresponding measured transmissions. The wall thickness used here is 50 nm. Despite the variations at the sharp bend, the measured transmission is robust within the measured wavelength range.

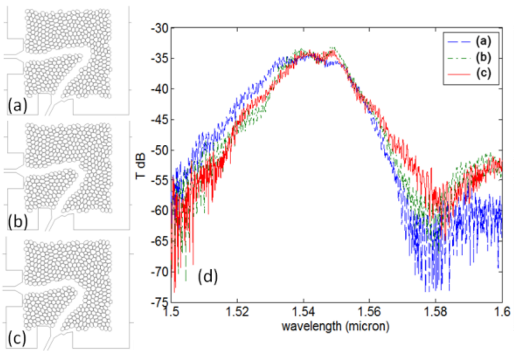


Figure 3. (a)-(c) Sketches of channels with a 50^o bending angle and with various modifications at the bending corner. (d) Their corresponding measured transmissions.

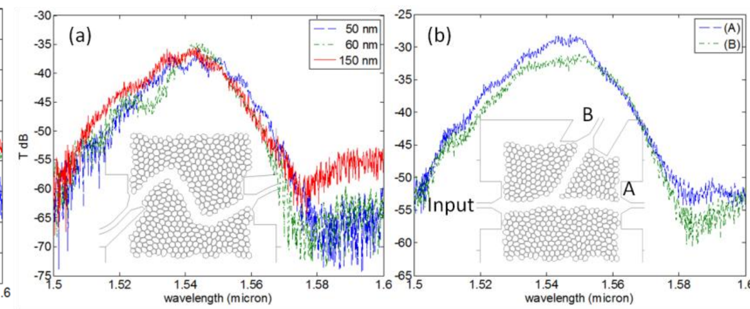


Figure 4. (a) A sketch of an S-shape waveguide channel (insert) and the measured transmission through such channels in the disordered PBG structures with various wall thickness thicknesses (50, 60 and 150 nm). (b) A sketch of a Y-shape Junction and the measured power splitting through it.

Figure 4(a) shows the measured transmissions through a few S-shape channels in disordered wall-network structures with different wall thickness. The sketch of the S-shape channel is shown as the insert. Again, photons with wavelengths around 1.55 microns are robustly guided through the bending S-shape channels in the disordered structures with various wall thicknesses. Moreover, transmissions through two paths of a Y-shape junction are shown in Fig. 4(b). The photon energy is evenly split into the two paths with arbitrary orientations.

In summary, for the first time we have experimentally fabricated this novel class of isotropic disordered PBG materials at sub-micron scale and demonstrated their ability and flexibility to guide, bend, and split light in the infrared regime along arbitrary paths. We have shown 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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