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Invited Paper

Isotropic band gaps, optical cavities, and freeform waveguides in hyperuniform disordered photonic solids

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ABSTRACT

Hyperuniform disordered solids are a new class of designer photonic materials with large isotropic band gaps comparable to those found in photonic crystals. The hyperuniform disordered materials are statistically isotropic and possess a controllable constrained randomness. We have employed their unique properties to introduce novel architectures for optical cavities that achieve an ultimate isotropic confinement of radiation, and waveguides with arbitrary bending angles. Our experiments demonstrate low-loss waveguiding in submicron scale Si-based hyperuniform structures operating at infrared wavelengths and open the way for the realization of highly flexible, disorder-insensitive optical micro-circuit platforms.

Keywords: photonic band gaps, photonic crystals, optical cavities, waveguides, disordered strctures

1. INTRODUCTION

Nanophotonics is expected to have a disruptive impact over coming years on a wide range of technology areas by dramatically shrinking the physical size and power consumption of devices such as modulators, switches and lasers, enhancing the emission or absorption of light and improving the energy efficiency of LEDs and solar cells and enabling on-chip integrated optical circuitry for performing quantum information processing tasks. Novel functionalities enabled in nanophotonics arise from the specific photonic properties of individual wavelength and sub-wavelength scatterers, as well as the controlled interference between them. Examples that have been thoroughly investigated include photonic crystals and meta-materials, both relying upon arrayed structures that are typically periodic. On the other hand, current nano-fabrication capabilities offer an enormous number of degrees of freedom in creating aperiodic and complex geometries, such as patterns that are quasi-periodic, fractal, or random, which when appropriately designed can lead to performance superior to the one offered by periodic systems [1], [2].

In the quest for the optimal platforms for nanophotonics devices, photonic crystals and metamaterials have emerged as unique and promising family of materials. Photonic crystals were originally proposed by John and Yablonovitch as means to realize two fundamentally new optical principles— localization and trapping of light [3], and the complete inhibition of spontaneous emission [4]. A photonic band gap (PBG), the analogue of the electronic band gap in semiconductors, enable confinement of light in small volumes and can guide electromagnetic radiation through narrow channels and around sharp bends [5]. Conventional PBG materials are crystalline or quasi-crystalline [6], [7] and depend upon Bragg scattering for formation of PBGs. However, 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.

Recently, we have introduced a new class of isotropic, aperiodic structures, namely hyperuniform disordered materials [8], [9], [10] (shown in Figure1) with large complete, isotropic PBGs for all directions and polarizations. The idea that a complete PBG (blocking all directions and polarizations) can exist in isotropic disordered systems, is striking, since it contradicts the longstanding intuition that Bragg scattering and translational order is necessary to form photonic band gaps.

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The contrast between, periodic, quasiperiodic and disordered hyperuniform structures is illustrated in Figure 1. For periodic and quasiperiodic point patterns, the Fourier spectrum consists of discrete Bragg peaks (left and centre plots in Figure 1), whereas for hyperuniform disordered patterns, the Bragg peaks are replaced by continuous, circularly symmetric rings (right plot in Figure 1), which result in statistically isotropic photonic band gaps.

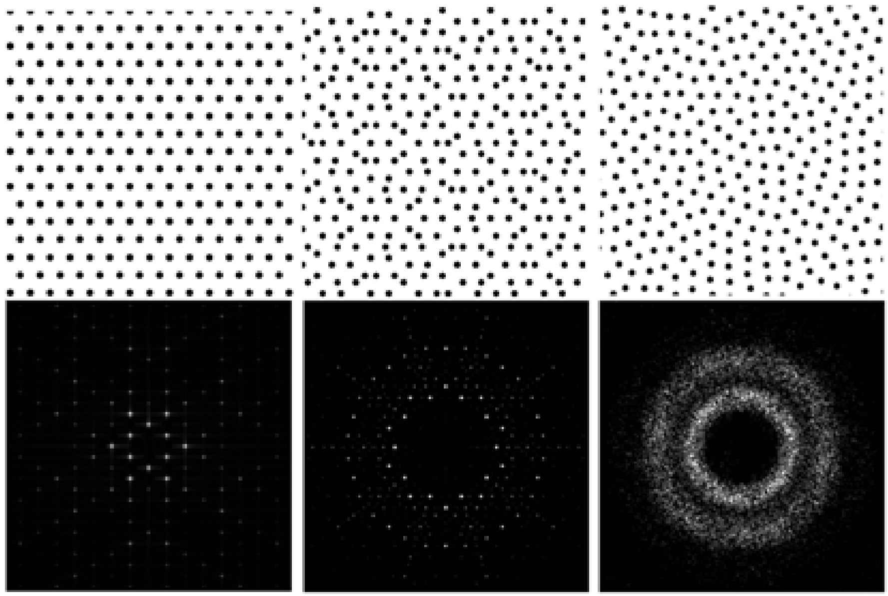

Figure 1. Top Row: Crystalline (left), quasicrystalline (middle) and hyperuniform disordered (right) structures. Bottom row: Fourier transforms of crystalline (left), quasicrystalline (middle) and hyperuniform disordered (right) structure. The Fourier transforms of the crystalline and quasicrystalline structures consist of discrete Bragg peaks, while the disorder hyperuniform structures present a Fourier spectrum consisting of diffusive scattering rings.

PBG structures built upon hyperuniform disordered point patterns combine advantages of both isotropy due to disorder and controlled scattering properties due to hyperuniformity and uniform local topology. Hence, it becomes possible to construct novel types of optical cavities [11] and waveguiding channels displaying arbitrarily bending angles [9].

2. THEORY AND DESIGN

A point pattern in real space is hyperuniform if for large R the number variance $\sigma^2(R)$ within a spherical sampling window of radius R (in d dimensions), grows more slowly than the window volume, i.e., more slowly than R^d. In Fourier space, hyperuniformity implies that the structure factor $S(k)$ approaches zero as $k \rightarrow 0$ [12]. Examples of photonic structures that can be generated from hyperuniform point patterns include not only crystals and quasicrystals, but also disordered structures, the focus of this work. The structures analyzed here are generated from hyperuniform samples comprising N points contained in a square box of size L, with a characteristic length scale $a = L/\sqrt{N}$, such that the hyperuniform pattern has density $1/a^2$. The hyperuniform point patterns are generated using the collective coordinate method in Ref. [13] with a stealthy order parameter $\chi = 0.5$. After generating the point pattern, hyperuniform disordered-network structures are designed by employing a centroidal tessellation to generate a “relaxed” dual lattice, whose vertices are trivalent (a similar procedure can be applied to three-dimensional patters and results in tetravalent hyperuniform disordered structures [14]). The lattice vertex pairs are then connected with dielectric walls to generate network photonic architectures. For high index of refraction contrast (corresponding to Si), the structures display large TM and TE band gaps of width/centre frequency ratio of about 40%, and, more remarkably, a complete band gap of up to 15% of the central frequency [8].

In an otherwise unperturbed HD structure, it is possible to create localized states of the electromagnetic field by reducing or enhancing the dielectric constant at a certain points in the sample [11]. For a photonic crystal consisting of a triangular lattice of holes it is common practice to fill a single hole to make a cavity which is often labelled a H1 cavity. Similarly, we fill a single cell to create a H1 cavity. Due to the presence of the defect, a number of localized cavity modes are

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created within the photonic band gap at specific frequencies. The mode profiles are shown in Figure 2. Despite the statistical isotropy of the network structure surrounding the cavity, the modes display well defined (approximate) symmetries. We use the finite difference time domain software "MEEP" [15] to calculate the 2D quality factor of the two-dimensional confined mode which is for all modes higher than 10^9, which demonstrates very good in-plane confinement.

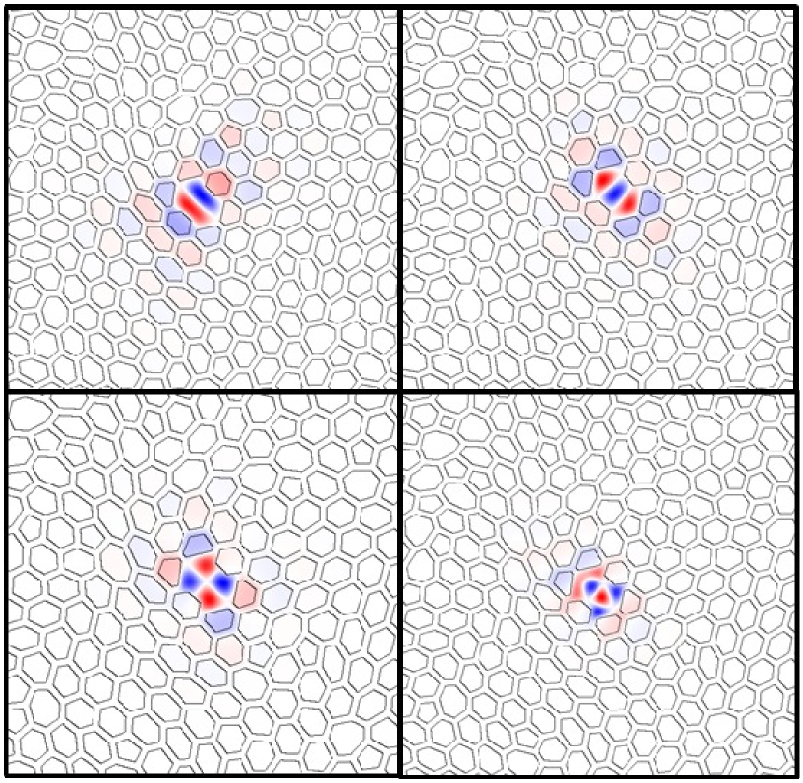

Figure 2. Magnetic field distribution for various cavity modes obtained by filling a network cell with high-index dielectric material. The network structure is generated using the protocol described in the text with wall thickens, *w*/*a*=0.22.

Next, we have analyzed finite-height structures. In photonic-slab architectures, there exists a "pseudo-band-gap" [16], a spectral region where modes under the light cone cannot couple to the continuum of states outside the slab. Similar to the photonic crystal case, an unmodified H1 cavity produces a moderate quality factor Q<500. A conventional modification of this is to reduce adjacent holes slightly in size and shift them outwards along the lattice directions. In the hyperuniform disordered structure considered here, we instead shift and shrunk cells along the direction given by the center of mass of the cavity to the center of mass of the neighboring cells. We find that this simple optimisation scheme can provide a dramatic increase of the quality factor to values of Q~30,000.

3. EXPERIMETAL IMPLEMENTION

To fabricate hyperuniform disordered photonic devices, we have employed conventional silicon-on-insulator (SOI) wafers with 220 nm crystalline silicon height and 2 μm buried oxide layer [17]. Devices were fabricated using standard electron beam lithography and inductively-coupled plasma reactive ion etching that is used in rapid prototyping of large-scale silicon photonics [18]. The characteristic length is a=499 nm, which corresponds to TE PBG centered around 1.55 μm. The wall thickness was varied in the 35-150 nm range.

The presence of large photonic band gaps in hyperuniform structures has inspired waveguide designs, which exploit the statistical isotropy of the band gap [11]: if the "linear" defect mode created by filling of network cells falls within the PBG, the waveguide bends can then be oriented at an arbitrary angle. Initial waveguide design, shown in Figure 3a, was obtained using the cell-filling protocol described above to create a connected path expected to support propagation of

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light through it. A fully-etched sub-wavelength grating coupler with 127 μm pitch was employed at the input/output of the waveguide to provide efficient coupling of light from the single mode optical fibers used for testing [19]. We performed measurements in the wavelength range of 1.5-1.6 μm using an automated measurement setup as described in Ref. [19].

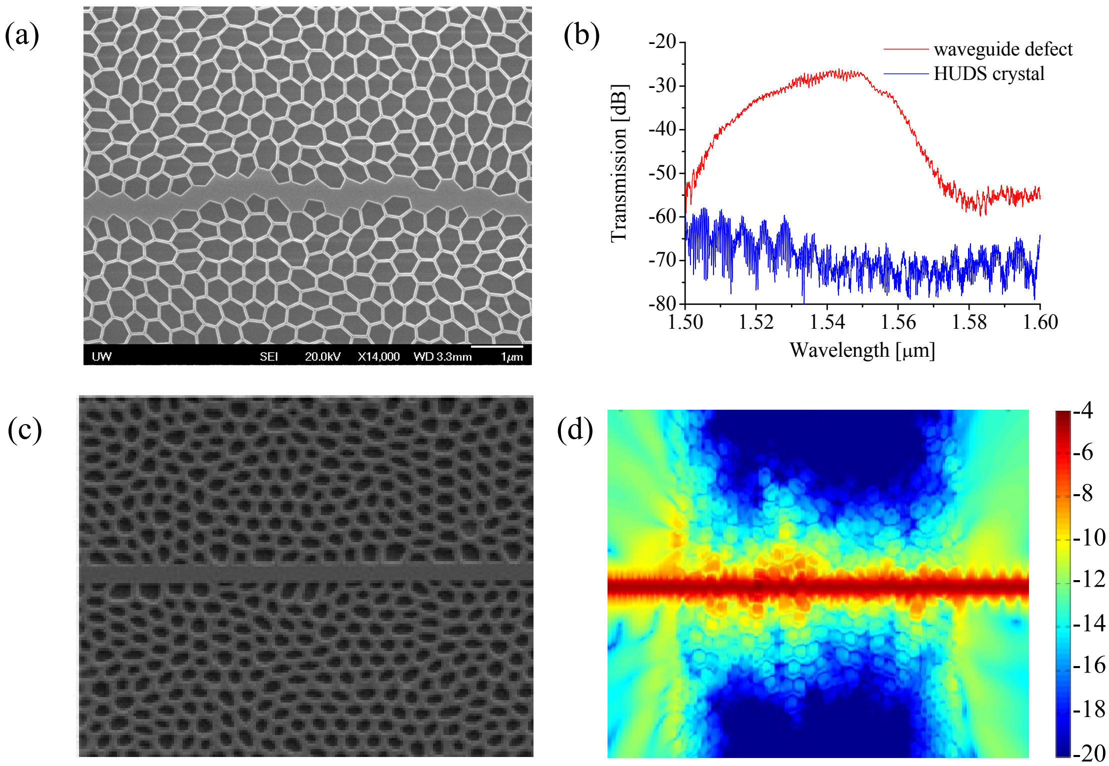

Figure 3. (a) SEM image of an optimized silicon HUDS waveguide with 35 nm wall thickness . (b) Transmission spectrum of a hyperuniform disordered structure with and without waveguide defect (including coupling losses) c) Optimized straight waveguide in a hyperuniform disordered structure with propagation losses of 13 dB/cm. d) Log scale transverse electric field distribution for the optimized waveguide at 1550 nm.

Figure 3b displays the transmission spectrum through a hyperuniform disordered structure with and without a waveguide defect. The measured transmission through the waveguide defect is about three orders of magnitude higher than that without the waveguide defect, thus confirming the PBG mediated guiding. A simple optimization procedure substantially reduced propagation losses of the un-optimized design, (originally relatively high >30 dB/cm) to the substantially lower 13 dB/cm at 1550 nm wavelength. The TE field profile shown in Figure 3(d) confirms the presence of tightly-confined mode in the waveguide core, with little to no leakage into the surrounding structure.

4. CONCLUSIONS

In conclusion, we have introduced new architectures for optical cavities and waveguides in hyperuniform disordered materials and presented initial results on waveguides in Silicon structures operating at around 1550 nm. The novel optical devices introduced here can provide the building blocks for advanced passive and active optical components, together enabling SOI hyperuniform-disordered photonic integrated circuits for wide-ranging applications at optical communication wavelengths.

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