New Designer Dielectric Metamaterial with Isotropic Photonic Band Gap

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***Abstract*— A new designer dielectric metamaterial featuring an isotropic photonic bandgap at 1550 nm wavelength designed as a finite thickness, 220 nm thick 2d slab, is fabricated in a CMOS-compatible silicon-on-insulator process. This "hyperuniform disordered solid" (HUDS) is neither crystalline nor quasicrystalline.**

Keywords—photonic band gap; hyperuniform disordered solid; hyperuniform disordered structure; HUDS; metamaterial; silicon-on-insulator; photonic band gap

I. Introduction

Until recently, the only known photonic band gap structures were photonic crystal (PC) structures consisting of regularly repeating, orderly lattices of dielectric materials [1] [2]; it was generally assumed that crystal order was essential to have photonic band gaps. This longstanding assumption is now known to be false. Whole new classes of photonic band gap (PBG) structures characterized by suppressed density fluctuations (hyperuniformity) have recently been invented [3] [4]. One of these new classes includes disordered structures exhibit large photonic band gaps which are both complete and isotropic [4]. This means that light propagates the same way through these new PBG structures independent of direction – a feature which is impossible for a photonic crystal.

II. Summary

This new kind of disordered designer dielectric leveraging hyperuniformity and exhibiting direction-independent photonic band gaps has, for the first time, been designed, fabricated, and tested for operation at optical wavelengths in the silicon-on-insulator material system. The hyperuniform disordered structures (HUDS) were monolithically integrated with silicon photonics vertical couplers for chip-scale testing. Standard processes from the CMOS fabrication industry and an automated test system developed for wafer-scale testing of silicon photonics chips were used to demonstrate ease of manufacture and test.

As compared to periodic or quasi-periodic photonic band gap (PBG) devices in which waveguides must always be aligned along the crystal axes, the ability to orient HUDS waveguides in any direction on the wafer and with any bending angle improves layout flexibility. As well, since periodicity is not a requirement of the hyperuniform disordered structures, the manufacturing tolerance constraints so important to the commercial viability of PBG-based photonic integrated circuits are expected to be substantially relaxed with the use of HUDS.

Compared to the use of conventionally-clad waveguide devices, the following two advantages of using photonic band

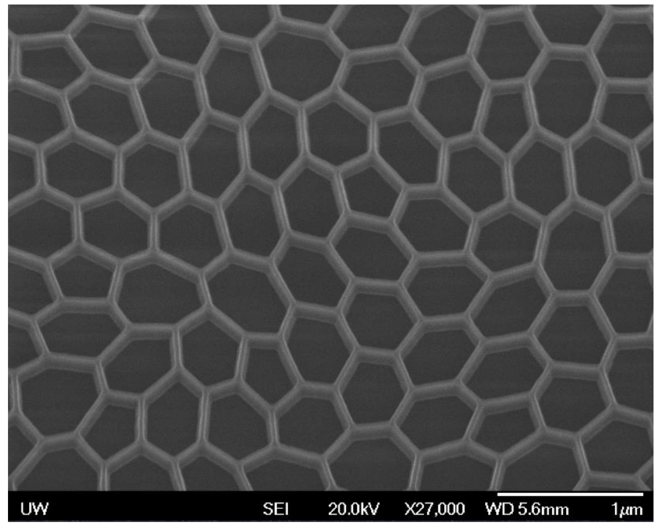

Figure 1 – SEM photograph of a hyperuniform disordered "network of walls" designed to exhibit a photonic band gap in the 1550 nm wavelength range. Wall height is the 220 nm thickness of the top silicon layer of a standard CMOS-grade silicon-on-insulator wafer.

gap based waveguide devices are well-known: smaller device size leading to improved density on the wafer, and the potential to make active devices capable of modulating light with less energy per bit [5] [6] [7] [8].

III. Design, Fabrication, and Test

A two-dimensional “network of walls” HUDS was designed and dimensioned for operation and testing with TE polarized light in the 1550 nm wavelength range. The structure’s dimensions were scaled in accordance with the dielectric constant of its constituent silicon for a range of wall thicknesses predicted to provide photonic band gaps ranging from 0.15eV to ~0.24 eV, corresponding to 30% of the 0.8 eV energy of a 1550 nm wavelength photon. In addition to parameterizing the effect of wall thickness on the band gap of the structure, tiles for testing several different kinds of waveguide channels as shown in the optical micrograph in Figure 2, were included along with other passive structures.

A key feature in the design-for-test was the planar integration of the HUDS test structures with silicon photonics waveguides and one or the other of several different kinds of vertical couplers requiring only a single mask layer, as shown in Figure 2 [9] [10]. An e-beam lithography and inductively-coupled plasma RIE process that was originally developed for rapid prototyping of substantially larger-scale silicon photonics

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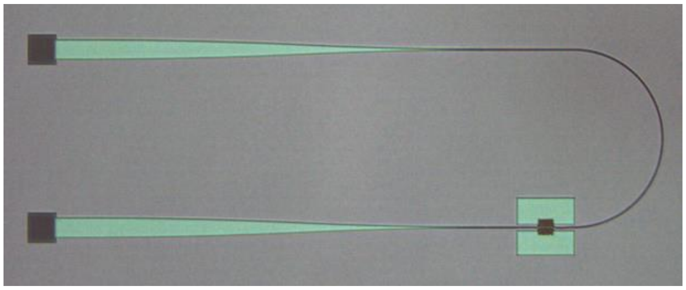

Figure 2: Vertical coupling into the HUDS test structures was demonstrated using several different vertical coupler designs, chosen for fabrication with a binary mask in a single layer fabrication step. Optical micrographs of (above) square lattice photonic crystal of holes, biquadratic taper [9], *HUDS channel; (at left) curved binary grating coupler, triangular taper* [10] *and a HUDS channel.*

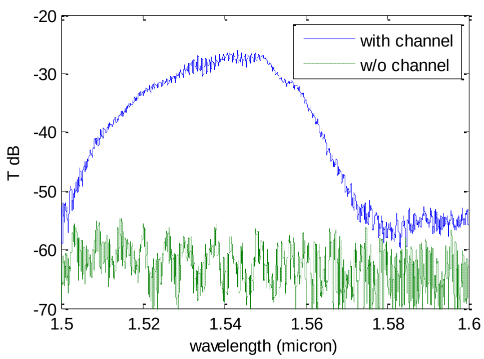

Figure 3: Transmission spectrum through a HUDS network structure having 80 nm thick walls, with (solid blue line) and without (dashed green line) a line defect to form a waveguide channel.

rib waveguides and vertical couplers [11] was used to fabricate the test structures

Automated testing [12] of the results prior to oxide removal demonstrated that the vertical grating couplers were effective at coupling light into and out of the various HUDS test structures. The probe wavelength was scanned from 1.5 to 1.6 microns, and the transmission through the test structures was measured.

Comparing the optical transmission through HUDS of varying wall widths confirmed that the structures exhibited photonic band gaps in the 1550±50 nm measurement wavelength range for the chosen wall widths between 30 nm and 120 nm.

As well, we see that filling in lattice holes with silicon creates channels (as shown for example in the test structure photograph in Figure 2) through which light of energy within the band gap can be guided as shown in Figure 3, that the chosen vertical couplers are effective at coupling light into HUDS light channels, and that light can be split and bent in these channels at angles which would not be allowed in a photonic crystal.

IV. Conclusion and Future Work

Passive HUDS have, for the first time, been designed and fabricated for optical wavelengths in a 2d finite slab geometry. Preliminary measurements prior to oxide removal confirm the presence of a photonic band gap at the design wavelength. Anticipating that the structures survive removal of the underlying oxide, the transmission characteristics of the air-clad slab waveguides will be reported.

Acknowledgments

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