Hyperuniform disordered photonic band gap devices for silicon photonics

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Abstract: We report experimental and simulation results for silicon waveguides and resonant cavities in hyperuniform disordered photonic solids. Our results demonstrate the ability of disordered photonic bandgap materials to serve as a platform for silicon photonics.

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Isotropic photonic band gap structures requiring neither periodicity nor quasi-periodicity are known as Hyperuniform Disordered Solids (HUDS) [1-3]. As cladding for silicon photonics waveguides, HUDS is expected to lead to substantially higher component density per chip area than is possible with silicon nanowires, while at the same time providing both improved layout flexibility and improved fabrication tolerance relative to the use of photonic crystals or photonic quasi-crystals. This paper describes design optimization, CMOS-compatible fabrication, and test of low-loss HUDS waveguides in silicon-on-insulator; the use of HUDS to clad a high-Q photonic crystal cavity; and a HUDS resonant cavity design exhibiting 500 times improved temperature stability compared to typical microring resonators made in silicon-photonics systems via CMOS-compatible processes.

Standard silicon-on-insulator (SOI) wafers with 220 nm crystalline silicon height and 2 μm buried oxide layer were used to fabricate HUDS waveguides and resonant defects using standard electron beam lithography and inductively-coupled plasma reactive ion etching that was originally developed for rapid prototyping of large-scale silicon photonics [4]. 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 were necessarily trihedrally coordinated by construction. More details about the design can be found in Ref. [1].

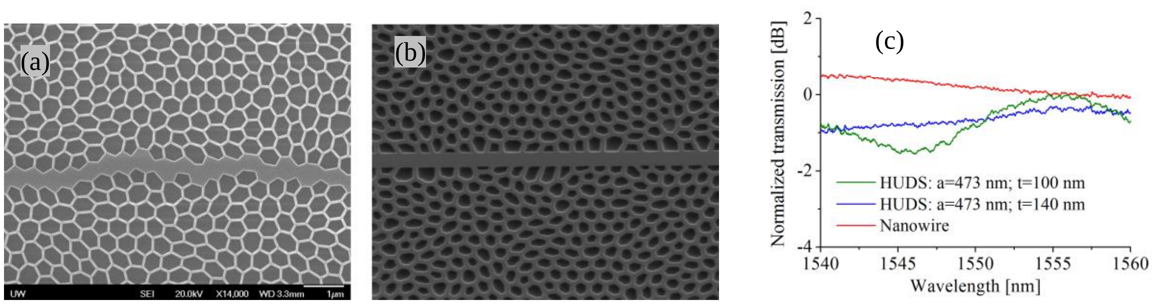

Fig. 1. Scanning electron micrograph image of a fabricated: silicon HUDS waveguide (a) before, and (b) after, the waveguide optimization. (c) Transmission of HUDS waveguides compared to silicon nanowire. HUDS waveguides feature average unit cell dimension a=473 nm and two different wall thicknesses of t=100 and 140 nm.

The average lattice constant was 499 nm, corresponding to a TE polarization photonic band gap (PBG) with zero density-of-state centered around 1.55 μm. The wall thicknesses were varied in the range of 80-150 nm. A fully-etched sub-wavelength grating coupler with 127 μm pitch was used at the input/output of the waveguide to provide efficient coupling of light from/to the single mode optical fibers used for testing [5]. The measurements were performed in the wavelength range of 1.5 to 1.6 μm using an automated measurement setup as described in Ref. [5].

Figures 1(a) and (b) show scanning electron micrograph (SEM) images of two different designs for fabricated HUDS waveguides. Initial waveguide designs featured simple substitutions of one or two rows of polygon-shape air cells along desired paths with filled-in silicon (Fig. 1(a)). Waveguide design optimization substantially reduced the initially high backscattering loss of >30 dB/cm to 13 dB/cm for 500 nm wide waveguides at 1550 nm wavelength (Fig. 1(b)), per simulation analysis using Lumerical software. Both simulations and experiments confirmed that HUDS structures with 499 average lattice spacing and 100 nm to 150 nm wall thickness exhibit TE photonic band gaps covering 1550±50 nm. Figure 1(c) compares the measured optical transmission spectra of a short silicon nanowire and HUDS waveguides of the same length. Estimated coupling losses between the HUDS waveguide test structure and the nanowire waveguides to which they were coupled, estimated at around 2 dB, have been accounted for in this Figure. The optical transmission through HUDS waveguide was particularly flat for higher wall thicknesses, and comparable to transmission through a silicon nanowire of the same length. Figures 2(a) and (b) shows transmission spectrum of HUDS waveguides having 120 nm thick walls before and after the waveguide design optimization procedure. We measured around 5.5 dB and 17 dB improvement in total insertion loss at around 1550 nm wavelength compared to the initial 1000 nm and 500 nm wide waveguide design, respectively. A very flat high transmission profile in the wavelength range of 1.5 to 1.6 µm was demonstrated. Further systematic optimization, use of wider waveguides and post-fabrication treatments (thermal oxidation and removal of the SiO_2 layer underneath) are planned to reduce propagation losses.

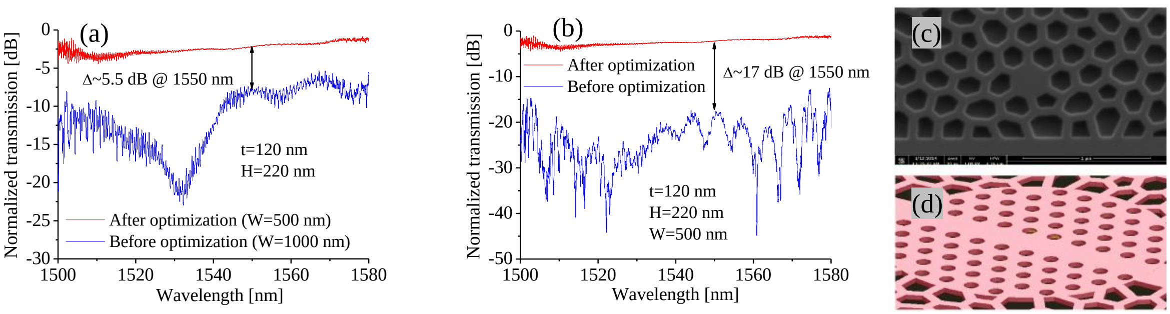

Fig. 2. Insertion loss reduced by (a) 5.5 dB and (b) 17 dB and a flat transmission spectrum was achieved after waveguide optimization. (c) SEM of a silicon HUDS resonant defect. (d) Starting design for high-Q in-line HUDS resonant defect.

Several HUDS resonant filters exhibiting both high extinction ratio and improved temperature stability as compared to micro-ring resonant filters have been designed and fabricated, an example of which is shown in Fig. 2(c). Simulations of HUDS resonators indicate that they can exhibit very low temperature-dependent resonant wavelength shifts of around ~0.15 pm/K. This is 500 times lower than the temperature-induced wavelength shift of a typical CMOS-compatible silicon micro ring resonator (~80 pm/K) [6]. Temperature-dependent resonant wavelength shifts in ring resonators depend on the resonator size and coupling from a straight waveguide [6]. Our results indicated that the reduction in temperature sensitivity is related to the relatively small defect size and lower light interaction with silicon than in the case of ring resonators. Since HUDS isotropically confines light, HUDS can be used to optimally clad a high Q photonic crystal defect. Fig. 2(d) illustrates a starting design for such a system, optimizations of which indicate that a high-Q cavity of ~10^6 can be achieved.

In conclusion, we have presented our preliminary results on silicon photonics HUDS waveguides and devices at around 1550 nm wavelength. The devices demonstrate an ability to guide light in the infrared regime with low insertion loss associated with predicted propagation loss of ~13 dB/cm. The temperature-induced wavelength shift of a CMOS-compatible HUDS resonator was estimated to be ~0.15 pm/K which is more than 500 times lower than that of the standard silicon microring resonators. Temperature-insensitive and low-loss HUDS devices therefore provide a building block for more complex passive and active devices, together enabling SOI HUDS photonic integrated circuits for wide-ranging applications at optical communication wavelengths.

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