Silicon waveguides and filters in hyperuniform disordered photonic solids for the near-infrared

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Abstract: We report preliminary results for silicon waveguides and devices in hyperuniform disordered photonic solids. Temperature sensitivity of resonant defects is more than 500 times lower than that of the standard silicon microring resonators.

OCIS codes: (130.3120) Integrated optics devices; (160.6840) Thermo-Optical Materials; (230.5750) Resonators; (230.7370) Waveguides.

1. Introduction

Hyperuniform disordered solids (HUDS) [1-3] are of increasingly strong interest for photonic integrated circuits (PIC) sensor and communications chips because they provide isotropic photonic band gaps, without requiring the periodicity or quasi-periodicity of photonic crystals or quasi-crystals. HUDS exhibit large, complete, and statistically isotropic photonic band gaps, capable of blocking light of all polarizations. HUDS also provide solutions to the following two challenges associated with the cost-effective application of CMOS-compatible optical filters to optical interconnects: device density per unit chip area and temperature sensitivity. HUDS-based PIC components not possible with traditional photonic band gap structures include narrow waveguides with arbitrary curvature, splitters at arbitrary angles, new types of temperature-insensitive resonant filters, and novel active devices.

In this paper we report preliminary results on the design, fabrication and characterisation of silicon-on-insulator (SOI) strip waveguides and devices based on the HUDS platform. Waveguide propagation losses of around 13 dB/cm are estimated, while temperature sensitivity of HUDS resonant defects is predicted to be around 0.15 pm/K, more than 500 times lower than that of the standard silicon microring resonators [4,5].

2. Design, fabrication and measurement results

To fabricate HUDS devices, we used standard silicon-on-insulator (SOI) wafers with 220 nm crystalline silicon height and 2 µm buried oxide layer. Refractive indices and corresponding thermo-optic coefficients for silicon and SiO_2 were assumed to be equal to those used in Ref. [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. The lattice vertex pairs were connected with dielectric walls. This trihedral-network photonic architecture features a transverse electric (TE) polarization photonic band gap. More details about the design can be found in Ref. [1].

Devices were fabricated using standard electron beam lithography and inductively-coupled plasma reactive ion etching that was originally developed for rapid prototyping of large-scale silicon photonics [6]. Average lattice constant was 499 nm which corresponds to 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 35-150 nm. Initial waveguide designs such as those shown in Figure 1a were formed by filling in adjacent holes to create a path of HUDS defects expected to support the propagation of light through the HUDS. 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 [7]. Measurements were performed in the wavelength range of 1.5-1.6 µm using an automated measurement setup as described in Ref. [7].

Figure 1b shows transmission spectrum comparing the optical transmission through HUDS having 80 nm thick walls 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. Our experimental results also show that the structures exhibit photonic band gaps in the 1550±50 nm wavelength range for the chosen wall width range between

35 nm and 150 nm. In agreement with theoretical predictions, it was found that HUDS wall thickness defines both the central wavelength and bandwidth. A waveguide optimization procedure substantially reduced propagation losses of the earliest HUDS defect path waveguide, (originally relatively high >30 dB/cm) to the substantially lower 13 dB/cm at 1550 nm wavelength, per simulation analysis using Lumerical software. Figure 2 shows simulated TE mode field profile for originally lossy defect path waveguides and an optimized HUDS waveguide. It can be seen that the light is confined in the waveguide core, and that there is little to no leakage into the surrounding HUDS crystal. Further design optimisation and post-fabrication treatments are planned to reduce propagation losses.

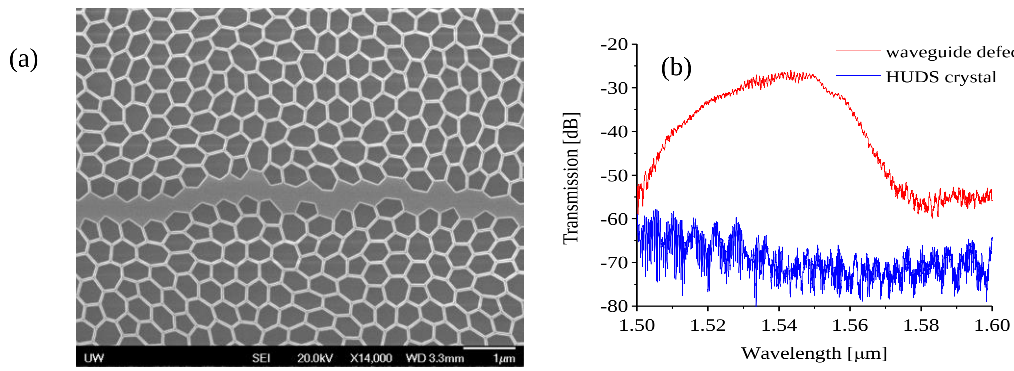

Fig. 1. (a) Scanning electron micrograph image of fabricated silicon HUDS waveguide prior to waveguide optimization, for a HUDS wall thickness of 35 nm. (b) Transmission spectrum of the HUDS with 80 nm thick walls with and without waveguide defect, prior to improvement of light coupling into and out of the waveguide.

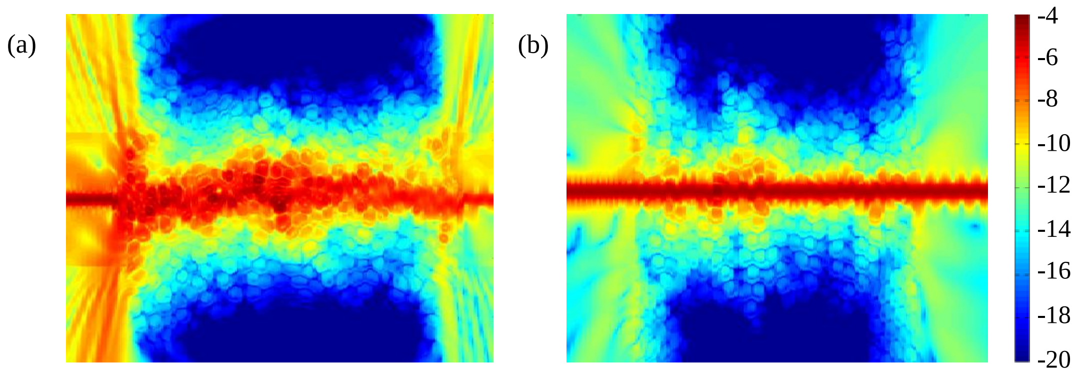

Fig. 2. Log scale transverse electric field distribution at 1550 nm of: (a) an original lossy HUDS waveguide, and (b) optimized HUDS waveguide with propagation losses of 13 dB/cm.

A HUDS resonant filter exhibiting both high extinction ratio and 500 times less temperature sensitivity than a ring resonant filter has been designed and is being fabricated. Figure 3a shows its transmission spectrum. Simulated resonant wavelength shifts as a function of temperature for both HUDS and a ring resonator are shown in Figs. 3b and c. The HUDS resonator exhibited a very low resonant wavelength shift of around ~0.15 pm/K, approximately 500 times better compared to that of the 80 pm/K temperature-induced wavelength shift of a ring resonator. Resonant wavelength shift in ring resonators depends on the resonator size and coupling from a straight waveguide [4]. The HUDS resonator is also less sensitive to temperature than other state-of-the-art SOI resonators (Table 1).

Temperature sensitivity of resonant photonic devices represents an important issue in the development of silicon photonics for ultralow power optical interconnects. Extensive efforts to reduce the temperature sensitivity of silicon photonics without using photonic band gap structures have deleteriously increased cost and power consumption, degraded performance, and consumed additional space. Thermal stress effects, ion implantations, combinations of different passive devices such as Mach-Zehnder interferometers, ring resonators and sub-wavelength grating waveguides have all been tried, but still the required heaters or thermoelectric coolers consume both too much power and too much space. While polymer claddings can reduce the temperature sensitivity of ring resonators [4,5], they are incompatible with standard CMOS processing and therefore undesirable in high volume manufacturing.

Our results indicate that the reduction in temperature sensitivity that we see is related to the relatively small defect size and lower light interaction with silicon than in the case of ring resonators. Experimental results are being performed to confirm these results.

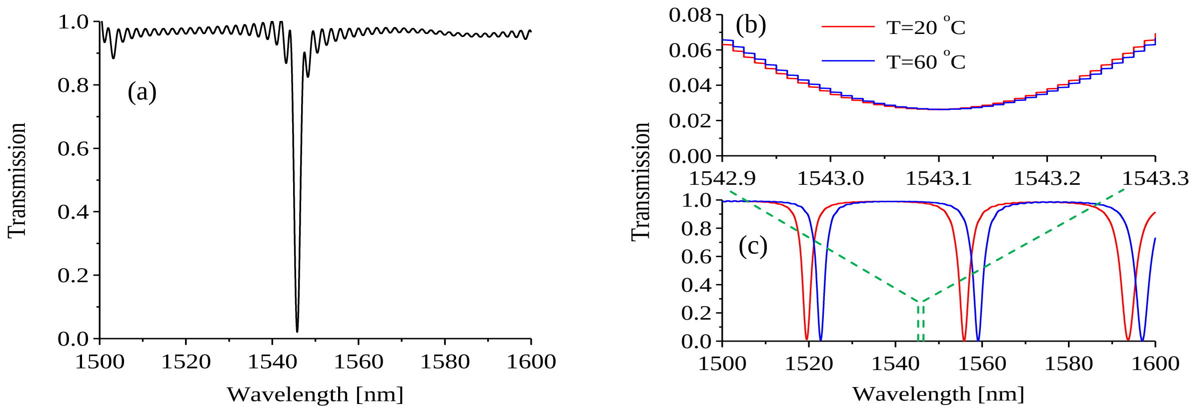

Fig. 3. (a) Transmission spectrum of HUDS resonant defect. Resonant wavelength shift as a function of temperature for: (b) HUDS resonant defect, and (c) standard ring resonator with the radius of R=20 µm. Both resonators were based on 500×220 nm^2 waveguides.

Table 1. Comparison between state of the art results for low temperature sensitive silicon photonics resonators.

Reference	TDWS [pm/K]	T [ºC]	λ [nm]	W×H [nm²]
ETAPHASE	**0.15**	**20-60**	**1543**	**500×220**
Surrey	0.2	9-25	1550	335×220
	2.4	25-70		
MIT	0.5	25-45	1520	700×206
	4	45-60		

3. Conclusions

In conclusion, we have presented our preliminary results on HUDS waveguides and devices at around 1550 nm wavelength. Simulated propagation losses for HUDS waveguides were ~13 dB/cm, while the temperature-induced wavelength shift of a CMOS-compatible HUDS resonator was estimated to be ~0.15 pm/K. This represents more than 500 times improvement compared to a standard microring resonator. Temperature insensitive and low loss HUDS devices can now serve as a building block for more complex passive and active devices, and eventually for SOI HUDS PICs which will be used in a host of applications at optical communication wavelengths.

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5. References

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