Hyperuniform Disordered Platform for Silicon Photonics

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Abstract: We introduce hyperuniform-disordered structures (HUDS) for the realization of near-IR photonic bandgaps on a silicon-on-insulator (SOI) platform, demonstrating the functionality of these structures in a 1.5-micron photonic integrated circuit (PIC) platform unconstrained by crystalline symmetries. An integrated design for a compact, sub-volt, sub-fJ/bit HUDS-clad, electrically-controlled resonant optical modulator suitable for fabrication in the silicon photonics ecosystem is presented with simulation results. The HUDS design platform advantageously leverages the large, complete, and isotropic photonic band gaps provided by hyperuniform disordered structures. We also report simulation and experimental results for passive device elements, including waveguides and resonators realized in this platform for the first time. These devices are seamlessly integrated with conventional SOI strip waveguides and vertical couplers. We show that the hyperuniform-disordered platform enables improved compactness, improved energy efficiency, and improved temperature stability compared to the silicon photonics devices based on rib and strip waveguides.

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1. Introduction

Broad worldwide academic and commercial efforts in silicon photonics have, in the past three decades, realized Terabit-scale optical data communications at increasingly lower-costs as required for the rapidly-growing demand for interconnects between servers in data centers. Explosive growth in cloud computing and entertainment-on-demand pose increasingly challenging cost, energy, and interconnect density requirements on data transmission, processing, and storage. Optical data links now replace traditional copper-based solutions in long haul, metro, and top-of-rack data center interconnect (DCI) networks. These optical interconnects advantageously offer steadily-increasing potential to minimize latency and power consumption while maximizing bandwidth, interconnect density, device density, and reliability. Silicon photonics leverages the large-scale complementary metal-oxide semiconductor (CMOS) manufacturing processes and facilities to produce high performance optical transceivers with high yield at low cost [1-3], making its application to optical transceivers increasingly compelling over shorter and shorter distances [4-7].
Soref’s prescient identification of silicon as a promising material for photonic integration over three decades ago [8] led to steady development and now-rapid productization of increasingly-complex photonic integrated circuits (PICs) containing hundreds to thousands of components [9] using the same CMOS lithography tools that enabled multi-decadal Moore’s Law growth in the semiconductor electronics industry. Wide-ranging applications of photonic integration including data communications, computing, and sensing all share a common need for compactness, sensitivity, and energy-efficiency. Particularly for the interconnection of servers in data centers, the massively-parallel compact integration of large numbers of energy-efficient optical components on a single chip is increasingly important for the continued scaling of cloud computing applications ranging from search and advertising to deep learning, artificial intelligence, the internet of things, and digital signal processing [10]. The very high levels of integration afforded by silicon photonics substantially increases the functionality of individual chips, beneficially driving-down costs by minimizing both the number of components in each package, and the number of packages on each board. The compactness of commercial silicon photonics systems based on conventional rib or strip waveguides is limited by bending losses in waveguides, which constrains the minimum practical radius of resonant ring modulators to bending radii below which the losses of conventional rib and strip waveguides are unacceptably high, as well as by the extended lengths of Mach-Zehnder modulators. Photonic crystal architectures, by contrast, promise smaller device sizes but suffer strict layout constraints imposed by the requirement that all waveguides must be oriented along the photonic crystal’s axes.

Silicon waveguide technology has encompassed several waveguide architectures such as rib and strip waveguides [8-10], corrugated and slot waveguides [14-17], and photonic band gap (PBG) structures [18-21]. Propagation losses as low as 0.7dB/cm and 0.1dB/cm set the standard for submicron strip and rib waveguides, respectively [10]. Until recently, PBG structures that can efficiently guide light and potentially serve as a platform for photonic integrated circuits (PICs) were limited to photonic crystals (PhCs) [20-21]. Newer classes of PBG structures include photonic quasicrystals (PhQC) [22, 23], hyperuniform disordered solids (HUDS) [24-27] and local self-uniform structures (LSU) [28]. In particular, HUDS exhibit large PBGs which are both complete and isotropic. This allows light to propagate through the structure in the same fashion independent of direction - a feature impossible to achieve with PhCs and other waveguide architectures [4-7, 29-32]. Additionally, the HUDS platforms promise to address two key challenges associated with the cost-effective application of CMOS-compatible optical filters to optical interconnects: device density per unit chip area (as compared to rib and strip waveguide platforms) and improved layout flexibility [30-35] (as compared to PhC platforms). Another advantage of the disordered systems, as compared to their periodic counterparts is increased flexibility to locally-engineer the structure to create high-quality factors resonant defects, narrow waveguides with arbitrary curvatures and arbitrarily high-order splitters [33, 34]. And, since disorder is a design resource in these structures, prospects for leveraging the structures’ tolerance to disorder may suggest new approaches to improving manufacturing yields of optical systems leveraging photonic band gap structures.

In this paper, we introduce a HUDS platform as a locally-engineered photonic system and a generic architecture for photonic integrated circuits. Simulation and experimental results for straight and curved waveguides, and filters reveal a great potential of silicon-on-insulator (SOI) HUDS PICs to be used in a host of applications at optical communication wavelengths. Several resonator types such as in-line cavity resonator with and without an air-slot, and resonant cavities adjacent to the waveguide were examined in terms of compactness, quality factor and temperature stability. We show that HUDS resonators as compared to standard micro-ring resonators (MRR) or Mach-Zehnder interferometers (MZI) exhibit less temperature-dependent resonant wavelength shift (TDWS) and an increased compactness. We also analyze simulated performance of sub-volt and sub fJ/bit electrical modulation of a compact, yet high quality factor PBG resonator when actively driven with ohmic contacts in a p+pinn+ configuration. The results reveal promising prospects for device density improvements of several times and a
few orders of magnitude lower power consumption per bit compared to silicon optical modulators based on micro-ring resonators and Mach-Zehnder interferometers.

2. Methods

The structures considered in this paper are designed on hyperuniform disordered network platforms. A point pattern is classed as 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 \( R^d \) [36]. As a consequence, in Fourier space, the structure factor associated with the hyperuniform pattern, \( S(k) \), approaches zero as \( |k| \to 0 \) [37,38]. The hyperuniform disordered wall-network structure was designed by employing centroidal tessellations of hyperuniform point patterns to generate a “relaxed” dual lattice, a connected network structure whose vertices are trihedrally coordinated. The protocol for generating these networks consists of Delaunay triangulating the hyperuniform point pattern and connecting the center of mass of the Delaunay triangles to form polygonal cells with walls of a finite thickness [23-24]. Optimally-designed cavities and waveguides were then designed into this HUDS environment, using a \( 1/r^4 \) potential to relax mismatched boundaries, where \( r \) is the separation distance between scatterers. Design-optimization using full vectorial 3D FDTD Lumerical software (together with in-house developed simulation codes) was employed, leveraging a TE photonic band gap with zero density-of-states centered at around 1.55 \( \mu \)m. HUDS waveguides and resonant defects were fabricated using electron beam lithography (EBL) and inductively-coupled plasma reactive ion etching (RIE) at the University of Washington’s Nanofabrication Center [39]. Standard SOI wafers with 220-nm-thick crystalline silicon layer (on a 2 \( \mu \)m thick buried oxide layer) were used. HUDS devices with different average lattice spacings in the (473,500) nm interval, fill ratio of covering from 37% to 43%, and the following wall thicknesses of 40, 80, 120, 160 and 200 nm were chosen aiming for high compactness, good temperature stability and an isotropic photonic bandgap in the 1.5 - 1.6 \( \mu \)m wavelength range. The optimal PhC cavity, embedded in hyperuniform disordered environment, featured an average lattice spacing and fill ratio of 420 nm and 55%, respectively. Fully-etched focusing sub-wavelength grating couplers (lined up in an array with 127 \( \mu \)m spacing) were used at the input/output of the waveguide to provide efficient coupling of light from/to the single mode optical fibers used for testing [34]. The measurements were performed in the wavelength range of 1.5-1.6 \( \mu \)m using an automated measurement setup as described in Ref. [40].

This silicon photonic optical modulator was designed aiming for compactness and minimal energy per bit modulation. The modulator features both low- and high-dose doping regions (for ohmic contacts formation) targeting doping densities of phosphorus and boron ions of \( n=5\times10^{18} \) \( \text{cm}^{-3} \) and \( n=1\times10^{19} \) \( \text{cm}^{-3} \), respectively (as shown in Figure 4a). Distances between the n and p regions, and between the aluminum electrodes were equal to 4.4 and 10 \( \mu \)m, respectively, while the widths of the n and p regions were 2.5 \( \mu \)m. The bias arrangement was to ground the p region while applying a negative voltage to the n region. The arrangement is known as a forward bias configuration, in which the pin diode acts as a variable resistor for voltages above a threshold voltage, because the resistance of the intrinsic region decreases with increasing current [41, 42]. Full 3D simulations of both the optical performance and electron-hole dynamics were performed using a commercial-grade simulator of optical propagation based on the finite-difference time-domain method [43] and a device simulator that self-consistently solves the Poisson and drift-diffusion equations in the active device [44].

3. Results

Figure 1a shows a scanning electron micrograph (SEM) image of a HUD network fabricated using electron beam lithography on a 220-nm-high silicon-on-insulator wafer. The average spacing separating the centers of the network cells is 499 nm and the wall thickness is 120 nm. FDTD simulation results of transmission spectrum for TE polarized light through similar
networks, which have an average separation of 500 nm and various wall thickness, are shown in Figure 1b. As shown previously [24], these networks possess wide TE polarization bandgaps, with a relative gap width of 25%. Also, the central wavelength of these bandgaps can be tuned by modifying the wall thickness of the HUDS. Since the bandgaps are wide, for wall thickness ranging from 140 nm to 220 nm, the wavelength range of 1.5µm-1.6µm can be easily covered. This property makes such networks a particularly well-suited platform for photonic circuit design, allowing straightforward integration of HUDsian devices with the full ecosystem of conventional rib and strip-waveguide components.

Figure 2a, 2b and 2c show SEM images of fabricated 220nm thick SOI HUDS waveguides. The waveguides were initially designed as a series of in-line defects by simply substituting one row of polygon-shaped air cells along desired paths with filled silicon (Figs. 2a and 2b). The intrinsic isotropy of HUDS allows a waveguide with arbitrary sharp bends [31,32]. Next, to minimize backscattering losses, we performed a simple optimization of the waveguide structure in Fig. 2a by setting a uniform width of 500 nm and adjusting the adjacent silicon walls to be nearly perpendicular to the waveguide channel as shown in Figure 1c. This one-step optimization substantially reduced the initially high backscattering loss of >3 dB/mm to 1.3 dB/mm at 1550 nm wavelength. Both simulations and experiments confirmed that structures exhibit TE photonic band gaps, covering the 1500 nm to 1600 nm wavelength range for the chosen wall widths and that the guiding mechanism is dominated by the photonic bandgap. Figure 2d shows the measured transmission spectrum comparing the transmission spectrum through HUDS waveguides before and after partial optimization, as well as the transmission in the absence of the waveguide channel. A 17-dB improvement at around 1550 nm associated with the above optimization was experimentally verified. A very flat high transmission profile in the wavelength range of 1.5-1.6 µm was also observed. The results in Figure 2e, demonstrated that the total coupling losses between the HUDS and nanowire waveguides are around 2 dB, while the optical transmission through HUDS waveguide is similar to that through a 500nm wide silicon strip waveguide.
Fig. 2. (a) SEM image of a fabricated SOI HUDS waveguide by simply skipping a row of etched air holes. (b) SEM image of a waveguide with an arbitrary sharp bend. (c) SEM image of a fabricated SOI HUDS waveguide (with optimization). (d) Experimentally measured transmission spectrum comparing performance of HUDS waveguide before (a) and after (c) optimization shows 17dB improvement due to optimization. A flat transmission spectrum across a large range was achieved after waveguide optimization. (e) Experimentally measured transmission spectrum comparing performance of the optimized HUDS waveguide with silicon strip waveguide, shows low loss (~2-3 dB) mainly due to the input/output coupling loss between HUDS waveguide and the rest of the devices.

Next, we demonstrate that HUDS platforms advantageously support a rich set of new resonator designs including resonant cavities with symmetries that are not available in photonic crystal structures [32-33]. The mode profile of such a cavity is shown in Figure 3a and features Q-factors larger than 20,000. We also investigated HUDS resonant filters consisting of a point defect and a nearby, adjacently-coupled waveguide as shown in Figure 3b. Simulation of a typical transmission spectrum shown in Figure 3c exhibits a high extinction ratio of approximately -20dB. Benefitting from the large PBG of the HUD network, all these HUDS-based cavity designs generally provide higher quality factors in a smaller footprint than micro-ring resonators.

Figure 3d shows the resonant mode field profile for the HUDS-embedded photonic crystal cavity mentioned previously for potential electrical-optical modulation applications. In Fig. 3e, we compare the simulation results of the Q-factors vs. footprint areas for such HUDS-embedded photonic crystal cavities to previously-reported results for micro-ring resonators (MRR) designs. The square markers, green circles, blue circles and shaded grey areas, represent the HUDS-embedded PhC cavities, MRR (A to H) [45-52] and racetrack resonators [53-56], respectively. For the HUDS designs, since the optical mode is confined more tightly in the direction perpendicular to input and output waveguides, these devices can be densely packed (2.5-3.0 µm from the waveguide center in the direction perpendicular to the waveguide) while maintaining a quality factor of 1 million. Even when the resonator’s size in this direction is reduced to 2 µm, the Q factor was still as high as 5.6×10^4.
Next, we analyze an electrically-controlled optical modulator, featuring an air-bridged resonant cavity in a HUDS structure in p+pinn+ configuration. A schematic of the structure is shown in the Figures 4a-c. The high-Q ($3 \times 10^6$) photonic crystal in-line cavity design chosen for this demonstration features a resonant cavity formed by very small translational shifts of holes by 3, 6, and 9 nm (Fig. 4c), respectively, as described in Ref. [41].
Three rows of the triangular lattice holes were preserved on either side of the waveguide, beyond which the PBG structure continuously transitions from photonic crystalline to HUD network.

Fig. 4. (a) A schematic of resonant modulators clad with HUDS in p+pinn+ configuration. Top view illustrates waveguide-coupled cavity clad with HUDS, and positions of doping regions. (b) Side view of the device illustrating approximate distributions of p (Boron) and n (Phosphorus) dopants. (c) HUDS resonant cavity design. (d) Pseudo-color display of simulated electron density (log scale) and (e) Pseudo-color display of simulated index of refraction distribution (linear scale) for the p+pinn+ device as a function of direct-bias voltage. (f) Resonant wavelength shift as a function of the applied voltage. (g) Resonant wavelength peak position as a function of voltage illustrating linear and steep resonant peak shifts for voltages higher than 0.8V.

Figure 4d shows the electron distribution density as a function of the bias voltages for a stripe running between the two Al-electrodes and going through the center of the cavity. Correspondingly, Figure 4e shows the local refractive index distribution as a function of the biased voltages. It is obvious that both can be easily tuned by small applied voltages. Figure 4f demonstrates that the transmittance spectrum shifts towards a shorter wavelength when a forward bias is applied. This implies that the refractive index of silicon has been reduced, as expected for the plasma dispersion effect [57]. According to Figure 4f for voltages up to 0.8 V,
the optical Q factor of the resonant peak remains larger than $10^5$, indicating little change in the corresponding line width $<0.016$ nm.

A voltage as small as 0.48 V will be enough to shift the resonance peak away from the 0 V peak more than their widths, separating them sufficiently to assure a 10 dB on/off ratio (Fig. 4g). We thus predict 0.48 V to be the threshold voltage to operate this modulator at a 10 dB on/off ratio. For voltages above 0.7 V, we found the voltage dependence of wavelength to be 1.6 nm/V as shown in Figure 4h. Therefore, this modulator can work at an AC drive voltage much less than 100 mV (peak to peak) to turn the signal on and off. Both threshold voltage and anticipated peak-to-peak drive voltage is 2-3 times smaller than what has been reported recently in “ultra-low voltage” MRRs [49]. Correspondingly, an anticipated power consumption of 0.4 fJ/bit for a 6 dB on/off ratio was calculated, following the methodology described in [41]. This low power operation is due to the small size and high-Q of the resonant cavity.

Finally, we compare the simulated performance of the HUDS-embedded and pure photonic-crystal-based modulators with modulators based on MRRs and MZIs. As shown in Figure 5a, HUDS-based and PhC-based modulators display orders of magnitude improvement in both compactness and energy efficiency. Since the refractive index of Si is highly temperature-sensitive, all Si-based photonic devices suffer temperature dependence, typically above 0.1nm per Kelvin for resonance near 1500 nm, including MRRs [48-52]. In Figure 5b, we show quality-factor of different PBG-resonator-types as a function of temperature-dependent resonant wavelength shift (triangles for pure PhC resonators and squares for PhC resonator embedded in HUDS), as compared to previously-reported MRRs (circles). PBG resonant cavities featuring a 250 nm wide rectangular air slot along the waveguide direction can reduce the TDRWS to 0.04 nm per Kelvin.
Fig. 6. a) HUDS-based modulator (red star) and photonic crystal-based modulator (black star) designs share with photonic crystal modulators the same orders of magnitude improvement in compactness and energy efficiency as compared to modulators based on MRRs and MZIs. b) Quality-factor of different PBG-resonator-types as a function of temperature dependent resonant wavelength shift (triangles for pure PhC resonators and squares for PhC resonator embedded in HUDS), as compared to previously-reported MRRs circles. When an air slot is added at the center of the PBG-material based cavity (empty triangle for PhC and empty square for HUDS-based), the temperature dependence can be significantly reduced, while maintaining a relatively high Q factor comparable to many MRRs.

4. Discussion

Our simulation and experimental results of HUDS passive devices demonstrate the functionality of HUDS as a platform for compact for silicon photonic integrated circuits (PICs). We demonstrate propagation losses of 1.3 dB/mm for partially-optimized HUDS waveguides, comparable to propagation losses of PhC waveguides. Further reductions in the loss of HUDS waveguides are anticipated via more advanced optimization techniques. Moreover, further reduction of the propagation losses can be achieved by improvements in the fabrication process (for comparison, within the same fabrication run, we fabricated standard 500×220 nm² strip waveguides and measured propagation losses of around 3.5 dB/cm which was higher than the typical state of the art, which are less than 0.1 dB/mm). On the other hand, the insertion losses of 2 dB can be further reduced by optimizing the transition between the HUDS and the strip waveguides as well as by designing the HUDS with an average lattice constant of 500 nm and wall thickness of 120 nm. Further systematic optimization, use of wider waveguides and post-fabrication treatments (thermal oxidation and removal of the SiO₂ layer underneath) are also planned to reduce propagation losses. Performance of a curved waveguide with sinusoidal shape and power splitters with nearly equal power splitting into the two paths with arbitrary orientations can be improved by careful design of the structure [59-60]: instead of designing a PBG structure first and then designing waveguide paths accordingly, one can first define the path of the waveguide, then build the structure around it according to a specific protocol. Using this method, further reductions in propagation loss and in corresponding insertion losses are anticipated, along with improved designs for further reducing the temperature sensitivity of appropriately high-Q resonant optical cavities.

The results in Figure 3 demonstrate the potential of designing various HUDS resonator types such as adjacently-coupled resonators, in-line HUDS resonant cavities and in-line resonant cavities. We also showed that HUDS can be employed to facilitate light confinement in predefined PhC resonant cavities and enhance their temperature stability. Adjacently-coupled HUDS resonators exhibit a few orders of magnitude improvement in temperature stability compared to MRRs but moderate Q-factor of up to 5000. Since a temperature dependent resonant wavelength shift depends on the resonator size and coupling from a straight waveguide
we suggest that the TDWS reduction of a HUDS resonator is related to the relatively small defect size and lower light interaction with silicon than in the case of MRRs (as it can be seen from Figure 2.) On the contrary, HUDS in-line resonant cavities experienced much higher TDWS due to higher mode size interaction with silicon and a Q factor of ~1M. Use of an air slot with widths from 100 to 250 nm successfully reduced the TDWS of the HUDS in-line resonant cavities, however, it is still comparable to a standard TDWS of MRRs. Therefore, adjacent-coupled PBG cavities are preferred for improved temperature stability. In all cases, the size of the cavity was much lower than a typical area of a standard MRRs implying higher compactness of HUDS platform for PICs applications.

Optical modulation using HUDS platform provides device density improvements of several times and a few orders of magnitude lower energy per bit compared to silicon optical modulators based on micro-ring resonators and MZIs. For comparison, we have also analyzed pin structure. Simulations of the voltage dependence of wavelength shifting, Q-quenching, and corresponding optical cavity lifetimes show a similar behavior for the pin and the p+pinn+ device designs. However, we find that the operating speed of a pin modulator is up to two times lower compared to a configuration with ohmic contacts. In the current configuration, operating speed slightly exceeds 1 Gb/s, which is still an improvement to similar design described in Ref. [41]. In order to achieve higher operating speed, it is necessary to use MZI configurations, already proven to enable up to 32 Gb/s operation for PhC based modulators [61-63]. As indicated in Figure 3d and e, threshold voltage of 0.48 V operates the current modulator structure at a 10 dB on/off ratio. However, the worst-case estimation of signal broadening due to factors such as side wall roughness (Q factor may be reduced to 106), a DC voltage of 0.8 V and with 60 mV (peak to peak) AC voltage can be used to operate the device at a 6dB on of ratio using the square wave. Both voltages are still lower than what have been reported recently in “ultra-low voltage” MRRs. As shown in Figure 5, our HUDS modulators have the following three major advantages over MRR and MZI-based modulators: a much smaller footprint, increased device density, and an order of magnitude lower energy per bit. These electrically-controlled optical modulators are designed to be fabricated in the same SOI material system using fully-CMOS-compatible fabrication processes as are being used to fabricate MRR devices currently undergoing very rapid commercialization efforts, and their layouts are not constrained to follow the axes of photonic crystals.

5. Conclusion

In conclusion, we introduced HUDS platform as a locally-engineered environment for PIC applications by experimentally demonstrating the lithographic fabrication of HUDS waveguides and resonant cavities in silicon-on-insulator for operation over the range of ~1.50 to 1.65 microns. The intrinsic isotropy of these novel disordered PBG materials demonstrates potential for photonic device design by offering compactness, low power consumption and improved temperature stability combined with unprecedented freedom not limited by crystalline structures and periodicity. The disordered character of hyperuniform materials makes them less sensitive to fabrication errors that create randomly-distributed disorder, as compared to their periodic counterparts. The devices demonstrate an ability to guide light in the infrared regime with low loss and lower TDWS than that of the standard silicon microring resonators. Design optimization of an optical modulator based on an inline-coupled resonant PBG cavity predict sub-volt and sub-fJ/bit electrical modulation when driven with ohmic contacts in a p+pinn+ configuration. Temperature-stabilized, low-loss, compact and energy-efficient HUDS devices therefore provide new building blocks for the design of more complex systems featuring both passive and active devices, enabling new opportunities for cost-effectively increasing the data rates supportably in SOI, as well as in other semiconductor material platforms, and for other applications.
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