Periodic waveguide structures for on-chip modulation and sensing

Xiaochuan Xu1,2*, Chi-Jui Chung2, Zeyu Pan2, Hai Yan2, and Ray T. Chen1,2*

1Omega Optics Inc., Austin, TX 78759, U.S.A.
2Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, TX 78758, U.S.A.

Received February 14, 2018; accepted May 12, 2018; published online July 12, 2018

In this paper, we summarize the recent progress on silicon photonics modulators and sensors with an emphasize on the innovation in waveguide structure. We will introduce two types of waveguide, one-dimensional (1D) slot photonic crystal waveguide (SPCW) and subwavelength grating (SWG) waveguide. The simple geometry of 1D SPCW makes it more robust to fabrication imperfections and helps reduce its propagation loss, while still maintaining the benefit of slow light. The effective electro-optic (EO) coefficient increases to 490 pm/V. The electromagnetic (EM) wave sensor developed based on this waveguide shows a sensitivity of 1.8 V/m at 14.1 GHz, which is the most sensitive EM wave sensor that has been reported. The SWG waveguide ring resonator has a bulk sensitivity more than 400 nm/RIU, which is much higher than its strip waveguide counterpart. Furthermore, its surface sensitivity is relatively independent of the thickness of analytes accumulated on its surface. These features make it an appealing sensing platform. © 2018 The Japan Society of Applied Physics

1. Introduction

Silicon photonics has been attracting substantial interest in past decades. The enthusiasm behind it roots from the vision that CMOS compatible fabrication process can be leveraged to massively produce high density integrated photonic chips at a low cost. It was originally proposed as a complement to optical interconnect, and has been naturally spreading into other applications such as sensing. Numerous devices of promising performance have been demonstrated on silicon-on-insulator (SOI) platform. Despite the impressive progress, silicon is recognized as one of the worst optical materials. On one hand, silicon cannot generate photons because of its indirect bandgap; on the other hand, due to the symmetric lattice structure, silicon does not have second-order nonlinearity and thus the electro-optic (EO) effect is also absent. The two intrinsic issues necessitate hybrid integration, which can potentially let silicon photonics benefit from advantages of multiple materials. However, the high index contrast of silicon prevents the efficient interaction between optical guided modes and functional materials. For the same reason, the sensitivity of silicon photonics based sensors is also limited.

To alleviate these issues, many innovative optical waveguide structures have been investigated for hybrid modulators and sensors. For instance, silicon–organic hybrid (SOH) modulators are considered as an intriguing alternative to plasma dispersion based modulators. Polymer EO materials possess appealing second-order nonlinear optical property, and can be applied easily through spin-casting. The SOH platform can potentially combines advantages of silicon photonics and polymer materials, and give birth to devices with significantly improved performance. Numerous hybrid waveguide structures have been proposed to maximize the interaction of photons and polymers, such as slot waveguide, two-dimensional (2D) slot photonic crystal (PC) waveguide and one-dimensional (1D) PC waveguide. High modulation efficiency has been reported in slot waveguides because of the strong confinement of optical mode in the low index slot region infiltrated with EO polymers. Slow light waveguides, like 2D slot PC waveguides, have also been demonstrated, which utilize the slow light effect to further enhance the photon–matter interaction. Among these attempts, 2D slot PC is very promising because it enhances the photon–matter interaction in both space and time domain. However, the optical loss in slow light region and its robustness to fabrication variations is detrimental.

Silicon photonics based sensors face similar challenges. There has been a growing interest in silicon photonic biosensors driven by the demand of point-of-care diagnosis systems with affordable price, high sensitivity and throughput, real-time and label-free detection. Plenty devices have been proposed and demonstrated, such as surface plasmon devices, micro-ring resonators, silicon nanowires, nanoporous silicon waveguides, 1D and 2D PC microcavities. These structures are based on the interaction between the evanescent wave and the analytes immobilized on the sensor surface, e.g., micro-ring resonators on SOI substrates. Intensive efforts focus on boosting the sensitivity and improving the detection limit. However, due to the exponential decay of evanescent wave, the surface sensitivity decreases as the thickness of the analyte layer accumulated on the surface increases. The analyte's amount to a total layer thickness ranging from several to a few tens of nanometers, within which the sensitivity of the evanescent wave could drop considerably before it reaches the final target to be detected.

In summary, the efforts to develop high performance modulators and sensors are essentially the searching for waveguide structures allowing for strong photon–matter interaction in space and time domain while maintaining low propagation loss. In this paper, we introduce our recent efforts in exploring innovative waveguide structures to increase the interaction between guided modes and functional materials or analytes in time and space domain. Based on these waveguides, modulator and sensors have been demonstrated with significant improvement in performance.

2. One-dimensional slot photonic crystal waveguide

2.1 One-dimensional slot photonic crystal waveguide structure

The photon–matter interaction in space domain can be quantified by mode-volume overlap, which is defined as the percentage of optical energy existing in materials or analytes of interest. To increase the mode volume overlap, slot
waveguide was proposed, in which light is confined in low-refractive-index material. To further improve the photon–matter interaction, slow light structure is introduced to prolong the interaction time. Intensive study has been focused on introducing slot defects into 2D photonic crystal waveguide (PCW), but the effort is eventually in vain due to the tremendous loss. It is believed that the loss is primarily induced by the scattering from rough side walls. The increase of interaction between optical mode and rough sidewalls in 2D PCW must be avoided. The formation of slow light modes can be understood as the forward and backward wave move out of phase but still interact, resulting in a slowly moving interference pattern. It implies the structural slow light phenomenon is induced by periodic perturbation along the propagation direction, meaning the complicated 2D structure can be avoided to reduce the loss and footprint of slow light waveguide.

Based on the analysis, we introduce periodic perturbation along the propagation direction by adding periodic teeth on the outer edges of the rails in conventional slot waveguides, as shown in Fig. 1. This novel structure is referred as slow light 1D slot PCW (SPCW), which exploits both the strong mode confinement in the low-index region of a conventional slot waveguide and the slow light enhancement from the 1D PCW. Its simple geometry makes it robust to fabrication imperfections and helps suppress the scattering loss.

The 1D SPCW can be analyzed with three-dimensional (3D) plane wave expansion method. A typical band structure of the quasi-transverse-electric (TE) modes is shown in Fig. 2(a). Devices can be designed to operate at different bands based on the requirements of specific applications. For instance, the region close to the boundary of the Brillouin zone of the lowest band is frequently chosen to generate slow light effect. It supports propagation mode in the SPCW and has a high group index \( n_g > 40 \) close to the band edge [as shown in the inset of Fig. 2(a)]. The electric field intensity distribution of the mode at the band edge is shown in Figs. 2(b)–2(d). Optical power is strongly confined in the slot and the ratio of the optical power in the EO polymer region is calculated to be \( \sigma = 0.35 \). With the 1D SPCW, the interaction between photons and EO polymer can be enhanced in both space and time domain which is essential to the device performance.

### 2.2 High performance silicon–organic hybrid phase shifter

Based on the aforementioned waveguide structure, we demonstrated an SOH phase shifter on SOI with 220 nm device layer. The 1D SPCW sits on top of a silicon dioxide layer and is covered with EO polymer (Soluxra SEO 125, \( n = 1.63 \)). The waveguide parameters are tailored to assure an operating wavelength near 1550 nm. The period, width, and length of the teeth are 415, 124.5, and 300 nm, respectively. The slot waveguide has a width of 150 nm and a rail width of 100 nm. To characterize the SOH phase shifter, an MZI structure was designed with one arm loaded with a 200 µm long 1D SPCW, as illustrated in Fig. 3. The insets are the SEM images of the fabricated silicon SPCW, strip-to-slot mode converter and grating coupler and also the microscopic image of the multimode interferometer (MMI). The details of the fabrication can be found in Ref. 53.

Figure 4(a) shows the transmission spectrum of the fabricated Mach–Zehnder interferometer (MZI) with one arm loaded with the 1D SPCW. The fringes in the spectra are induced by the group velocity difference between the two arms of the MZI. The oscillation period decreases rapidly at the band edge around 1567 nm, indicating the increase of the group velocity difference and thus the group velocity of the 1D SPCW. The group indices estimated from the interference pattern are plotted together with the transmission spectrum in Fig. 4(a). The slow light region covers 1.5 nm (colored region) and can be further extended through band engineering. Group index over 25 is observed. The total insertion loss of the MZI structure is \( \sim 10 \) dB, including approximately 15 dB/mm propagation loss of the 1D SPCW. The propagation loss of the 1D SPCW is higher than conventional...
slot waveguide infiltrated with EO polymer (4 dB/mm) because of the increased scattering loss at the periodic structure, but it is significantly smaller than the typical loss of 2D SPCW under the same fabrication condition. The reduction of loss primarily attributes to the reduce of scattering centers due to the simplified periodic structure.

To demonstrate the enhanced photon-matter interaction, electric fields were applied across the waveguide and the interference fringes are plotted in Fig. 4(b). The spectra shifts to a longer wavelength as electric field increases from 0 to 10 V/µm. The electrical field induced phase shift can be estimated by \( \Delta \phi = 2 \pi \Delta \lambda / \text{FSR} \), where FSR is the free spectral range of the MZI. EO modulation figure-of-merit \( (V_L \pi) \) of 0.91 V·cm is calculated near the wavelength of 1562 nm. The effective EO coefficient, \( r_{33e} \), is estimated to be 490 pm/V near 1562 nm.\(^{20} \) Figure 4(c) shows the group index at different wavelengths and the corresponding \( r_{33e} \). It is clear that the \( r_{33e} \) is enhanced by the slow light effect.

### 2.3 Silicon–organic hybrid electromagnetic wave sensor

The phase shifter demonstrated in the previous section can be used as a building block for a vast variety of applications when equipped with proper elements. For example, when high speed electrodes were implemented, the phase shifter could be used to form high speed modulators. In this section, we introduce a high sensitivity electromagnetic (EM) wave sensor based on the SOH phase shifter. It utilizes bowtie antennas to collect EM wave and convert into the electrical field crossing the SOH waveguide. The photons propagating through the SOH waveguide will be modulated by the electrical field. The schematic of the sensor is illustrated in Fig. 5(a). To convert the phase modulation into intensity modulation, an MZI structure with one arm of SOH 1D SPCW and the other arm of conventional strip waveguide with teeth of subwavelength pitch and width is squeezed into the gap between the two antenna poles. The design of the antennas can be found in many literatures.\(^{55} \) Compared to the basic 1D SPCW design described in the previous section,\(^{53} \) a set of narrow teeth is used to connect the 1D SPCW to the bulk silicon region to ensure the voltage drop primarily occurs in the slot region, as shown in Fig. 5(b). The 1D SPCW is optimized for 220 nm SOI wafer with a 3 µm buried oxide layer and an operation wavelength of 1550 nm. The slot is refilled with the same EO polymer, SEO125.\(^{56} \) The optimized period, center silicon strip width, tooth width, and tooth length of the strip waveguide arm are 400, 79.2, and 1175 nm, respectively. The waveguide length is also chosen to be 300 µm. The simulated group index is 3.79.

---

*Fig. 3. (Color online) Schematic of an MZI modulator based on 1D SPCW. Insets: SEM images of the waveguides and the grating coupler, and microscopic image of the MMI.\(^{51} \)*

*Fig. 4. (Color online) (a) Measured transmission spectrum of the MZI structure and the calculated group index of the 1D SPCW. (b) Measured transmission spectra of the MZI modulator with different DC electric field applied on the electrodes. (c) Group index (from both simulation and experiment) and effective \( r_{33} \) as a function of wavelength.\(^{33} \)*
at 1550 nm. Inverse tapers with polymer overlay are used to interface single mode fibers. Scanning electron microscopy (SEM) images of the sensor are shown in Fig. 6.

The EM wave sensing experiment is then conducted and the setup is described in Ref. 55. Figure 7 plots the detected signal versus the input microwave power into the horn antenna. When the input microwave power decrease to 4.31 mW/m², the MSA reading is −87.43 dBm which is close to the noise floor. Therefore, the limit-of-detection of the device at 14.1 GHz is 4.31 mW/m², which is correspond-


ing to a minimum detectable electric field of 1.8 V/m. According to the authors’ best knowledge, this is the most sensitive hybrid electromagnetic wave sensor that has been demonstrated to date. The sensor operates at 14.1 GHz with 3 dB bandwidth of 4.84 GHz. 14.1 GHz falls into Kᵤ band and can be applied for satellite communication for commercial as well as military networks.

3. Subwavelength grating waveguide
3.1 High quality factor subwavelength grating waveguide ring resonators
Subwavelength grating (SWG) waveguide is formed by a periodic arrangement of two or more materials with a pitch much smaller than the wavelength inside the waveguide. Photons can propagate in the form of Bloch–Floquet mode with negligible propagation loss. SWG and the advance semiconductor fabrication technology provide the option to precisely tune a number of important waveguide properties, such as refractive index, dispersion, and mode overlap volume, which originally are only determined by natural materials constituting the waveguides. The control of these properties leads to the performance improvement of a wide range of photonic devices, including grating couplers, directional couplers, sensors, filters, and modulators. In light of the micro-ring resonator, it is appealing to replicate the ring structure with SWG waveguide micro-ring resonators (SWGMRs). A few early demonstrations, such as filters and sensors, have shown encouraging results. However, the reported SWGMRs could only provide a small quality factor (<5,600), even with a large radius of 15 µm, which significantly deter the application of SWGMRs. According to the time-domain coupled-mode theory, the quality factor of ring resonator, including SWGMR, is ultimately limited by the loss of the ring, specifically, the bend loss. To thoroughly understand the issue, we start with a conventional SWG waveguide, the schematic of which is shown in Fig. 8(a). The period of the SWG structure Λ equals 300 nm, L = 150 nm, w = 500 nm, and h = 250 nm represent the length, width, and height of silicon pillars, respectively. SU-8 (n ≈ 1.58) is the top cladding. In this review, we focus on quasi-TE polarization, while the results can be readily extended to quasi-TM polarization. Based on the effective medium theory (EMT),
Our recent work shows that replacing rectangular silicon pillars with trapezoidal silicon pillars can create an asymmetric effective index profile for the pre-distortion compensation and thus significantly increase the quality factor of SWGMR. The 3D schematic of the SWGMR with trapezoidal silicon pillars (T-SWGMR) is shown in Fig. 8(b), where $r$ and $g$ denote the radius of the T-SWGMR and the center-to-center gap between the SWG bus waveguide and the SWGMR, respectively. The trapezoidal silicon pillars have two adjustable parameters, top base $L_T$ (at the outer circumference of SWGMRs) and bottom base $L_B$ (at the inner circle of SWGMRs), which could be optimized to minimize bend loss through 3D finite-difference time-domain (FDTD).

It is found that a trapezoidal silicon pillar with $L_T = 140\,\text{nm}$ and $L_B = 210\,\text{nm}$ could minimize the bend loss to 0.192 dB per 90° bend, which is only 50.1% of the loss of an SWG waveguide bend built with conventional rectangular silicon pillars (0.383 dB per 90° bend).

To experimentally demonstrate the improvement of quality factor, we designed 5 µm radius T-SWGMRs with $L_T = 140\,\text{nm}$, $L_B = 210\,\text{nm}$, $h = 250\,\text{nm}$, and $w = 500\,\text{nm}$. For comparison, 10 µm radius T-SWGMRs are also designed and fabricated. A control group of 5 µm radius and 10 µm radius rectangular SWGMRs (R-SWGMRs) are also fabricated and characterized. Figure 8(c) shows a typical top-view of the simulated optical field of a T-SWGMR ($r = 5\,\text{µm}$ and $g = 800\,\text{nm}$) on resonance. All devices are fabricated on SOI chips with 250 nm thick top silicon layer and a 3 µm thick buried oxide (BOX) layer. Figures 9(a) and 9(b) are the SEM images of the 5 µm radius R-SWGMR and T-SWGMR, respectively. Figure 9(c) shows the coupling region between the bus waveguide and the micro-ring of a 5 µm radius T-SWGMR. Figures 10(a) and 10(b) are the transmission spectra of the four types of SWGMRs after subtracting the contribution of grating couplers. Figures 10(c) and 10(d) show the magnified pictures of the resonance peaks with the highest quality factor. Both the 5 µm radius and the 10 µm radius T-SWGMR show significantly improved quality factors compared to R-SWGMRs of the same radius. The 5 µm radius T-SWGMR ($g = 780\,\text{nm}$) has a resonance peak with a quality factor as high as 11,500, which is 4.6 times of the highest quality factor $(\sim 2,800)$ obtained from the 5 µm radius R-SWGMR ($g = 570\,\text{nm}$). For the 10 µm radius ring, the T-SWGMR ($g = 1020\,\text{nm}$) has a resonance peak with a quality factor as high as 45,000, which is 3 times of the highest quality factor $(\sim 15,000)$ obtained from the 10 µm radius R-SWGMR ($g = 870\,\text{nm}$). This approach paved the way of building high performance SWG based optical devices and circuits.

### 3.2 Subwavelength grating waveguide ring resonator based sensors

In an SWG waveguide, the interaction region between light and cladding materials is significantly enhanced compared to evanescent wave based biosensors, e.g., strip waveguide ring resonators. Therefore, SWG structure has great potential in integrated photonic sensors. In Refs. 47 and 75, micro-ring resonators based on SWG waveguides were first demonstrated with bulk sensitivity better than 400 nm/RIU, which is several times higher than conventional micro-ring resonators based on strip waveguides. In biology sensors, the refractive index variation only occurs within a few to
several tens of nanometers away from the waveguide surface. Therefore, surface sensitivity is a more important figure-of-merit (FOM) for biology sensors. Surface sensitivity $S_s$ is defined as the resonance wavelength shift as a function of the increment of the thickness of molecule layers $t$ accumulated on top of the waveguides:

$$S_s = \frac{\Delta \lambda}{\Delta t} = n_g \left( \frac{\partial n_{\text{eff}}}{\partial t} \right).$$

Here, $n_g$ is the group index of the waveguide. The biomolecules are considered as a uniform layer with a refractive index of 1.48. For strip waveguide based sensors, surface sensitivity decreases as $t$ increases due to the exponential decay of the evanescent field. In this section we show that the SWG waveguide based sensors not only have significantly improved bulk sensitivity, but also have enhanced surface sensing capability in SWG waveguide which is independent of $t$.

Figure 11(a) is the schematic of a typical SWG waveguide. Figures 11(b)–11(d) are the electric field distribution in cut planes shown in Fig. 11(a). From the mode profile, it can be seen clearly that there is a significant portion of the mode field existing on the light propagation path between silicon pillars which increases the sensing area of SWG waveguide based micro-ring biosensors.

We use an SWGMR with similar structure as the one mentioned in the previous section. Duty cycle of the grating (ratio of silicon pillar width to grating period) $\eta$ and waveguide width $w$ are optimized to maximize the optical field overlap with the sensing medium. $\eta = 0.65$ and $w = 450 \text{ nm}$ are chosen, resulting in the calculated overlapping factor $\sigma = 0.4$. The width of the rectangular pillar is $\eta \Lambda = 130 \text{ nm}$. The top and bottom bases ($L_T$ and $L_B$) are then determined through the bending loss simulation as described in the previous section. The optimized $L_T$ and $L_B$ are 100 and 150 nm, respectively. The gap between micro-ring and the bus waveguide is $d = 50 \text{ nm}$. The height of the silicon layer is $h = 220 \text{ nm}$. As shown in Fig. 12(a), layers of SiO$_2$, chemical and proteins consecutively formed on the surface of the SWGMR. We assume the sensing medium is water ($n = 1.32$). The susceptibility of the SWG structure can be simulated with a 3D plane wave expansion solver. The
simulation results are shown in Fig. 12(b). The $dn_{eff}/dt$ in SWG waveguide is 4–6 times larger than that in a conventional strip waveguide due to large mode overlapping factor ($\sigma \sim 0.4$). Furthermore, the value remains constantly high in SWG structure for the first 25 nm, while in conventional strip waveguide, $dn_{eff}/dt$ decreases monotonically. This simulation result coincides with the above mode profile analysis by showing that SWG structure has superior surface sensing capability over evanescent wave based sensors like conventional micro-ring resonator, in terms of both absolute surface sensitivity $S_s$ and the ability to maintain high surface sensitivity when the thickness of surface layer grows.

For experimental demonstration, SWGMR and conventional strip waveguide micro-ring are fabricated side-by-side on the same chip. The regular micro-ring resonator has the same radius of 10 µm and the waveguide is 450 nm wide by 220 nm high. SEM images of the fabricated SWG micro-ring resonator are shown in Fig. 13(a). Transmission spectrum of the SWG micro-ring is shown in Fig. 13(b). The free spectral range is measured to be 12.5 nm, corresponding to group index $n_g = \lambda^2/(2\pi R \cdot FSR) = 3.0$. The estimated quality factor ($Q \sim \lambda/\delta\lambda$) is as high as 9100 due to the use of trapezoidal pillars in the SWG microring. The bulk refractive index sensitivity of the SWGMR was characterized by flowing the glycerol solution of different concentration through the flow cell. The resonance peak wavelength was monitored during the experiment and plotted in Fig. 13(c). The bulk sensitivity $S_b$ is estimated to be 440.5 nm/RIU by linearly fitting the resonance shift versus refractive index change plot, as shown in Fig. 13(d). It is about 4 times of that of a conventional micro-ring resonator.

The biology sensing (surface sensing) procedure and results are summarized in Fig. 14. Figure 14(a) is the real-time resonance shift of SWGMR biosensor during the sensing experiment. The blue regions are PBS buffer washing steps between the flow of reagents. The resonance shift to a longer wavelength when a binding event occurs. PBS buffer removes unbounded biomolecules and forms a baseline for each step. The resonance shifts of the conventional micro-ring were also recorded at each buffer washing step. The resonance shifts of both rings are shown in Fig. 14(b). The resonance shifts in SWGMR are several times larger than that in regular micro-ring as predicted in the simulation. It can also be seen in this figure that with more and more layers accumulated on the surface, the resonance shift difference between the two types of rings also increases. To explicitly show the difference, surface sensitivity with respect to the thickness of surface layer is compared and shown in Fig. 14(c). It is clear that the sensitivity of the micro-ring resonator drops monotonically compared to that of the SWG ring as thickness of accumulated biomolecules grows continuously.

4. Conclusions

In this paper, we introduce two types of waveguide, 1D SPCW and subwavelength grating waveguide, to enhance the photon–matter interaction. The simple geometry of 1D SPCW makes it more robust to fabrication imperfections and helps reduce the propagation loss, while still maintaining the benefit of a slow light waveguide. The effective EO coefficient increases to 490 pm/V due to slow light enhancement. The EM wave sensor developed based on this waveguide has demonstrated a sensitivity of 1.8 V/m at 14.1 GHz, which is the most sensitive EM wave sensor that has been reported. We showed that the loss of SWG bending can be significantly reduced through tuning the shape of the pillars. Based on this approach, the $Q$ of SWG ring resonator can be significantly improved. The SWG ring resonator has a
bulk sensitivity more than 400 nm/RIU, which is much higher than its strip waveguide counterpart. Furthermore, its surface sensitivity is relatively independent of the thickness of the analytes accumulated on its surface. These features make it an appealing sensing platform.

Acknowledgments

The research was supported by Department of Energy (DoE) small business innovative research (SBIR) program (DE SC-0013178), Air Force Office of Scientific Research (AFOSR) SBIR program (FA9550-16-C-0033), Air Force Research Laboratory (AFRL) Small Business Technology Transfer Research (STTR) program (FA8650-14-C-5006), and AFOSR Multidisciplinary University Research Initiative (MURI) program (FA9550-08-1-0394).

Fig. 14. (Color online) (a) Real time monitoring of the resonance shift in SWG micro-ring biosensor during the biosensing experiment; Blue region indicate buffer washing steps and other steps are marked with the corresponding reagents used. Anti-SA: anti-streptavidin antibody, SA: streptavidin, bio-BSA: biotinylated BSA. (b) Resonance shift in both SWG micro-ring and regular micro-ring; insets show SEM images of both micro-rings; GLU: glutaraldehyde (c) Surface sensitivity with respect to estimated thickness in both SWG micro-ring and regular micro-ring.78

25) V. M. N. Passaro, C. de Tulio, B. Troia, M. La Notte, G. Giannoccaro, and