Towards a Fully Packaged High-performance RF Sensor Featuring Slotted Photonic Crystal Waveguides


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ABSTRACT

A low loss and high sensitivity X-band RF sensor based on electro-optic (EO) polymer filled silicon slot photonic crystal waveguides (PCW) and bowtie antenna is proposed. By taking advantage of the slow light enhancement in the PCW (>20X), large EO coefficient of the EO polymer ($r_{33} > 200 \text{ pm/V}$), as well as significant electric field enhancement of bowtie antenna on silicon dioxide substrate (>10000X), we can realize a large in-device EO coefficient over 1000 pm/V so as to realize a high performance RF wave sensor. In addition, on-chip Mach-Zender interferometer (MZI) layout working under push-pull configuration is adopted to further increase the sensitivity of the sensor. Furthermore, inverse taper couplers and slotted photonic crystal waveguides are carefully designed and discussed in this paper to reduce the insertion loss of the device so as to increase the device signal-to-noise ratio. The minimum detectable electromagnetic power density is pushed down to 2.05 mW/m², corresponding to a minimum sensing electric field of 0.61 V/m. This photonic RF sensor has several important advantages over conventional electronics RF sensors based on electrical scheme including high data throughput, compact in size, and great immunity to electromagnetic interference (EMI).

Keywords: radio frequency detection, electro-optic modulation, microwave photonics, slow light effect, photonic crystal waveguides, bowtie antenna, inverse taper couplers

1. INTRODUCTION

Radio Frequency (RF) Electromagnetic (EM) field sensors have substantial applications for communication and sensing fields [1-5] including electromagnetic compatibility measurements, radio frequency (RF) integrated circuit testing, environmental electromagnetic interference analysis, electrical field monitoring in medical apparatuses, ballistic control, as well as detection of directional energy weapon attack. Conventional EM wave sensors based on electrical schemes normally require several discrete electronics components and large active high speed conductive probes which disturb the EM waves to be measured and make the device bulky as well. Recently, there has been growing interest in the field of RF photonics. Processing and transmission of RF signals by photonic systems offer significant advantages in terms of data throughput, the size, weight, and power (SWaP) requirements, and immunity to electromagnetic interference (EMI) [6]. Therefore, integrated photonic sensing of electromagnetic field devices in which optical signal is modulated by RF signals coupled by an antenna has been developed [7-9]. These antenna coupled modulators have some additional advantages including overcoming the high transmission loss at high frequencies, eliminating extra electronics compared to systems with separate antenna and optical modulator units, and improving the sensitivity without sacrificing the bandwidth [10].

Silicon-on-insulator (SOI) platform has attracted researchers’ attention as a platform for integration of photonic devices and complementary metal–oxide–semiconductor (CMOS) electronics [11] due to high refractive index and high transparency of silicon at communication wavelength range and CMOS process compatibility. The centro-symmetric crystal structure of silicon, however, eliminates any efficient linear electric field modulation, leaving the free carrier plasma dispersion effect as the choice for most the reported high speed silicon modulators [12-14]. Nevertheless, for the plasma dispersion based silicon modulators, the modulation bandwidth is intrinsically limited by the lifetime of the free carriers [15]. On the other hand, EO polymers as the active material in optical modulation devices have shown several advantages [16] over III-V, lithium niobate, and silicon materials including 1) large EO coefficient as high as 200 pm/V
reported with bandwidth up to 1.6 THz, and 2) the capability of spin-coating. Therefore, silicon-organic hybrid (SOH) integrated photonic electromagnetic field sensors are promising for achieving high sensitivity, compact size, and broad bandwidth.

Our group has previously published the results from the first SOH integrated device for the photonic sensing of EM waves. The sensing of electromagnetic field at 8.4 GHz was experimentally demonstrated, with a minimum detectable electromagnetic power density of 8.4mW/m², corresponding to a minimum detectable electric field of 2.5 V/m [20]. However, the device still has room for improvement from the EM wave sensing point of view. First, the EO polymer infiltrated PCW works as a phase modulator, and it requires other discrete components like light splitter, variable optical attenuator, and combiner to realize the amplitude modulation. We designed an on-chip MZI structure that we can have a compact and high sensitivity sensor operating in a push-pull configuration. Second, the EO polymer used in [20] was SEO 125 from Soluxra, LLC which is inferior to the new SEO 250 with larger EO coefficient of 230 pm/V at 1550nm. Third, the antenna was built on regular SOI substrate in [20]. The silicon handle has a low resistance and high loss tangent which will induce loss for the RF electrical signal. We will build the device on insulating substrate like silicon on silicon dioxide wafer. Fourth, the device in [20] had high loss due to the band-engineered slow light structure and grating coupler utilization. We will re-design the PCW for the new EO polymer with higher refractive and adopt inverse taper couplers to reduce the loss and increase the signal-to-noise(S/N) ratio. Therefore, in this paper, we design and preliminary demonstrated a highly integrated, low loss, and high sensitivity electromagnetic wave sensor based on on-chip PCW MZI and high gain bowtie antenna on silicon on silicon dioxide substrate. It display potentials for a wide range of RF signal detection applications.

2. DESIGN

2.1 Design overview

The schematic view of the proposed EM wave sensor consisting of an EO polymer filled silicon slot PCW MZI coupled with a pair of bowtie antennas is shown in figure 1. The working principle of the integrated photonic EM wave sensor is described as follows: A continuous wave (CW) laser light is coupled in and out through the inverse taper couplers. The bowtie antenna collects the impinging RF EM waves, which is applied between the feed gaps of the bowtie antenna and transforms into a high power-density AC electric field. The AC electric field directly interacts with the light propagating along the slotted PCW (i.e., slow light region) and changes the refractive index of the EO polymer due to EO effect. The two arms of the MZI are poled in different directions so that the MZI can work in a push-pull configuration and double the phase change of the laser light. By measuring the modulated optical power amplitude at the output end of the MZI, an incident electromagnetic field from free space can be detected.

![Figure 1. A schematic view of the electromagnetic field sensor consisting of an EO polymer refilled silicon slot PCW MZI and a pair of bowtie antennas featuring slot PCW with significant slow light effect, efficient mode convertor, and a pair of inverse taper couplers](image-url)
The EO polymer used here is SEO 250 from Soluxra, LLC which has EO coefficient $\gamma_{33}$ value of 230 pm/V, low optical loss, and good temperature stability up to 130 °C. This EO polymer in refilled in a silicon slot PCW with a slot width of 320nm. The PCW parameters are band engineered to achieve low-dispersion slow light propagation. The slow-light enhanced effective in-device $\gamma_{33}$ of the SOH modulator can reach over 1000 pm/V [18]. The slot PCW is located right inside the feed gap of the bowtie antenna, and the silicon layer is selectively doped with two different ion concentrations for high frequency operation [21]. The bowtie antennas are used as receiving antenna, driving electrodes, and poling electrodes for EO polymer.

2.2 Design of slotted PCW

The PCW is designed for SEO 250 EO polymer which has a high refractive index of 1.72 at 1550nm. The group index taper and the band engineered structures for low dispersion slow light also need to be designed. The schematic of the slot PCW is shown in figure 2. The critical parameters of the slot PCW structure are lattice constant ($a$), hole radius ($r$), slot width (SW) and waveguide width (W). The slot PCW is patterned on a 220 nm thick silicon layer and sandwiched between a 3 um thick silicon dioxide layer (buried oxide layer) and a 2 um thick EO polymer layer. The whole structure is designed using a commercially available RSofT software and its band diagram is calculated by 3D plane-wave expansion method. We iteratively alter the parameters and calculate the band diagram until we reach an optimized design that supports a defect-guided mode that falls inside our experiment observation window of 1520 ~ 1610 nm. The optimized design parameters are $a = 415$ nm, $r = 132$ nm, $SW = 320$ nm and $W = 1.28\sqrt{3}a$. Figure 2(a) also shows the dispersion diagram of the optimized slot PCW. The red curve indicates the propagation mode in the slot PCW. The 3D mode profile at group index $n_g = 30$ is plotted in the inset. The polymer light line ($n = 1.72$) and the silicon dioxide light line ($n = 1.46$) are also marked in the diagram. The corresponding group index spectrum is calculated from the dispersion diagram and shown in figure 2(b). The band edge lies at around 1545 nm.

![Slot PCW Diagram](image)

Figure 2. Schematic of the slot PCW, (a) its dispersion diagram Inset: 3D mode profile, and (b) group index versus wavelength plot.

The group index mismatch between the regular slot waveguide and slot PCW will induce severe coupling loss due to Fresnel reflection. This problem can be solved by using a PCW coupler consisting of group index taper which provides a smooth transition in group index as shown in figure 4(a). The taper is formed by gradually reducing the width of the line defect waveguide from the regular slot waveguide to the slot PCW. As shown in figure 3(a), at a certain wavelength, the group index is decreased as the waveguide width is reduced. Figure 3(b) plots the group index versus waveguide width at the wavelength of 1547 nm (where $n_g = 30$ in the slot PCW). The group index changes parabolically with waveguide width. Therefore, to make a smooth transition in the group index, we parabolically reduced the width as shown in figure 4(b) (black curve) so that the group index changes linearly along the taper region (blue curve in figure 4(b)). There are 10 periods in the taper in total in this design.

To achieve slow light operation over a large optical bandwidth, an additional lattice shift is introduced into the slot PCW. The method we adopted is to laterally shift the first three rows closest to the slot labeled as s1, s2, and s3, as illustrated by the color arrows in figure 4(a). Figure 5 shows the results of a band engineered slot PCW. In comparison to figure 2(b), the band engineered PCW has a flat band region where the group index keeps at a high value for certain bandwidth. The group index is around 17.5 and we have around 10 nm optical bandwidth while maintaining a strong slow light effect.
Figure 3. (a) The group index versus wavelength for different waveguide widths; (b) The group index for different waveguide widths at 1547 nm (dashed vertical line in (a)).

Figure 4. (a) Schematic of the group index taper between regular slot waveguide and slot PCW; (b) Waveguide widths and group indices in the designed group index taper.

Figure 5. Group index at different wavelength in a band engineered slot PCW.
2.3 Design of Inverse Taper Coupler

Our group have previously designed and demonstrated a single step, through-etched sub-wavelength grating (SWG) coupler, which can be patterned together with photonic components without any additional patterning steps [22]. However, due to difficulties of patterning the sub-100nm grating structures, the typical loss we can achieved is -7 to -8 dB per grating coupler. Adopting inverse taper coupler can reduce the coupling loss down to <1 dB as reported [23]. In addition, grating couplers are inherently bandwidth-limited device with 3 dB optical bandwidth of tens of nanometers. The inverse taper typically has hundreds of nanometer of 3 dB bandwidth [23]. Hence, an inverse taper coupler design is proposed here for efficiently coupling light into the input silicon waveguide.

The schematic drawing and the geometrical parameters of the inverse taper coupler are shown in figure 6, which are optimized using commercial available FIMMWA VE software from PhotonDesign. The structure width is adiabatically tapered from 450 nm (device end) to 160 nm (fiber end). An SU-8 polymer waveguide is designed and overlaid on the silicon waveguide so that the $3 \mu m \times 3 \mu m$ cross-section area matches with the mode area of input lensed fiber. A top view simulation result showing efficient coupling of light from the SU8 polymer input waveguide into a single mode silicon waveguide with an inverse taper of length $L$ and a tip width of 160nm is shown in figure 7. The coupling loss per inverse taper is simulated to be less than 0.5 dB.

![Figure 6. Schematic drawing and designed parameters of the inverse taper coupler](image)

![Figure 7. Top view simulation result showing mode coupling from a 3um x 3um SU8 polymer waveguide into a 160nm tip adiabatic silicon taper and single mode waveguide](image)
2.4 Design of bowtie antenna and the antenna substrate consideration

The bowtie antennas concentrate the EM wave at certain range of designed frequency and provides a strong near-field electrical enhancement. Not only is the metallic structure of the bowtie important for the resonant antenna performance, but also the substrate material properties plays a pivotal role when interacting with the EM wave. Two common materials used as substrate for antennas are silicon dioxide and SOI. The previously optimized [21] gold bowtie parameters are used here for comparing the two different substrates. The bowtie structure, shown in figure 8, consists of a conventional bowtie antenna with capacitive extension bars attached to the apex points of the bowtie. The bowtie has an arm length of 4.5mm, and a flare angle of 60 degrees. The extension bars have a length, b=300μm, width, w=10μm and a feed gap, g=10μm. The thickness of the gold film is chosen to be t=5μm.

![Figure 8. Geometrical parameter of bowtie antenna with extension bars](image)

First, we used finite element method (HFSS from ANSYS, Inc.) to simulate the S11 parameter (return loss) of the optimized structure mentioned above. The thickness of the substrate are 1 mm for the silicon dioxide substrate and 1 mm silicon handle layer and 3 μm buried oxide layer for the SOI. The simulation model in HFSS is shown in figure 9. The dielectric constant of are set as 4 for silicon dioxide and 13.9 for silicon handle layer respectively for frequency from 1-30 GHz. The loss tangent is set as 0.015 for silicon and 0.0036 for silicon dioxide. We also setup a perfect impedance matching condition of 50 ohms for the two terminal of the bowtie for the range of frequency. The simulated S11 parameters of the antenna for silicon dioxide and SOI substrates from 1-30 GHz are shown in figure 10.

![Figure 9. Trimetric view of the bowtie antennas in HFSS](image)
We can clearly see from $S_{11}$ parameter versus frequency plot that the resonance frequency shift to lower region of 6.34 GHz from designed 8 GHz when using SOI as substrate (high dielectric constant) since resonance frequency.

$$f_r \propto \frac{1}{\sqrt{\varepsilon_r}}$$

For the resonance frequency, the bowtie antenna on silicon dioxide has lower drop of -13.22 dB compared to -8.58 dB on silicon. That means that bowtie antenna on silicon dioxide has higher antenna gain when working as a transmitting antenna if we assume the absorption loss is negligible. We also notice that the bowtie on silicon has many undesired transmission/reflection around 15-30 GHz. The abnormal transmission/reflection signal will affect the signal detection for our designed range of frequency. When we change the thickness of the substrate in the simulation, the nadir shifts. Therefore, it should results from the interference of the multiple reflection and transmission RF waves (Fabry–Pérot-like effect) of the interfaces.

3. FABRICATION

The fabrication flow of the proposed RF sensor is illustrated in figure 11. The fabrication starts with a silicon on silicon dioxide wafer with a 220 nm-thick top silicon and a 0.5 mm-thick buried oxide layer, as shown in figure 11(a). Next, the PCW is patterned by e-beam lithography (EBL) and all the top silicon region except the PCW area are etched away by reactive-ion etching (RIE). Then, a two-step ion implantation is performed on the sample, as shown in figure 11(b). After performing a rapid thermal annealing process to activate the dopants and annihilate the induced defects, we deposit a thin gold seed layer for electroplating, as shown in figure 11(c). Then, a buffer mask for the bowtie antenna is patterned on a 10 μm-thick AZ9260 photoresist using photolithography. Next, a 5 μm-thick gold film is electroplated using Techni-Gold 25ES electrolyte under a constant current of 8 mA. The AZ9260 buffer mask and gold seed layer are finally removed by lift-off and wet etching, as shown in figure 11(d). A 3 μm X 3 μm SU-8 layer for lensed fiber endfire coupling is patterned using photolithography, as shown in figure 11(e). After cleaving, the EO polymer, SEO250, is formulated and infiltrated into the holes and the slot of the silicon PCW region by spin-coating, as shown in figure 11(f), followed by baking at 80°C in vacuum oven for 12 hours. To align the polymer chromophore and activate the EO effect of the EO polymer, the EO polymer is poled in a constant electric field of 100 V/μm at the EO polymer glass transition temperature of 130 °C, in which the bowtie antenna serves as poling electrodes. The two arm of the MZI are poled in opposite directions so that we can operate the MZI in a push-pull configuration, as shown in figure 12.
The bowtie antenna... The conductivity of the electroplated gold film is measured to be $2.2 \times 10^7$ S/m. The bowtie antennas on silicon device layer of the SOI and on silicon dioxide and optical microscope images are shown in figure 13.

In order to demonstrate the effect of the substrate material of the fabricated bowtie antenna, a network analyzer (HP 8510C) and a GS high speed probe are used to measure the $S_{11}$ parameter over a frequency range of 1-15 GHz using a GS high speed microprobe. The measurement results are shown in figure 14. The measurement results show the same trend as in simulations: 1. the resonance frequency shifts to shorter wavelengths when building bowtie antenna on SOI, 2. higher antenna gain when building bowtie antenna on silicon dioxide 3. No undesired transmission for bowtie antenna on silicon dioxide at a frequency of 14.4 GHz. Silicon dioxide as an antenna substrate has low dielectric constant and lower loss tangent; therefore, it has lower reflection and lower attenuation of the input RF wave. Therefore, bowtie on
silicon dioxide substrate enables a more sensitive, more energy efficient device RF sensor. Bowtie antenna on silicon dioxide also enables better immunity to undesired noise compared to bowtie on buried oxide layer of the SOI.

Figure 14. Measurement results of the bowtie antennas

The designed inverse taper coupler is fabricated on 2 cm X 2 cm SOI wafers with buried oxide of 3 μm, and the testing layout is shown in figure 15. Seven waveguides with different silicon waveguide length are fabricated on the same chip. Two s-bends with radius of curvature 100 μm were added on each waveguide in order to suppress the stray light collected by the output fiber.

Figure 15. Testing layouts of the inverse taper coupler: silicon waveguide (in white) and SU-8 overlaid layer (in orange)

The silicon waveguide is patterned using EBL and RIE. The overlaid SU-8 structure is patterned using Karl Suss MA-6 photo aligner. The SU-8 used here is MicroChem SU-8 2002 and the photolithography conditions such as spin-speed, pre-bake condition, exposure dosage, post-bake condition, and develop time are firstly optimized on silicon wafer and then inspected before we started to pattern on the silicon waveguide samples. The scanning electron microscope (SEM) images and the surface profile inspection results of optimized SU-8 structure are showed in figure 16. The optimized SU-8 pattern is 3.048 μm in width and 3.06 μm in height with side wall angle larger than 85° which are very close to the designed parameters. After the SU-8 photolithography test, we started to...
pattern SU-8 layer on the silicon waveguide sample using the optimized condition. The alignment error for both X and Y direction are less than 0.5 μm between the waveguide layer and SU-8 layer which are shown is figure 17.

![Figure 16. (Left) SEM images of the patterned SU-8 structure (Right) depth of the SU-8 structure](image1)

![Figure 17. (Left) Alignment results of the SU-8 layer and silicon layer (Right) Alignment marks with vernier scales, showing the good alignment between silicon layer and SU-8 layer.](image2)

The preliminary insertion loss measurement results for the waveguide which include two inverse taper coupler, silicon single mode waveguide loss (6628 μm long), and SU-8 waveguide loss (3560 μm long) is -4.264 dB. Using -3.6 dB/cm propagation loss for silicon single mode waveguide [25], and -1 dB/cm for SU-8 waveguide, the best result for one inverse taper is -0.74 dB, which will reduce the coupling loss from ~ -15 dB for 2 grating couplers to ~ -1.5 dB for 2 inverse taper couplers.

5. DEVICE PERFORMANCE SPECULATION

We can speculate the performance of the proposed integrated photonic EM wave sensor based on the results of previously developed sensor in [20] and the verification results mentioned above. The previous SOH device for the photonic of EM wave sensing of electromagnetic field at 8.4 GHz was experimentally demonstrated, with a minimum detectable electromagnetic power density of 8.4 mW/m², corresponding to a minimum detectable electric field of 2.5 V/m [20]. Since we are using the on-chip MZI structure with push-pull configuration, the minimum detectable electromagnetic power density can be halved theoretically. Also benefiting from the γ33 value improvement from previous 135 pm/V (SEO 125) to 230 pm/V (SEO 250), if the modulation interaction length is fixed and the slow light effect remains, we should achieve 1.7X higher sensitivity. The antenna on silicon dioxide also provide 1.2X input enhancement for the EO modulation. By combing these three effect, the minimum detectable electromagnetic power density should be reduced to 2.05 mW/m², corresponding to a minimum detectable electric field of 0.61 V/m. Besides, by replacing the low loss and insulating silicon dioxide substrate, the antenna gain of the bowtie antenna should increase which will result in further reduction of the minimum detectable electromagnetic power density. Also the optical insertion loss is reduced by ~ 4.5 dB due to the introduction of inverse taper coupler.
6. CONCLUSIONS

In summary, we have proposed a highly integrated, low loss, and high sensitivity electromagnetic wave sensor based on electro-optic (EO) polymer filled slot photonic crystal waveguides (PCW) and bowtie antenna is proposed. Design of key components is discussed and preliminary experiments are performed in order to demonstrate these key building blocks. Based on the experimental data gathered, and comparing those to our previously developed sensor devices, we speculate to achieve a minimum detectable electromagnetic power density of 2.05 mW/m², corresponding to a minimum detectable electric field of 0.61 V/m at 8.4 GHz. The miniaturized and integrated device has several important advantages including high data throughput, reduced SWaP requirements, and immunity to electromagnetic interference (EMI).

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REFERENCE


