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Hybrid Micro-Ring Resonator Hydrogen Sensor Based on Intensity Detection

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ABSTRACT

In this paper, a photonic integrated device fabricated on a silicon-on-insulator (SOI) platform is studied numerically to investigate its hydrogen sensing potential based on intensity variations. A single-slot hybrid structure consisting of a coaxial micro-ring resonator (MRR) and a palladium (Pd) disk is utilized for this purpose. The results of the numerical study reveal a hydrogen sensing ability of 2.83×10^{-4}/(v/v-% hydrogen) and limit of detection (LOD) of 9.93×10^{-3} which is more than 10 times of that of the hydrogen sensors based on the traditional resonance shift. The proposed hydrogen sensing technique presents a compatible SOI-based technology and also provides a reliable detection of the slightest changes from the zero concentration in an analytical procedure.

Keywords: Hydrogen sensor, micro-ring resonator, optic sensor, intensity-based sensor.

Introduction

Hydrogen is the most common element, making up 75 % of the mass of the entire universe and has been used as a fuel for many decades in a wide range of applications. Hydrogen requires a high sensitive detection for human safety not only because it possesses a wide flammability range of an explosive nature (lower and upper explosive limits of 4% and 75% in air, respectively) but also it's great leaking tendency feature [1]. Many studies have been carried out for the purpose of hydrogen detection including fiber-based sensors, chemical sensors, photonic crystal sensors and micro-cavity optical sensors [2-5]. Among these, the micro-cavity/micro-resonator sensors have high potential in high sensitive detection [6, 7]. Hybrid structures of micro-resonators which might in hold different materials such as Pd is considered as a high-sensitive, low-cost, compact, durable, and high performance hydrogen detector compared to conventional hydrogen gas detecting instruments [5, 8].

Typical Pd involved optic micro-ring resonator (MRR) hydrogen sensor utilizes resonance-shift analysis to probe the presence of hydrogen in the sensing chamber. In such a sensing scheme the resonance wavelength/frequency alters with the change in hydrogen concentration of the sensor system. In order to detect low concentration levels, a generally high quality factor is required for a detectable resonance-shift [9]. It is well-known that due to the absorption feature of metals, the quality factor of a metal involved optical sensing system is typically low, which consequently leads to a lower detection limit [10, 11]. In addition, the perceptibility of the resonance-shift of this kind of optical sensor becomes smaller as the bandwidth of the resonance decreases, which also results in a lower detection limit [12].

As an alternative, intensity-based optical sensors may be advantageous over those based on resonance-shift. The intensity-based sensors measure the output intensity variation of a resonance peak such that the absorption due to the metal component helps to increase the performance rather than to decrease. In addition, such sensors are free from bandwidth restrictions so that they can operate in a wide-range of wavelength.

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It has been reported that a single-slot hybrid MRR hydrogen sensor provides a sensitivity 23 times higher than its counterparts [8]. However, this resonance-shift based sensor has quality-factor issues due to Pd presence which is vital for a higher detection limit as mentioned before. To solve this problem, intensity-based analysis can be performed considering advantageous over resonance-shift that is mentioned above. Therefore, in this paper, the single-slot hybrid MRR hydrogen sensor is re-analysed based on intensity changes in case of hydrogen entrance to the sensing chamber and results are discussed.

## Hybrid Micro-Ring Resonator Sensor

Proposed Geometry

The proposed hydrogen sensor geometry is presented in Figure 1. As it can be seen from Figure 1-a, the structure consists of an SOI (Silicon on Insulator) based micro-ring resonator enclosing a Pd disk with a gap distance of w_{slot} ($w_{slot} = R_{in} - R_{Pd}$). The 4-port MRR with an outer radius of R_{out} and a width of W_{MRR} ($W_{MRR} = R_{out} - R_{in}$) couples to a pair of 400 nm width bus waveguides nearby and generates whispering galley modes (WGM) within an air sensing medium. In the calculations, the refractive indices of air and silicon MRRs are used as 1.000293 and 3.476, respectively for Telecom wavelengths. The optical parameters of Pd is provided from the Reference [13].

Intensity distribution of excited WGMs in MRR is highly depended on W_{MRR}. As can be seen from Figure 1 b, c in a single mode waveguide with W_{MRR}=300 nm and W_{MRR}=400 nm, respectively, TE polarised e- field forms different distribution patterns. The figures show that the light tightly confines in a wider waveguide than in a narrower one. In addition, the evanescent field at the wider waveguide fades away within a short distance which is highly effective on sensing performance of the sensor under investigation of this paper. Therefore, in this work, sensing performance is numerically investigated based on the geometries which include two sizes of MRR waveguide width of 300 nm and 400 nm.

This study is carried out using two-dimensional Finite Difference Time Domain (FDTD-Meep) method to simulate the proposed 4-port MRR structure to investigate its hydrogen sensing potential. The computer based simulations are performed in 2D because of the limitation of resources. Even if 3D simulations are needed for real-world applications, 2D calculations allow you to see 3D performance with approximate numerical results with less resource and time consumption [14]. A grid size as small as 2 nm and sufficient working time is used for high accuracy and reliability of simulations. For calculations, we assume that the silicon MRR and the combined waveguide system are in the air sensing environment.

Operation Principle

An incident beam with Gaussian spectrum is injected into the system via input port as sketched in Figure 1 a. Excited WGMs
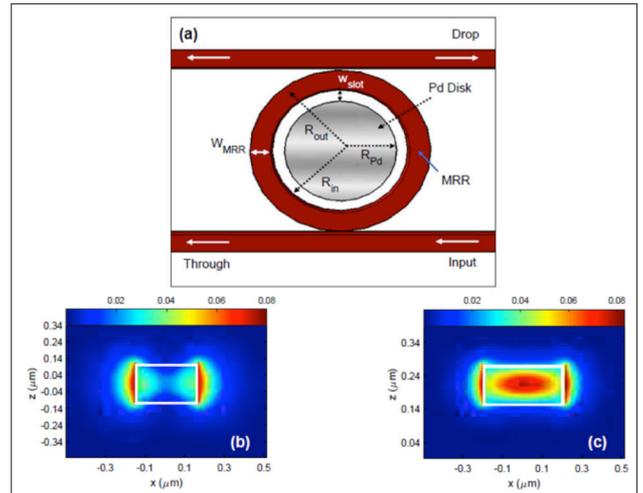

Figure 1. Schematic architecture of proposed hydrogen sensing device (a); e- field distribution at the cross-section of W_{MRR}= 300 nm (b); and W_{MRR}= 400 nm waveguide at the wavelengths of 1512 nm and 1517 nm (c), respectively
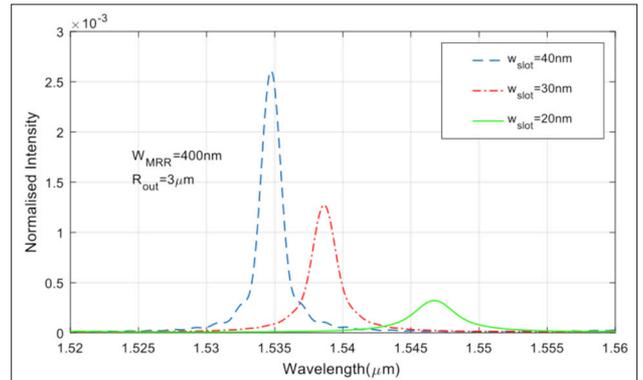
Figure 2. Resonant wavelength changes in case of w_{slot}=40/30/20 nm observed from a M_{RR} sensor with w_{slot}=400 nm and R_{out}=3 μm.

within the resonator, interact with the surrounding medium via evanescent waves, the tail of WGMs which lie along the ring cross-section, Figure 1 b, c. It is well-known that any change in sensors cladding or surrounding medium causes WGMs to shift in wavelength/frequency spectrum.

With the introduction of hydrogen to the sensing chamber, the resonance wavelength experiences a redshift as shown in figure 2. In classical perspective of sensing, this shift is directly correlated with hydrogen concentration which has already been studied [8]. It also can be seen from the figure that along with the wavelength shift there is a significant change in intensity of resonance during the sensing process. This is mainly because of the existence of Pd which as a metal possesses a complex refractive index coefficient at a wide range of wavelength causing considerable absorption. Thus, a constant flow of hydrogen into the sensing chamber causes the Pd disk to expand in diameter leading to contact more with evanescent
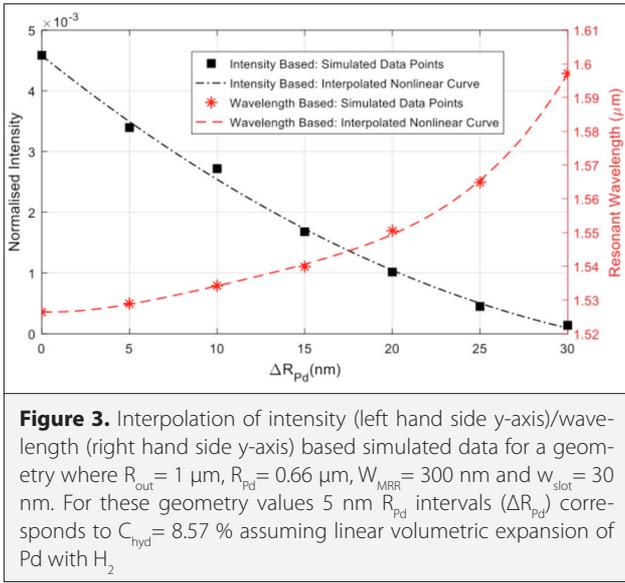
Figure 3. Interpolation of intensity (left hand side y-axis)/wavelength (right hand side y-axis) based simulated data for a geometry where R_{out}= 1 μm, R_{Pd}= 0.66 μm, W_{MRR}= 300 nm and w_{slot}= 30 nm. For these geometry values 5 nm R_{Pd} intervals (ΔR_{Pd}) corresponds to C_{hyd}= 8.57 % assuming linear volumetric expansion of Pd with H_2

field and resulting an exponential decrease in intensity of the WGMs as shown in Figure 3.

It is clear from the figure that the slope of intensity plot decreases as w_{slot} decreases (R_{Pd} increases). This means that the rate of intensity change exponentially decreases as the Pd disk approaching the MRRs inner face. This phenomenon occurs in resonance-shift based sensors in such a way that any change in w_{slot} emerges an inversely proportional effect on resonance wavelength shift, as shown in Figure 3.

In the following section, the hydrogen sensing potential of intensity-based hybrid MMR sensor is investigated for a hydrogen concentration range of 0% to 1%, a range that allows a reversible expansion in Pd.

Results

It is a fact that, palladium lattice expends 0.087 % within 1 % H_2 sensing environment [15]. In the reference of this, numerical calculations are performed for various geometry parameters of sensor. Each sensor geometry is simulated changing the Pd radius for each calculation loop assuming the change is due to the hydrogen absorption. However, the 2 nm grid size employed in this study is not sufficient for pico-meter level changes. Therefore, the simulations are performed changing the Pd size with 5 nm intervals at each calculation loop. Then, resulted ΔI (intensity change) values are interpolated by non-linear curve fitting to observe at the pico-meter level corresponding to small hydrogen concentration changes as presented in Figure 3. Under all this assumption, the relation between hydrogen concentration (C_{hyd}), in volume/volume percent (v/v - %), and ΔI is investigated.

Figure 4 shows ΔI values as a function of C_{hyd} observed from drop port of the sensors for a range of geometric parameters.

From the figure, it is seen that, both w_{slot} and W_{MRR} have a large effect on ΔI. Figure 4 a, shows that, when a 300 nm wide MRR with R_{out}=1 μm and w_{slot}=40 nm is employed, ΔI gradually increases up to 1.4×10^{-4} along with the hydrogen concentration increment in the range of C_{hyd}=0 % to C_{hyd}=1 %. This value reaches to 1.01×10^{-4} and 0.7×10^{-4} with smaller slot sizes of w_{slot}= 30 nm and w_{slot}= 20 nm, respectively. While R_{out} increases from 1 μm to 3 μm the rate of ΔI increases directly with the w_{slot} size. As presented in Figures 4 b, c; ΔI reaches higher values of 1.8×10^{-4} and 2.2×10^{-4} for devices with R_{out}=2 μm and R_{out}=3 μm, respectively when w_{slot}=40 nm. It is evidence from the Figures 4 a-c, that regardless of R_{out}, the highest ΔI rates are observed when w_{slot}=40 nm. On the other hand, the rate of ΔI in response to hydrogen concentration slightly increases for W_{MRR}=400 nm wide MRRs as compared to W_{MRR}=300 nm, as shown in Figure 4 e, f. As such, the highest shift can be obtained for a design where w_{slot}=40 nm and R_{out}=3 μm is around 2.8×10^{-4}. It needs to be noted that, in Figure 4 d the observed ΔI for the geometry with w_{slot}=20 nm and R_{out}=1 μm is higher than the one with w_{slot}=40 nm for the same radius.

This is due to the decreasing behaviour of the slope of the intensity plot for this particular geometry through the w_{slot}; other computed geometries (presented in other sub- figures) exhibit an increasing trend for the same plot. The reason for this intensity trend difference might be because of the loss (includes scattering, bending and absorption losses) rate in case of each w_{slot} value [6].

In order to determine the efficiency of the sensor, the sensitivity ($S= \Delta I/\Delta C_{hyd}$) as function of hydrogen concentration is calculated. According to the calculations, hydrogen could be detected with a sensitivity of as high as 2.20×10^{-4}/(v/v - % hydrogen) employing an R_{out}=3 μm MRR system where w_{slot}= 40 nm and W_{MRR}= 300 nm. In addition, S could be further increased up to 2.83×10^{-4}/(v/v - % hydrogen) with same R_{out} and w_{slot} but a wider resonator width of W_{MRR}=400 nm.

Another factor to describe the performance of an optical sensor is the Limit of detection (LOD) which is the lowest concentration of hydrogen that can be distinguished from the zero concentration level. LOD of proposed intensity-based sensor is calculated based on the standard deviation of the response (L_r) of each linear curve and the slope of the calibration curve (L_{sl}) of ΔI vs C_{hyd} at levels approximating the LOD according to the formula LOD=$(3.3 \times L_r)/L_{sl}$ [16]. L_r is determined based on the standard deviation of y-intercepts of regression lines and both L_r and L_{sl} are computed via MS Excel. It is found that the intensity-based hybrid MMR sensor offers an LOD of 9.93×10^{-3} for a geometry that present highest sensitivity. In comparison with this study, the LOD of the most sensitive geometry in reference [8] is also calculated with the same theory and found to be 7.16×10^{-2} which is around 10 times higher than the one with intensity- based sensing.
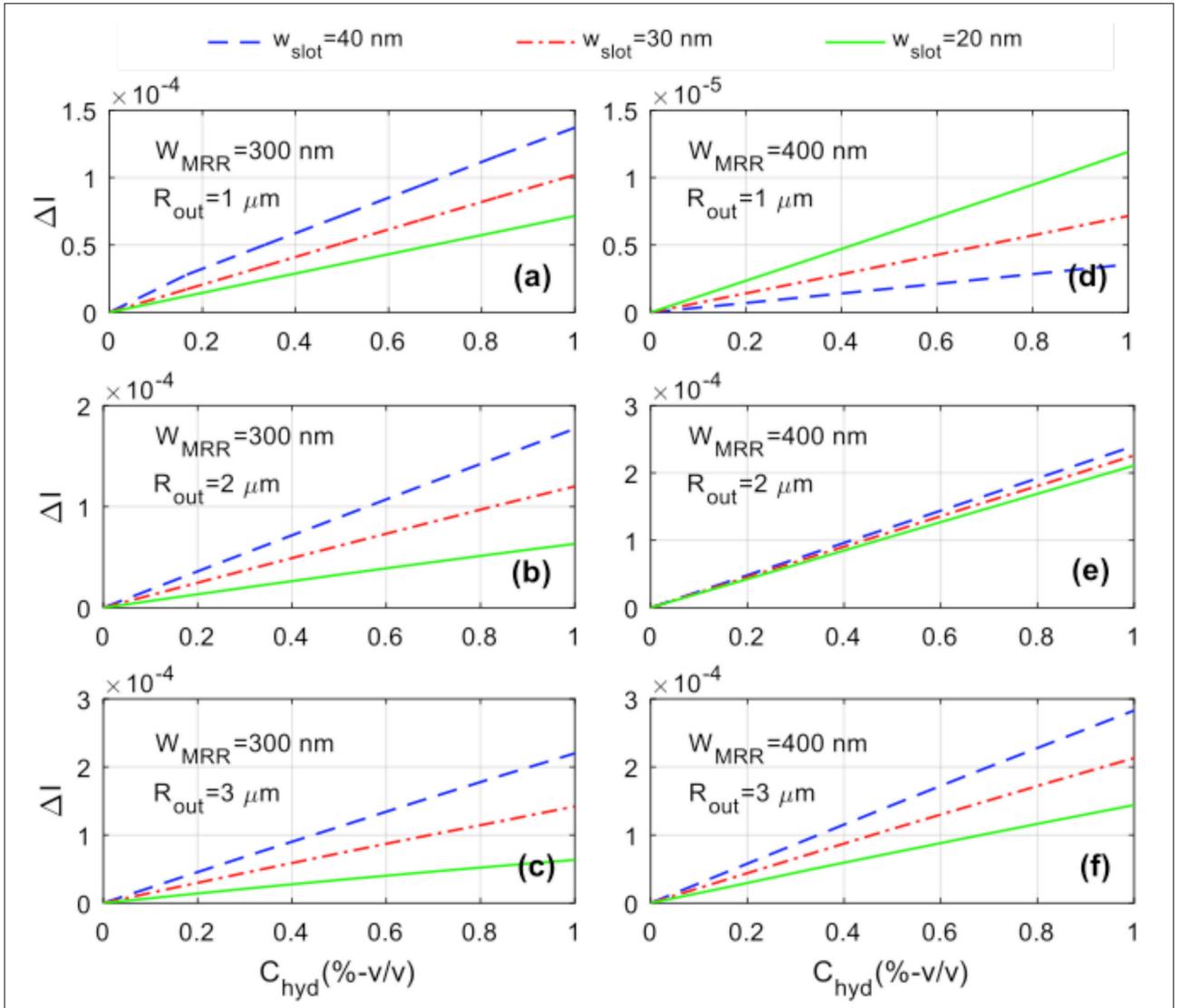
Figure 4. a-f. Intensity changes observed from an M_{RR} of, R_{out}=1.00 µm and W_{MRR}=300 nm (a); R_{out}=2.00 µm and W_{MRR}=300 nm (b); R_{out}=3.00 µm and W_{MRR}=300 nm (c); R_{out}=1.00 µm and W_{MRR}=400 nm (d); R_{out}=2.00 µm and W_{MRR}=400 nm (e); R_{out}=3.00 µm and W_{MRR}=400 nm as a function of C_{hyd} for various wslot values (f)

Conclusion

This paper presents a numerical study of a hybrid MRR system for hydrogen sensing purposes based on intensity change. The sensitivity of 2.83×10^{-4}/% hydrogen and the LOD of 9.93×10^{-3} testify the high performance of intensity-based hybrid sensor in hydrogen gas sensing. Thus, the suggested novel technique is highly promising with its sensitive, highly reliable, compact, robust, low cost and small footprint hydrogen detection ability.

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