Porous SiO_2 cladding for novel PIC-based humidity sensor

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Photonic integrated circuit (PIC) based humidity sensors have been interesting for many applications because of their small footprint, high-sensitivity and immunity to electromagnetic interference. Here we report on a novel humidity sensing technology based on water adsorption in porous SiO_2 that is compatible with any commercially available PIC platform. A micro-ring resonator is used to sense the adsorbed water and hence the air humidity. The shift in resonance wavelength indicated a good correlation with relative humidity conditions varying between ~24-40%.

Introduction

Humidity sensors are one of the most needed sensors for industries such as food, automotive, agriculture and semiconductor processing where the ability to measure small variations in humidity is crucial [1]. Nowadays there are different types of humidity sensors available. Most used is a sensor which measures the Relative Humidity (RH) [2]. Most commercially available humidity sensors available are electric or mechanical, but these have many disadvantages including size and inaccuracy [3]. To solve these issues, humidity sensors implemented with photonic integrated circuit (PIC) technologies can be a good alternative. Because PIC-based sensors offer advantages like high sensitivity, immunity to electromagnetic interferences and a smaller footprint compared to electronics-based sensors and fiber-optic sensors. Additionally, multiple sensors can be integrated into a single PIC chip [3]. In this work, a novel technique for realizing an RH sensor using PIC technology is presented. This technique is established on the usual water adsorption properties on the hydrophilic silicon oxide (SiO_2) surface [3,4]. It has been reported that this adsorbed water layer thickness can vary between 0.5 nm to 1.5 nm with respect to relative humidity varying between 20% to 70% at room temperature conditions [4]. This varying adsorbed water thickness depending on the relative humidity can affect the light-guiding mode in a waveguide if placed in close proximity. By increasing the surface area, the sensitivity to this change can be potentially enhanced. Therefore a porous material *i.e.* low-quality SiO_2 is used as cladding on a photonic device that has nano-pores in the layer which increases the total surface [5]. Based on this idea, a proof-of-concept demonstration of a PIC-based relative humidity sensor is made with porous SiO_2 cladded on standard hydrogenated amorphous silicon (a-Si:H) based micro-ring resonator (MRR).

Experimental details

For the fabrication of the photonic device, crystalline silicon wafer (<100> orientation, 525 µm thick, p-type) was used with 2 µm wet thermal oxide. A hydrogenated amorphous silicon layer of 210 nm thickness was deposited by inductively coupled plasma-enhanced chemical vapor deposition (ICP-PECVD) at 80 °C [6]. The MRR was fabricated by patterning with an electron-beam lithography system and dry-etched using a reactive ion etching (RIE) system. The 25 µm radius MRR consists of *a*-Si:H waveguide that is 480 nm in width by 210 nm in height. The SiO_2 cladding was deposited using an ICP-PECVD system with a deposition temperature of 80 °C. The thickness of the cladding was 590 ±

10 nm with a refractive index of n=1.388 at 1550 nm which was determined using a spectroscopic ellipsometry measurement. This indicates that the SiO_2 layer is porous in nature as the refractive index is low compared to standard thermal SiO_2 (n=1.445 at 1550 nm). A graphical representation, with an intersection of the chip is given in Figure 1.

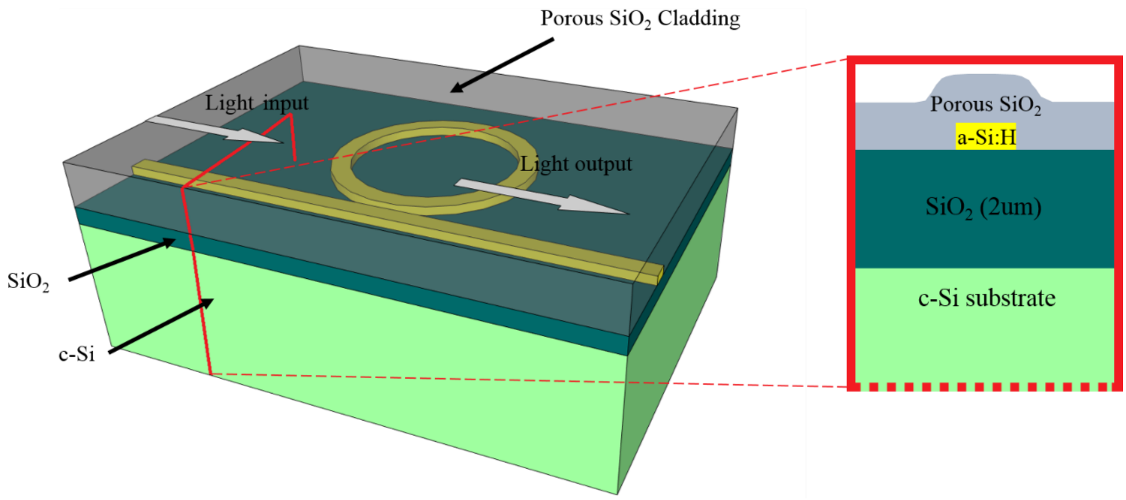

Fig. 1 A visual representation of the design consisting of an MRR with a porous SiO_2 cladding. At the right, a cross-section of the waveguide with cladding is presented.

The MRR was measured in a PIC vertical coupling setup, where two fiber probes are placed on the grating couplers to direct the light through the MRR as shown in the setup of Figure 2. The chip is placed on top of a temperature controller to secure a constant temperature of 21.95 ± 0.03 ^{0}C during the measurement (Fig. 3b). First, the light passes through a polarization controller (PC) to allow only one polarization to go through. The optical attenuator (OA) controls the input power that can go into the PIC. To prevent reflections into the system an optical circulator (OC) is used. A Fiber Bragg grating (FBG) creates a stable resonance at one wavelength and therefore it can be used as a reference external to the chip. A tunable laser source (HP 81989A) was used scanning the spectrum between 1541 to 1553 nm with a 0.02 nm step size. The corresponding laser power intensity was measured using a power sensor (HP 81532A). The measured spectrum of one the fabricated MRR is shown in Figure 3a.

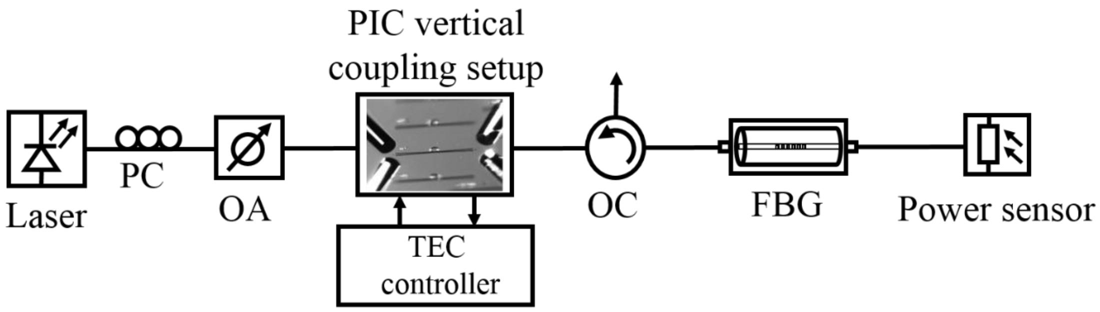

Fig. 2 The measurement setup used for characterizing MRR.

In the measured spectrum, the position of one MRR resonance was analyzed over time to see the movement. To measure the response of the device corresponding to relative humidity, every half hour measurement of the MRR was done. For the RH measurement, a wall-mounted Honeywell [70NR010MT-125HRL] sensor is used which measured the RH every hour.

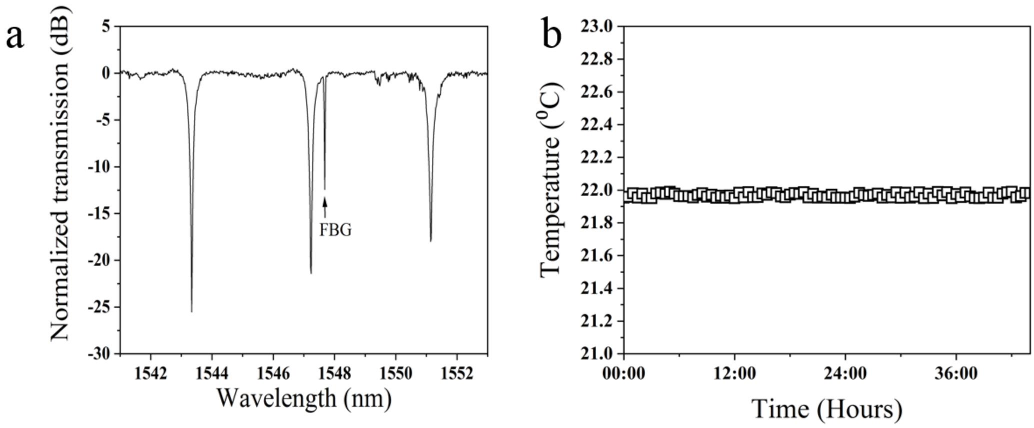

Fig. 3 (a) The measured spectrum of the MRR where the shift of the resonance notches are used to track the change in wavelength. A Fiber Bragg Grating (FBG) is used as a reference notch. (b) The temperature variation during the MRR measurements, which stayed constant at around 21.95 ± 0.03^{0}C.

Results and discussion

The non-cladded MRR measurements showed no correlation between the resonance wavelength (λ_{res}) and RH, for RH changing between 20 and 37% (Fig. 4a), when measuring for 16 hours. On the other hand, the porous SiO_2 cladded MRR did show a clear correlation between the RH and the wavelength (Fig. 4b). The λ_{res} of the MRR red-shifted from 1546.7 nm to 1547.4 nm with increasing RH from 27 % to 39 % as shown in Figure 4b, which indicates that the effective refractive index of the guiding mode increased as more water was adsorbed within the porous SiO_2. The λ_{res} responds quickly to changes in humidity, both for rising and falling values, which is essential for its application as a sensor. The humidity was measured from a standard Honeywell wall-mounted sensor, which was not placed close to the PIC. This may contribute to the discrepancy in the measured MRR response and RH.

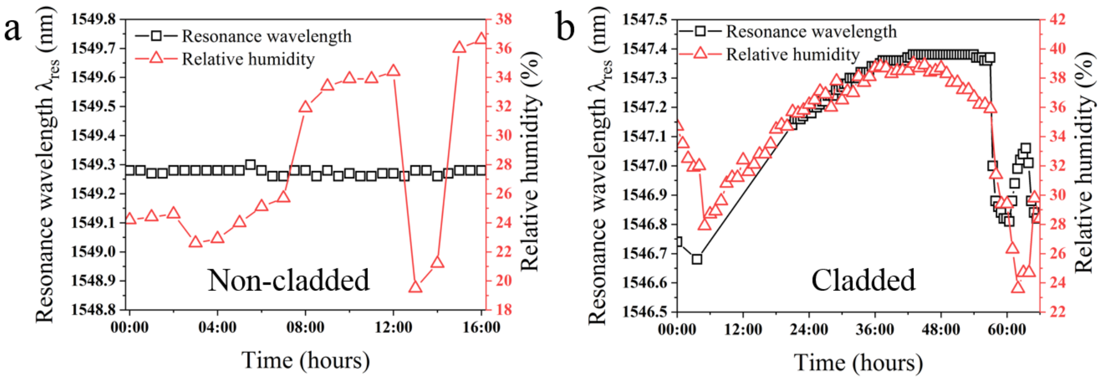

Fig. 4 Correlation between the resonance wavelength and relative humidity (RH) of a non-cladded (a) and a porous SiO_2 cladded (b) micro-ring resonator (MRR). Where the resonance wavelength of the cladded MRR does follow the behavior of the RH change over time.

The measurements indicate that the cladding causes the correlation between the λ_{res} and RH. The reason for this can indeed be the bounding of the water molecules to the porous SiO_2 surface replacing air. As the refractive index of water is higher than the refractive index of air the total refractive index of the cladding will increase. As a result, with increasing relative humidity, the effective refractive index of the MRR waveguide guided mode the will increase and cause an increase in λ_{res} (red-shift). Alternatively, decreasing RH will result in blue-shift of the λ_{res}. Further research is needed to optimize the performance of such a senor implementation in terms of sensitivity, reproducibility and whether this gives better results when compared to a regular RH sensor. Different parameters such as thickness and material porosity can be investigated which can potentially yield improvement in higher sensitivity and suitable for a large range of RH variation.

Conclusion

The work presented here demonstrates that porous SiO_2 cladding adsorbs humidity over a large range and that can affect an underlying resonant photonic integrated device. A micro-ring resonator will show measurable shifts in its resonance as a result of the change in the refractive index of the cladding which is demonstrated as the relative humidity changed between ~24-40%. We believe that the principal demonstrated here can be used for humidity sensing applications in most, if not all commercially available PIC platforms due to the fact that the SiO_2 is practically available for all semiconductor processing foundries.

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