

On-chip interrogation of a silicon-on-insulator microring resonator based ethanol vapor sensor with an arrayed waveguide grating (AWG) spectrometer

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ABSTRACT

Silicon-on-insulator (SOI) optical microring resonators fabricated with the standard CMOS fabrication technology have recently gained considerable attention for energy efficient, compact and low cost biomedical and environmental sensing applications. High sensitivity to the surrounding refractive index variations, high compactness, direct wavelength multiplexing capabilities, simplicity, and the promise for mass fabrication are among the interesting features supported by SOI microring resonators. On the other hand, despite the strong case for microring resonators for sensing, there exist some issues which need to be addressed in order to ensure the feasibility of such sensors. One major limitation currently is the cost of optical sources and/or spectrum analyzers required to drive and interrogate these sensors. Either expensive light sources or spectrum analyzers are usually used with sensors built around microring resonators. An attractive approach to address this problem is the use of on-chip spectrometers along with cheap broadband light sources. We experimentally demonstrate on-chip interrogation of an SOI microring resonator based gas sensor with a compact Arrayed Waveguide Grating (AWG) spectrometer. We have designed and fabricated a 200GHz AWG with strongly overlapping output channels, and used it to interrogate the wavelength shift from a ring resonator based ethanol vapor sensor on the same chip. Ethanol vapor concentrations in 100-1000ppm range are readily detected by monitoring the intensity ratio between two adjacent AWG channels to which the microring resonance overlaps. Such an integrated sensor-interrogator approach is presented as an alternative to the current costly and off-chip read-out systems used for ring resonator based sensors.

Keywords: On-chip spectrometer, arrayed waveguide grating, microring resonator, silicon-on-insulator, gas sensor, ethanol

1. INTRODUCTION

Portable and low cost sensing technologies are sought to provide attractive solutions to a number of challenging applications today. Patient health care and light weight applications are some interesting areas where compact gas sensors can potentially play a significant role. Among different gas sensing technologies available today, optical sensors are attractive from several aspects such as low power consumption and light weight. Recent advancements in integrated photonic structures and device fabrication have opened new opportunities in various industrial, environmental and medical applications. Silicon photonic devices in particular are highly attractive owing to features such as compatibility with CMOS fabrication technology, high compactness, multiplexing capabilities and potential for low power operations. Integrated bio-chemical and gas sensing is one of the areas where photonic sensors fabricated on silicon on insulator platform have recently drawn a considerable interest. Exploiting the benefits of the well-established CMOS fabrication technology, and the high index contrast material system, Silicon-on-Insulator (SOI) micro-optical sensors are highly promising for ultraportable and low cost sensor implementation. SOI microring resonators (MRRs) in particular are very attractive for sensing. Microring resonators are characterized by interesting features such as high sensitivity to the surrounding refractive index variations, readiness for wavelength multiplexing, and compactness [1,2]. Gas sensors based on microring structures have been recently demonstrated [3]. On the other hand, despite the considerable potential, there exist some technological issues to be addressed in order to ensure the feasibility of MRRs for sensing applications. The current trend is that, expensive tunable laser light sources or spectrum analyzers are commonly employed for operation and interrogation of MRR based sensors [1,2]. An attractive low cost and compact alternative can be a

broadband source driven and on-chip interrogated sensor system. Taking advantage of current advancements in on-chip spectrometers such a goal can potentially be attained. Integrated Planar Concave Gratings (PCGs) and Array Waveguide Gratings (AWGs) have been widely studied and used for wavelength division multiplexing applications [4]. In contrast to PCGs, narrow channel spacing AWGs can be realized on much smaller footprints on an SOI platform providing convenience for compact device implementation [4]. Different techniques based on AWGs have been recently reported for wavelength shift interrogation in Fiber Bragg Grating sensors [5-7]. In previous demonstrations, either silica based AWGs or larger footprint high resolution SOI AWGs were used. Moreover, the application of such interrogators for on-chip sensors such as ring resonators has been barely demonstrated. By monitoring the intensity ratios between two adjacent channels of a high resolution, 0.18nm channel spacing SOI AWG, it has been demonstrated that very small wavelength shifts from an FBG sensor can be interrogated [6]. However, such a high resolution comes at the cost of larger device size (8mm x 8mm), and the reported insertion loss was high. In addition, for very sensitive sensors, where large resonance shifts can be achieved at low analyte concentrations, moderate channel resolutions offer a better dynamic range for interrogation with intensity ratios. Here, we demonstrate that a 1.6nm channel spacing AWG designed to have broad spectral response can be used to interrogate very sensitive MRR based gas sensors. The AWG used in this work, which is fabricated on a chip consisting of the MRR sensor and several other structures, takes a footprint of only 500 μ m x 200 μ m. The MRR based gas sensor is coated with a porous ZnO nanoparticle film for ethanol vapor detection. The ZnO nanoparticle suspension is prepared by colloidal chemistry. Ethanol vapor concentrations in 100ppm -1000ppm range are readily monitored with our sensor–interrogator system by measuring the intensity ratios between adjacent AWG channels.

2. SENSOR INTERROGATION SCHEME

Our AWG-interrogated MRR sensor system is designed such that the drop port of the microring resonator serves as an input to the AWG spectrometer. The AWG design is tailored to have strongly overlapping adjacent output channels. As a result, the MRR resonance can simultaneously be detected at any two of such overlapping channels around the resonance wavelength. Ultimately, variations in the intensity ratio between these adjacent channels can be used to measure the MRR resonance shift due to environmental effects such as gas adsorption in coating materials.

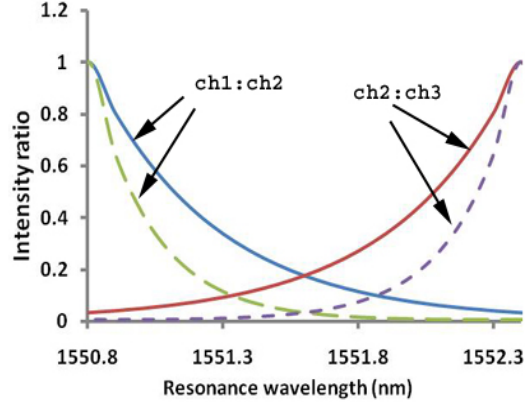


Figure 1. Given three neighboring AWG channels centered at 1550nm, 1551.6nm and 1553.2nm, theoretical estimates of intensity ratios between adjacent channels as a function of the MRR resonance wavelength for Gaussian profiles of 1.5nm FWHM (dotted lines), and 2nm FWHM (solid lines)

Approximating the MRR resonance and the AWG channel response by Lorentzian and Gaussian profiles, respectively, equation 1 can be used to estimate the intensity ratio variations between the kth and (k+1)th channels with the resonance shift [5, 6].

$$\frac{I_k}{I_{k+1}} = \frac{\int_0^{\infty} T_{MRR}(\lambda) \cdot T_{AWG}(k, \lambda) \cdot d\lambda}{\int_0^{\infty} T_{MRR}(\lambda) \cdot T_{AWG}(k+1, \lambda) \cdot d\lambda} \quad 1$$

Where, $T_{MRR}(\lambda)$, $T_{AWG}(k, \lambda)$, $T_{AWG}(k+1, \lambda)$ represent the transmissions from the MRR drop port, kth AWG channel and (k+1)th AWG channel respectively, at an arbitrary wavelength, λ .

For instance, for a MRR with a FWHM of 0.05nm and a 200GHz AWG, figure 1 show how the intensity ratio evolves across three neighboring AWG channels centered at 1550nm, 1551.6nm and 1553.2nm, as a function of the resonance wavelength. The solid and dotted curves show values calculated for Gaussian channel profiles with FWHM of 2nm and 1.5nm, respectively.

Most importantly, figure 1 demonstrates that sufficient channel overlap is crucial in order to achieve well-resolvable power ratio changes corresponding to small resonance shifts. This criterion is more critical for a MRR with a very narrow resonance bandwidth, and the effect becomes apparent as the resonance shifts further towards the center of a channel.

3. DESIGN AND FABRICATION

In an AWG-interrogated MRR sensor configuration, the drop port of the microring resonator is connected to an AWG input port. The AWG is designed such that its adjacent output channels overlap significantly, so the MRR resonance will consequently be detected at any two of such overlapping channels. Ultimately, the variations in the intensity ratio between the adjacent channels can indicate the MRR resonance shift due to environmental effects.

For wavelength shift interrogation, fairly sharp response is required while maintaining an adequate channel overlap. In such an application, a simple broad input waveguide can be used to obtain broader channel profiles. In this work, a 16 channel, 200GHz (1.6nm channel spacing), AWG is designed such that the output from a MRR drop port overlaps with any two adjacent channels. For this particular sensor interrogation application, an adiabatically tapered input waveguide with start width of 0.45 μ m and a broader end width of 4 μ m is chosen in order to broaden the channel response, and hence, enhance the overlap between adjacent channels. Fig. 2 shows an optical microscope image of the fabricated AWG interrogated ethanol vapor sensor.

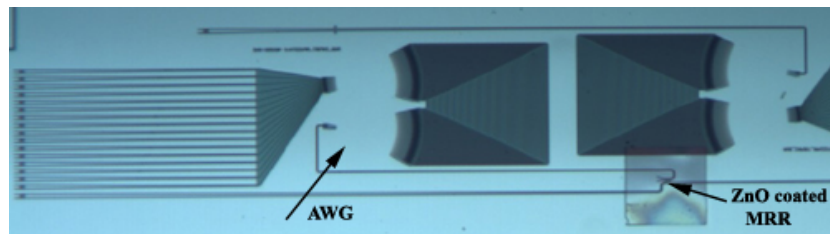


Figure 2. An optical microscope image of the AWG interrogated ethanol vapor sensor with ZnO porous film on the MRR. The AWG used for the spectral response characterization is partially shown in the image.

Silicon microring resonator used here for gas detection has a radius of 5 μ m, and has been designed to operated in the telcom range near 1550nm. The bus and ring waveguides are 220nm high and 450nm wide in dimension. For coupling light in and out of the rings, grating couplers are connected to the bus waveguides through adiabatic tapers. The fabrication of the sensor –interrogator system has been done in a standard CMOS fabrication facility at IMEC-Leuven. The standard fabrication process starts with wafer scale photo-resist patterning of a silicon –on-insulator substrate through 193nm deep-UV lithography. The nano/micro optical structures are later on formed by dry etching the top 220nm thick silicon layer. The SOI substrate consisted of a 2 μ m thick SiO₂ layer sandwiched between the top silicon layer and a bottom silicon substrate [3].

For coating with gas sensitive chemical films, the optical chips are lithographically patterned with a photoresist. After the coating step , the photoresist is removed with lift-off process leaving local films on the rings.

In this work gas sensitivity is achieved by about 240nm thick porous ZnO film locally coated on a MRR. The ZnO film is prepared from colloidal nanoparticles suspended in ethanol. The porous nature of the film offers a large surface area for gas adsorption. The detailed nanoparticle synthesis and sensitive film preparation procedures are presented in [2].

4. EXPERIMENTAL RESULTS

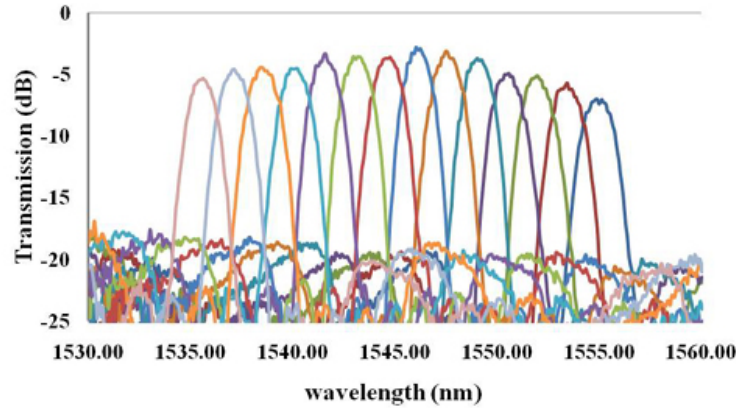


Figure 3. Normalized transmission spectrum of an AWG with 4 μ m wide input waveguide

For the purpose of preliminary studies on the AWG channel response, an additional AWG is fabricated on the same chip without a ring attached to it. The spectral response from an AWG with a 4 μ m input waveguide measured with a superluminescent LED (SLED) and a spectrum analyzer is shown in fig. 3. The transmission is normalized to that of a 450nm wide photonic waveguide on the same chip. The insertion loss for the central channels is about -3dB, and the nearest neighbor cross talk is around -17dB, which is of a typical order for such compact SOI AWGs. Notably, a strong overlap between neighboring channels is achieved as sought in this application. The 3dB bandwidth of a channel response is approximately 2.3nm with over 0.9nm overlap with channels at either side.

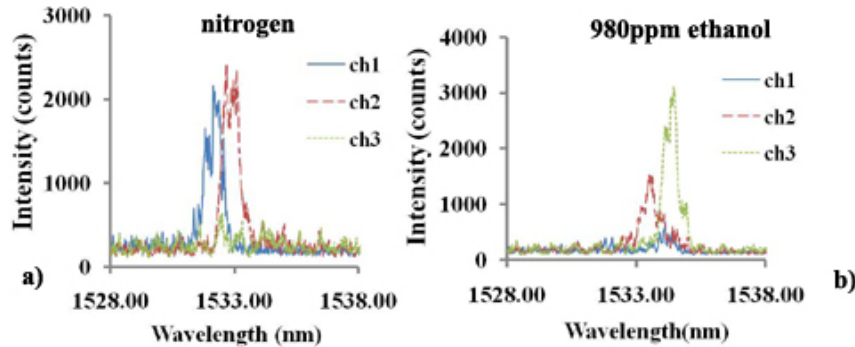


Figure 4. Illustrations of intensity changes measured from three neighboring channels: a) at 0ppm(pure nitrogen), b) at 980ppm ethanol vapor concentrations.

In the eventual sensing system, the broadband source and the detectors will be co-integrated with the sensing chip. However, for the present experiment the sensing chip is placed in a small gas chamber and the light source and the detector were kept outside. Vertical coupling through gratings is used to couple light in and out of the sensor. The top side of the gas chamber is covered with a glass window to facilitate the coupling. While a single mode fiber is used for in-coupling, the output light is collected by an Infrared Camera. Further details on the setup are presented in [3]. The measurement accuracy of this setup is highly influenced by the noise due to the light which is scattered from the sample surface and reaches the camera. Due to the typically low power spectral density of a broadband source, we have chosen to use a tunable laser source of about 3mW to couple sufficient light through the glass cover. Operating at such low powers reduces the noise on the camera measurement and allowed us to characterize the device in a gas environment.

The output intensities from three consecutive AWG channels are simultaneously monitored before and after exposure to 120ppm, 240ppm, 480ppm and 960ppm ethanol vapor concentrations. Figure4 illustrates how the intensity across

adjacent channels changes with changing gas concentration. The noisy features are due to the distant coupling through the glass window, and the scattered light.

The average intensity measured from each channel is then used to calculate the fractional intensity between adjacent channels at a given gas concentration. To better visualize the relation between the resonance wavelength and the intensity ratios, the resonance shifts at these vapor concentrations are recorded from the MRR through-port. Figure 5a depicts the average channel intensities as a function of vapor concentration, and figure 5b shows the intensity ratios calculated at the corresponding measured resonance shifts. The solid line in figure 5b is an exponential fit to the ratios between channels 2 and 3.

As observed on figure 5, fairly smooth transition from a pair of adjacent channels to the next pair is readily achieved indicating a good overlap between neighboring channels. More interestingly, the third channel emerges to take part in the play as the intensity ratio between the first two channels begins to fall below 0.2, which is comparable with the simplified theoretical estimate for a 2nm FWHM AWG as shown in figure 1. The 3dB bandwidth of the MRR measured at the through port is less than 50pm. While our on-chip sensor-interrogator system is very suitable for highly sensitive gas sensors as demonstrated in this work, it can as well be used to detect small resonance shifts. From the trend shown in the figure 4b, resonance shifts of 20pm to 800pm should be readily interrogated with the ratio between just two channels.

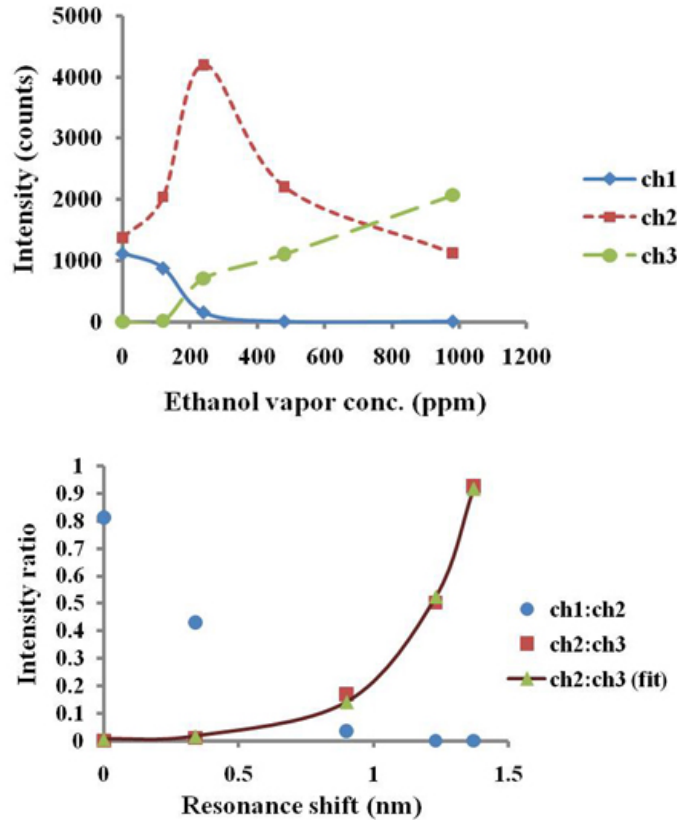


Figure 5 a) average intensities measured from three channels at different ethanol vapor concentrations, b) calculated intensity ratios as a function of resonance shifts corresponding to vapor concentrations shown in fig (a) with an exponential fit to ch2:ch3 (solid line)

5. CONCLUSION

On-chip read-out of a silicon microring resonator based gas sensor is demonstrated. An SOI microring resonator is coated with ZnO nanoparticle film for ethanol vapor detection and a compact on-chip AWG spectrometer is used to interrogate the resonance shift upon interaction with gas molecules. The 200GHz AWG used in this work is designed in such a way that its adjacent output channels strongly overlap. As a result, shifts in the microring resonance have been

tracked by monitoring intensity ratio changes from two adjacent AWG channels. Ethanol vapor concentrations in 100-1000ppm range are readily detected with our sensor-interrogator system. Such an on-chip interrogation system presents itself as an attractive solution to the current interrogation challenges, and opens opportunities for low cost and compact implementation of microring based sensors

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