Graphene-Coated Microring Resonator (MRR)-based Gas Sensor using Novel Intensity-Level Detection for low-cost, rapid, and label-free Sensing: Preliminary Simulated Results

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Abstract

Almost all current microring resonator (MRR) based sensors rely on a wavelength shift detection scheme. This involves (i) expensive tunable lasers as an input source and (ii) optical spectrum analyzers as a detector, which leads to overall bulky configuration, high cost, and complex arrangement. Here, we propose a low-cost, tapered waveguide MRR-based gas sensor that uses a simple intensity-level detection method. It employs (1) a low-cost laser source and (2) a photodetector. The MRR is coated with graphene to detect the specific target element. This design can significantly reduce the overall cost and complexity of the sensing system.

1. Introduction

Rapid, simple, high accuracy and low-cost bio/chemical/gas sensors are immensely important for food safety, environmental monitoring, and other diagnostic applications. Optical microring resonator (MRR)-based sensors are very attractive because of their advantages such as massive replication (fabrication), low cost, small size, rapid detection, and high accuracy. However, these existing MRR-based sensors rely on expensive wavelength shift detection schemes [1-3] to obtain high accuracy. Fig. 1 shows the typical wavelength shift detection scheme comprising expensive equipment needed such as (i) tunable lasers as a laser source, (ii) spectrum analyzers as a detecting tool, and (iii) computers for data acquisition and signal processing. This leads to overall high cost, bulky configuration, and complicated sensing systems.

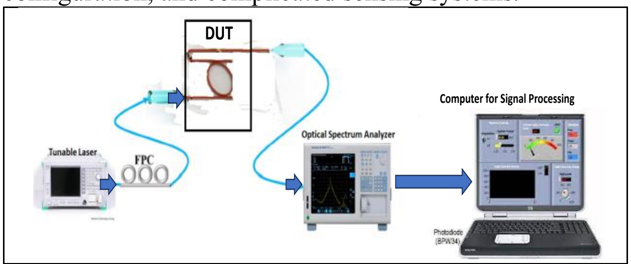

Figure 1. Conventional detection for DUT (such as MRR–based sensors) consists of expensive (i) tunable lasers, (ii) spectrum analyzers, and (iii) computers for data signal processing, which leads to high cost, bulky set-up, and complicated sensing systems.

The inset of Fig. 2a shows the typical measurement of the wavelength shifting technique. However, there are lots of sensor applications that do not require high-precision measurement but just only low-to-modest precision. It needs to detect only the presence or absence of some target element at a certain threshold level. For these applications, there is a need to simplify the detection method to reduce the overall cost.

In this paper, we introduce a new economical and straightforward approach using a simple intensity-level detection scheme rather than the wavelength shift detection for the MRR sensors in general and gas sensors in particular, as shown in Fig. 2b. It involves three stages. First, we design a low-loss MRR without any graphene coated which is depicted by the first figure (1) in Fig. 2b. This gives a sharp intensity Lorentzian profile. If we coated it with graphene but without any target material present, the final intensity profile is reduced as shown in figure (2) in Fig. 2b. However, if there is the presence of the target element, the intensity profile increases (with some deformation) in intensity-level profile as depicted by figure (3) in Fig 2b. The intensity-level changes can be detected by the photodetector. This detection scheme uses (i) fixed low-cost laser sources instead of expensive tunable laser sources, (ii) plain photodetector instead of spectrum analyzers, and (iii) On-Off LED instead of computers for signal processing. This significantly reduces the overall cost and complexity of the system.

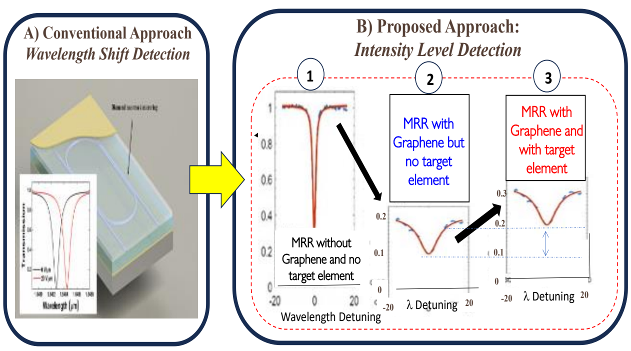

Figure 2. Summary of change-of-approach from (a) wavelength shift detection to (b) Intensity-level detection scheme using MRR sensor

2. Design of MRR-based Sensor

Fig. 3 shows the proposed MRR sensor design which features a low-loss microring tapered waveguide with optimizable width to enhance its interaction with target elements.

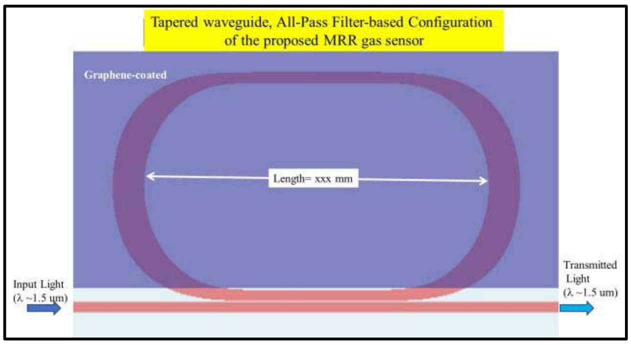

Figure 3. Schematic of the proposed MRR–based gas sensors. Front view of Graphene-based Tapered MRR with dark blue (upper) indicating Graphene coverage and lighter blue indicating no graphene coverage. Radii is 20 um, the tapered outer angle is 10 degrees, the inner angle is 120 degrees. The smallest width is 0.5 um, thickest is 1.75 um.

The MRR waveguide is coated by graphene which is used as the sensing/capturing material. When a target gas is present, the coated graphene undergoes a notable change in its conductivity properties, which are highly dependent on the chemical composition of the target gas. This interaction shifts in graphene's Fermi level, a critical factor in determining its electronic properties. As the Fermi level changes, it alters the way the waveguide mode (within the coated graphene) interacts with the propagating light. In short, the propagating modes in the waveguide lose more energy through evanescent waves (as well as shift its resonance wavelength), which is detectable as an intensity change of the final transmitted output of the MRR.

3. Graphene

A significant challenge in developing graphene-based photonic microring gas sensors is identifying graphene variants with strong gas binding properties. Fig. 4 shows the various graphene types, such as Pristine Graphene (a), Boron-doped Graphene (b), Nitrogen-doped Graphene (c), and Defective Graphene (d) have been previously investigated for their binding efficiencies, with the Defective graphene demonstrating strong binding with NO, NO_2, and NH_3 [4].

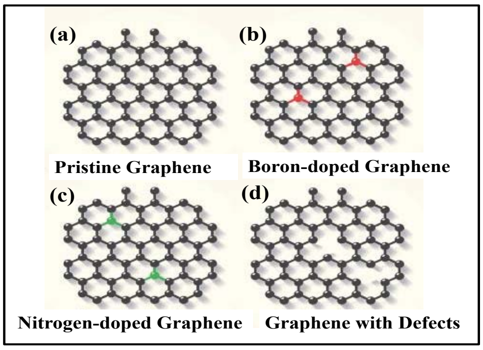

Figure 4. Various graphene types for use as gas adsorbing material, in which graphene with defects (d) show the most promise.

The material model used in the simulations is based on the analytic permittivity material model of Falkovsky (mid-IR) for graphene. It is defined by a set of parameters (x_1 to x_8) representing physical constants as well as properties and dimensions of graphene as seen below [5].

$$\varepsilon_{xx} = \varepsilon_{yy} = x_6 - \frac{x_1^2 x_3}{\pi x_2^2} \frac{w}{w^2 + \left(\frac{x_1 x_4^2}{x_5 x_3}\right)^2} \frac{1}{w x_8 x_7} + i \frac{x_1^2 x_3}{\pi x_2^2} \frac{w}{w^2 + \left(\frac{x_1 x_4^2}{x_5 x_3}\right)^2} \frac{x_1 x_4^2}{w x_5 x_3 x_8 x_7}$$

where the terms ε_{xx} and ε_{yy} are components of the permittivity tensor in the graphene layer, representing the diagonal component, linked to the material's response to electric fields in specific directions. It's critical to accurately define these parameters to ensure the fidelity of the model in the simulations.

As shown in Fig 3, the entire graphene is coated at the top of the Silicon/Silicon nitride resonator. Furthermore, we introduced a novel aspect into this design by embedding the Silicon/Silicon nitride layer into SiO2. This integration, while necessitating the development of new fabrication techniques, offers a more streamlined and efficient approach to resonator construction, enhancing both its performance and manufacturability. This design balances technical sophistication with practical manufacturability. Fig. 5 shows the simulated result of the interaction of the TM mode with the graphene layer.

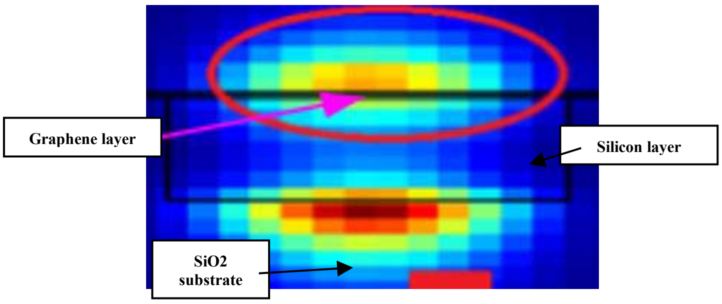

Figure 5. TM Mode interaction with graphene layer (encircled). Pointed arrow is the graphene layer on top.

4. Simulated Results

The interaction of gases with graphene is crucial in the context of a ring resonator, as it directly influences the intensity response of the resonator. The change in the intensity response is a result of the modified interaction between the mode and the graphene, which is now in a different electronic state due to the adsorption of gas. This phenomenon makes graphene an effective material for sensing applications, particularly in ring resonators, where the detection of gas presence and concentration is indicated by the change in intensity response, providing a sensitive and reliable means of gas detection. Preliminary simulations have identified specific frequency ranges (yellow-colored region as shown in Fig. 6). These are more effective for detecting intensity changes. The effectiveness of this approach is further highlighted by simulations conducted using ANSYS Lumerical software.

As shown in Fig. 6, we observed that at specific frequencies from 1.505 um to 1.510um (yellow-colored region), the transmission of light through the graphene-layered resonator exhibited noticeable variations corresponding to the presence of a different concentration of gas as indicated by the different Fermi levels of graphene (~0 eV, 1.5 eV, 3 eV). This variation in transmission is a direct indicator of the graphene's interaction with different gases, as the Fermi level changes reflect alterations in the graphene's electronic properties due to gas adsorption.

This finding underscores the potential of intensity-based detection methods in identifying the presence of specific gases and determining their concentrations. The challenge now lies in expanding the range of frequencies where this detection method is effective.

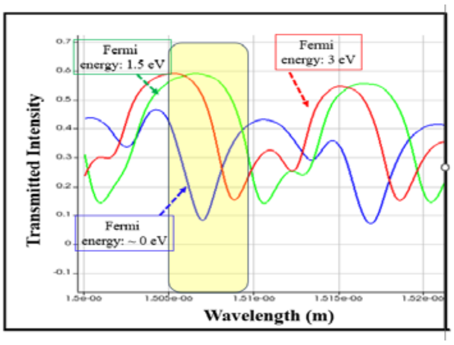

Figure 6. Preliminary result of the normalized transmission response for the tapered microring resonator with different gas concentrations indicated by the different graphene Fermi levels [~0 eV (blue colored= no gas presence), 1.5 eV (green-colored curve), 3 eV (red-colored curve).

More work is needed to optimize graphene's properties to ensure high accuracy and to optimize the waveguide structure of the sensor. Fig. 7 shows the TM mode interacting with the sensing graphene layer.

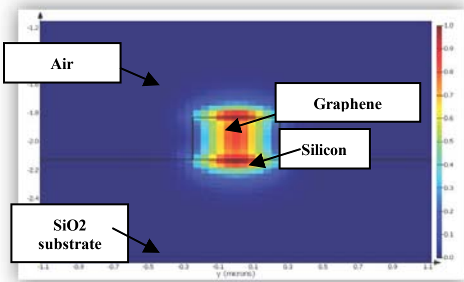

Figure 7. Optimizing the ring resonator's waveguide thickness to increase energy distribution of TM mode interacting with sensing graphene layer.

The current challenge involves optimizing the resonator's radius (approximately 10-15 um) to enhance the detection range for different graphene Fermi levels.

6. Challenges

The development of the graphene-based microring sensor resonator focuses on optimizing energy distribution to enhance its sensing capabilities. This involves reducing energy in the SiO2 substrate and increasing it in the upper layer where it interacts with graphene, thereby improving the sensor's responsiveness to gas adsorption.

The current research efforts concentrate on refining the sensor's design. We are also working on enhancing the sensor's sensitivity and selectivity for different gases, which would expand its application scope. Overall, the sensor's potential applications, especially in environmental monitoring and safety, are compelling due to its low cost, simplicity, and efficiency.

7. Conclusion

We proposed a new intensity-level detection, graphene-coated MRR sensor which can significantly advance the gas detection solutions for environmental monitoring and industrial safety practices. The design is advantageous due to its simplicity, reduced cost, and the elimination of complex fabrication processes. It can be a promising tool for a wide range of applications. However, addressing other crucial challenges like the sensor's potential reusability (due to graphene chemistry) is another crucial step to fully maximize its potential.

6. Acknowledgements

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