Highly Efficient Atmospheric Gases Detection Using Slow Light Effect Induced in Vertical Photonic Crystal Waveguide Arrays

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Abstract: We present a 2D hexagonal air hole lattice photonic crystal with a slow light effect, by introducing a vertical hollow core in the center as a spectrometer to confine light in a small volume and interact with the analytes at a low group velocity. This device offers the possibility for spatial compression and room-temperature operation.

1. Introduction

Currently, the precision measurement and quantification of the greenhouse gases, especially carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) mainly depend on high-cost laboratory equipment. A high-sensitivity, compact smart device with a low cost is more desirable for the industrial world. With more than 20 years' development and design of the photonic crystal (PhCs), it has brought us to a new field called "periodic electromagnetic media," which allow us to control light propagation by breaking the structure's symmetry and introducing a defect to guide the light in the desired direction. This is one of the most innovative applications of light absorption spectroscopy. A PhCs-based gas sensing approach is capable of addressing the size issues due to the slow light effect and is potentially suitable for on-chip gas detection with appreciable sensitivity and high-density integration in the Mid-IR region [1]. In contrast to the conventional optical fiber, which confines light inside the solid core via index guiding [2]. The cladding in the photonic bandgap "fiber"-like microstructure is designed as a two-dimensional array of air holes in a silicon platform, allowing a specific frequency band of light to be strictly guided in a hollow core using the band gap effect. The definition and performance of dielectric slow light devices scale with the refractive index contrast, with a 3.42:1 contrast between silicon and air confines the light tightly into the waveguide. This will greatly minimize the losses of optical confinement, and the fabrication process is simple. The forbidden frequency band is determined by the size of the photonic crystal bandgap (PBG), which is directly related to the geometry of the two-dimensional PhCs.

2. Method

In this paper, the PhCs on the silicon platform is a 2-D hexagonal lattice of air holes with a hollow core in the center. With the use of mid-IR absorption spectroscopy, we can simultaneously detect several analytes with a PhCs array. Based on the cavity-enhancing mechanisms, hollow core serves as the sampling cell which can efficiently trap light and interact with molecules in small volumes. With the method of slow light enhancement, the supported modes within the air core propagate at extremely low speeds, increasing the light-matter interaction by enlarging the effective path length and improving the detection sensitivity. The group velocity is calculated as follows [3]:

$$\mathcal{V}g = \frac{d\omega}{dk} = \frac{c}{n_g} \quad (1)$$

where c is the speed of light in the vacuum, and n_g is the group index. We use a vertical PhCs array here by shining an infrared LED, which allows the photodetector array to collect data and detect multiple gases at the same time. The schematic of the device is shown in Fig.1.(left). The band diagram of our structure is generated by modeling in the BandSOLVE simulation and performing band computations using the Plane Wave Expansion (PWE) method. The discrete frequency bands $\omega(k)$for both TE and TM polarization crossed the irreducible Brillouin zone, as shown in Fig. 1 (middle). As we can see from the diagram, the overlapping PBG for both polarizations has a normalized frequency of around 0.45 to 0.55, which lies in the mid-IR region where the greenhouse gas has the strongest absorption. In this paper, we choose three important global potential warming gases as our gas analytes,

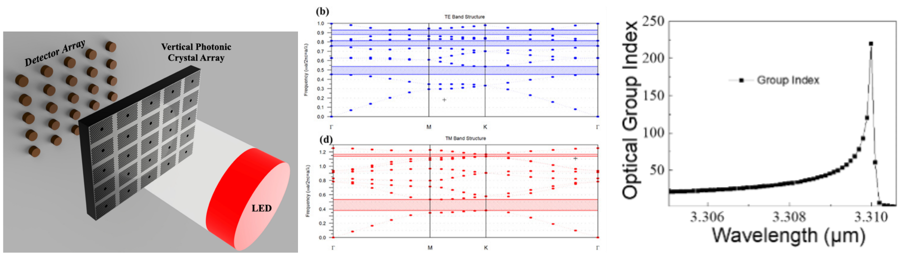

Fig. 1. Left: Schematic of gas sensing device comprising an LED light source, an array of gas selective vertical photonic crystals, and an array of detectors. Middle: Comparative analysis of band structure calculations using PWE simulation. Right: Group index at the wavelength 3.31μm.

which are carbon dioxide (4.25μm), nitrous oxide (4.47μm) and methane (3.31μm) which the group index can be as large as 215 as shown in Fig. 1 (right) by using the Mid-IR absorption spectroscopy.

3. Simulation Results

When $k_z = 0$, the Lumerical software simulates the three confined modes, each corresponding to a different wavelength, by assuming light propagates in the plane of periodicity. Notice that when the light is coupled in the z-direction, which is out of plane propagation, the mirror symmetry of the structure is broken. However, our structure has a complete gap at $k_z = 0$ with a silicon/air dielectric contrast of 3.42:1. Indeed, the gap will persist over a range of $k_z \neq 0$ values. We have presented three modes for detecting the global warming at the wavelength 4.25 μm, 3.31 μm and 4.47 μm as shown below in Fig. 2. Different from the conventional waveguide in the textbook

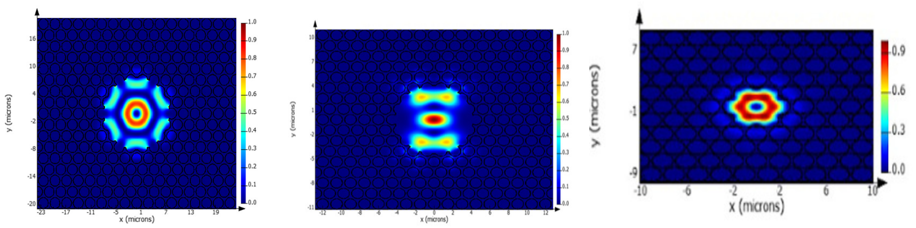

Fig. 2. Three excitation modes in the PhCs waveguide for CO_2, CH_4, and N_2O in sequence.

that has a negligible longitudinal field component, our modes are hybrid with E field in x,y and z directions. We optimize the performance of the PhCs structure by adjusting the termination of the hollow core in the center to eliminate the surface state. This will greatly decrease the guided mode losses due to the scattering in the rough surface and have the mode concentrated in the core to improve the detection sensitivity.

4. Conclusion

We designed a 2-D hexagonal lattice of air hole photonic crystal waveguide with a slow group velocity to confine and guide the light in the hollow core for use as a spectrometer. Slow light with a markable low group velocity can greatly enhance the interaction between light and matter and offer a possibility for compatible on-chip sensing at room temperature. The structure we designed is optimized with a large bandgap for both polarization in the Mid-IR wavelength range, by changing the filling ratio and core dimensions, it can be tuned to any wavelength that we are interested in with the high refraction indices and detect multiple gases simultaneously. This research was supported by the NASA STTR Phase I program Contract NASA-80NSSC22PB125.

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