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Short Communication

High Sensitivity Multiple Gases Sensor With an Array of Micro-ring Resonators

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A gas sensing system comprising an array of photonic wire waveguide-based ring resonators is proposed. As a ring resonator propagates resonant lights only, parameters of the resonator can be deliberately designed such that a resonant light of the resonator is tuned with an absorption spectral line of a gas. Thus, an array of ring resonators can be used to select a series of resonant lights tuned with spectral lines of multiple gases. Simulation results show that three gases, CH_4, CO_2, and HF for example, are simultaneously detected by the system with high sensitivity. The gas sensing system can be fabricated as compact and portable with current fabrication technology.

Keywords: Optical sensors; Gas detectors; Sensor systems and applications; Optoelectronic and photonic sensors

1. INTRODUCTION

Gas plays a very important role in our everyday life and industry activities. Methods monitoring concentration levels of different kinds of gases in specified zones are very useful. Harmful gas emissions such as exhausts from vehicles, toxic gas leakage from chemical plants, and hazardous gas accumulation in mines can be fatal to exposed creatures and are required to be accurately detected and strictly controlled. With global warming and environmental deteriorating, air analysis is also becoming more and more important [1]. Numerous gas sensing methods have been developed in recent years. Optically based gas sensing techniques [2-6] are most prominent as they can detect gases quickly, reliably, and with high sensitivity, by probing specified spectral lines of target gases. It is well known that a gas has characteristic spectral lines, which correspond to wavelengths of the emission or

absorption lights of the gas. Thus, a gas can be identified by an absorption spectral line which is not overlapped with any of other gases. Concentration level of a gas can be measured based on optical power attenuation of a spectral light passing through the target gas. Most optical-based gas sensors are based on optical absorption spectroscopy, which can be realized by methods such as non-dispersive infrared (NDIR) [7], optical filtering [8], Fourier-transform infrared (FTIR) [9], and etc. NDIR and optical filtering methods adopt very narrow wavelength-band lasers or optical filters to select absorption lines of a gas for detection. Laser sources such as tunable diode lasers [10,11] and quantum cascade lasers [12] are commonly used. As NDIR and optical filtering techniques usually tune light emissions with a single absorption line of a target gas, they are rarely applied to measure components of multiple gases simultaneously. FTIR method uses a broad-band laser source and analyzes absorption spectra of the interest with an interferometer. The measured absorbance can be used to determine constituents of multiple gases qualitatively and quantitatively. Although the FTIR method is highly accurate and efficient in detecting gas constituents, the involved optical systems are usually expensive and bulky. In this paper we propose a gas sensing technique that can detect multiple gases fast and reliably. The gas sensing system is also compact and portable as most of the components of the system can be integrated in a chip with current semiconductor fabrication technology. Although photonic micro-ring resonators have been used as biosensors [13-15], all the referred methods utilized micro-ring resonators as sensing device to detect surrounding bio-samples directly. In our method, the photonic micro-ring resonator arrays are functioned as wavelength filtering device. Light attenuations of different wavelengths filtered by the array of wire-waveguide based micro-ring resonators are detected by photodetectors. The respective light attenuations of the gases are used to simultaneously detect concentration levels of the constituents of the mixed gases with high sensitivity.

2. DESIGN AND PRINCIPLE OF THE PROPOSED SYSTEM

The proposed gas sensing system is shown schematically in Fig. 1. A broad-band optical source emits light that will be coupled into a straight optical wire waveguide. The optical source can be a lamp, tunable diode laser, quantum cascade laser, or pulsed laser, depending on the bandwidth of the specified absorption spectra of the interest. An array of three wire-waveguide based micro-ring resonators then couples resonant lights from the straight wire waveguide to respective coupling wire waveguides. It is worth mentioning that number of resonators in the array can be fabricated as many as four or more [16], depending on the number of gases to be detected. Diameters of the resonators are carefully selected such that the resonant wavelengths of the resonators are overlapped with the chosen spectral lines of target gases. Light in each coupling waveguide is split into two by a wire waveguide beam splitter. Wire waveguide-based optical power splitter can be realized with even outputs and low excess loss [17]. Resonant light in one arm of every beam splitter passes through a gas tube which contains gases of the interest and then reaches to a photodetector. Resonant light in another arm of every splitter will be guided to another photodetector directly. The waveguides, resonators, beam splitters, and photodetectors can be integrated in a chip with the current semiconductor micro-fabrication technology. Since the gas tube that is designed to be thin and long for better interaction

between the transmitting lights and gases stands alone from the integrated chip, optical fibers have to be used to couple lights into and out of the gas tube.

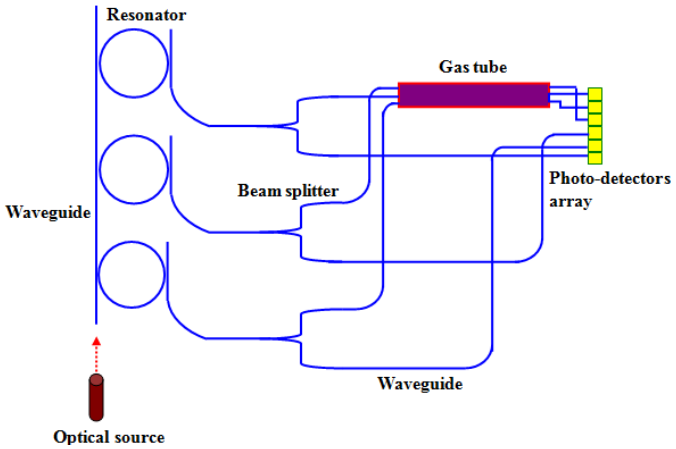

Figure 1. Schematic layout of the gas sensing system. Note that the components are not drawn to scale.

It is well known that resonant wavelengths in a photonic micro-ring resonator can be determined by the following equation,

$$n2\pi R = m\lambda, \tag{1}$$

where n represents effective index of the wire waveguide of the ring resonator, R is radius of the ring, λ is resonant wavelength, and m (=1,2,3…) is the order of the resonant modes. Hence, by selecting radius and materials of a ring resonator we can control wavelength of a resonant light to overlap with the center of a spectral line of a gas. All the radii of micro-ring resonators in the array can be selected in a similar way such that output lights of the resonators are respectively tuned with specified spectral lines of multiple gases. As light in the coupling waveguide of a resonator is split into two by a beam splitter, one arm of the light passing through the gas tube will be attenuated owing to the spectral absorption and the other arm of the light reaching to a photodetector directly will be used as reference for optical power measurement. All the photodetectors are arranged in an array so that they can be fabricated with the same process. From Lambert-Beer law we can obtain concentration level of a target gas by detecting optical power attenuation ratio of the light with the following equation [18],

$$I = I_0 \exp\left[-\frac{C \cdot P \cdot S_{line} \cdot \Phi(v - v_0) \cdot L \cdot}{kT}\right], \tag{2}$$

where I is the intensity of light after passing through a gas of interest, I_0 is the intensity of light without passing the gas, C is volume mixing ratio of the gas, P is pressure of the ideal gas at

temperature T, k is Boltzmann's constant, S_{line} is spectral line intensity of the gas, $\Phi(\nu-\nu_0)$ is the spectral line shape function at frequency ν, ν_0 is the central frequency of the spectral line, and L is length of light propagated in the gas. S_{line} and $\Phi(\nu-\nu_0)$ are characteristic parameters of the gas and can be referred to Hitran database [19]. Thus, if I and I_0 are measured, we can determine concentration level of the target gas with Eq. (2). In this paper concentration of a gas will be expressed in parts-per-million (PPM) by volume.

3. SIMULATION RESULTS

In our simulations we choose three gases, CO_2, CH_4, and HF, as an example for detection as the gases are widely found in atmospheres, coal tunnels, chemical plants, and semiconductor foundries. The criteria selecting detecting spectral lines of the gases are that, the spectral lines fall within wavelength band of optical source of the gas sensing system, are strong enough for detecting, and are not interfered by strong spectral lines from other gases. Spectral lines 6046.9647 cm^{-1}, 7823.8212 cm^{-1}, and 4989.9715 cm^{-1} of CH_4, HF, and CO_2 are chosen, respectively, as these lines have high spectral line intensities and are not interfered by spectral lines of the other gases. Figure (2) shows spectral lines of CO_2, CH_4, and HF in the range from 5000 cm^{-1} to 8000 cm^{-1}. The vertical axis in the left shows line intensities of CO_2 and CH_4, which are in the magnitudes of 10^{-21} cm^{-1}/(molecule×cm^{-2}), and the vertical axis in the right shows line intensities of HF, which are in the magnitude of 10^{-20} cm^{-1}/(molecule×cm^{-2}). We can observe from Fig. 2 that every cluster of spectral lines of a gas is several orders stronger than the surrounding spectral lines of the other gases. Hence, absorption in the band of clustered spectral lines of a gas can be regarded as caused by the gas only. The line intensities of the chosen spectral lines of CH_4, HF, and CO_2 are 1.335×10^{-21} cm^{-1}/(molecule×cm^{-2}), 7.693×10^{-20} cm^{-1}/(molecule×cm^{-2}), and 1.287×10^{-21} cm^{-1}/(molecule×cm^{-2}), which are illustrated in Fig. 2, respectively.

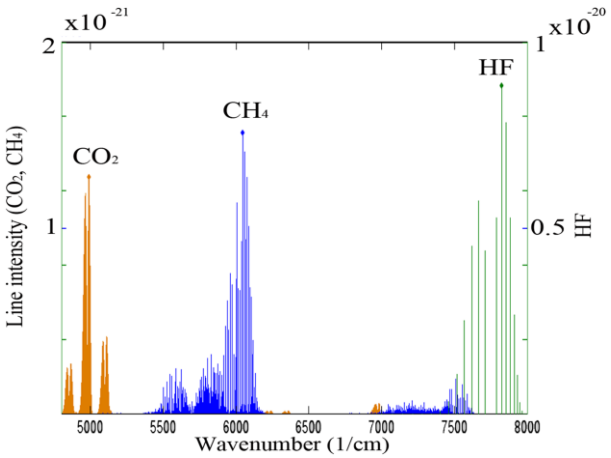

Figure 2. Spectral lines of CO_2, CH_4, and HF. The highest lines are chosen and will be used for detection.

The micro-ring resonators can be constructed on silicon-on-insulator (SOI) materials system, which is compatible with the current silicon micro-fabrication technology. Waveguide material of the resonators is crystalline silicon with a thickness of 220 nm. Width of the waveguides is 500 nm. The waveguide supports propagation of fundamental light modes only. Coupling gaps between waveguides and resonators are 250 nm wide. Radii of the three resonators are calculated as 4740 nm, 4848 nm, and 4916 nm, respectively. Thus, resonant lights of the three resonators are respectively tuned with the corresponding selected spectral lines of the three gases. In the simulations, owing to huge computation of a three-dimensional finite-difference time-domain (FDTD) method for this system, we use two-dimensional FDTD method from a commercial software package (RSOFT) to simulate light propagation in the resonators instead. Calculated effective index based on the 3D waveguide is used in the 2D FDTD simulations. Propagations and couplings of transverse electric mode of light in the ring resonator systems are shown in Fig. 3, where (a) the input light of the ring arrays is at wavelength of 1.2781 um and the ring of radius of 4916 nm resonates most strongly, (b) at wavelength of 1.6537 um and the ring of radius of 4848 nm resonates most strongly, and (c) at wavelength of 2.004 um and the ring of radius of 4740 nm resonates most strongly. It can be observed that the input lights in the resonator arrays are chosen as identical to the above selected spectral lines of HF, CH_4, and CO_2, respectively. Hence, with a broadband optical source, multiple resonators can be tailored to resonate with respective spectral lines of multiple gases. Resonant lights from the ring resonators pass through the gas tube and will be attenuated by the respective gases according to Beer's law. Except for selected resonant lights, other resonant lights of the ring resonators are not tuned with strong absorption lines of the gases and the resultant light attenuations will be negligible. Thus, lights coupled from the three resonators can be respectively used to detect three different gases simultaneously.

We also find from Fig. 3 that although selected resonant lights propagate most strongly in the designated rings, a small fraction of lights also propagate in the other rings. The reasons are that the transmission peaks of the resonators are not narrow enough to contain only the designed spectral lines and the resonant wavelengths of the resonators are not fully overlapped with the designed wavelengths of the input lights. To remedy the problems we need improve the fabrication capability to increase quality factors of the resonators such that the transmission peaks of the resonators are as narrow as possible and in the mean time optimize structure of the ring resonators to make transmission peaks of the ring resonators completely cover the absorption lines of the target gases. Quality factor of a ring resonator can be increased by decreasing sidewall roughness of the waveguide and optimizing the waveguide-ring coupling. For instance, we can improve resolutions of the photolithography and silicon etching process in the fabrication, and thus decrease light propagation loss of the waveguides of the system. In [20] a fabricated SOI ring resonator has a quality factor over 130000 and a corresponding transmission peak of the resonant light with full width at half maximum (FWHM) is less than 0.01 nm. Sensitivity of the gas sensing system can be estimated with Eq. (2). Suppose length and pressure of the gas tube is 100 cm and 1 atm at temperature 296 K, respectively. Wavelengths of the target spectral lines and line intensities of CH_4, HF, and CO_2 are chosen as given in the above. To calculate spectral line shape functions of the gases we need deal with line spreading effects such as Doppler and pressure broadenings. However, since lights coupled from a ring resonator can have FWHM in sub nanometers, the intensity absorbance of a gas as a function of wavelength can be regarded as uniform for rough

estimation. In this case we calculate the line shape functions using the center wavelengths of the spectral lines only.

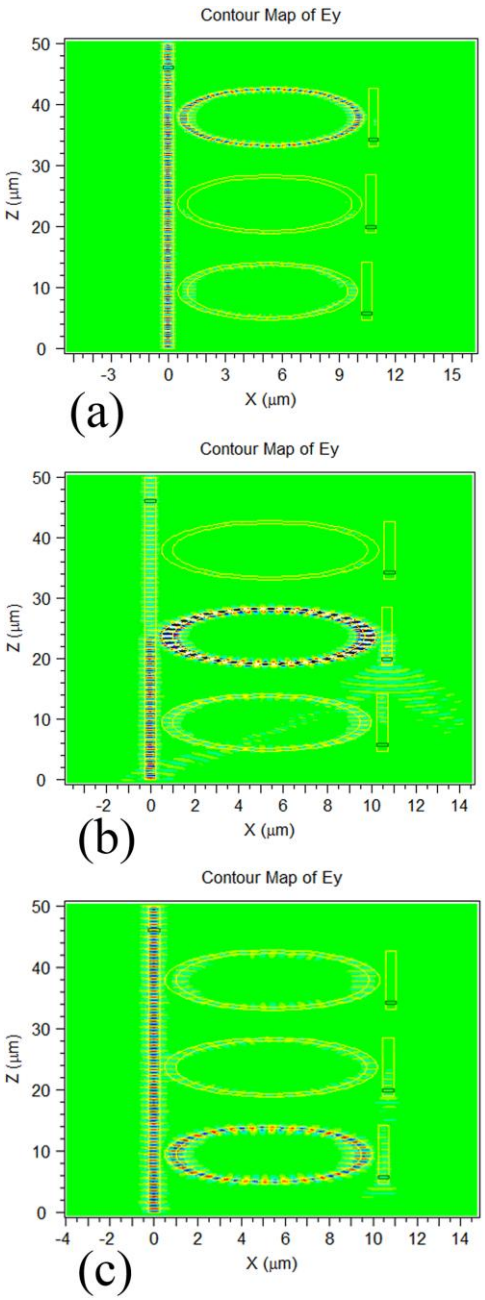

Figure 3. Light propagations with input lights at wavelengths of (a) 1.2781 um, (b) 1.6537 um, and (c) 2.004 um.

Thus, if 1 dB optical power attenuation ratio of light caused by a gas can be detected by a photodetector, the measured concentrations by volume would be about 3 PPM for HF, 80 PPM for CO_2, and 140 PPM for CH_4. As optical power attenuations resultant from absorbance of the three gases will be recorded by photodetectors in real time, concentrations of the three gases can be measured

dynamically. To increase detecting resolution of the system, we need select higher intensity spectral lines of the gases, a longer gas tube such as a cavity that can provide a path length of several kilometers in a small volume cell [5], and photodetectors with higher sensitivity.

4. CONCLUSION

A gas sensing system based on an array of photonic wire waveguide-based micro-ring resonators has been proposed. Resonant lights of the ring resonators are deliberately tuned with respective absorption spectral lines of different gases. Thus, multiple gases in a mixture can be simultaneously identified from the characteristic spectral line absorptions of light. Simulation results have shown that the concentration levels of the gases can be measured at PPM scale. The gas sensing system would be useful in the applications such as gas monitoring of industry productions, air quality analysis, environmental pollution gases detection, and so on.

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