An optic fiber sensor for multiple gases based on fiber loop ring-down spectroscopy and microring resonator arrays*

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A high-sensitivity sensor for multiple gases based on microring array filter and fiber loop ring-down spectroscopy system is proposed and demonstrated. The parameters of the resonators are designed so that the filtered signal from a broadband light source can be tuned with an absorption spectral line of gas. Therefore, through adding microring resonators horizontally and vertically, the number of target gases and filter range are increased. In this research, in the broad spectral range of about 0.9 μm, only the absorption spectral lines of target gases are filtered. The simulation results show that three target gases, CH_4, CO_2 and HF, can be simultaneously detected by the sensing system. Owing to the fiber loop ring-down spectroscopy, the whole system is optimized in mini-size and sensitivity, and we can choose different sensing methods to enhance the measurement accuracy for high and low concentration conditions.
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Compared with the electrical sensor[1,2], the optical sensor based on infrared spectral absorption has better stability, selectivity and longer working life[3-5]. The well-tuned microring resonator array is able to filter monochromic light at certain wavelength in a large spectral range[6-8]. Fiber loop ring-down spectroscopy system can ensure a long optical path for low concentration gas detection. The monochromic light signal propagates in the fiber loop and passes through the gas chamber repeatedly[9,10]. Therefore, the gas chamber does not need to be very long. If we need to measure several target gases, we have to prepare several tunable laser sources, which is expensive and complex. Thus, a wavelength division multiplexer (WDM) is needed for dividing compound light into several monochromic lights before the light gets into gas chamber[11]. A high-sensitivity sensor for multiple gases based on microring filter and non-dispersive infrared (NDIR) method was proposed in 2012[8].

In this paper, an integrated and stable sensing system for multiple gases is proposed, which is based on fiber loop ring-down spectroscopy and microring resonator arrays. The system can detect three target gases simultaneously with high sensitivity and a large range. Compared with the reported sensor system with microring resonators, this system is improved in mini-size, accuracy and sensitivity.

The multiple gases sensing system based on fiber loop ring-down spectroscopy system and microring resonator arrays is depicted schematically in Fig.1. Instead of the expensive narrow band tunable pulsed laser, we use broadband light generator, such as LED, lamp and tunable diode laser, as pulsed light source. The pulse width should be smaller than the time that the light travels through a loop. First, the broadband light signal passes through the microring arrays and gets filtered. Only the light signals with target wavelengths which correspond to sample gases are remained. Then the filtered light signal is coupled into the fiber loop ring-down spectroscopy system. This system consists of fiber, gas chamber, coupler, WDM and optic-electrical detector. Because the Beer-Lambert law is only applied to monochromatic light source, the signal light is divided into several beams of monochromatic light and passes through the chamber which is filled with multiple sample gases. The multiple mixed gases are with different concentrations. One wavelength corresponds to one gas. The spectral light with a certain wavelength attenuates after passing through the chamber. The attenuation intensity is related to the concentration level of corresponding gas. After the attenuation in gas chamber, the three monochromatic light signals combine again and are divided into two parts with 99:1 proportion in intensity by a coupler. 1% of the light intensity is guided to the detection section

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and the rest 99% is guided to the next loop. Similarly, 1% of the rest light intensity gets out and is detected in the next loop. This part of light signal is collected by another microring WDM and divided into several beams of monochromatic light again. These beams are separately detected by an optic-electrical detector array which turns the light signals into electrical signals. Finally, the electrical signals are recorded and processed by the computer. The sensing and data collecting process is not supposed to end until the signal light intensity attenuates to 1/e of the origin signal intensity, because the accuracy cannot be guaranteed when the signal intensity is too low. Compared with the traditional optical gas sensor based on absorption spectroscopy, the fiber loop ring-down spectroscopy system is smaller in size because the fiber can be coiled and the gas chamber is no longer necessary to be very long for full absorption. Besides, the microring resonator array filter, WDM and LED light source can be integrated in a micro optical chip.

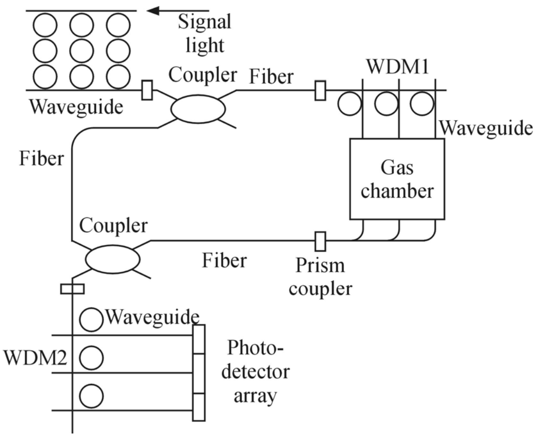


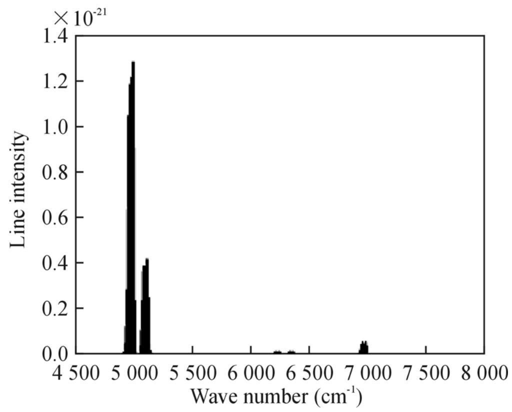
Fig.1 Structure of the proposed sensor for multiple gases

The resonant equation of the microring resonator is $n^2\pi=m\lambda$, where n is the effective index of the microring waveguide, λ is the resonant wavelength, and m is the order of resonant mode. Since the light source is broadband, we have to enlarge the free spectral range (*FSR*) to decrease the number of resonant modes within the source bandwidth. In order to expand the *FSR* remarkably, we use three cascaded microrings to filter out the broadband light. This system is designed to detect CO_2, CH_4 and HF gases. Thus, we need to design three groups of triple cascaded microrings for filtering three narrow band resonant peaks which are on the spectral absorption peaks of each gas. The concentration of target gas can be obtained by detecting the optical attenuation ratio of light signal following the equation of Beer-Lambert law, which is expressed as

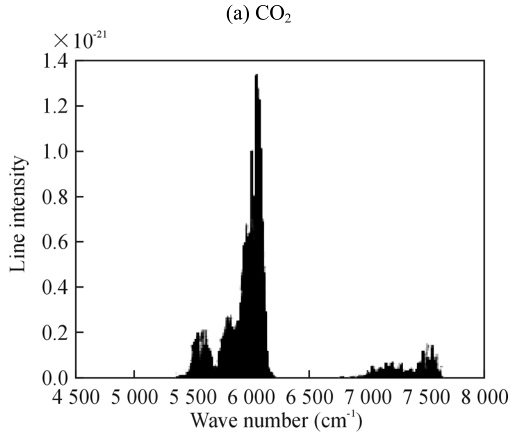
$$I = I_0 \exp[-CPS_{\text{line}}\Phi(\upsilon-\upsilon_0)L/kT], \qquad (1)$$

where I is the intensity of light after passing through the target gas, 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, $\Phi(\upsilon-\upsilon_0)$ is the spectral line shape function at frequency, υ_0 is the central frequency of the spectral line, and L is length of the light propagating in the gas. S_{line} and $\Phi(\upsilon-\upsilon_0)$ are characteristic parameters of the gas and can be referred to Hitran database. As a result, the concentration level of target gas can be determined by the measured values of I and I_0. The concentration of gas in this paper is expressed by volume.

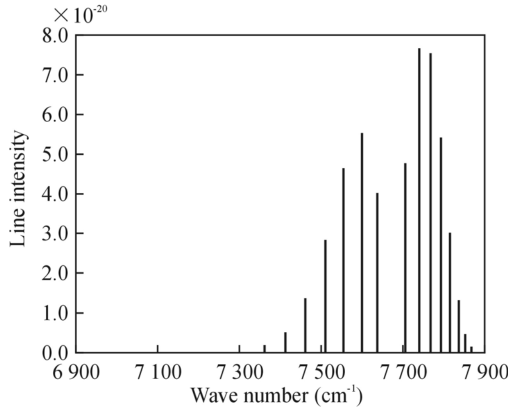
From the Hitran database, we obtain the absorption spectra of three target gases of CO_2, CH_4 and HF, which are shown in Fig.2. The absorption lines we choose should be within the source bandwidth, strong enough to be detected and not interfered by strong spectral lines of other mixed gases. Under this condition, spectral lines 4 989.971 5 cm^{-1} of CO_2, 6 046.964 7 cm^{-1} of CH_4, and 7 823.821 2 cm^{-1} of HF are carefully selected. If we convert the horizontal axis from wave number to wavelength, the absorption line wavelengths are 2.004 μm of CO_2, 1.653 7 μm of CH_4, and 1.278 1 μm of HF. We plan to test the mixed gases and background gas N_2, so the bandwidth of broadband light source has to be larger than 730 nm. The minimum wavelength of light source should be lower than 1.278 1 μm and the maximum wavelength should be higher than 2.004 μm.



(a) CO_2



(b) CH_4



(c) HF

Fig.2 Absorption spectra of three target gases

A 3×3 microring array is designed for light filtering. Three cascaded microrings as one group are designed to filter different monochromatic light from the broadband light. The radii of micorirngs are deliberately chosen for making the resonant light wavelength meet the absorption spectral lines of target gases. The distance between two cascaded microring groups is kept long enough for avoiding the disturbance from other microring groups. We have discussed how many cascaded rings in one group are enough for filtering monochromatic light. If the number is one, and the radius of the only ring is suggested as R_1 in Tab.1, the *FSRs* of output spectra from three groups are 69.6 nm, 42.1 nm and 42.2 nm, separately. If the number is two, and the radii of microrings are suggested as R_1 and R_2 in Tab.1, the *FSRs* of spectra from three groups are 426 nm, 351 nm and 668 nm. In order to filter only one wavelength from the broadband light signal, the *FSR* of output spectra should be larger than the bandwidth of source light. Thus, we decide to use three cascaded microring resonators in one group. The microring resonator is made of silicon on insulator (SOI) material. The width and the height of ring waveguide are 500 nm and 220 nm, respectively. The radii of microrings in each group are shown in Tab.1. The output spectra of three groups for three target gases are shown in Fig.3.

Tab.1 Radii of all microring resonators in the microring array filter

Gases	R_1 (nm)	R_2 (nm)	R_3 (nm)
HF	6.538	7.083	8.445
CH_4	5.99	7.047	8.104
CO_2	5.98	7.261	8.97

According to Fig.3, it is obvious that we can expand *FSR* remarkably through increasing the number of cascaded microring resonators in one group. Also, we can depress the pseudo mode by modifying the coupling coefficient between cascaded rings. Through the filtering of microring array, only three wavelengths are allowed to pass, which are just the absorption spectral lines of three target gases. Compared with the resonant mode, the disturbance of pseudo mode is small enough to be ignored. Compared with other optical filters, the microring array has better filter effect in narrow bandwidth around the target wavelength and better depression of pseudo mode, which improves the accuracy of gas sensor system.

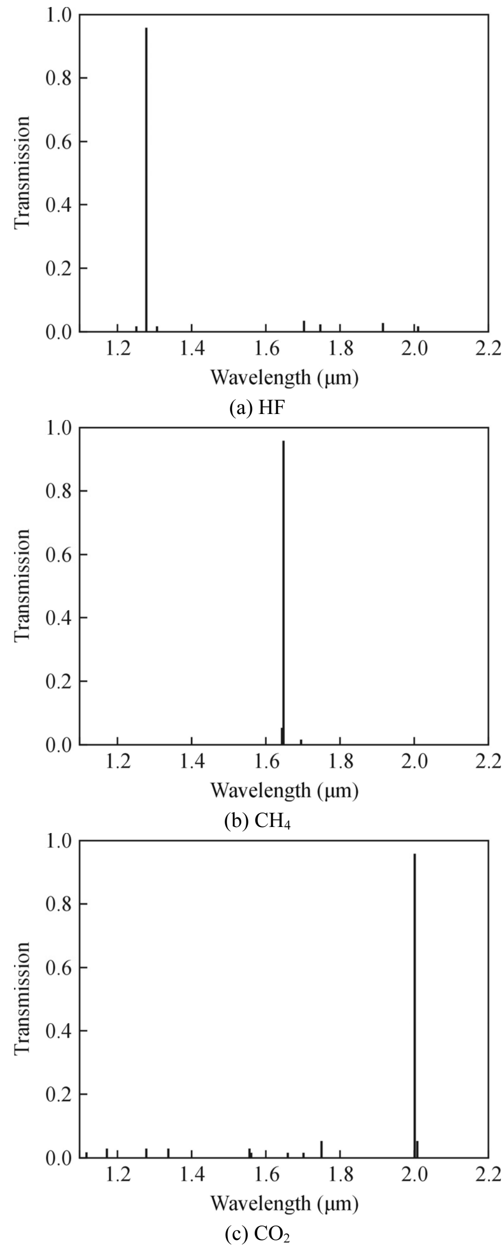


Fig.3 Output spectra of the microring array filter corresponding to three target gases

After the filtering process in the 3×3 microring array, the broadband signal becomes a beam of light with three wavelengths in spectrum. Because the Beer-Lambert law is only applied to monochromic light, we have to divide the filtered compound light into three monochromic light beams, whose wavelengths are 2.004 μm, 1.653 7 μm and 1.278 1 μm. The WDM consists of three microrings with different radii. The radii of three microrings can be randomly selected among the columns of R_1, R_2 and R_3 in Tab.1. In this system, two different columns of radii are utilized in two different WDMs. The ring radii in WDM1 are 7.083 μm, 7.047 μm and 7.261 μm, and those in WDM2 are 8.445 μm, 8.104 μm and 8.97 μm.

The length of gas chamber is designed to be 10 cm. Based on the Beer-Lambert law, the relationship between the intensity of monochromic light and the concentrations of three target gases is obtained and shown in Fig.4.

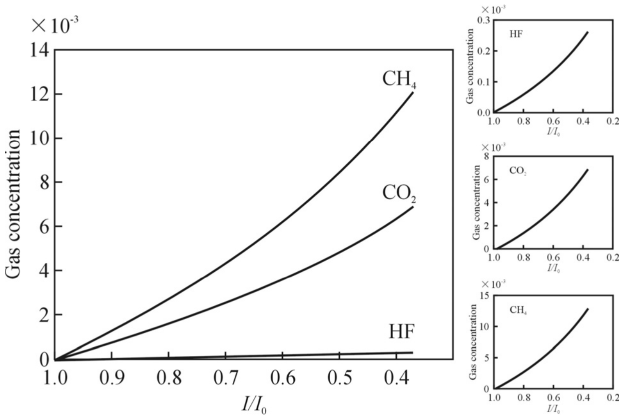


Fig.4 The relationship curves between normalized intensities of three monochromic light beams and the concentrations of three target gases, including local enlarged curves

Assume the intensity of monochromic light attenuates to 1/e while the light passes through the gas chamber. The light path is equal to the length of gas chamber. Among the three target gases, the absorbing ability of HF is the strongest, which only needs the concentration of 2.8×10^{-4} to complete the full range attenuation. CH_4 has the weakest absorbing ability, which needs the concentration of 0.013 to complete the full range attenuation. On the other side, CH_4 has the largest measurement range from 0 to 0.013, while HF has the shortest range from 0 to 2.8×10^{-4}. Thus, the order from high to low sensitivity is HF, CO_2 and CH_4.

There are two methods to detect the target gas concentration in the gas chamber by this sensor. One is to detect the output intensity in every loop and analyze the difference between this loop and the next loop. This method is effective when the gas concentration is relatively high, so the attenuation in every loop is obvious. The other method is to measure the time that the origin light signal attenuates to 1/e of the original intensity. From the time record, the number of loops that the signal light has propagated can be obtained and the optical path can be calculated. This method is effective when the gas concentration is relatively low. No matter which method we choose, the light intensity attenuation of the sensor system without target gases has to be tested first. Then the normalization is carried out to remove the disturbances of attenuation from the system itself. After that we can record the output light intensity and calculate the concentration of target gases by computer program. Compared with the long gas tube, this multiple gases sensor system has lower sensitivity threshold, larger measurement range and better accuracy by choosing the detection method properly.

A sensing system for multiple gases based on microring resonator filter and fiber loop ring-down spectroscopy is proposed. The gas sensing principle is infrared spectral absorption. The resonant light of the ring resonators is deliberately tuned with respective absorption spectral lines of different target gases. Compared with the optical gas sensing system with microring resonator reported before, this system has smaller gas chamber, less pseudo mode disturbance and lower sensitivity threshold. Owing to the proper measurement method we choose, this system can detect concentrations of multiple gases precisely in a large range with good sensitivity.

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