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Dual-point automatic switching intracavity-absorption photonic crystal fiber gas sensor based on mode competition

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ABSTRACT

Here we propose a dual-point channel-switchable intracavity absorption hollow-core photonic crystal fiber acetylene sensing system based on the mode-competition phenomenon in a ring fiber laser with a Sagnac loop filter. The experimental system operating at 1532.83 and 1534.10 nm is applied to 1% acetylene and shows the sensitivities of 398 and 1905 ppmv, respectively, at the absorption peaks around two operating wavelengths. The resolution error induced by the power fluctuation is no more than 7.2% for both gas cells and it takes ~50 s to scan the absorption spectra via applying gradient voltage to the tunable F-P filter. This approach is a potential cost-effective resolution for high-capacity intracavity absorption sensor network compatible hybrid gas detection.

1. Introduction

Intracavity laser absorption (ICLA) spectroscopy using Erbium-doped fiber (EDF) laser has been demonstrated to have an enhanced sensitivity by placing the gas cell in a laser cavity. And it has been widely used to realize the detection of many molecular species, such as acetylene, methane, carbon monoxide and ammonia, which exhibit absorption in the wavelength region accessible to EDF laser [1–4]. The ICLA technology makes it convenient to improve the sensitivity by increasing the length of the laser cavity so as to increase the number of light passing through the gas and also makes it possible to realize long-distance high-sensitivity remote sensing without using the EDF amplifier. Among the gas cells for the ICLA system [5,6], hollow-core photonic crystal fiber (HCPCF) has been demonstrated to be excellent because of its compactness and ease of improving the sensitivity by increasing its length to raise the interaction times. Z. Q. Zhao et al. demonstrated a single-point acetylene ring fiber laser sensor operating at 1530.37 nm based on hollow-core photonic crystal fiber and achieve a sensitivity about 5.4 parts per million by volume (ppmv). Compared with the gas cell reported in Ref. [6], the use of the HCPCF makes the sensitivity increase many times.

In addition, the wavelength-tunable ICLA system makes it have the capability of achieving multipoint gas detection via commercial fiber components including optical switch [7], pulse generator and modulator [1]. In order to reduce individual cost for the users in the multiplexing network, many passive optical devices, such as fiber Bragg grating (FBG) [3], dense wavelength division multiplexing (DWDM) [8], have also been employed in multipoint intracavity sensor network. However, the narrow bandwidths and fixed operating wavelengths of FBG and DWDM shrink the applicable scope and limit the multiplexing capability of ICLA system. Compared with FBG and DWDM, the Sagnac loop filter (SLF) has been reported as a tunable device with comb-like spectrum [9]. More importantly, since the Sagnac loop has been applied in multi-wavelength fiber lasers as a comb filter [10–13], the SLF can probably be used as an excellent device to realize multipoint detection based on the mode competition in the laser cavity by employing the different transmittance in its wave crest and trough.

In this letter, we propose and demonstrate a dual-point ICLA HCPCF acetylene sensor based on a cost-effective SLF combined with the compact HCPCF gas cell. Mode-competition is employed to switch the channels in a ring fiber laser automatically. When the gas cells are filled with 1.0% acetylene, we achieve their absorption spectra using voltage gradient method to sweep the output wavelength of the whole sensing system. The corresponding detection sensitivities around the absorption peaks at 1532.83 nm and 1534.10 nm are calculated to be about 398 ppmv and 1905 ppmv, respectively. The detection error is about 7.2 percent of the sen-

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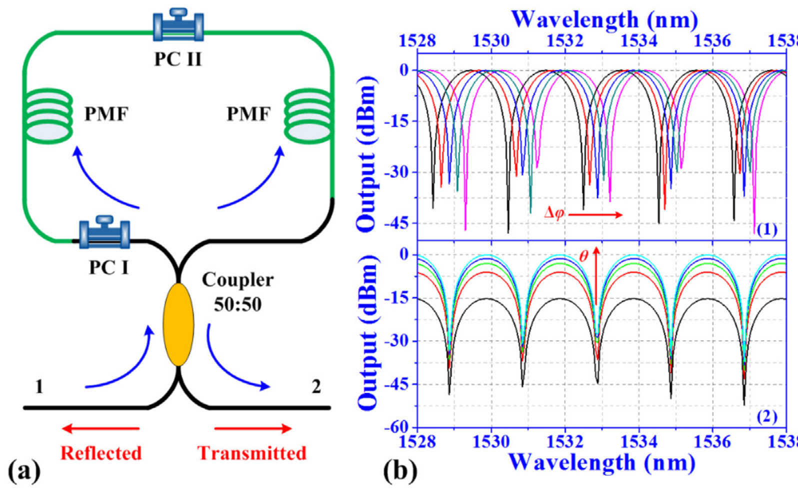

Fig. 1. (a) Schematic construction of SLF and (b) Transmission spectra of SLF with changes of (1) the phase shift and (2) the angles between the polarization states.

sitivities for both channels. To the best of our knowledge, the SLF is firstly used to realize a multipoint ICLA sensor via the mode-competition phenomenon in the ring fiber laser.

2. Principle and simulation

The schematic diagram of the SLF used in our proposed dual-point sensing system is depicted in Fig. 1(a). The SLF consists of a 2×2 3-dB coupler, a piece of polarization maintained fiber (PMF) as well as two polarization controllers (PCs). When the broad-band light is launched into the SLF, its transmission spectrum can be expressed as [14]:

$$T = \left[\sin(\theta) \cdot \cos\left(\frac{\pi l \lambda_0}{\lambda L_b} + \Delta\varphi\right)\right]^2. \quad (1)$$

where, θ denotes the rotated angle of the polarization state when anticlockwise-propagating light enters the PMF through the 3-dB coupler and it can be controlled by adjusting the PC I applied to the single mode fiber (SMF). L_b is the beat length of the PMF at λ_0. l is the length of the PMF. Δj represents the phase shift in the PMF and it depends on the changes of fiber length and the strain-induced birefringence caused by the PC II. Fig. 1(b) depicts the calculated transmission spectra of the SLF with different rotation angles θ of the polarization states and the strain-induced phase shift $\Delta\varphi$ by adjusting PC I and PC II, respectively. It is found that the transmission wavelength is dependent on the phase shift $\Delta\varphi$ while the rotation angle θ influences the spectral intensity. Therefore, the SLF can work as a low insertion-loss and tunable filter by adjusting the PCs precisely.

Considering that the acetylene has comb-like absorption peaks, we can make two absorption peaks locate in the wave trough of one of the SLFs but locate in the wave crest of the other one by changing the parameters of two SLFs. Both SLFs have the same parameters except the length of the PMF. 2-m-long PMF and 1.9-m-long PMF are used in SLF I and SLF II, respectively. By changing the phase shift precisely via PC II in the SLFs, we can achieve such spectra as depicted in Fig. 2 according to the absorption spectrum of acetylene in HITRAN database [15].

When the SLFs are placed in a ring fiber laser with a paralleling topology arrangement as illustrated in Fig. 3(a), an automatic channel-switched fiber laser can be achieved because of the mode-competition in the laser cavity. When the voltage applied to the F-P tunable filter changes linear as it is described in Fig. 3(b), the output wavelengths of the whole lasing system can be swept and the channels are switched periodically. As a result, we can find out that

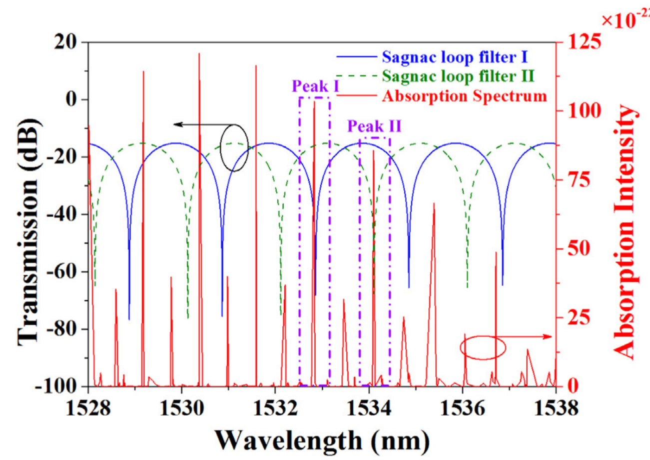

Fig. 2. Transmission spectra of SLFs (left) and absorption spectrum of acetylene (right) versus wavelength.

only the channel including SLF II will have a laser output around absorption peak I and only the channel including SLF I will have a laser output around absorption peak II.

Therefore, not only can the SLF be used to improve the detection accuracy for those gases with comb-like absorption peaks [16,17], but also the different transmittance in the wave crest and trough can be employed to realize an automatic channel-switched ICLA gas sensing system based on the mode-competition phenomenon by controlling the cavity loss precisely. The sensing system can be employed to monitor the gas concentrations for two users at the same time. Moreover, the wavelength-tunable SLF makes it more portable to realize the detection for different kinds of gases compared with FBG and DWDM that should be replaced every time for their fixed operating wavelength.

3. Experimental results and discussions

3.1. Experimental setup

In the experiment, a 2-m-long PMF is spliced to the 2×2 3-dB coupler to form a SLF. The PMF has a core diameter of 10 μm, cladding diameter of 125 μm and beat length less than 5 mm at 1550 nm (YOFC Inc.). Light from a broad-band ASE source ranging from 1500 to 1600 nm (AFR Inc.) is launched into the SLF, and the transmission spectrum of the SLF is measured using an optical spec-