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Simultaneous measurement of hydrogen and methane based on PCF-SPR structure with compound film-coated side-holes

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ABSTRACT

A special photonic crystal fiber based Surface Plasmon Resonance (PCF-SPR) sensor having ability of polarization filtering is designed for the simultaneous measurement of methane and hydrogen. In order to enhance the spectral response to the target gas, four ultra-large side-holes are symmetrically introduced into the cladding layer and two of them are coated with different compound thin-films. All geometrical parameters would be optimized for the selective detection of specific gas. Combined with the side-hole structure and polarization filtering, the gas mixture of methane and hydrogen can be accurately measured without interfering with each other. The approach also can be broadened to the qualitative identification of multiple gases.

1. Introduction

Photonic crystal fiber (PCF) has been widely investigated as a suitable candidate for the optical sensing, because of its unique light controlling capability and flexible structure design [1,2]. With the promotion of fabrication techniques, the structure of the PCF can be easily constructed to detect various parameters according to actual demands. Due to this characteristic, PCF-based gas sensors have shown their excellent performance in terms of sensitivity and spectral response. Researchers are still trying to improve the sensing ability by filling functional materials into the cladding air-holes [3,4]. In particular, there is often more than one gas in a real environment, and it is necessary to explore an effective sensing method for the detection of multi-component gas [5,6]. The present measurement principles are mainly based on optical absorption spectroscopy technology [7] and the biggest challenges is how to get the higher relative sensitivity and lower confinement loss (CL). As a consequence, the simpler PCF structures with higher sensitivity are required to avoid complex fabrication and high cost. Here, using silica as the background material, the PCF-based sensors should be designed to operate in the optical wavelength region.

Among these PCF-based designs, Surface plasmon resonance (SPR) technology by the use of coated metallic layer has attracted immense attention due to its special sensing mechanism [8]. With a strong coupling between the core mode and the surface plasmon polaritons (SPP) mode, a high sensitivity in refractive-index (RI) sensing can be achieved when the phase matching condition is satisfied. It's worth mentioning that the sensing characteristics can be characterized by analyzing the confinement loss spectra. So that, the current work proposes a novel PCF-SPR sensor based on gas-sensitive film-coating to detect the gas mixture of methane and hydrogen. The tunable RI characteristic of different gas-sensitive layers can be used to adjust the peak-wavelength and measure the gas concentration.

As the refractive index variation due to concentration change is usually very low, four ultra-large side-holes are introduced into the cladding layer of PCF to enhance the gas-sensitivity and simplify the manufacturing technology [9]. The fiber core is surrounded by two rows of smaller air-holes along the angle of 45 degree and 135 degree, which allows the ultra-large side-holes to be introduced much closer to the fiber core and hence results in much higher RI sensitivity. The combination use of SPR technology and side-hole structure would bring new vitality to the gas sensing [10]. The gas-sensitive composite film is relatively easy to be coated on the surface of ultra-large air-holes with enhanced sensing performance. Unlike some common gas sensors, the proposed sensor possesses higher sensitivity and linearity and can detect gas mixture without interfering with each other. The spectral response to different target gases can be improved just by optimizing the structural parameters [9], and the key matter is that the refractive index of the sensitive-film should change linearly with the gas concentration. In order to detect the methane and hydrogen without interference, the filtering ability should be combined to the PCF-SPR sensor [11].

Numerical simulation results demonstrate that the good filtering characteristic at special wavelengths is very useful for the detection of gas mixtures. In other words, the gas sensing channels should cause different peak-shifts at different wavelengths. The polarization filtering

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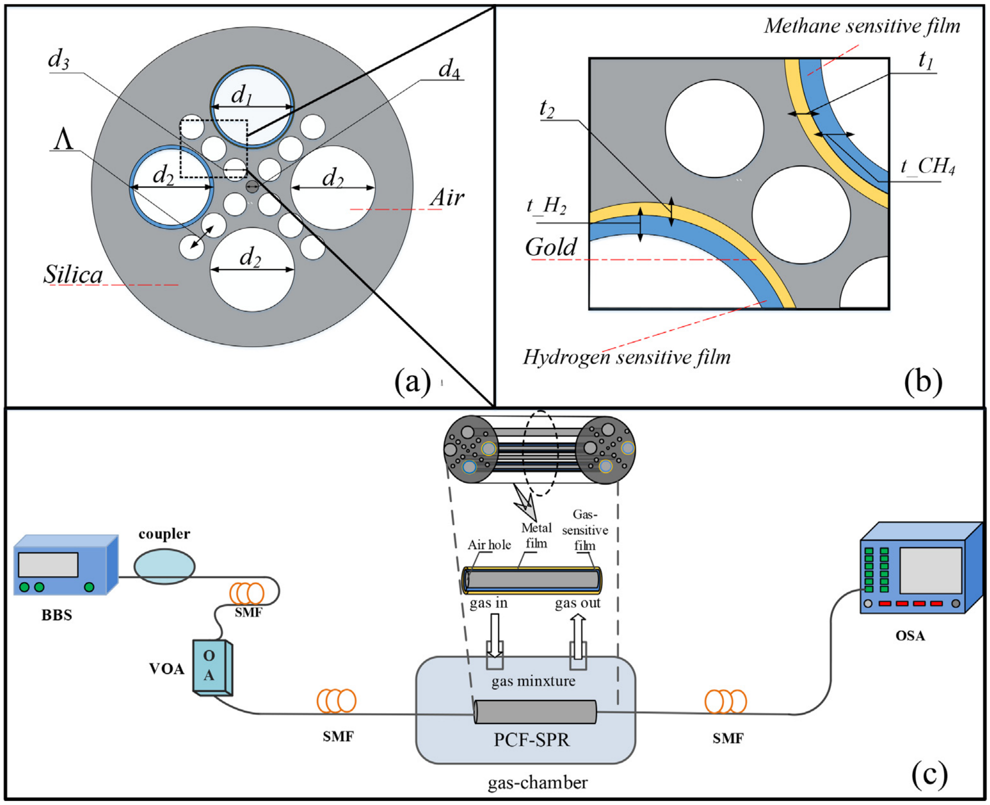

Fig. 1. The schematic and cross section of PCF sensor. (a), (b) structural parameters and (c) experimental scheme.

can be achieved at the wavelength of 1310 nm in y-polarization (y-pol) direction and 1190 nm in x-polarization (x-pol) direction through the structure parameter optimization. And the relative sensitivity can reach as high as −1.99 nm/% for methane and −0.19 nm/% for hydrogen, respectively. This paper is organized as follows. In Section 2, the polarization-dependent filtering characteristic and parameter optimization process are investigated to reveal the new sensing principle. In Section 3, the measurement method and sensing property are studied in great details. Finally, some conclusions are presented in Section 4. Compared with some reported sensors [12–15], the PCF-SPR sensor improves the gas-sensitivity for the methane and has a good repeatability for the multi-channel gas sensing. The selective detection method can be used for both the gas and other sensing applications.

2. Sensor design and structural parameters optimization

The cross-section of proposed PCF-SPR sensor is shown in Fig. 1(a-b). As is shown, the smaller air-holes are arranged along the angle of 45 degree and 135 degree, and four ultra-large air-holes are distributed vertically and horizontally. The structure can be achieved through multi-step “stack-and-draw” procedure. Firstly, three silica tubes should be collapsed to get three kinds of silica tubes with different inner diameters and outer diameters. The collapsing process can be carried out in the lathe of Modified Chemical Vapor Deposition (MCVD). And then, the optical fiber drawing tower (TGL-8S-A) is used to complete fiber drawing [16,17]. The layer composed of gold and gas-sensitive film is coated in the inner surfaces of left and top ultra-large air-holes. Moreover, the hydrogen-sensitive film is made of Pd-WO_3, and the coating can be achieved by using the sol-gel scheme. And a kind of ultraviolet curable fluoro-siloxane (UVCFS) nano-film with the inclusion of cryptophane A is selected as the methane-sensitive film which can be fabricated through a capillary dip-coating technique. According to the reference [18], the film absorbs methane rapidly but it desorbs the gas slowly. Even so, the reaction of methane to gas sensitive film is reversible. For the hydrogen-sensitive film, the conjugation reaction will reach equilibrium and stability in a certain period of time, which is useful for repeated testing [19]. It is worth mentioning that the manufacturing procedure to form a coating on the inner surface will become simpler when the air-holes are ultra-large.

The diameters of the ultra-large air-holes with coating layers are and d_2, respectively. Besides, other parameters are selected as: $d_3 = 1.5$ μm, $d_4 = 0.4$ μm and pitch $\Lambda = 1.9$ μm. The refractive index of the core (n_{core}) is higher than the base material to reduce the transmission loss [20]. As is shown in Fig. 1(c), an experimental scheme is designed, and the spectral response can be observed by using an optical spectrum analyzer (OSA). The silica is selected as the background material whose dispersion can be determined by the Sellmeier equation as shown in Eq. (1) [21]. The dispersion of gold is described by the Drude-Lorentz model and expressed in Eq. (2), where ε_{Au} is the permittivity of the metal and $\varepsilon_\infty = 9.75$ is the permittivity in infinite frequency. The $\omega_p = 1.36 \times 10^{16}$ rad/s, $\omega_\tau = 1.45 \times 10^{14}$ rad/s are the plasma frequency and collision frequency, respectively [22].

$$n^2 = 1 + \frac{0.6961663\lambda^2}{\lambda^2-(0.0684043)^2} + \frac{0.4079426\lambda^2}{\lambda^2-(0.1162414)^2} + \frac{0.8974794\lambda^2}{\lambda^2-(9.896161)^2} \quad (1)$$