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Fiber ring laser sensor based on hollow-core photonic crystal fiber

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ABSTRACT

We report an erbium-doped fiber ring laser intra-cavity sensor. Hollow-core photonic crystal fiber (HC-PCF) used as the gas absorption chamber is introduced into the laser cavity. When the HC-PCF is filled with gas, its absorption attenuation changes the cavity loss and the laser output. We use a modular NI PXI platform equipped with a programmable voltage and current source and a LabVIEW program to generate driving voltage for the tunable optical filter (TOF) to ensure high precision. The relationship between the concentrations of acetylene, coupling ratios, pump power and output power is theoretically and experimentally investigated. Different output spectra are measured by the optical spectral analyzer (OSA). A minimum detectable acetylene concentration (MDAC) of 5.4 ppm has been experimentally achieved.

1. Introduction

With the rapid development of erbium-doped fiber amplifiers (EDFA) which have broad gain bandwidth, there has been continuous interest in various types of erbium-doped fiber lasers (EDFL) [1]. A variety of regimes such as wide-range spectral tuning, stable Q-switching and multi-wavelength operation, are demonstrated in EDFL. EDFL is used for lots of applications such as spectroscopy, chemical sensing, mechanical strains, acoustics measurements and so on [2]. Among these applications, the use of EDFL for intra-cavity sensing is very important [3]. Intra-cavity technology was firstly applied to gas sensing in 1992 and this method showed great potential [4]. Since then, lots of work about intra-cavity gas sensing has been reported. In 2003, the sensitivity of intra-cavity measurement was compared with that of the single pass absorption measurement and a MDAC of 2253 ppm was obtained [5]. Then, the wavelength modulation technique (WMT) was applied to intra-cavity sensing and a MDAC of 1000 ppm was achieved [6]. Later, the wavelength sweep technique (WST) was introduced into the laser cavity and a MDAC of 200 ppm was obtained [7]. Lately, both of the WMT and the WST are used in the intra-cavity system; a MDAC of 75 ppm was measured [8]. All of the above systems used the ordinary gas cell for gas detection. Thus, it is very difficult for these systems to improve the sensitivity.

Photonic crystal fiber (PCF), with periodic arrangement of air holes running along the longitudinal direction, has been widely investigated in optical fiber devices and sensors because of its many interesting characteristics unachievable by conventional optical fiber [9,10]. Compared with traditional gas cells [5–8], it is much easier for PCF to increase the interaction length of the gas cell because PCF can be easily twined round a specific device and it does not need much space, which increases the interaction time and improves the sensitivity [11]. In 2001, it was proposed that PCF offers new alternatives for sensing technologies and the air holes in the cladding can be used directly for gas sensing [12]. Then, an all-fiber gas detector using PCF was demonstrated, and the PCF was placed outside the cavity [13]. Later, an easy-to-implement HC-PCF cell fabrication technique was presented [14]. An absorption transmission spectrum of CH_4 in a 16.9 cm long index-guiding PCF was obtained and its PCF was also put outside the cavity [15]. Lately, a methane detection system based on wavelength modulation spectroscopy and HC-PCF was proposed and this work was done outside the cavity, too [16]. Also, other gas sensing work about PCF has been reported [17–20]. However, the idea of putting HC-PCF into the laser cavity and using WST for high precision and sensitivity, has not been proposed before.

In this paper, we introduce HC-PCF into the intra-cavity system and use WST supported by the NI PXI platform in our experiment to ensure high precision. We have theoretically and experimentally investigated the relationship of some system parameters such as concentrations of acetylene, coupling ratios, pump power and output power. Different output spectra are measured. The high sensitivity of 5.4 ppm for acetylene has been achieved. This result is increased by two orders of magnitude compared with the MDAC of 1000 ppm without the intra-cavity technique and HC-PCF [21].

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And it is increased by one order of magnitude compared with the MDAC of 75 ppm without the HC-PCF [8].

2. Theoretical analysis

2.1. Output power of EDFL

The spectral property of Er^{3+} is showed here. Its signal wavelength ranges from 1520 to 1565 nm. It can be pumped at 510, 532, 665, 810, 980 and 1480 nm. 980 and 1480 nm are the most favorite ones because there is no excited-state absorption (ESA) at these two wavelengths [22].

A fiber laser with erbium-doped fiber (EDF) as gain medium, which is pumped by a 980 nm diode laser, can be considered as a three-level system [23]. In this case, by solving the rate equations and propagation equations, we can get the output power of the EDFL as below [22]:

$$P_{Las} = \eta\left(P_p^{in} - P_p^{th}\right) \quad (1)$$

where η denotes the slope efficiency, P_p^{in} denotes the pump power and P_p^{th} denotes the pump power threshold. η and P_p^{th} are given by

$$\eta = \frac{\eta_q\,\varepsilon_2(1-\kappa)}{T_{eff}}\frac{P_s^{IS}}{P_s^{CS}}\left[1-(G_{max}\,\varepsilon\kappa)^{-\delta}\right] \quad (2)$$

$$P_p^{th} = \frac{h\nu_p\,P_s^{CS}[\alpha_s L - \ln(\varepsilon\kappa)]}{1-(G_{max}\,\varepsilon\kappa)^{-\delta}} \quad (3)$$

where η_q is the quantum efficiency, $(1-\varepsilon_2)$ is a kind of loss, κ is the coupling ratio, T_{eff} is the effective output transmission, G_{max} is the maximum fiber gain, ε is the effective cavity transmission, δ is the saturation power ratio and ν_p is the pump light frequency. P_P^{IS} (P_S^{CS}) characterizes how signal (pump) absorption is saturated by pump light and P_S^{IS} (P_P^{CS}) characterizes how signal (pump) absorption is saturated by signal light. If an ion has high pumping efficiency and fast decay from the pump and terminal lasing levels, then $P_S^{IS} \approx P_S^{CS}$.

2.2. Gas absorption

Gas absorption obeys Beer–Lambert law [24]:

$$I_T(\omega) = I_0(\omega)\exp[-\gamma\alpha(\omega)CL_a] \quad (4)$$

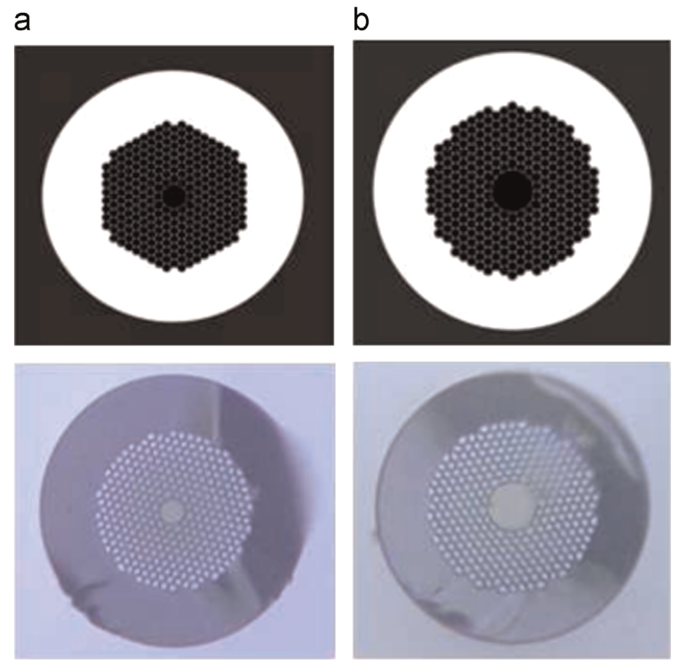

Fig. 2. (a) Cross-sectional structure of HC-1550-02 and (b) cross-sectional structure of HC19-1550-01.

where $I_0(\omega)$ ($I_T(\omega)$) denotes the intensity of output light without (with) gas absorption in the cavity, γ denotes the relative sensitivity, $\alpha(\omega)$ denotes the absorption coefficient, C denotes the gas concentration and L_a denotes the effective absorption length.

The relative sensitivity γ can be calculated with the equation below [25]:

$$\gamma = (n_r/n_{eff})f \quad (5)$$

where n_r is the refractive index of acetylene which is approximated to 1, n_{eff} is the effective refractive index of the mode field and f is the ratio of the transmission power in the air area of the fiber core to the total power. f is given by

$$f = \int_{core}(E_x H_y - E_y H_x)dxdy \Big/ \int_{total}(E_x H_y - E_y H_x)dxdy \quad (6)$$

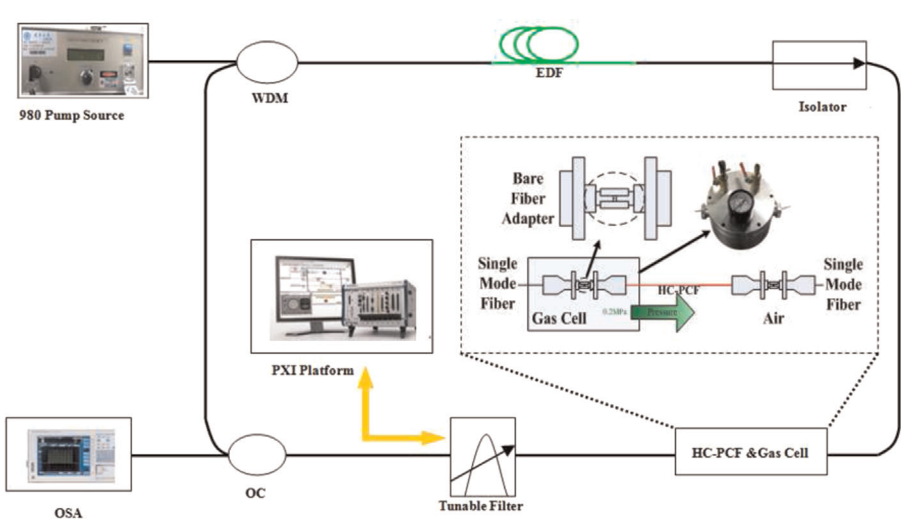

Fig. 1. Schematic diagram of the gas sensing system.