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Measurement of concentration and temperature using a fiber loop ring-down technique with core-offset structure

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ABSTRACT

Fiber-loop ring-down spectroscopy (FLRDS) technique can be used for measurement by indirectly measuring the ring-down time. This is advantageous because it is free from fluctuations of the light source and has a high sensitivity. A novel sensing system for measuring the concentration and temperature based on the FLRDS technique and Mach–Zehnder interferometer (MZI) is proposed in this work. The intra-cavity losses were compensated, which depended on the erbium-doped fiber amplifier. The sensor head was a section of 4 cm single-mode fiber that was spliced into the fiber loop ring cavity in a core-offset way, and its characteristics were tested by experimenting with different solution concentrations and temperatures. The experimental results showed that the detection limit of this system is 0.0014 g/ml, in the range of 0.010–0.400 g/ml. In the temperature sensing experiment, when the temperature varied from 30–200 °C, a sensitivity of 1.83 μs/°C was achieved. This research demonstrated that the MZI-based FLRDS sensing system has a clear response to the solution and temperature; therefore, it provides a reference for the measurement of stress, pressure, curvature, and other physical quantities.

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1. Introduction

Fiber-loop ring-down spectroscopy (FLRDS) is a highly sensitive spectroscopic measurement technique, which has recently become a research topic, that combines the advantages of optical fiber sensing and cavity ring-down spectroscopy (CRDS) with high sensitivity. It is well suited to characterizing low-loss processes in fiber optic transmissions, independent from power fluctuations of the light source [1,2]. Compared with the conventional CRDS system, the FLRDS system uses a fiber loop rather than a high-reflectivity mirror as the resonant cavity and has rapidly gained popularity in the scientific community [3]. However, the ring cavity consisting of reflective layers ($R > 99\%$) or high splitting ratio (99:1) fiber couplers cause the universal drawback of the FLRDS system as an almost 100% coupling loss occurs when the light pulse is coupled into the cavity [4]. An effective way to solve this problem is to employ an erbium-doped fiber amplifier (EDFA) to compensate for loss and increase the ring-down time of the ring cavity [5]. In recent years, there have been some reports on intra-cavity signal amplification, such as Zhang et al. [6], who investigated the sensitivity of an erbium-doped fiber laser intra-cavity loss both theoretically and experimentally. Silva et al. [7] demonstrated the effect of using an EDFA for signal amplification inside the fiber ring of a cavity ring-down configuration. Liu et al. [8] proposed an optical fiber amplifier loop (OFAL) for intra-cavity and ring-down cavity gas sensing, in which the theoretical sensitivity limits of both forms were 1 and 10 ppm, respectively.

Based on the development of fiber Bragg grating (FBG) [9], long-period grating (LPG) [10], and Mach–Zehnder interferometer (MZI) [11], various types of fiber concentration and temperature sensing systems have been extensively studied. For example, a practical pass-through-type FBG temperature sensor has been experimentally fabricated, which was embedded in the conventional thermocouple housing with a sensitivity of 10.3 pm/°C [12]. The etched and packaged LPG has also been studied to detect the temperature variation, and a resolution of ~0.005 °C was achieved [13]. A peanut-shape fiber-structure-based MZI for temperature measurement has been proposed, and it is found that for an interferometer length of $L = 22$ mm, the temperature sensitivity of the device was ~46.8 pm/°C [14]. The concatenated strong FBG and a weak LPG have been presented for simultaneous temperature and solution concentration measurements, in which the coupled-mode theory and experiments were analyzed [15]. The real-time measurement of the variation of the concentration and temperature of a solution in

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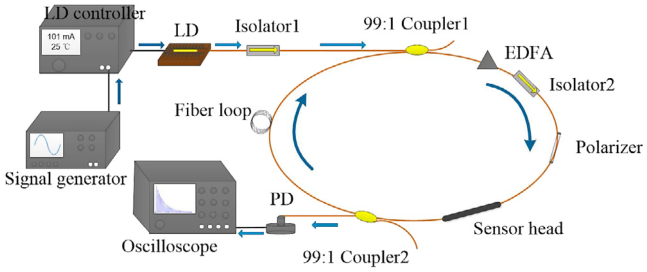

Fig. 1. Experimental setup of the MZI-based FLRDS sensing system.

the liquid-phase using contactless MZI has been performed, and the relationships between the temperature, concentration, and refractive index of solution have been investigated [16]. Though these traditional configurations have a superior performance, most have issues, including cross-sensitivity, fluctuation of the light source, and system connection losses, which limit the further development of sensors.

In order to solve the problems above, this work proposes a concentration and temperature sensing system based on MZI and FLRDS. The proposed sensor head was fabricated by splicing a section of a single-mode fiber (SMF) between two SMFs in a core-offset way. As an all-fiber system, the universal drawback of FLRDS is the coupling loss when the light pulse is coupled into the cavity. An effective way to solve this problem is to employ an EDFA to compensate for loss and increase the ring-down time of the ring cavity.

2. Experimental setup

Fig. 1 is the schematic diagram of the MZI-based FLRDS sensing system for concentration and temperature, which consisted of two standard fiber couplers (2×2 99:1) and an EDFA that provided the gain to compensate for the large loss inside the fiber loop. The EDFA was built with a 2 m erbium-doped fiber (peak absorption of 20.04 dB/m @ 980 nm Furukawa); a 980 nm pump laser (LC962UF74P-20R/750 mW, 974 nm Oclaro) via a 980/1550 WDM coupler; a fiber loop of ~3.6 km (SMF-28 Corning); two isolators to ensure unidirectional transmission and that the light source was not damaged; and a pigtailed distributed feedback laser diode (DFB LD SFL-19807 Thorlabs) as the laser source. The current and temperature of the LD controller were set to 101 mA and 25 °C. A series of pulse waves (1 KHz, 2 V, 14 μs) by a digital signal generator (33500B Keysight) were transported into the LD controller through its “analog modulation input” port and modulated to produce light pulses. The modulated light pulses from the DFB LD were coupled into the fiber loop via the 1% arm of coupler 1, then circulated around the fiber loop, before being coupled out of the fiber loop by the 1% arm of coupler 2. Meanwhile, most of the light pulses were kept inside the fiber loop and continued to travel around the fiber ring cavity. The output periodic trains of decayed pulses were converted into electrical signals by a photo-detector (PDA10CS-EC Thorlabs) and eventually displayed on a digital oscilloscope (DSO6054A Agilent).

3. Principle

The structure schematic diagram of the sensor head is shown in Fig. 2. A length of 4 cm SMF was fused between two segments of SMFs in a core-offset way at two splicing joints. The offset point value d was 3.75 μm. When a pulse signal passes through a sensor head, the output light intensity I can be described as follows:

$$I = \sum_m 2 I_{core} I_{cladding,m} \left(\cos \Delta\varphi_m - \frac{I_{core} + \sum_m I_{cladding,m}}{\sum_m 2\sqrt{I_{core} I_{cladding,m}}} \right)^2 \tag{1}$$

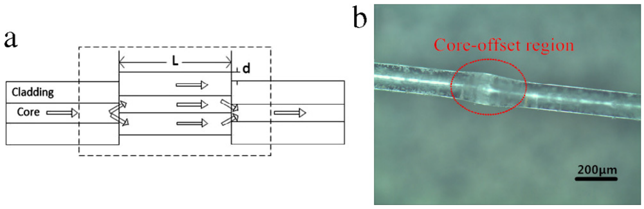

Fig. 2. (a) Schematic diagram of the sensor head, and (b) the core-offset photograph under the light microscope.

Here, I_{core} and $I_{cladding,m}$ are the light intensities of the core mode and the mth cladding mode, respectively, and φ_m is the phase difference of light in the fiber loop, which can be expressed as:

$$\varphi_m = \frac{4\pi \Delta n_{eff}^{m} L}{\lambda} \tag{2}$$

Here, $\Delta n_{eff}^{m} = n_{eff}^{core} - n_{eff}^{cladding,m}$ represents the effective refractive index difference, n_{eff}^{core} is the effective index of the core, $n_{eff}^{cladding,m}$ is the effective index of the mth cladding mode, L is the effective interference length, and λ is the light wavelength. Based on interference theory, the mth wavelength λ_m in the transmission spectrum of the interference can be described by:

$$\lambda_m = \frac{2\Delta n_{eff}^{m} L}{(2m+1)} \tag{3}$$

Here, m is the interference order from Eqs. (1), (2), and (3), which implies that a change of concentration leads to a phase difference, resulting in a change of the output light intensity.

The time-domain method usually determines the optical loss within the fiber loop by monitoring the decay lifetime of the light pulses introduced into the fiber loop. Eq. (4) describes the temporal decay behavior of the light intensity detected by the oscilloscope [17]:

$$I = I_0 e^{-\frac{cA}{nd}t} \quad t = t_0 + (N-1)T, \quad N = 1, 2, 3, \ldots \tag{4}$$

Where I is the light intensity of Nth light pulse at $t_0 + (N-1)T$, I_0 is the incident initial light at t_0, and $t = t_0 + (N-1)T$ is the sampling time to obtain the light intensity of the output pulse. The ring-down time τ is defined as the time taken for the light I to decay to $1/e$ of I_0, which is given by:

$$\tau = \frac{nd}{c(A+B-G)} \tag{5}$$

Here, d is the fiber loop length, c is the speed of light, n is the refractive index of the fiber loop, G is the gain of the EDFA, A is the total of the cavity losses in each cavity decay process (including the absorption, insertion, and scattering losses) and B represents the transmission attenuation which is caused by the temperature or concentration. A and G in Eq. (5) are fixed, and τ depends only on B. In particular, when the temperature or concentration changes, the transmission attenuation of the sensor head will change accordingly. Therefore, the temperature or concentration can be obtained by using the relationship between the ring-down time and the temperature or concentration.

4. Experiments and results

The transmission spectrum of the sensor head in air based on the SMF core-offset structure is shown in Fig. 3(a). In this experiment, the working wavelength of the laser was 1550 nm. It can be seen from Fig. 3(a) that the range of the interference spectrum was 1535–1565 nm, and the single peak depth at 1552.5 nm was more than 12 dB, in which the shape was regular and provided an observable signal. The wavelength of the transmission spectrum varied with the physical quantity change, so it could be used for measurements of concentration and temperature. Fig. 3(b) shows the ring-down spectrum

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