Sensors and Actuators A 279 (2018) 140–144

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

# Optical fiber liquid refractive index sensor based on Fresnel reflection of anti-Stokes light

Dong Wang*, Jingkuo Tong, Baoquan Jin, Yu Wang, Mingjiang Zhang

*Key Laboratory of Advanced Transducers and Intelligent Control System, Ministry of Education, and Shanxi Province, College of Physics and Optoelectronics, Taiyuan University of Technology, No. 79 West Main Street, Yingze, 030024, China*

ARTICLE INFO

*Article history:*
Received 31 January 2018
Received in revised form 5 June 2018
Accepted 6 June 2018

*Keywords:*
Refractive index sensing
Optical remote sensor
Fresnel reflection
Raman anti-Stokes light

ABSTRACT

An optical fiber liquid refractive index (RI) sensing method based on Fresnel reflection of Raman anti-Stokes light is firstly proposed and demonstrated. A specially fabricated sensor head formed by a fiber end and a fiber coil is designed, and they are used to sense RI and temperature respectively. Experimental results show that the sensor has a RI resolution up to 0.0002 RIU (Refractive Index Unit) and a temperature accuracy of ±1 °C within a measurement range of 10 km. The performance confirms that the sensor has potential to act as a remote refractometer and thermometer. Its case of simple fabrication of using only one multimode fiber offers attractive remote RI and temperature sensing applications involving chemical and biological fields.

## 1. Introduction

RI is not only an important parameter in optical related fields, but also a crucial metric in food production, pharmaceutical, and other physicochemical or biochemical-based industries to monitor process engineering applications [1]. However, the reference books can't offer enough RI data of liquid, which means it has to be measured as needed. At present, the optical fiber-based RI sensors have been extensively focused due to their distinct characteristics of low cost, small dimensions, simple fabrication, immunity to electromagnetic interference, biological and chemical inert, as well as can be integrated in complex networks for real-time multi-parameter sensing [2]. The optical fiber-based RI sensors include photonic crystal fiber interferometer [3], microfiber coil resonator [4], long-period gratings [5–7], multimode interferometer [8,9], Mach-Zahnder interferometer [10], Fabry-Perot interferometer [11,12], Fresnel Reflection [13,14]. Some of these fiber-based RI sensors possess high sensitivities, but the sensing units are susceptible to ambient temperature perturbations. To compensate the RI measurement uncertainty caused by temperature perturbation, the simultaneous measurement of RI and temperature is a feasible choice, and several approaches have been proposed including a surface plasmon resonance-based RI sensor [15], a hybrid single-mode fiber structure for RI measurement [16], in-series double cladding fibers [17], which are not capable of making remote sensing. However, schemes for simultaneously on-line measuring liquid RI and temperature are often demanded.

Thus, in this paper, a novel sensing method for remotely measuring liquid RI by detecting Fresnel reflection of Raman anti-Stokes light in a multimode fiber (MMF) is proposed and experimentally demonstrated. The proposed liquid RI sensing system is similar to the Raman distributed temperature sensing (DTS) system, in which the temperature is demodulated by the intensities ratio of the Raman anti-Stokes and Stokes backscattered light, meanwhile, the RI is demodulated based on Fresnel reflection of Raman anti-Stokes light. Therefore, it can remotely measure the RI and temperature simultaneously. The highlight of this work is using the Fresnel reflection intensity of Raman anti-Stokes at the MMF end to measure the RI, which means to add a new functionality to the DTS. In the following, we will briefly outline the RI sensing principle and experimental setup, discuss and analyze the experimental results, and demonstrate the feasibility of measuring the liquid RI and temperature simultaneously with the proposed sensor.

## 2. RI sensing principle

The Fresnel formula reveals the reflection of light on the contact interface of substances with different RIs. For a fiber end (perpendicularly cleaved fiber end), the power reflection coefficient can be given as follows [19]:

$$I_{end} \propto \left(\frac{n_f - n_m}{n_f + n_m}\right)^2 \qquad (1)$$

---

* Corresponding author.
*E-mail address:* wangdong@tyut.edu.cn (D. Wang).

https://doi.org/10.1016/j.sna.2018.06.015
0924-4247/

Where $n_f$ is the effective RI of the MMF, $n_\mathrm{m}$ is the RI of the sample liquid. For different liquids, the intensity values of reflection signals are different, thus it can be used as an indicator for measuring the RI. Here, with the purpose of eliminating the system error might be caused by the bending loss of the fiber, or the instability of the light source, or the loss of the optical fiber transmission, or the loss of the fiber joint, or the coupling loss in the optical fiber transmission process, a reference value $I_0$ is adopted. To obtain the reference value $I_0$, the MMF end needs to be immersed in a sample with a known RI $n_0$ (e.g. air or water). And then, the MMF end is immersed in the measuring liquid for obtaining $I_m$. Therefore, the relative intensity $R$ can be expressed as shown below,

$$R = \frac{I_m}{I_0} = \left(\frac{n_f - n_m}{n_f + n_m} \cdot \frac{n_f + n_0}{n_f - n_0}\right)^2. \tag{2}$$

In theory, the Fresnel reflections of both Raman Stokes and anti-Stokes light can be utilized to measure the liquid RI. But it should be pointed out that, the zero-dispersion wavelength of the fiber under test (FUT) is 1320–1365 nm.That is to say, compared with the Raman anti-Stokes light (1450 nm), the wavelength of Stokes light (1660 nm) is farther from the zero-dispersion wavelength, and the chromatic dispersion of Raman Stokes light should be more serious, which makes the power reflection coefficient worse and the Fresnel reflection curve of Raman Stokes light becomes more ambiguous. Besides, the power reflection coefficients can be influenced by the pulse width of the light launched into the fiber under test. Therefore, considering effects of the chromatic dispersion and pulse width of the light launched into the fiber under test, the Raman anti-Stokes light is chosen. Accordingly, the Eq. (2) can be rewritten as shown below.

$$R(\lambda) = \frac{I_m(\lambda)}{I_0(\lambda)} = \left[\frac{n_f(\lambda) - n_m(\lambda)}{n_f(\lambda) + n_m(\lambda)} \cdot \frac{n_f(\lambda) + n_0(\lambda)}{n_f(\lambda) - n_0(\lambda)}\right]^2, \tag{3}$$

where λ is the wavelength of the anti-Stokes light. $I_m(\lambda)$ and $I_0(\lambda)$ can be detected by the photodetector. From Eq. (3), one obtains

$$n_m(\lambda) = n_f(\lambda)\left\{1 - \frac{\sqrt{R(\lambda)}}{[n_f(\lambda) + n_0(\lambda)]\,/\,[n_f(\lambda) - n_0(\lambda)]}\right\} \Big/ \left\{1 + \frac{\sqrt{R(\lambda)}}{[n_f(\lambda) + n_0(\lambda)]\,/\,[n_f(\lambda) - n_0(\lambda)]}\right\}. \tag{4}$$

This means $n_m(\lambda)$ can be calculated by the detected $I_m(\lambda)$ and $I_0(\lambda)$.

## 3. Experimental setup

Considering the liquid RI can be affected by temperature, an optical fiber liquid RI sensing head that can simultaneously detect the RI and temperature is designed as shown in Fig. 1. The MMF end is designed as the RI sensing unit, which is cleaved as a vertical smooth surface. A fiber coil, which is more than 3 m in length and about 5 cm in diameter, is designed as the temperature unit.

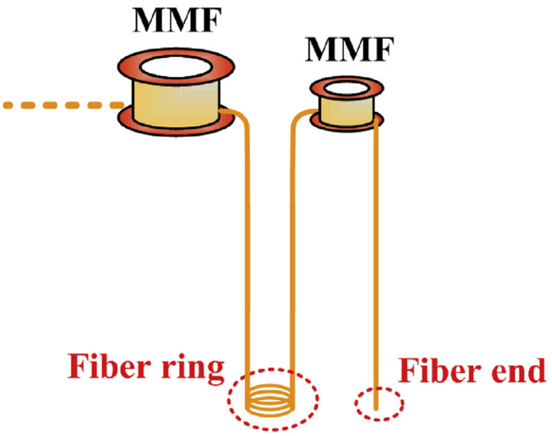

**Fig. 1.** Schematic diagram of the sensor head.

In order to verify the proposed method, an experimental setup for the liquid RI and temperature sensing is established as shown in Fig. 2. It consists of two parts: optical part and electrical part. The optical part consists of a pulse laser, a wavelength-division multiplexing (WDM) and the sensing fiber; the electrical part consists of a two-channel photodetector (PD), a data acquisition card (DAQ) and a personal computer (PC). All of the fiber used in the experiments are ordinary multi-mode fiber (G651, 62.5/125 μm, Yangtze Optical Fiber & Cable Corporation), and the fiber group index $n_f$ is 1.488 at the room temperature. The light source operates in the center wavelength around 1550 nm with a repetition frequency of 8 kHz. The WDM operates in the center wavelengths of 1450 nm&1550 nm&1660 nm. The light pulses emitted from the laser pass the WDM to go into the FUT and generate Stokes (ST) and anti-Stokes (AS) light in the whole fiber (even at the fiber end face). The WDM separates the generated ST and AS light spectrally from the backscattered or reflected light. ST as well as AS light is detected and converted into electrical signals by separate photodetectors and acquired simultaneously by DAQ. Finally, the electrical signals are processed by PC. In order to assure synchronization between the pulse laser emitting and data acquisition, when the pulse light is emitted, the DAQ is triggered synchronously to acquire the signals from the photodetector.

## 4. Experimental results and discussion

Firstly, a length of 8982 m MMF is utilized to take a remote RI measurement. The deionized water ($n_0$ = 1.3325) is used as the reference liquid. The sodium chloride solutions to be measured have a concentration step of 2.5% from 0% to 25%. The sensor head is immersed in the deionized water to obtain the reference signal $I_0(\lambda)$. Then, it is sequentially immersed in the sodium chloride solutions with different concentrations, and the signal $I_m(\lambda)$ can be sequentially measured accordingly.

As shown in Fig. 3, it can be seen that anti-Stokes traces and Stokes traces both have Fresnel reflection peaks at the end of the FUT. However, their Fresnel reflections seem to appear at different distances (Stokes located at 8983 m, anti-Stokes located at 8982 m). The reason for this is the difference in optical path length caused by different wavelengths. As we know, the optical path length $L$ in a fiber is defined by $L = n_{eff} {}^* l$, where $n_{eff}$ is the effective RI of the FUT and $l$ is the geometrical fiber length. The $n_{eff}$ depends not only on the wavelength but also on the mode in which the light propagates. In addition, compared with the anti-Stokes Fresnel reflection peaks, the Stokes Fresnel reflection peaks seem to be ambiguous, we believe that this phenomenon is caused by the chromatic dispersion. Besides, the anti-Stokes Fresnel reflection peak changes monotonically with the change of the liquid concentration. Therefore, we choose the anti-Stokes Fresnel reflection peaks to indicate the liquid concentrations. Due to the RI of a solution is a function of its concentration [20], the anti-Stokes Fresnel reflection peak can also be used to indicate the liquid RI indirectly.

As shown in Fig. 4, the horizontal axis represents the concentration of sodium chloride solution, the left vertical axis represents anti-Stokes intensity, and the right vertical axis represents RI. The black square dots represent the anti-Stokes intensity decreases monotonically with the increase of the liquid concentration, while the blue dots represent the liquid RI increases monotonically with the increase of the liquid concentration. The red solid