Refractive index sensing based on chaotic correlation fiber loop ring down system using tapered fiber

Jun Tian, Lingzhen Yang, Chong Qin, Tianlong Wu, Juanfen Wang, Zhaoxia Zhang, Kang Li, Nigel Copner

***Abstract*—A novel refractive index sensing using the tapered single mode fiber (TSMF) is proposed based on the chaotic correlation fiber loop ring down system (FLRDs). A chaotic fiber laser is used to drive the fiber loop cavity. The performance of the proposed TSMF chaotic correlation FLRDs refractive index sensing was demonstrated by measuring the ring down time of the peaks of correlation coefficient of the sensing system at different refractive index. The sensing demonstrates a good stability and repeatability. The influence of the change in fiber loop length on the sensing system was also investigated. The results show that the sensitivity of chaotic correlation FLRDs increases with the decrease of the loop length and the change of the loop length has little effect on the detection limit (DL) of the system. The DL of 10^{-4} RIU were achieved. Compared with the pulsed FLRDs, the chaotic correlation FLRDs significantly simplify the light source of sensing system and eliminate the trade-off problem between the length of fiber loop cavity and the light source, and makes fiber loop length more flexible.**

***Index Terms*—Chaotic fiber laser, fiber loop ring down, refractive index sensing.**

I. INTRODUCTION

REFRACTIVE index is one of the fundamental properties of a material. The measurement of refractive index has important applications in chemical [1], biological [2], environmental monitoring [3], [4] and food safety. In recent years, the evanescent field (EF) based on refractive index sensors have attracted great interests in the measurement for refractive index owing to the easy fabrication and small size [5].

The EF phenomenon results from the total internal reflection of light at the interface of two media. When the light propagates in the fiber, the EF phenomenon only exists in a small range at the interface between the core and the cladding of the fiber, so the measurement must be taken to make the EF interact with the solution outside the cladding. The chemical etching [6], side polishing [7] and drawing a taper [8] are the commonly used methods for exposing EF of the fiber. It is well known that the intensity and spectrum would be changed when light pass through the EF. H.A. Rahman *et al.* proposed an intensity modulated tapered multimode plastic fiber optic sensor for salinity detection [9]. Pengfei Wang *et al.* demonstrated an enhanced evanescent field fiber refractometer using a tapered multimode fiber sandwiched between two single mode fibers based on the wavelength shift of the transmission spectrum [10]. Compared with measuring spectrum and intensity, FLRDs have great advantages, such as insensitivity to source fluctuations, fast response, the ring down enhanced detection sensitivity and low cost [11].

FLRDs, which was put forward by Stewart *et al.* in 2001 [12], where a coupler replaces the high reflectivity mirror, is a variant of cavity ring down spectroscopy (CRDs) [13]. In 2004, the feasibility of combining EF sensing mechanism with FLRDs was proved by Tarsa *et al.* [14]. In 2010, Chuji Wang *et al.* proposed a FLRDs glucose sensor using refractive index difference EF attenuation effect as a sensing mechanism [15]. In 2019, Panpan Niu *et al.* proposed a fiber optic refractive index sensor based on FLRDs with an S fiber taper structure [16].

For the pulsed FLRDs, the device for generating the pulsed laser is generally composed of a light source, an intensity modulator and a signal generator [17], [18]. Optical time-domain reflectometer (OTDR) was proposed as a FLRDs light source [19], [20]. It needs to consider the trade-off problem between the length of fiber loop and the width and frequency of the pulse [21]. The frequency must ensure that there are only one group pulses in the fiber loop cavity. Furthermore, the ring down time is also greatly affected by pulse width, the narrower pulse width is achieved the longer ring down time [20], [22]. To overcome the obstacle, the chaotic correlation FLRDs was proposed by our group [23].

The chaotic correlation FLRDs is composed of a chaotic laser, two couplers and the sensor, which is similar to the traditional FLRDs [24]. Compared with the pulsed FLRDs, the chaotic correlation FLRDs significantly simplify the light source of sensing system and eliminate the trade-off problem between the length of fiber loop cavity and the light source, and makes fiber loop length more flexible.

The evanescent field sensing with chaotic correlation FLRDs detection scheme is achieved for a novel refractive index sensing using TSMF. The refractive index characteristics of TSMF chaotic correlation FLRDs are investigated in the time domain by detecting the ring down time of the peaks of

---

This work was supported in part by the National Natural Science Foundation of China under Grant 61575137, 61975141 and 61675144, in part by the Top Young and Middle-aged Innovative Talents of Higher Learning Institutions of Shanxi, China. (Corresponding author: Lingzhen Yang.)

Jun Tian, Lingzhen Yang, Chong Qin, Tianlong Wu, Juanfen Wang, Zhaoxia Zhang are with the College of Physics and Optoelectronics, Taiyuan University of Technology, Taiyuan Shanxi, 030024, China. (e-mail: tianjunoffice@yeah.net; office-science@tyut.edu.cn; qinchong@opt.cn; wutianlongtyut@yeah.net;wangjuanfen@tyut.edu.cn;zhangzhaoxia@tyut.edu.cn).

Kang Li, Nigel Copner are with the Wireless & Optoelectronics Research & Innovation Centre, Faculty of Computing, Engineering & Science, University of South Wales, Wales, CF37 1DL, UK. (e-mail: kang.li@southwales.ac.uk; nigel.copner@southwales.ac.uk)

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JSEN.2019.2961693, IEEE Sensors Journal

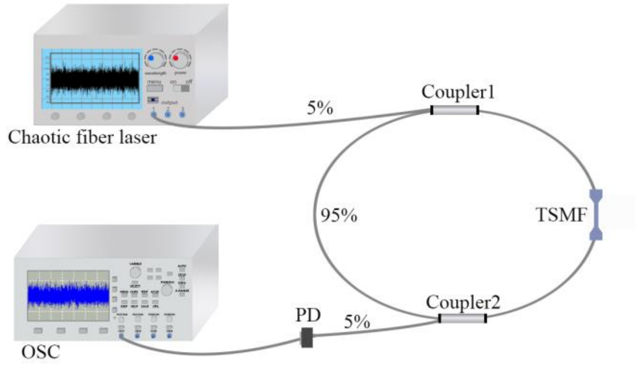

Fig. 1. Schematic diagram of the TSMF chaotic correlation FLRDs refractive index sensing system.

autocorrelation coefficient at different solutions. The paper is organized as follows. The experimental setup of the TSMF chaotic correlation FLRDs is described in the next section. The experimental results and discussions are analyzed in Section III. Finally, the conclusion is presented in the Section IV.

II. EXPERIMENTAL SETUP

The schematic diagram of TSMF chaotic correlation FLRDs sensing is depicted in Fig. 1. The two 95:5 couplers, a TSMF and a section of the SMF were spliced together to form a fiber loop cavity. The light from chaotic fiber laser is coupled into the fiber loop cavity via coupler1 and travels inside the fiber loop cavity for many round trips. The decayed chaotic laser is exported out via coupler2 and is detected by a photoelectric detector (PD). The output of the PD is collected by an oscilloscope (OSC).

To alter the refractive index around TSMF, TSMF was immersed in sodium chloride solutions with different concentrations. Sodium chloride solution was prepared in advance. The refractive indices are 1.3347, 1.3400, 1.3453, 1.3505, 1.3558, 1.3612, 1.3666, 1.3721, and the concentration of the sodium chloride can be found in [25].

The sensor was made by drawing a section of SMF to make the EF interact with the solution outside the cladding. TSMF is composed of a waist region and two transition regions and has a waist diameter of 17 μm and a length of 8 mm. Fig. 2. shows the waist region of TSMF observed by the electron microscope. When TSMF is immersed in the liquid with lower refractive index, there is a new step waveguide structure formed by TSMF and the solution. Different refractive indices of liquids have different effects on light passing through EF.

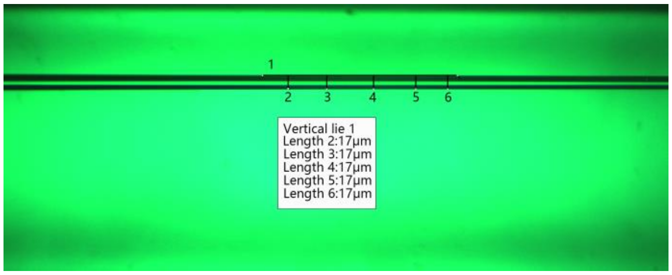

Fig. 2. Optical microscope images of the TSMF.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The wavelength and power of chaotic fiber laser was tuned to 1550 nm, 36.12 mW, respectively. The spectrum, time series, and autocorrelation curve of the chaotic fiber laser were shown in Figs. 3(a)-3(c). Fig. 3(a) shows that the central wavelength of chaotic laser is 1550nm with the full width at half maximum (FWHM) of 0.25 nm. Fig. 3(b) and 3(c) demonstrate that the chaotic laser has a noise-like time series and the autocorrelation curve of chaotic laser has the properties of delta-like function of which the FWHM is 0.8ns, respectively.

The chaotic correlation FLRDs utilizes chaotic fiber laser to achieve sensing by the detection of the ring down time of the peaks of autocorrelation coefficient. In this experiment, τ_{R} is the ring down time when the TSMF is immersed in distilled water (n=1.318), and τ_{R} is given by [23]:

$$\tau_{R0} = \frac{n_c L}{cA} = \frac{t_r}{A}, \tag{1}$$

where L, c, n_c, A, t_{r} are fiber loop length, the velocity of light in vacuum, the refractive index of fiber, total transmission loss of the light in each round trip, and the round-trip time of the light, respectively. TSMF was immersed in the distilled water, and the autocorrelation curve of the decayed chaotic laser exported out via coupler2 is shown in Fig. 3 (d). As can be seen from the Fig. 3 (d), the autocorrelation curve of the decayed chaotic laser is a series of attenuation peaks. The time interval between two adjacent spikes of 38.2 ns demonstrates that the length of fiber loop cavity in this experiment is 7.85 m. τ_{R0} is 88.68 ns obtained by exponentially fitting the chaotic autocorrelation coefficient peaks.

When TSMF was immersed in sodium chloride solutions with different concentrations, the additional loss B is introduced to fiber loop, which causes a change in the ring down time from τ_{R0} to τ_{R}.

Where τ_{R} is given by:

$$\tau_R = \frac{n_c L}{c(A+B)}. \tag{2}$$

So the additional loss B is:

$$B = \frac{n_c L}{c}\left(\frac{1}{\tau_R} - \frac{1}{\tau_{R0}}\right) = t_r\left(\frac{1}{\tau_R} - \frac{1}{\tau_{R0}}\right). \tag{3}$$

The basic principle of the proposed TSMF chaotic correlation FLRDs refractive index sensor is expressed by (3). Additional loss B can be obtained by measuring the ring down time τ_{R} and τ_{R0} and B is essentially determined by the refractive index n around TSMF [26], [27]. The additional loss B versus refractive index n curves follow a linear relationship when the refractive index n is larger than 1.33. The relationship between B and refractive index n in the range of 1.3347 to 1.3721 can be expressed as:

$$B = kn + b, \tag{4}$$

where k and b are constants related to TSMF.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JSEN.2019.2961693, IEEE Sensors Journal

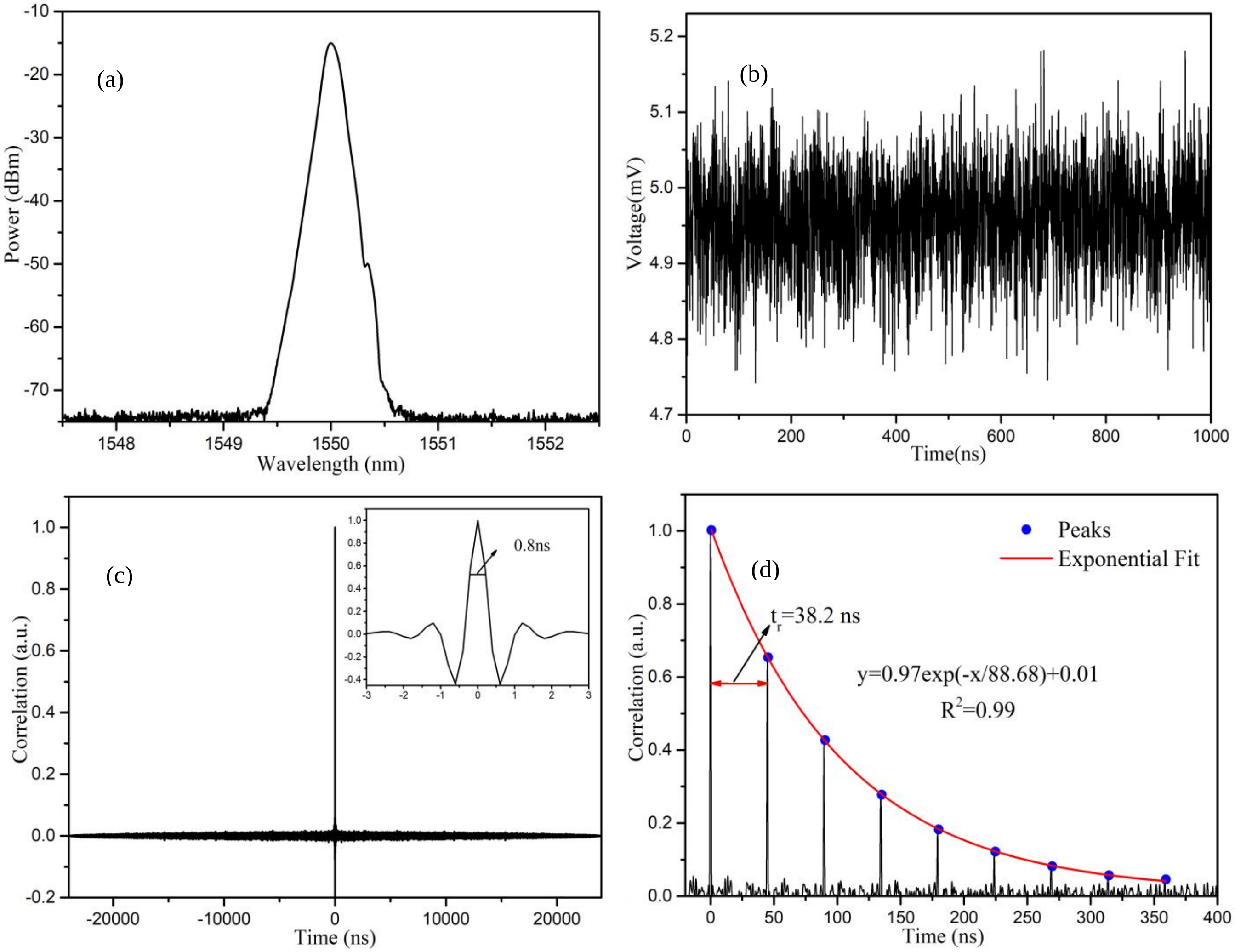

Fig. 3. (a) Spectrum, (b) Time series, (c) Autocorrelation curve, and (d) Autocorrelation curve of the decayed chaotic laser.

From (3) and (4), we have：

$$\left(\frac{1}{\tau_R}-\frac{1}{\tau_{R0}}\right)=\frac{k}{t_r}n+\frac{b}{t_r}=p_1 n+p_2\,, \tag{5}$$

$$p_1=\frac{k}{t_r}\,, \tag{6}$$

$$p_2=\frac{b}{t_r}\,. \tag{7}$$

Equation (5) shows that ($1/\tau_R$-$1/\tau_{R0}$) is proportional to the refractive index *n*. The sensing can be achieved by establishing the relationship between ($1/\tau_R$-$1/\tau_{R0}$) and *n*. Equation (6) indicates that the sensitivity p_1 of the sensing system can be improved by decreasing t_r.

TSMF was immersed in sodium chloride solutions with different concentrations, and the ring down time τ_R was measured in each case. The TSMF was rinsed with water and the next solution to be tested. Fig. 4 shows the autocorrelation coefficient evolution under different refractive indices and also illustrates the fast measurement in chaotic correlation FRLDs. Fig. 5 shows that ($1/\tau_R$-$1/\tau_{R0}$) has an excellent linear relationship with the refractive index *n*, and R^2 is as high as 0.997. And ($1/\tau_R$-$1/\tau_{R0}$) increases significantly with the increase of refractive index *n*. The proposed refractive index sensing based on TSMF chaotic correlation FRLDs provides a high sensitivity of 0.045 ns^{-1} RIU^{-1} in range from 1.3347 to 1.3721. Equation (5) has been experimentally validated via determining the relationships between ($1/\tau_R$-$1/\tau_{R0}$) and the refractive index *n*.

In order to investigating the stability and repeatability of the TSMF chaotic correlation FRLDs, TSMF was immersed in the sodium chloride solution with a refractive index of 1.3721. The output chaotic laser was collected by PD and oscilloscope every five minutes within fifty minutes, grouped into five. It is shown in Fig. 6 that the maximum standard deviation of the ring down time in five groups is 2.35×10^{-5} ns^{-1}. The refractive index sensing based on TSMF chaotic correlation FLRDs has a good stability and repeatability. The DL of 5.16×10^{-4} RIU is experimentally achieved.

The same experiment was used to study the variation of the parameters of the sensing system by changing the length of the

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JSEN.2019.2961693, IEEE Sensors Journal

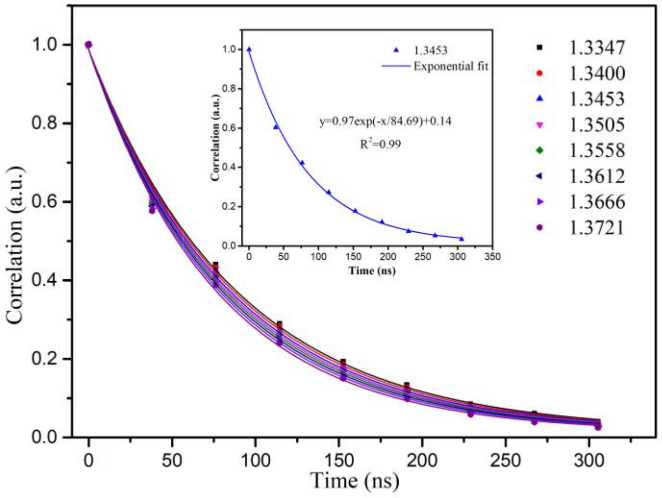

Fig. 4. Autocorrelation coefficient evolution under different refractive indies.

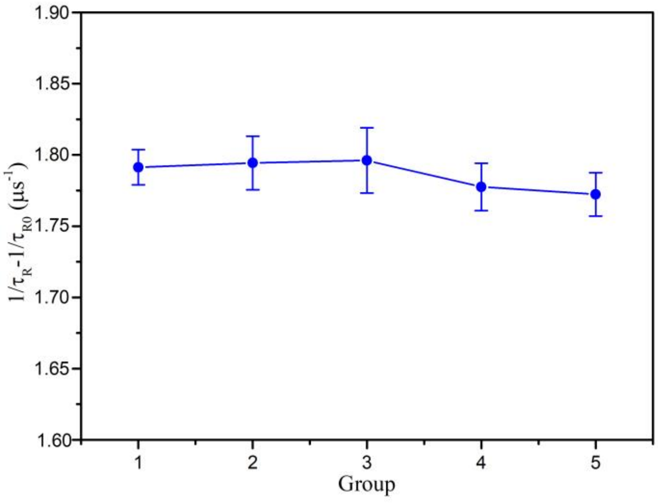

Fig. 6. The repeatability and stability of the sensing system.

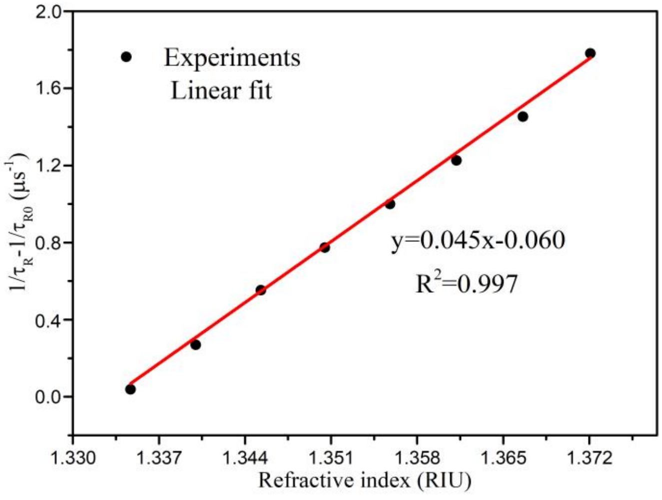

Fig. 5. The relationship between refractive index and $(1/\tau_R-1/\tau_{R0})$.

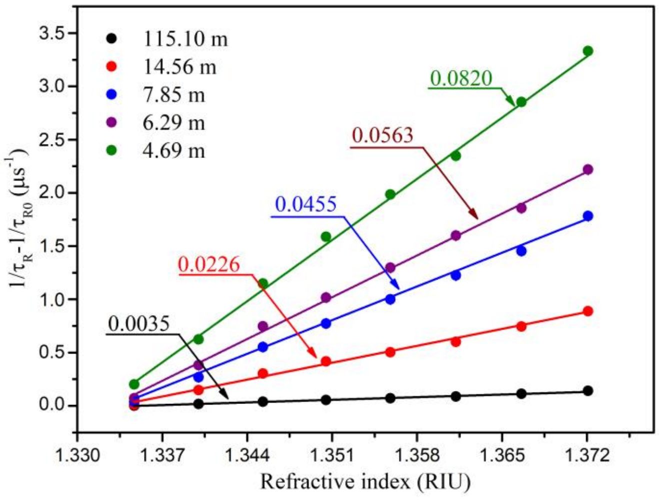

Fig. 7. Comparison of sensitivity of different loops.

TABLE I
COMPARISON OF PARAMETERS FOR DIFFERENT LOOPS

Length of the cavity (L) (m)	4.69	6.29	7.85	14.56	115.10
t_r (ns)	22.8	30.6	38.2	70.8	560
k	1.88	1.72	1.74	1.60	1.96
b	2.64	2.14	2.29	2.29	2.49
DL (RIU)	5.19×10^{-4}	6.53×10^{-4}	5.16×10^{-4}	4.29×10^{-4}	3.89×10^{-4}

fiber loop cavity with the same chaotic fiber laser. The results are shown in Fig. 7 and Table I. The sensitivity p_1 are increased with the decrease of the loop length, which is consistent with (6). The sensitivity of the ring length of 4.69 m is about 23 times larger than that of 115.10 m.

The same TSMF was used in the five sensing systems. According to (4), k and b should be the same in value. k and b can be calculated by (6) and (7). k and b remain basically unchanged known from Table I, which is consistent with that described in (4).

The experiments were performed with the same sensor element in the same environment. The loop length has little effect on the DL of the system. Compared with the pulsed FLRDs, the chaotic correlation FLRDs significantly simplify the light source of sensing system and eliminate the trade-off problem between the length of fiber loop cavity and the light source, and makes fiber loop length more flexible.

IV. CONCLUSION

A refractive index sensing based on the TSMF sensor and chaotic correlation FLRDs is proposed. The sensing demonstrates a good stability and repeatability. The results show that the sensitivity of the sensing system can be improved by decreasing the loop length. The change of the loop length has little effect on the DL. Compared with the pulsed FLRDs, the chaotic correlation FLRDs significantly simplify the light

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JSEN.2019.2961693, IEEE Sensors Journal

source of sensing system and eliminate the trade-off problem between the length of fiber loop cavity and the light source. The DL of this system can be drastically improved by selecting a sensor element with high sensitivity and low loss or applying loss compensation to chaotic correlation FLRDs. Such the simple and low-cost sensing based on the chaotic correlation FLRDs has great potential applications in the medical pharmaceuticals, industrial fluids, photochemical plastics and food industry.

REFERENCES

[1]Y. Zhao, M. Lei, S. X. Liu, and Q. Zhao, “Smart hydrogel-based optical fiber SPR sensor for pH measurements,” Sensors Actuators, B Chem., vol. 261, pp. 226–232, 2018.

[2]T. K. Yadav, R. Narayanaswamy, M. H. Abu Bakar, Y. M. Kamil, and M. A. Mahdi, “Single mode tapered fiber-optic interferometer based refractive index sensor and its application to protein sensing,” Opt. Express, vol. 22, no. 19, pp. 22802–22807, 2014.

[3]S. Pevec and D. Donlagic, “Miniature fiber-optic Fabry-Perot refractive index sensor for gas sensing with a resolution of $5x10^{-9}$ RIU,” Opt. Express, vol. 26, no. 18, pp. 23868–23882, 2018.

[4]X. Qian, Y. Zhao, Y. N. Zhang, and Q. Wang, “Theoretical research of gas sensing method based on photonic crystal cavity and fiber loop ring-down technique,” Sensors Actuators, B Chem., vol. 228, pp. 665–672, 2016.

[5]C. Wang and C. Herath, “High-sensitivity fiber-loop ringdown evanescent-field index sensors using single-mode fiber,” Opt. Lett., vol. 35, no. 10, pp. 1629–1631, 2010.

[6]C. Wang and C. Herath, “Fabrication and characterization of fiber loop ringdown evanescent field sensors,” Meas. Sci. Technol., vol. 21, no. 8, pp. 085205–1–085205–10, 2010.

[7]J. V. Ittiarah, S. Sidhik, and T. K. Gangopadhyay, “Refractometry using evanescent field based fiber loop ringdown spectroscopy,” Sensors Actuators, A Phys., vol. 223, pp. 61–66, 2015.

[8]D. Wu, Y. Zhao, and Q. Wang, “SMF Taper Evanescent Field-Based RI Sensor Combined with Fiber Loop Ring Down Technology,” IEEE Photonics Technol. Lett., vol. 27, no. 17, pp. 1802–1805, 2015.

[9]M. A. Mustapa, M. H. Abu Bakar, A. S. Amir Hamzah, and M. A. Mahdi, “Tapered multimode fiber sensor for salinity detection,” Proc. ICP 2014 - 5th Int. Conf. Photonics 2014, vol. 171, no. 2, pp. 227–229, 2015.

[10] P. Wang, G. Brambilla, M. Ding, Y. Semenova, Q. Wu, and G. Farrell, “High-sensitivity, evanescent field refractometric sensor based on a tapered, multimode fiber interference,” Opt. Lett., vol. 36, no. 12, pp. 2233–2235, 2011.

[11] C. Wang, “Fiber loop ringdown-A time-domain sensing technique for multi-function fiber optic sensor platforms: Current status and design perspectives,” Sensors, vol. 9, no. 10, pp. 7595–7621, 2009.

[12] G. Whitenett, G. Stewart, K. Atherton, P. Shields, and B. Culshaw, “An investigation of an optical fibre amplifier loop for intra-cavity and ring-down cavity loss measurements,” Meas. Sci. Technol, vol. 12, pp. 843–849,2001.

[13] L. van der Sneppen, F. Ariese, C. Gooijer, and W. Ubachs, “Liquid-Phase and Evanescent-Wave Cavity Ring-Down Spectroscopy in Analytical Chemistry,” Annu. Rev. Anal. Chem., vol. 2, no. 1, pp. 13–35, 2010.

[14] P. B. Tarsa, A. D. Wist, P. Rabinowitz, and K. K. Lehmann, “Single-cell detection by cavity ring-down spectroscopy,” Appl. Phys. Lett., vol. 85, no. 19, pp. 4523–4525, 2004.

[15] C. Wang, M. Kaya, and C. Wang, “Evanescent field-fiber loop ringdown glucose sensor,” J. Biomed. Opt., vol. 17, no. 3, pp. 037004–1–037004–10, 2012.

[16] P. Niu et al., “S Fiber Taper-Based Fiber Loop Ring-Down Refractometer,” IEEE Sens. J., vol. 19, no. 3, pp. 970–975, 2019.

[17] Q. Wang, X. Liu, J. Xia, and Y. Zhao, “A Novel Long-Tail Fiber Current Sensor Based on Fiber Loop Ring-Down Spectroscopy and Fabry – Perot Cavity Filled,” IEEE Trans. Instrum. Meas.,vol. 64, no. 7, pp. 2005–2011, 2015.

[18] N. Ni, C. C. Chan, L. Xia, and P. Shum, “Fiber cavity ring-down refractive index sensor,” IEEE Photonics Technol. Lett., vol. 20, no. 16, pp. 1351–1353, 2008.

[19] M. Fabian, E. Lewis, T. Newe, and S. Lochmann, “Optical fibre cavity for ring-down experiments with low coupling losses,” Meas. Sci. Technol., vol. 21, no. 9, pp. 094034–1–094034–5, 2010.

[20] X. Li, X. Wang, P. Niu, J. Zhao, C. Zhang, and E. Gu, “Refractive index measurement using OTDR-based ring-down technique with S fiber taper,” Opt. Commun., vol. 446, no. May, pp. 186–190, 2019.

[21] D. J. Passos, S. O. Silva, J. R. A. Fernandes, M. B. Marques, and O. Frazão, “Fiber cavity ring-down using an optical time-domain reflectometer,” Photonic Sensors, vol. 4, no. 4, pp. 295–299, 2014.

[22] W. C. Yan, Q. Han, Y. Chen, H. Song, X. Tang, and T. Liu, “Fiber-loop ring-down interrogated refractive index sensor based on an SNS fiber structure,” Sensors Actuators, B Chem., vol. 255, pp. 2018–2022, 2018.

[23] L. Yang et al., “Optical sensors using chaotic correlation fiber loop ring down,” Opt. Express, vol. 25, no. 3, pp. 2031–2037, 2017.

[24] C. Qin et al., “Temperature sensing based on chaotic correlation fiber loop ring down system,” Opt. Fiber Technol., vol. 47, no. November 2018, pp. 141–146, 2019.

[25] W.M. Haynes, “THERMOCHEMISTRY, ELECTROCHEMISTRY, AND SOLUTION CHEMISTRY” in CRC Handbook of Chemistry and Physics, 97rd ed., CRC Press, BocaRaton, FL, pp. 5-129, 2012.

[26] K. Sharma, M. I. M. Abdul Khudus, S. U. Alam, S. Bhattacharya, D. Venkitesh, and G. Brambilla, “Comparison of detection limit in fiber-based conventional, amplified, and gain-clamped cavity ring-down techniques,” Opt. Commun., vol. 407, no. June 2017, pp. 186–192, 2018.

[27] K. Sharma, D. Venkitesh, S. Bhattacharya, B. Srinivasan, and G. Brambilla, “Non-linear behavior of ring-down time in cavity ring-down spectroscopy with tapered fibers,” in Conference on Lasers and Electro-Optics, OSA Technical Digest (online)(Optical Society of America, 2016), paper JW2A.12.

Lingzhen Yang was born in Shanxi, China, in November1973. She received her B.S. and M.S. degrees, respectively, in 1998 and 2001 from Taiyuan University of Technology. And she received her Ph.D. degree in2005from Xi'an Institute of Optics and Precision Mechanics Chinese Academy of Sciences, China. She has been a professor at the College of Physics and Optoelectronics at Taiyuan University of Technology. She is the author of 35 articles, one book, and more than 4 inventions. Her research interests the application of chaotic fiber lasers.

Juanfen Wang was born in Shanxi, China, in May,27. She received B.S. and Ph.D. degrees, respectively, in 2003 and 2008 from Shanxi University. Since 2011, she has been an associate professor at the College of Physics and Optoelectronics, Taiyuan University of Technology, Taiyuan Shanxi, China. She has published more than 20 articles. Her research interests the transmission and control of pulses in fiber.

Zhaoxia Zhang was born in Shanxi, China, in August 1997. She received her B.S. in 1998 from the Taiyuan University of Technology. She received her M.S. and Ph.D. degrees, respectively, in 2006 and 2010 from Taiyuan University of Technology. She became a professor in 2018. She is the author of more than 30 articles, one book and one invention. Her research interests include ultra wideband radar signal detection and processing, microwave photon radar.

Kang Li was born in Xianyang, Shaanxi, P.R. China in 1980. He received the B.S. degree in Optoelectronics from Changchun University of Science and Technology, Changchun, China, in July 2002 and the Ph.D. degree in Optics, University of Chinese Academy of Sciences, Xi’an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi’an, in July 2007.

From July 2007 to July 2009, he was a Research Officer in Institute of Advanced Telecommunications, Swansea University, UK. From July 2009 to July 2011, he was a Research Assistant in the Faculty of Advanced Technology, University of South Wales (Glamorgan University). From January 2011 to June 2015, he was a Research Fellow with Wireless and Optoelectronics Research and Innovation Centre (WORIC), Faculty of Computing, Engineering and Science, University of South Wales. Since 2015, he has been a Lecturer with WORIC, University of South Wales. He is the author of more than 50 articles, and more than 5 inventions. His research interests include solid state lasers, optical fiber lasers, nonlinear optics, new wavelength, novel applications laser sources, and Nano waveguide and applications.

Nigel Joseph Copner received the B.S. degree in Physics with First Class from Reading University, UK, in July 1988. He received University Diploma of Analytical Physics in July 1990 and Ph.D. degree in Laser Physics in Oct 1992 from Swansea University, UK.

From 1992 to 1993, he was a Research Fellow with the Aston University, UK. From 1993 to 1998, he was an Assignment Manager and Project Manager in The Defence Research Agency in Malvern, UK. From 1998 to 2003, he worked as a Senior Manager and Technical Director in JDS Fitel, JDS Uniphase, USA and Procen Ltd, UK. From 2005 2008, he was a Senior Research Fellow in Swansea University, UK. Since 2009, he has been A Senior Research Fellow and Professor (Chair) with the Faculty of Computing, Engineering and Science, University of South Wales. He has an extensive patent portfolio (>30) generated during his successful career in Silicon Valley working at JDS Uniphase (Senior Manager, San Jose), DERA (Research Fellow, Malvern), Renishaw and through his work at the University. His research interests include tunable lasers, laser metrology, photonics sensing, metamaterial, and nano plasmonics.