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Optical sensors using chaotic correlation fiber loop ring down

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Abstract: We have proposed a novel optical sensor scheme based on chaotic correlation fiber loop ring down (CCFLRD). In contrast to the well-known FLRD spectroscopy, where pulsed laser is injected to fiber loop and ring down time is measured, the proposed CCFLRD uses a chaotic laser to drive a fiber loop and measures autocorrelation coefficient ring down time of chaotic laser. The fundamental difference enables us to avoid using long fiber loop as required in pulsed FLRD, and thus generates higher sensitivity. A strain sensor has been developed to validate the CCFLRD concept. Theoretical and experiment results demonstrate that the proposed method is able to enhance sensitivity by more than two orders of magnitude comparing to the existing FLRD method. We believe the proposed method could find great potential applications for chemical, medical, and physical sensing.

OCIS codes: (140.3510) Lasers, fiber; (140.1540) Chaos; (130.6010) Sensors.

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1. Introduction

Optical sensors have been playing an increasing important role in the sensing community attributing to their unique features, such as immunity to electromagnetic interference, capability to perform remote sensing, and high sensitivity. Over the past few decades, a variety of optical sensing mechanisms have been proposed and developed, such as interferometer [1, 2], surface plasmon resonance [3, 4], surface enhanced Raman spectroscopy [5], Infrared spectroscopy [6], and cavity ring down spectroscopy [7]. Fiber loop ring down (FLRD) technique, fundamentally evolved from cavity ring down spectroscopy, utilizes multi-pass nature of the optical absorption path, is especially attractive due to its advantages of low cost, light weight, immunity to intensity fluctuations of light source, being configurable with existing fiber network, and capability to cover long distance and provide multiplexed detection within a system, etc. So far, many kinds of FLRD-based physical, chemical, and medical sensors, such as fiber current sensor [8–10], refractive index sensor [11, 12], concrete crack sensor [13], biosensors [14], have been reported. More details about FLRD are available in recent review papers [15, 16].

The majority of optical sensing methods employ detection of spectrum change, but FLRD operates in time-domain sensing. FLRD is based on using inexpensive detector (rather than expensive optical spectrum analyzer) to measure ring down time of a pulsed laser that is usually generated by modulating light using an intensity modulator controlled by signal generator [17–19]. Recently, a commercial optical time-domain reflectometer (OTDR) was used to send pulses down into the fiber cavity [20, 21]. FLRD offers high sensitivity because its detection sensitivity is enhanced by the number of round trips laser propagating in a fiber loop. However, there is a tradeoff between detection sensitivity and pulse width in FLRD: shorter fiber loop makes shorter round trip time and thus gives rise to higher detection sensitivity [15]; but when the round-trip time is smaller than laser pulse width, the output laser pulses will overlap and signal will become distinguishable. One could reduce laser pulse width to picosecond or even femtosecond to alleviate aforementioned problem, but it will greatly increase system complexity and operation cost since faster laser source and electronic detection devices are required. The reported FLRD usually have fiber loop length from hundred to thousand meters. In such a long fiber distance in FLRD, light signal inevitably suffers from distortion due to fiber chromatic dispersion and loss [20, 22]. Aim to increase FLRD sensitivity and accuracy, researchers recently used active fiber loop to compensate light loss [23]. The compromise condition between the pulse and the cavity length can be skipped all at once with the CW ring down technique. But that requires laser injection into a single cavity resonance and it comes with its own technical difficulties [24].

Chaotic laser has very broad bandwidth, high frequency and correlation properties due to its intrinsic randomness and has many great applications for optical communication [25], random number generation [26], fiber fault detection [27–29], sensing [30, 31], etc. In this paper, we have proposed and experimentally developed a novel chaotic correlation fiber loop ring down (CCFLRD) sensing method. In contrast to the existing FLRD technique, this method utilizes chaotic laser source rather than pulsed laser, and detects autocorrelation coefficient decay time of chaotic laser. The autocorrelation has extremely narrow bandwidth (a few nanoseconds), and thus allows very short fiber loop length. Therefore, detection sensitivity is significantly increased. We verified the proposed concept by applying CCFLRD for strain sensing. The paper is organized as below. In section II, theory and experimental setup of CCFLRD were demonstrated. We show experimental results for CCFLRD strain sensor in section III. Finally, we made conclusion in section IV.

2. Theory and Experimental Setup

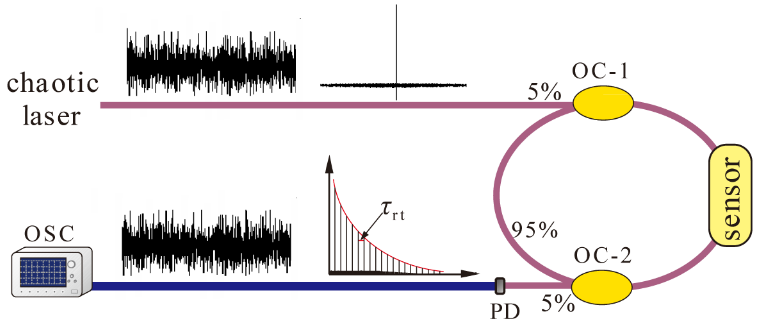

Fig. 1. Illustration of the proposed CCFLRD. OC, PD, OSC represent optical coupler, photo detector, and oscilloscope, respectively.

Our CCFLRD concept is illustrated in Fig. 1. A chaotic laser is coupled into a fiber loop through OC-1 and travels inside the fiber loop for many round trips. In each round trip, a small fraction of chaotic laser is coupled out of the loop by OC-2 and detected by PD and OSC. The output chaotic laser intensity observed from PD decays exponentially and can be modeled by [32]

$$\frac{dI}{dt} = -\frac{cA}{nL} I. \tag{1}$$

Where I is light intensity at time t, and L, c, n, A are fiber loop length, light speed in vacuum, fiber refractive index, and total transmission loss in each round trip, respectively. The solution of Eq. (1) describes the temporal behavior of the light intensity observed by the PD:

$$I = I_0 e^{-\frac{cA}{nL}t}. \tag{2}$$

Where I_0 is incident chaotic laser intensity. OSC receives chaotic voltage signal $V(t)$ from PD and is then processed the data by LabVIEW program in real time. We implement autocorrelation of $V(t)$ and get delta-function-like characteristic of the autocorrelation of chaotic signal:

$$R_{\mathrm{vv}}(\tau) = V(t) \otimes V(t) \approx e^{-\frac{cA}{nL}} \delta(\tau). \tag{3}$$

Where $\otimes$ is correlation operation. The time required for the autocorrelation coefficient to decrease to 1/e of the initial coefficient is referred to as autocorrelation coefficient ring down time and is given by

$$\tau_{\mathrm{R0}} = \frac{nL}{cA}. \tag{4}$$

When an external action, such as a change of absorption, pressure, temperature, stress, or refractive index of ambient material, occurs at the sensor head of the fiber loop (see Fig. 1), additional loss B is introduced to fiber loop, which cases change of the autocorrelation coefficient ring down time:

$$\tau_{\mathrm{R}} = \frac{nL}{c(A+B)}. \tag{5}$$

$$\left(\frac{1}{\tau_{\mathrm{R}}} - \frac{1}{\tau_{\mathrm{R0}}}\right) = \frac{c}{nL} B. \tag{6}$$

We can see that the induced loss B changes linearly with ($1/\tau_{\mathrm{R}}$-$1/\tau_{\mathrm{R0}}$). Therefore, the CCFLRD concept can be applied for various chemical, medical, and physical sensing platforms. The detection sensitivity (detection of loss B) is determined by

$$B = \tau_{\mathrm{rt}} \frac{\tau_{\mathrm{R0}} - \tau_{\mathrm{R}}}{\tau_{\mathrm{R}} \tau_{\mathrm{R0}}}. \tag{7}$$

Where is τ_{rt} is round trip time of the chaotic laser in fiber loop. It notes that detection sensitivity can be improved by decreasing L to decrease τ_{rt}, which is the same to the traditional FLRD method. In our method, since we measure autocorrelation coefficient ring down time and the autocorrelation of chaotic laser has delta-function-like pulse with ultra-narrow width, we are allowed to use much shorter fiber loop than that in FLRD and thus greatly improve sensitivity.

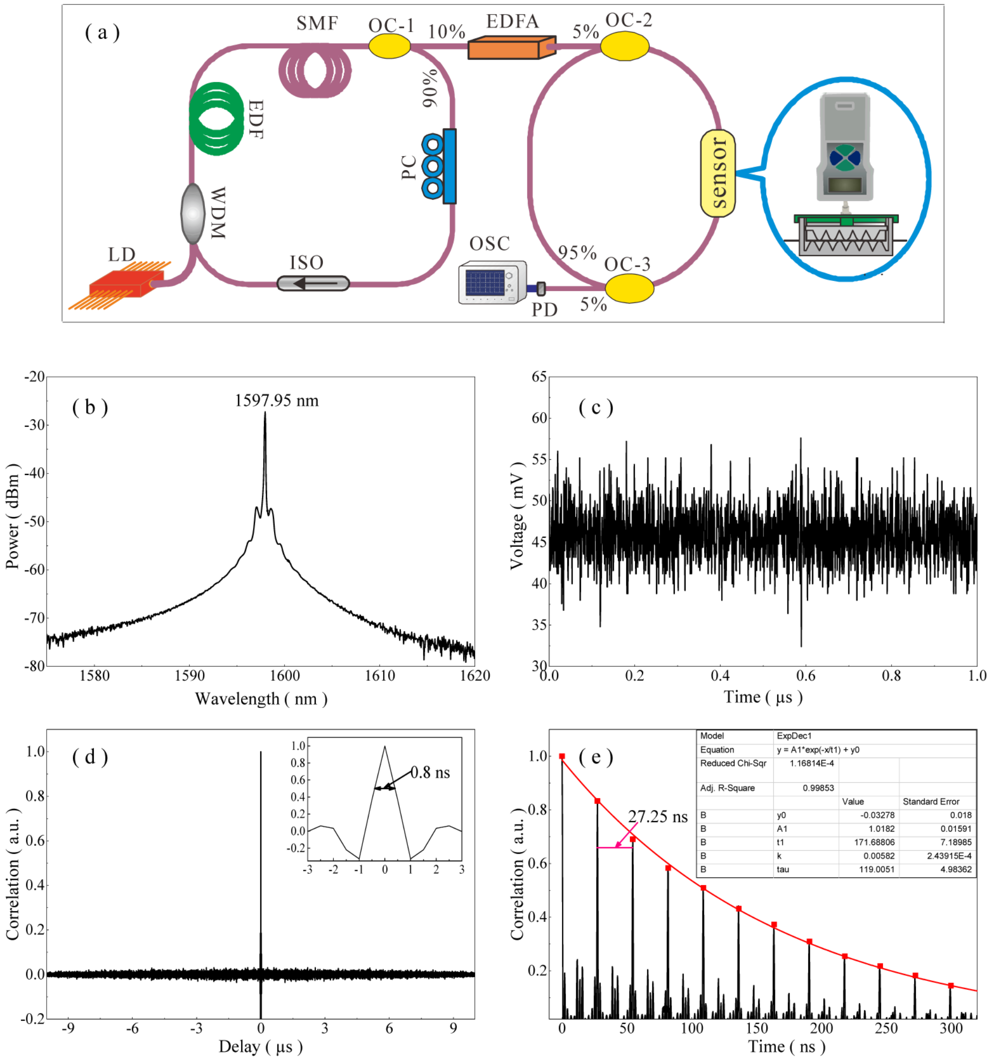

Fig. 2. Experimental verification of the CCFLRD concept. (a) Schematic diagram of CCFLRD system. Chaotic laser spectrum (b) and time series (c), and autocorrelation coefficient (d). (e) Chaotic laser decay rates in fiber loop. Here, laser diode (LD), wavelength-division multiplexer (WDM), erbium-doped fiber (EDF), single-mode fiber (SMF), optical coupler (OC), polarization controller (PC), erbium-doped fiber amplifier (EDFA), polarization insensitive isolator (ISO).

In order to experimentally verify the CCFLRD concept, we generated a chaotic fiber laser and coupled into a fiber loop, as schematically depicted in Fig. 2(a). The chaotic laser was obtained by a 980-nm laser diode (LD) into a single mode fiber (SMF) ring cavity consist of a 980/1550 nm wavelength-division-multiplexer (WDM), a 6-m erbium-doped fiber (EDF), an optical coupler (OC-1) with a coupling ratio of 90:10, a polarization controller (PC) and a polarization insensitive isolator (ISO). We amplified the generated chaotic laser by erbium-doped fiber amplifier (EDFA) before coupling it into fiber loop. The spectrum, time series, and autocorrelation curve of the chaotic laser with the output power of 50mW (after EDFA and before fiber loop) were obtained and plotted in Figs. 2(b)-2(d). It shows that the chaotic laser has a narrow bandwidth with central wavelength of 1597.95 nm and noise-like time series. We observe from Fig. 2(d) that the laser has delta-function-like autocorrelation with ultra-narrow bandwidth of ~0.8 ns, which is corresponding to fiber length of 16 cm. Comparing to FLRD that usually has fiber loop length of hundred to thousand meters, CCFLRD supports much shorter fiber loop and theoretically is able to enables three orders of magnitude improvement in sensitivity. For an experiment, meters long fiber loop is more practical and thus two orders of magnitude improvement in sensitivity can be easily achieved.

In our experiment, the chaotic laser travels in a fiber loop, and the decay signal was coupled out by an output coupler (OC-3) and detected by a photo detector with bandwidth of 1 GHz connected with OSC and then processed by LabVIEW in real time. The autocorrelation was obtained and is fitted to an exponential decay curve of autocorrelation coefficient, as is shown in Fig. 2(e). The autocorrelation coefficient ring down time τ_{R0} is 171.69 ns. The round trip time τ_{rt} is 27.25 ns and indicates that fiber loop length in our experiment is 5.6 m.

3. Strain sensor based on CCFLRD

We further evaluated the performance of the proposed CCFLRD by applying it for strain sensing. A 154 mm^2 micro-bend strain sensing head was fabricated and placed in fiber loop, as shown in Fig. 2(a). The sensing head has a saw tooth pitch of 8.6 mm and a 43 mm fiber sections to receive external force. We applied different force to the sensor head and detected autocorrelation coefficient evolution, as demonstrated in Fig. 3. We observed that the ring down time of the autocorrelation coefficient τ_R decease with external force in Fig. 3(a). The error bars show the differences between experimental results and fitting results. It is consistent with theoretical expectations since larger external force induces larger loss in fiber loop. We also measured and obtained the ($1/\tau_R$-$1/\tau_{R0}$) versus external force when $L = 5.6$ m, 7.1 m, and 8.8 m, respectively Fig. 3(b). The sensor becomes sensitive when external force is higher than 4N and ($1/\tau_R$-$1/\tau_{R0}$) increase linearly with external force; Sensitivity is improved when fiber loop length L is shorter. These agree with theoretical prediction in Eq. (6). We can see from Fig. 3(b) that the ($1/\tau_R$-$1/\tau_{R0}$) has a slope of 0.00262 ns^{-1}N^{-1} when $L = 5.6$ m, which is about 50 times higher comparing to the FLRD strain sensor reported in [33]. The sensitivity of our sensing system can be further increased by shortening fiber loop. If we use 3 m fiber loop, for example, our sensor's sensitivity will be 100 times higher. The sensor is insensitive when external force is lower than 4N. The sensitivity of the proposed CCFLRD can be further enhanced by decreasing the round trip loss in fiber loop cavity related to the splitting ratio of the two couplers and the insertion loss of sensor.

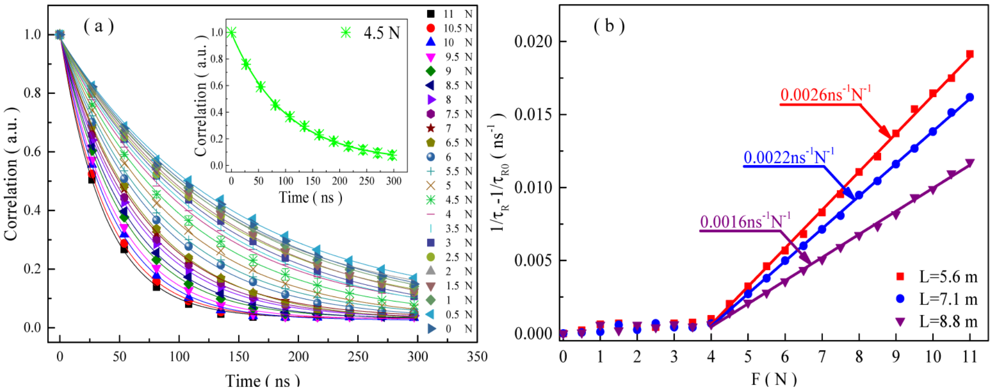

Fig. 3. (a) Autocorrelation coefficient evolution under different external force when $L = 5.6$ m. (b) ($1/\tau_R$-$1/\tau_{R0}$) versus external force when L = 5.6 m, 7.1 m, and 8.8 m, respectively.

We also investigated the repeatability of our sensor by measuring the response of the autocorrelation coefficient ring down time to periodic external force, as shown in Fig. 4. The lower and upper curves are corresponding to 7N force and without force, respectively. It demonstrates that the CCFLRD sensor system has fast response and good repeatability.

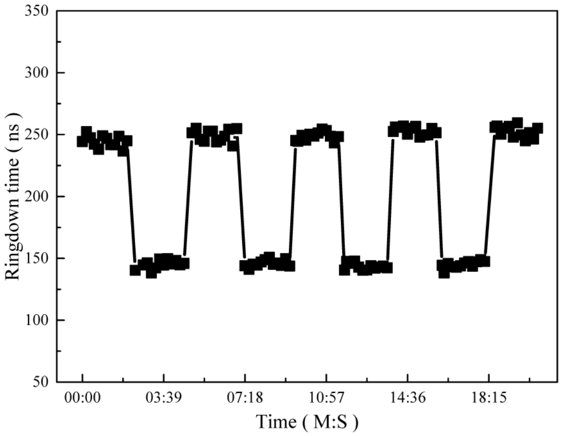

Fig. 4. The response of the autocorrelation ring down time to external force when $L = 8.7$ m. Here, M and S represent time in minutes and seconds, respectively.

4. Conclusion

In this paper, we have introduced a novel and cost effective fiber loop ring down sensor method based on chaotic laser. As a proof of concept, we experimentally verified the concept by applying it for strain sensing. Comparing to the well-established FLRD technique, our CCFLRD utilizes extremely narrow bandwidth characteristic of the autocorrelation of chaotic laser and optical sensing is achieved based on the autocorrelation coefficient ring down time. The proposed method can improve sensitivity by more than two orders of magnitude. We believe the proposed method could find great potential applications for chemical, medical, and physical sensing.

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