# The stability of chaotic correlation fiber loop ring down system with loss compensation

Jianjun Yang, Lingzhen Yang, Juanfen Wang, Zhaoxia Zhang, Yongkang Gong, and Kang Li

***Abstract*—The chaotic correlation fiber loop ring down system with loss compensation is initially developed. We use a chaotic laser to drive a fiber loop and measure the autocorrelation coefficient ring down time of chaotic laser. In this system, the input signal not only acts as a seed signal for amplification but also acts as signal power stabilization in the loop. Due to the chaotic signals continuously injected into the loop , this is different from injecting only one pulse signal in pulse fiber loop ring down with loss compensation and do not worry about crosstalk of the signals. The system is characterized in terms of the ring down baseline stability and the minimum detectable optical loss. The detectable optical loss of 1.03×10$^{-4}$ Np and the baseline stability of 0.846% can be easily obtained.**

***Index Terms*—Chaotic laser, chaotic correlation, fiber loop ring down, loss compensation.**

## I. Introdu ctione

PULSE fiber loop ring down (FLRD) technology is a popular detection technology using time domain features for chemical, medical, and physical sensing [1-4]. The light pulse is coupled into the fiber loop and travels inside the fiber loop for many round trips in the pulse FLRD technology. For a given pulse FLRD sensor system, the more round trips induce the less minimum detectable optical loss. In order to obtain higher number of round trips, it is first proposed to apply loss compensation to pulse FLRD technology in 2001 by G. Stewart *et al* [5]. They demonstrated that the ring down times of several microseconds was obtained and noted that gain control was one of the most important issues. Subsequently, the gas detection by cavity ring down absorption with a fiber optic amplifier loop was reported by K. Atherton *et al* [6]. They demonstrated that ring down times of 0.1ms was obtained. The pulse light passes approximately 350 times around the cavity within the ring down time. However, the fluctuations measured the ring down times are very large, in the region of 10%. Therefore the 1% change in the pulse is clearly not possible. In order to improve the sensitivity and stability of the system, G. Stewart *et al.* proposed gain clamp measurement to stabilize the gain of the system in 2004 [7], and pointed out that the important beneficial factors in gain-clamped systems and the stability of the system are still not sufficient for monitoring the low gas concentrations. As we know the loss compensated FLRD provides an improvement of the number of round trips. However, the amplified spontaneous emission (ASE) noise and gain fluctuations limited the accuracy and repeatability. For eliminating the instability of ring down cavity caused by ASE noise and gain fluctuations. N. Ni et al. applied a digital least-mean-square adaptive filter to reduce the ASE noise and the gain fluctuation was decreased significantly but small signal fluctuations were still observed [8]. Y. Zhao *et al.* proposed the dual wavelengths differential absorption method to efficiently eliminate the influence of the cavity loss variety and photoelectric device drift in the system [9]. Then the effect of ASE noise produced by the erbium-doped fiber amplifier (EDFA) on the performance of amplified fiber loop ring down gas sensing systems was theoretically investigated by C. Cheng *et al.* [10]. Moreover, an alternative approach was to use two loop cavities with a common path through the amplifier. The two loops were a signal loop for the ring down measurement and a lasing loop for stabilization. However, the balance of the signal loop around threshold and the stabilization loop above threshold is not a simple task in this case [6]. Recently, the relative performance and detection limit of conventional, amplified, and gain clamped cavity ring down techniques in all-fiber configurations were compared experimentally for the first time by K. Sharma *et al.* [11]. The experimental results proved once again that it was easier to achieve higher number of round trips in the pulse FLRD with loss compensated system and the gain fluctuations since the power of the pulse progressively decreased with each round trip limited the accuracy and repeatability of the system.

Our group has developed the chaotic correlation fiber loop ring down (CCFRLD) technology [12] without loss compensation. The CCFRLD technology uses a chaotic laser to drive a fiber loop and measures the autocorrelation coefficient ring down time of chaotic laser. The chaotic laser because of the intrinsic randomness has the application for sensing [13, 14], random number generation [15, 16], optical communication [17], *etc.* In this article we will report on the research progress

This work was supported in part by the National Natural Science Foundation of China under Grant 61575137 and 61675144, in part by the Social Development by Department of Science and Technology of Shanxi Province 20140313023-3, in part by the Top Young and Middle-aged Innovative Talents of Higher Learning Institutions of Shanxi, China.

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of minimum detection optical loss and stability of CCFRLD system with loss compensation. Note that chaotic signals only have correlation peaks and it means the correlation between the sequences of chaotic signals at other moments is 0. So chaotic signals can be continuously injected into the loop without worrying about crosstalk of the signal, which is different from injecting only one pulse signal in pulse FLRD with loss compensation. Therefore, the input chaotic signal not only acts as a seed signal for amplification but also acts as signal power stabilization in CCFRLD system with loss compensation. This situation is similar to use two loop cavities with a signal fiber loop for the ring down measurement and a lasing loop for stabilization. So, the gain fluctuations can be effectively suppressed and it is different that the power of the pulse progressively decreases with each round trip in pulse FLRD with loss compensated system. Therefore, compare with CCFRLD without loss compensated, the number of round trips have a significant improvement due to the inner loss can be effectively reduced in this system. Compare with pulse FLRD with loss compensation, the stability of CCFRLD with loss compensation would be better.

## II. Principle

The minimum detectable optical loss is determined by [18]

$$B_{min} = \frac{t_r}{\tau}\cdot\frac{\Delta\sigma_\tau}{\tau} = \frac{1}{m}\frac{\Delta\sigma_\tau}{\tau}. \qquad (1)$$

Where $B_{min}$ is the minimum detectable optical loss measured in Nepers (Np). $\tau$ is the autocorrelation coefficient ring down time of chaotic laser. $t_r$ is the round trip time of the chaotic laser in the fiber loop. m is the number of round trip. $\Delta\sigma_\tau$ is the standard deviation of the autocorrelation coefficient ring down time of chaotic laser. The measurement uncertainty of $B_{min}$ is mainly determined by the ring down time baseline stability, $\Delta\sigma_\tau/\tau$ [19]. In loss compensated configuration, the equation of autocorrelation coefficient ring down time is modified as [11]

$$\tau = \frac{t_r}{\alpha - G}. \qquad (2)$$

Where the inherent loss $\alpha$ includes the loss of couplers, splices, transmission and insertion. G is the single pass gain in fiber loop. For a given fiber loop, $t_r$ and $\alpha$ are constants. Therefore the stability of G can be reflected by the ring down time baseline stability $\Delta\sigma_\tau/\tau$.

## III. Experimental Set up and Results

The CCFLRD system with loss compensation consist of a continuous chaotic laser source, two 2×1 fiber optical couplers (OC), a section of single-mode fiber, a bandpass filter (BPF), a polarization-independent optical isolator (ISO), a photodetector (PD) and an EDFA with erbium-doped fiber (EDF), wavelength division multiplexer (WDM) and 980nm laser diode (LD). The schematic setup of the loss compensated CCFLRD system is shown in Fig. 1.

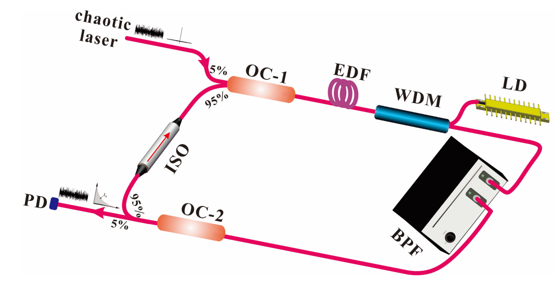


Fig. 1. Schematics of the loss compensated CCFLRD system.

The total length of the fiber loop is 19.5 m, which contains an erbium doped fiber (EDF) of about 13 m, single mode fiber (SMF), the two identical OC were fabricated with a split ratio of 95:5. The chaotic laser is injected from the 5% port of the OC-1 and is outputted from the 5% port of the OC-2 to the PD recorded by an oscilloscope. ISO is used to ensure the single path propagation of the chaotic laser. The BPF shown in Fig. 1 is used for the critically adjustment of the fiber's lasing wavelength in relation to the wavelength of the injection chaotic laser.

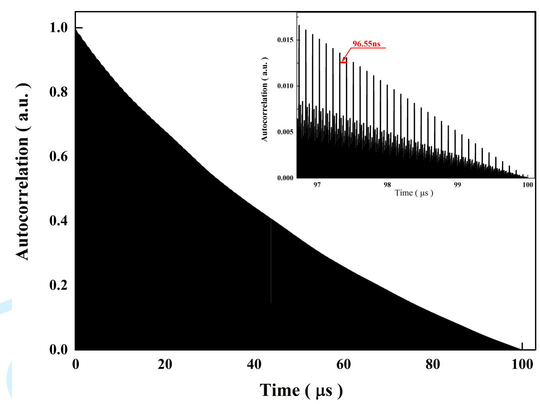


Fig. 2. Experimental autocorrelation peaks in CCFRLD with loss compensated when the bandwidth of the filter is 25GHz, the injection power is 1mW and the pump current is 390mA.

The chaotic laser at 1550.05nm wavelength was launched into the fiber loop cavity to produce ring down signals. The lowest loss of fiber loop cavity and the longest ring-down times occur when the wavelengths are coincident within the ~1nm filter bandwidth [7]. Therefore, we set the bandwidth of the filter to 25GHz and the center frequency is 193.3875THz to obtain the longest ring down time of the system. When the injection power is 1mW and the pump current is 390mA, the autocorrelation curve of the output signal is shown in Fig. 2. The illustration at the top right shows a partial enlargement of the horizontal axis time from 96.73μs to 100μs. It can be seen from the figure that the autocorrelation peak of the output signal is still much higher than the noise floor, which is very beneficial for the extraction of peak data. The time interval between two adjacent autocorrelation peaks represents the round trip time of the light in the loop. The experimentally measured round trip time $t_r$ is 96.65 ns.

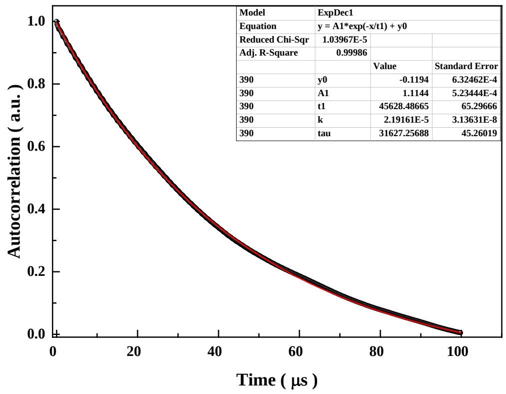


Fig. 3. The corresponding ring down time is 45.63μs.

The peak in Fig. 2 is extracted and fitted with exponent to obtain the Fig. 3. From Fig. 3 we can see that the correlation coefficient $R^2$ of the fitting is as high as 0.99986, and the ring down time τ is about 45.63μs. The chaotic light passes approximately 470 times around the cavity within the ring down time. Refer to (1) the minimum detectable optical loss is enhanced by 470 times. Compare with CCFRLD without loss compensation [13], the number of round trips has an extremely significant improvement.

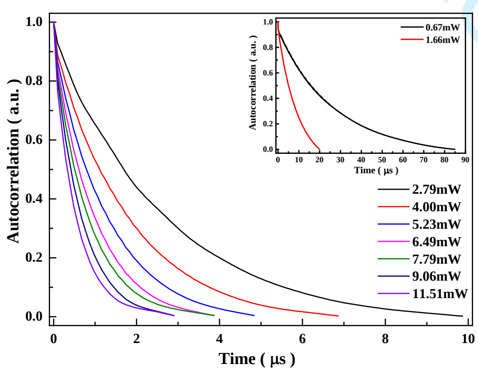


Fig.4. The decrease in ring down time as the injection power increase.

It is found the fluctuation of the light has a noticeable effect on the measurement of the gas concentration in the amplified FLRDS gas sensing system [12]. The longer ring down time can be obtained by reducing the injection power due to the lower the injection power, the larger G of the EDFA. Fig. 4 shows the decrease in ring down time as the injection power increase when the pump current is 300mA in the fiber loop. It is evident that the loss compensated result obtained is in good agreement with existing results relating to loss compensated fiber loop. In addition, the higher the injection power is, the bigger the gain fluctuation is. It is because of the more instability caused by EDFA which induces pulse-to-pulse gain fluctuations since the power of the pulse progressively decreases with each round trip in loss compensated pulse FLRD. However, in our system, the input chaotic laser not only acts as a seed signal for amplification but also acts as signal power stabilization in the ring. This situation is similar to use two loop cavities that a signal loop for the ring-down measurement and a lasing loop for stabilization [6]. Analogy to one of the conditions under which the two loop cavities system can operate stably. The injection power of the signal should be much lower than the laser power for maintaining the stability of the EDFA. Therefore, in our system when the pump current is constant, the higher the injection power can achieve the more stable gain coefficient of the EDFA. Obviously, our system is simpler and easier to operate. It should be pointed out that the most unstable state of our system is similar with the loss compensated pulse FLRD system when the injection power is extremely weak or even unable to stabilize the power in the loop.

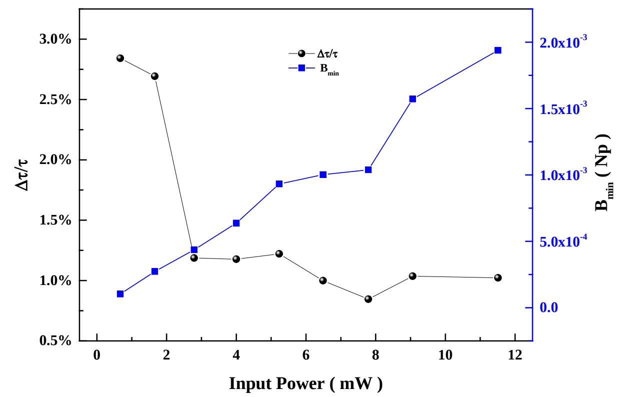


Fig. 4. The ring down time baseline stability $\Delta\sigma_\tau/\tau$ and the minimum detectable optical loss $B_{min}$ in the case of each injection power in Fig. 3.

The standard error in ring down time ($\Delta\sigma_\tau$) is calculated using a set of 50 data points, after averaging 50 ring down events. Then, $\Delta\sigma_\tau/\tau$ and $B_{min}$ are calculated by Refer (1). $\Delta\sigma_\tau/\tau$ and $B_{min}$ in the case of each injection power in Fig. 3 are represented by each solid dot and solid square point in Fig. 4, respectively. From the variation trend of $\Delta\sigma_\tau/\tau$, we can confirm that the higher injection power in our system can get the better stability of the system. The $\Delta\sigma_\tau/\tau$ reaches the minimum value of 0.846% when the injection power is 7.79mW. This value is much lower than pulse FLRD with loss compensation [6] and can be satisfied monitoring the low gas concentrations, therefore the 1% change for the signal measuring is easily achieved using our system. The minimum detection loss of our system can reach $1.03\times10^{-4}$Np with the uncertainty of 2.84% when the injection power is 0.67mW,. Compared with the results [11], the minimum detection loss has increased by an order of magnitude and the accuracy has also been greatly improved. Furthermore, as the injection power increases, the minimum detection loss of the system increases, and the minimum detection loss of our system can still reach $1.94\times10^{-3}$Np with the uncertainty of 1.02% when the injection power is 11.51mW.

## IV. Conclusion

In conclusion, we demonstrated the loss compensated CCFLRD system and analyzed the stability. We have already obtained 45.63μs of ring down time. The number of signal passed around the cavity within the ring down time is 470 times. The minimum detection loss and baseline stability of the ring down signal of this system are experimental investigated under different injection power. The results show that the higher injection power can achieve the better stability of the system. We believe the proposed method could find great potential applications for chemical, medical, and physical sensing.

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