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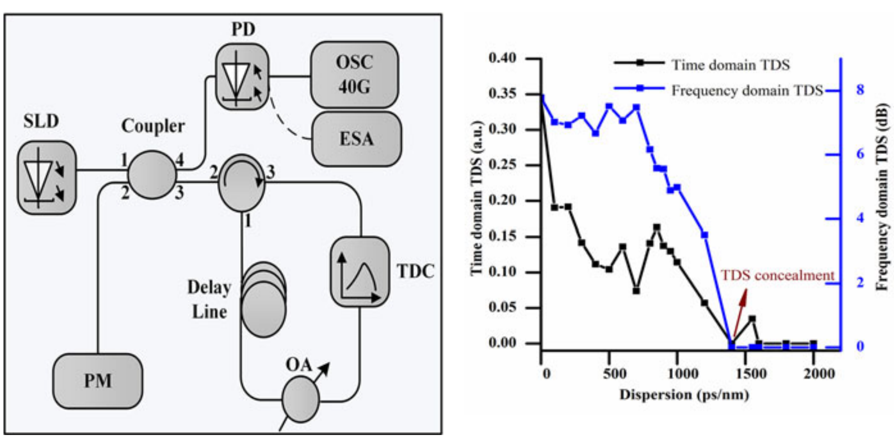

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Time Delay Concealment in Feedback Chaotic Systems With Dispersion in Loop

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Abstract: The concealment of time delay signature is one of the most critical issues in delayed-feedback optical chaotic systems. In this paper, we present a method to address this problem without significantly complicating the original architecture. By properly introducing a dispersion module into the feedback loop, a different frequency component of chaotic spectrum will be subject to different time delay in feedback loop, thus destroying the generation mechanism of time delay signature (TDS). The concealment performance is verified by both time-domain and spectrum analysis methods. The relation between the amplitude of TDS and cavity dispersion value is evaluated in detail. Since the dispersion module has no filtering effect, the chaotic bandwidth will not be affected during the TDS concealment process. This proposal solves the security problem of feedback chaotic systems without introducing much extra effort in implementation, and the underlying principle is not restricted to all-optical chaotic systems but applies for other optelectrical chaotic dynamics, which include a feedback cavity.

Index Terms: Fiber non-linear optics, nonlinear optical effects in semiconductors.

1. Introduction

Thanks to the broadband, noise-like, and unpredictable nature of chaotic signal [1], [2], optical chaotic dynamics has been widely studied for security applications, such as random number generation and chaos-based hardware encryption systems [3]–[6]. Its potential for practical application has been proved by several field demonstrations using chaotic laser to mask the optical information [7], [8]. Most of the chaotic generation architectures contain delayed-feedback loops for the generation of chaotic signal, thus is called as feedback chaotic systems. Unfortunately, it has been proved that the delay time in the delayed-feedback chaotic systems can be cracked with several methods such as autocorrelation functions and mutual information [9]–[11]. Once the time delay is cracked, the chaotic system can be reconstructed [12]; thus, the security of these systems is threatened. Therefore, time delay signature (TDS) concealment is a key research topic in chaotic optical communications. There have been a number of TDS concealment methods, such as using double feedback cavity [13], variable time delay [14] and choosing the feedback delay time around the relaxation frequency of the chaotic lasers [15], but according to a report exploiting spectrum analysis method [16], fixed time delay cannot be concealed in optical feedback chaotic systems, even for those using multiple feedback cavities. Besides, the TDS can be inferred from the phase dynamics even when they are concealed in the intensity dynamics [17]. Introducing a digital key into a double feedback loops has been proved to effectively conceal the TDS both in the intensity and phase time traces [18]–[20], but only numerical simulation has been performed. Another effective way for TDS concealment proposed recently is using a frequency-detuned fiber Bragg grating (FBG) instead of a mirror to form the optical feedback cavity [21]–[24]. The FBG is similar to a mirror in perturbing the laser into chaos, but it provides wavelength-dependent distributed reflections, leading to TDS concealment if the reflective spectrum of FBG is carefully designed. It was explained the TDS concealment is attributed to the associated dispersion of the FBG. Since the spectral filtering property of FBG is related with dispersion property, larger dispersion value will lead to narrower bandwidth, which will affect the spectral characteristics of the broadband chaotic carrier. Detuned FBG can increase the dispersion with less bandwidth sacrifice, but wavelength alignment between the laser and the detuned FBG will increase the difficulty of chaotic synchronization. Besides, the relation between the amplitude of TDS with dispersion value should be evaluated in detail to guide the design of the dispersion-supported TDS concealment chaotic structure.

In this work, we propose that by properly introducing a dispersion module without filtering effect into the feedback loop, the TDS can be effectively concealed both in time domain and frequency domain. The underlying principle may be better understood in this way: dispersion can be considered as the gradient of the group delay spectrum, and when different spectral components of the chaotic laser are subjected to different group delay in feedback cavity, this difference will suffer sustained amplification in feedback loop, thus the relationship between the chaotic signal and its delayed form is eliminated, and eventually the TDS is concealed. The dispersion can be achieved either using a dispersion compensation module (DCM) or a dispersion compensating fiber (DCF). Here we use a commercial tunable dispersion compensator (TDC) formed by cascaded G-T etalons from II-VI photonics. This component has no filtering effect attributed to the total reflection characteristics of Gires-Tournois (G-T) etalon, which will not change the chaotic spectrum during the TDS concealment process, therefore the dispersion information will not leak from the spectral characteristics of the chaotic carrier. The relation between the amplitude of TDS with dispersion value is extensively evaluated, and we found the TDS can be effectively concealed using both time-domain and spectrum analysis methods when the cavity dispersion exceeds 1400 ps/nm, which can be a guideline to the design of the dispersion-supported TDS concealment chaotic structure. Note that the proposed TDS concealment method can be used in all chaotic systems with feedback loops due to the underlying principle, and here, we only take all-optical chaotic generator as a proof-of-concept.

2. Experimental Setup

The experimental setup for TDS concealment evaluation is shown in Fig. 1(a), where a TDC module is inserted into the feedback loop of a traditional all-optical feedback chaotic generator. As is depicted in Fig. 1(a), the light from a semiconductor laser diode (SLD) with an output power of 9 dBm and a bias current of 90 mA is launched into a 98:2 coupler from input port 1. The laser beams from port 4 with 2% power of input port 1 is used for time domain measurement and frequency domain measurement, after being converted into electrical signal by a photo-detector (PD) with a response of 200 mV/mW. While the laser from output port 3 with 98% power of input port 1 plays the role of feedback light, which is sent into an optical circulator (OC) from port 2 to port 3. The key component in the feedback cavity, i.e., the TDC module, is used to generate a tunable dispersion value for TDS concealment evaluation. The delay line is used to tune the cavity length to ensure the chaos generation and the existence of time delay signature under zero dispersion, and the optical attenuator is used to tune the feedback strength to observe chaos generation. 98% of the feedback light is sent back to the laser again for all-optical feedback and the other part with 2% of the feedback light is used for optical power detection with an optical power meter. By setting the feedback strength to a proper range through adjusting the cavity attenuation, a chaotic laser can be generated. We set the feedback strength as −20 dB, a typical value for chaotic generation.

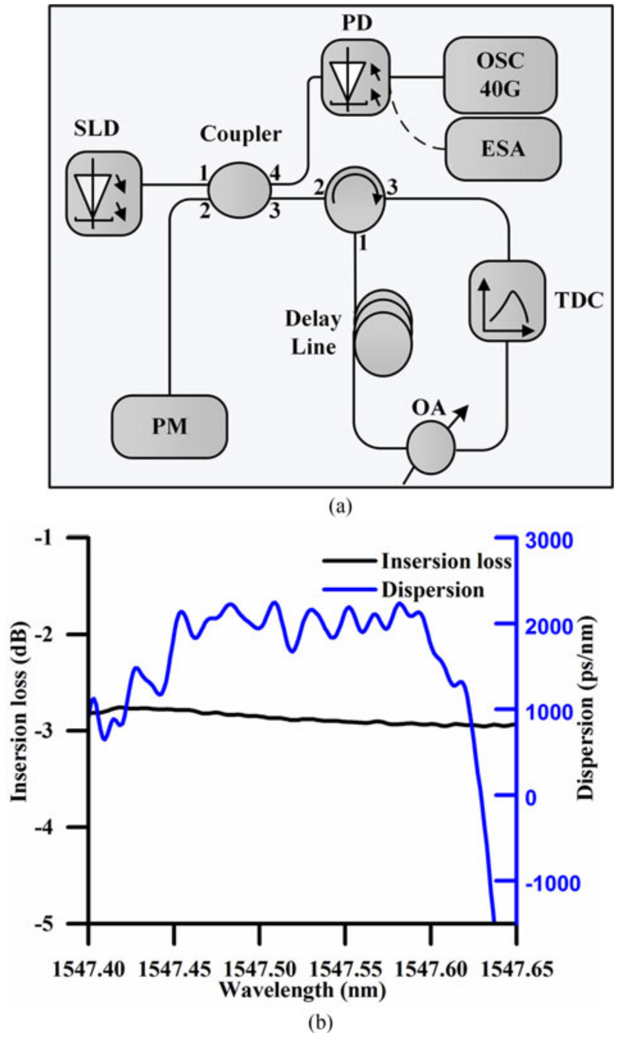

Fig. 1. (a) Experimental setup for TDS concealment evaluation. (b) Example dispersion and insertion loss spectra of the TDC module.

Instead of using an optical mirror, an optical circulator is used in our experiment to construct the external cavity. This chaotic generation architecture has a long feedback length due to the fiber pigtail. Finally, a digital oscilloscope (LeCroy SDA 8 Zi-A) is used to record the time series of the chaotic output. An electrical spectrum analyzer (Anritsu MS266C7) is used for spectrum analysis. Fig. 1(b) is presented as an example of the dispersion and insertion loss spectra generated by the TDC module. The insertion loss is a constant value within the chaotic spectrum; therefore, the influence of filtering effect is excluded.

3. Results

3.1 Chaotic Spectrum

First, to verify the chaotic generation capability of this architecture, we investigated the output signal in both time domain and frequency domain. Fig. 2(a)–(d) show the waveforms captured by oscilloscope under different feedback settings but in zero dispersion, which are labeled in figure legends. Fig. 2(a) shows the situation when feedback strength is $-\infty$, which means no feedback is imposed on the architecture, while the feedback strength in Fig. 2(b)–(d) varies from -33 dB to

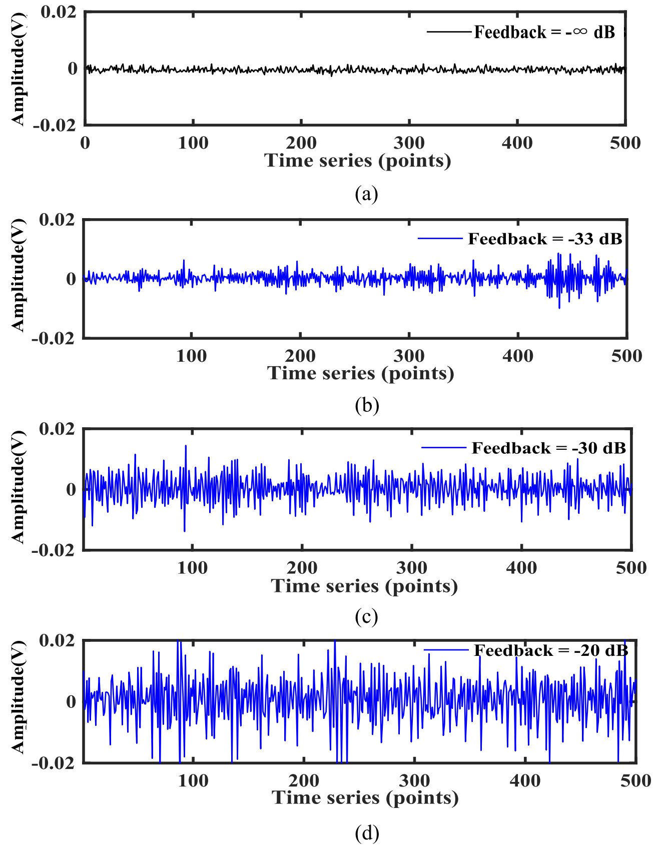

Fig. 2. Generated time series with different cavity feedback strength.

−20 dB. We observed that there is only small scale noise fluctuation in Fig. 2(b) for −33 dB feedback strength. When the feedback strength increases to about −30 dB, the fluctuation scale enlarges suddenly and behaves chaotic dynamics, but not much stable. While the feedback strength rises to −20 dB, the output signal behaves chaotic dynamics in a stable manner.

We then tested the optical spectrum and radio frequency (RF) spectrum evolution of the chaotic laser by tuning the feedback strength and the dispersion value. Fig. 3(a) and (b) respectively show the evolution of optical spectrum and radio frequency (RF) spectrum under different parameter settings, which are distinguished by colored lines and described in the figure legend, where α is defined as the feedback strength, and D(λ) is the dispersion value of the TDC module.

To exclude the influence of insertion loss and delay time, in the zero dispersion case, we take another optical attenuator with the same insertion loss and delay time as a replacement of the TDC module. The black line in each figure presents zero feedback situation for comparison. Similar to the time domain evolution, when the feedback strength increases from $-\infty$ to −20 dB, the optical spectrum becomes widen and the RF spectrum raises, showing the system behaves chaotic dynamics, and there exists periodic fluctuation in the red optical spectrum of Fig. 3(a), because the chaos oscillation is weak when the feedback is −30 dB, but when the feedback strength is increased to −20 dB, the chaos become strong, and optical spectrum become flat. Besides, by comparing the optical and RF spectra at different dispersion values, we can conclude that the introduction of extra dispersion will not influence the chaotic spectra significantly. This is an important advantage of our TDS concealment method because many other methods proposed before, like introducing an optical filter in the feedback loop, will narrow down the chaotic bandwidth and affect chaotic performance. It should be noted that we observe no significant change of both the optical and RF

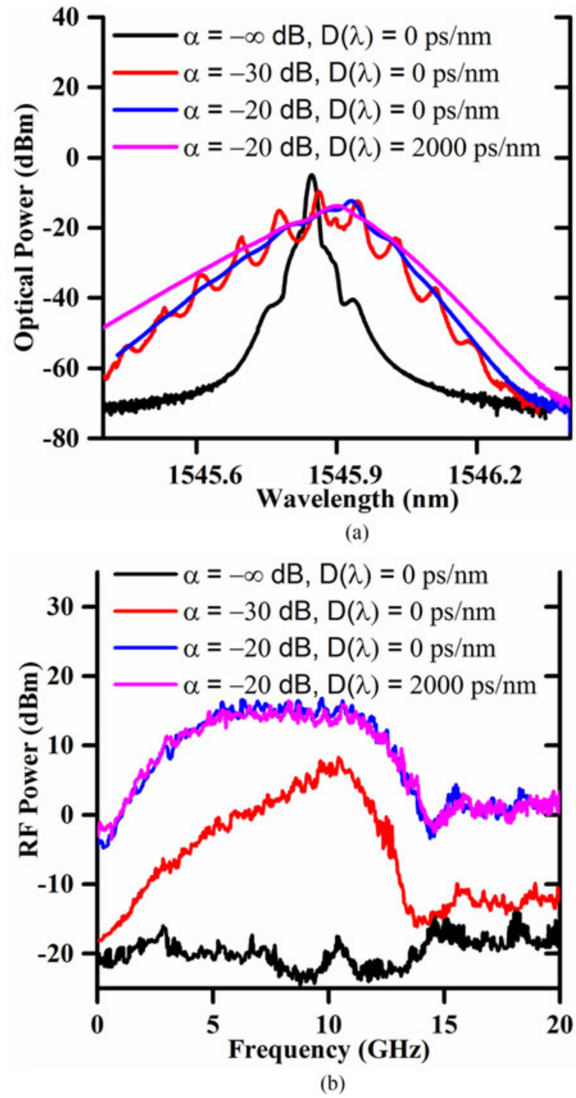

Fig. 3. Evolution of optical spectrum and RF spectrum under different parameter settings. (a) Optical spectra. (b) RF spectra.

spectra during increasing the dispersion value from 0 to 2000 ps/nm; therefore, only the situations of $D(\lambda) = 0$ ps/nm and $D(\lambda) = 2000$ ps/nm are presented here to simplify the figure.

3.2 TDS Concealment Performance

Since the TDS concealment capability is relevant with the additional dispersion, the question that how much dispersion value is enough to completely conceal the TDS comes naturally.

We tested a series of dispersion values to clarify the critical point. Fig. 4(a) show the autocorrelation (AC) results of the chaotic time series recorded by the OSC by increasing the dispersion from 0 to 2000 ps/nm. The sample length is 200000 and the sampling rate of the digital oscilloscope is 20GS/s, thus the sampling time is 10 us, which is sufficient for time delay identification. Fig. 4(b) show the corresponding enlarged RF spectra recorded by the ESA. The AC results with low dispersion value show peak around 269 ns and the enlarged RF spectra show ∼4.4 MHz resonance frequency accordingly, which are approximately matched with the cavity length because of the

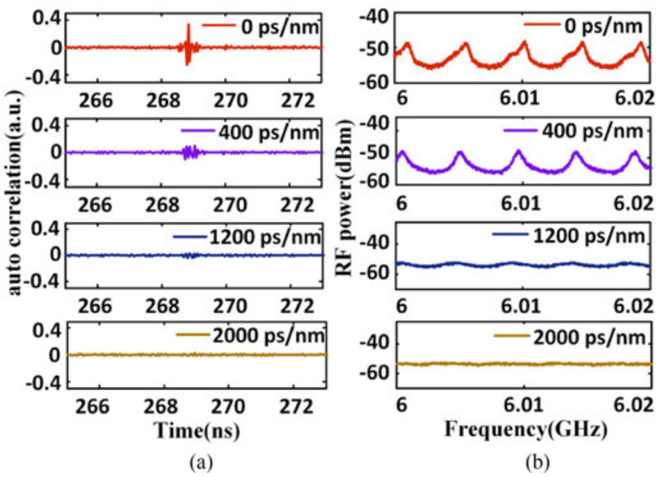

Fig. 4. Time delay concealment in time domain and frequency domain. (a) Auto correlation result of chaotic time series. (b) Enlarged RF spectrum of chaotic signal.

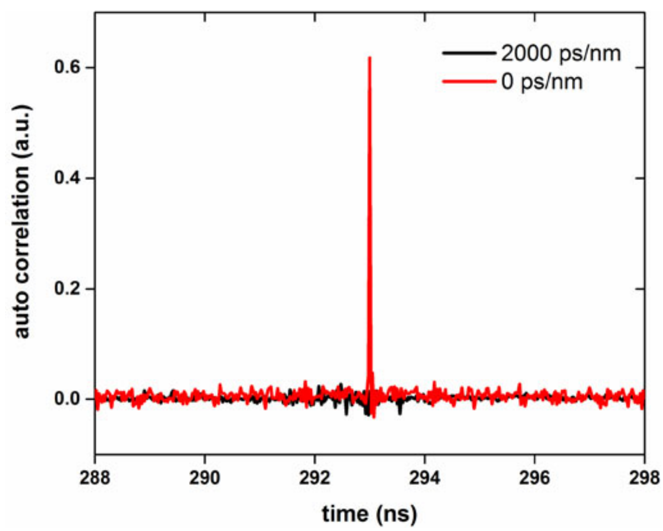

Fig. 5. Auto correlation result of chaotic time series in phase.

limitation of the measurement precision, but the case with sufficient dispersion value of 2000 ps/nm is different, where no peak in both time domain and frequency domain are observed therefore the TDS is effectively concealed. The accordance between frequency-domain and time-domain results further validate the effectiveness of the proposed method. Further, the auto correlation of phase time series is calculated through simulation when the dispersion is 0 ps/nm and 2000 ps/nm. As shown in Fig. 5, the TDS in phase dynamics can be concealed when the dispersion is 2000 ps/nm. Therefore, the TDS can be simultaneously concealed in the intensity and phase time traces when the dispersion is 2000 ps/nm. By comparing different dispersion cases, it can be deduced that the TDS peak value decreases with the dispersion value, and vanishes when the dispersion value increases to around 1400 ps/nm, and the dispersion value for TDS concealment is related to the TDS peak value in zero dispersion. If the TDS peak value in zero dispersion is larger, the more dispersion needs to be used for TDS concealment. The same group delay of different spectral components in feedback cavity accounts for the TDS generation, but the dispersion results in different group delay

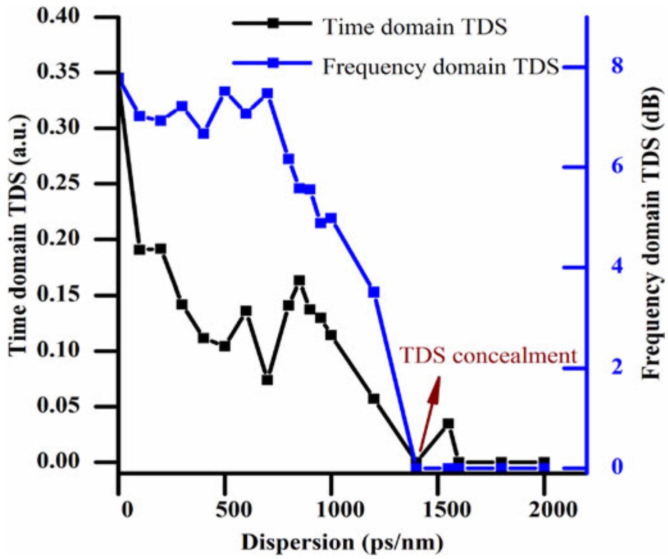

Fig. 6. Evolution of periodical peak to peak value of AC results and RF power spectrum with dispersion values.

of different spectral components in feedback cavity therefore break the frequency periodicity and conceal the TDS peak. In addition, the feedback strength and the precision of measurement have influence on this value because of the relationship between the TDS peak value and the feedback strength or the precision of measurement. The tendency can be clearly observed in Fig. 6, which describes the evolution of the periodical peak to peak value of AC results and RF spectra, with respect to the dispersion values, where black and blue points represent the data recorded by the OSC and the ESA, respectively. However, because of the measurement precision in our experiment, AC results is easy to find TDS than the RF spectra, accounting for TDS disappearance in frequency domain but occurrence in time domain when the dispersion is 1600 ps/nm. The experimental results above clearly show the TDS can be concealed by cavity dispersion only, meanwhile the spectral bandwidth of the chaotic signal will not be affected. The required dispersion value is thoroughly evaluated for TDS concealment, which can be a guideline for other dispersion-supported TDS concealment methods.

4. Conclusions

We solve a major problem in chaotic optical communication systems, the TDS concealment, by simply introducing a dispersion module into the chaotic feedback loop. The concealment effectiveness is proved with both time domain and frequency domain analysis methods. The proposed method will not change the chaotic dynamics significantly except for conceal the TDS since no filtering effect is associated with the dispersion, and is supposed to be effective for all delayed-feedback chaotic optical systems. This research is expected to solve the security problem for the implementation of high-speed chaos optical communication systems.

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