Generation of wideband chaos with suppressed time-delay signature by delayed self-interference

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Abstract: We demonstrate experimentally and numerically a method using the incoherent delayed self-interference (DSI) of chaotic light from a semiconductor laser with optical feedback to generate wideband chaotic signal. The results show that, the DSI can eliminate the domination of laser relaxation oscillation existing in the chaotic laser light and therefore flatten and widen the power spectrum. Furthermore, the DSI depresses the time-delay signature induced by external cavity modes and improves the symmetry of probability distribution by more than one magnitude. We also experimentally show that this DSI signal is beneficial to the random number generation.

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References and links


1. Introduction

Semiconductor laser with optical feedback (OFSL) has attracted widespread attention because of its excellent nonlinear dynamics and important applications, such as encrypted communications [1, 2], physical random number generation (RNG) [3, 4], lidar [5, 6], and time domain reflectometry [7–9]. Unfortunately, the chaotic intensity oscillation in semiconductor laser is usually dominated by laser’s relaxation oscillation [10]. In frequency domain, the power spectral distribution has an obvious peak at the relaxation frequency. Consequently, the effective bandwidth is normally restricted to several gigahertz, and thus, the speed of encrypted data, the generation rate of RNG and the spatial resolution of lidar and reflectometry are limited [7, 11]. In addition, the energies of low-frequency components are suppressed, which confines the utilization efficiency of chaotic light because most electronic acquisition devices act like a low-pass filter. Furthermore, because of the external cavity modes, the intensity chaos in laser has obvious time-delay signature [12], which can be identified by methods such as autocorrelation function (ACF), mutual information function, and local spectrum analysis [13]. For example, in ACF trace, there are some peaks located at the delay time and its integer multiple [12, 13]. This means that the laser intensity chaos is correlated to its previous state at a delay time; in other words, the laser chaos has periodicity. The delay signature resultantly reduces the randomness of chaotic light and is therefore harmful to RNG [4]. Some postprocessing like Exclusive OR operation is needed for de-correlation [3, 4]. Moreover, the delay signature induces security flaw of chaos-based communications because transmitter using delayed feedback system may be reconstructed if the delay time is identified [14].

Many methods have been proposed to enhance the bandwidth of chaotic laser light and to suppress the time-delay signature. For example, the limited bandwidth can be enlarged up to 20 GHz by optical injection method, injecting a chaotic laser into a static laser [11, 15] or in opposite direction [10, 16, 17]. Some recent reports show that dual injection from two external lasers can further enlarge the bandwidth [18, 19]. The delay signature can be hidden
by setting feedback delay close to laser’s relaxation period [12, 20, 21], and can be depressed by using complex feedback such as dual feedback [22], polarization rotated feedback [23], and grating feedback [24]. However, because their physical processes take place in laser cavity, the methods mentioned above cannot remove the domination of laser relaxation oscillation. Resultantly, the power spectrum is still nonuniform with very low energy in low frequency band.

In this paper, we present that delayed self-interference (DSI) of a chaotic laser with optical feedback can generate a bandwidth-enhanced signal with suppressed time-delay signature. Our experimental and theoretical results show that the DSI signal has wider and flatter power spectrum than that of laser intensity chaos. Besides, the domination of laser relaxation oscillation is removed, and the energy in low frequency band is enlarged dramatically. Simultaneously, the time-delay signature is suppressed. Furthermore, our results reveal that the distribution symmetry is also increased greatly. At last, we demonstrate the potential of the DSI signal for application in the random number generation.

2. Experimental setup and theoretical model

The experimental setup is shown in Fig. 1. A distributed feedback semiconductor laser subject to optical feedback from a mirror is used to generate chaotic light. In the feedback path, a variable attenuator and a polarization controller are used to adjust the strength and polarization state of feedback light, respectively. After an optical isolator, the chaotic laser light is injected into a Mach-Zehnder interferometer (MZI) which consists of two 3-dB fiber couplers and a fiber delay line introducing optical path difference (OPD). The DSI signal is the difference between the two outputs of the MZI, which is obtained by using a balanced photodetector (40-GHz bandwidth, Discovery DSC-R410) consisting of two identical photodetectors and a differential amplifier. In experiments, feedback delay was 73.88 ns, and the laser was biased at 17.0 mA, which is 1.4 times the threshold current. We employed an RF spectrum analyzer (Agilent N9020A) and a real time oscilloscope (6-GHz bandwidth, LeCroy SDA 806Zi-A) to record power spectrum and time series, respectively.

Theoretically, denoting the light from the chaotic laser as \( E(t) = A(t)e^{i(\omega t + \phi)} \), we can deduce the DSI signal as follows,

\[
\text{DSI} = \dot{A}(t)(A(t - \tau_d) \cos[\omega t + \phi(t) - \varphi(t - \tau_d)]),
\]

where, \( \tau_d \) is the delay time corresponding to the optical path difference in MZI, \( \omega \), \( A \) and \( \phi \) are the angle frequency, amplitude and phase of the laser field. Under optical feedback, the laser field can be numerically governed by the following rate equations based on the Lang-Kobayashi model [12, 15, 25].

\[
\frac{d}{dt}(\dot{A} + \tau_d \dot{A}) = \frac{1}{2} \left[ \frac{g(N - N_c)}{1 + \varepsilon A} \tau_d - \tau_d \right] A + \tau_d \dot{A} \cos[\omega t + \phi(t) - \varphi(t - \tau_d)],
\]

\( g \) is the coupling coefficient, \( N \) is the laser field intensity, \( N_c \) is the laser field intensity threshold, \( \varepsilon \) is the feedback strength, \( \tau_d \) is the delay time, and \( \dot{A} \) is the complex conjugate of the laser field intensity.
\[ \dot{\phi} = \frac{1}{2} \left( -g(N - N_e) \tau_d - \tau_e \kappa_f \frac{A(t - \tau_e)}{A(t)} \sin[\omega(\tau_e) - \phi(t(t - \tau_e))] \right), \]  

\[ \dot{N} = J - \tau_e' N - \frac{g(N - N_e)}{1 + \epsilon A^2} A^2, \]

where, \( \kappa_f \) and \( \tau_f \) are the feedback factor and feedback delay, respectively. The intensity feedback strength is \( 10 \log(\kappa_f^2) \) dB. The following laser parameters were used in simulations: transparency carrier density \( N_0 = 0.455 \times 10^6 \mu m^{-3} \), differential gain \( g = 1.414 \times 10^3 \mu m^3 ns^{-1} \), gain saturation parameter \( \epsilon = 5 \times 10^{-5} \mu m^3 \), carrier lifetime \( \tau_N = 2.5 \) ns, photon lifetime \( \tau_p = 1.17 \) ps, linewidth enhancement factor \( \alpha = 5.0 \), round-trip time in laser cavity \( \tau_{in} = 7.38 \) ps, threshold current density \( J_{th} = 4.239 \times 10^5 \mu m^{-3} ns^{-1} \), \( \omega = 2\pi c/\lambda \), where \( \lambda = 1550 \) nm and \( c = 3 \times 10^8 \) m/s.

### 3. Results

![Simulated time series, Fourier spectra, and autocorrelation functions](image)

We first qualitatively interpret the reason that DSI can improve power spectrum and depress time-delay signature by numerical simulation. By solving Eqs. (2)–(4) with parameters \( J = 1.8J_{th} \), \( \tau_f = 5 \) ns and \( \kappa_f = 0.08 \), we obtained a numerical chaotic laser light. Figures 2(a)–2(c) plot the time series, Fourier spectrum, and ACF trace of the laser intensity chaos. As shown in Fig. 2(b), the spectrum has a sharp peak at relaxation frequency \( f_{RO} \) (about 3.5GHz). That is, the relaxation oscillation dominates the intensity chaos. The relaxation-oscillation signature is also observed by ACF; depicted in Fig. 2(c), the ACF trace has slight fluctuation with a period \( \tau_{RO} = 1/f_{RO} \). Although this fluctuation can be damped rapidly by increasing feedback strength, the first valley approximately located at \( \tau_{RO}/2 \) always exists and thus indicates the relaxation oscillation. Furthermore, the time-delay signature can be identified by the side peak of ACF [12, 13, 20–22], as shown in Fig. 2(c).

According to Eq. (1), when \( \tau_d \) exceeds the coherence time of the chaotic laser, the DSI converts the phase dynamics into intensity through a cosine function. We therefore show the time series, Fourier spectrum, and ACF trace of \( \cos(\phi) \) in Figs. 2(d)–2(f). Unlike the intensity chaos, the phase dynamics has a flat and wide spectrum (Fig. 2(e)) without any peak or dominant component. Correspondingly, the ACF trace in Fig. 2(f) has no periodic fluctuation.
and obvious valley. The disappearance of the relaxation-oscillation signature can be attributed to the nonlinear phase feedback. On the right side of Eq. (3), the feedback term including the factor $\sin[\omega \tau_f + \phi(t) - \phi(t - \tau_f)]$ is nonlinear which will induce change of frequency and excite new oscillations. As the feedback strength increases, the effects of nonlinear feedback on the variation of phase will exceed that of the carrier change, and then the relaxation oscillation in phase signal is no longer dominant. In addition, the size of the ACF peak at $\tau_f$ is a little smaller than that of intensity chaos [26].

Benefiting from the merits of laser phase mentioned above, the DSI signal is expected to have an enhanced spectrum and suppressed time-delay signature. For example, Figs. 2(g)–2(i) display the time series, spectrum, and ACF of a DSI signal numerically obtained with $\tau_d = 8.75$ ns. We can find that the spectrum of the DSI signal is expanded and flattened, and that the ACF trace is cleaned without signatures of relaxation oscillation and feedback delay. In the following, we will quantitatively study the DSI signal of chaotic OFSL both experimentally and numerically.

3.1 Flattening spectrum and enhancing bandwidth

![Fig. 3. Experimental power spectra of chaotic OFSL and its DSI signal. The bandwidth increases from 7.81 to 9.65 GHz and spectral flatness improves from ±10 to ±3 dB. Bias current: 1.4 times threshold; feedback strength: −13.6 dB; feedback delay: 73.88 ns; OPD: 2.74 ns. Resolution bandwidth: 1 MHz; Video bandwidth: 3 kHz.](image)

In experiments, we generated a chaotic laser light by setting feedback strength as $-13.6$ dB, and used a 56-cm optical fiber as delay line which introduces an OPD of 2.74 ns between the two arms of MZI. Note that, the experimental feedback strength is estimated as the power ratio of the feedback light to the laser output, which is larger than the real level because the unknown coupling loss between laser chip and pigtail fiber is not included. Figure 3 shows the power spectra of the chaotic laser and its DSI signal by the blue and orange thin lines; the black and red thick curves denote the corresponding spectra after the subtraction of background noise (dash line) of the spectrum analyzer. Obviously, the DSI spectrum is wider and flatter than that of the chaotic laser light, which agrees well with the numerical results in Figs. 2(b) and 2(h). Quantitatively, we define the bandwidth as width of the band from zero to the frequency which contains 80% of the signal energy, and the spectral flatness as the range of power fluctuation in the band. As shown in Fig. 3, the bandwidth and the spectral flatness of the chaotic laser are calculated as 7.81 GHz and ±10 dB, respectively. In contrast, the DSI spectrum has an increased bandwidth of 9.65 GHz and an improved flatness of ±3 dB. Furthermore, the relaxation oscillation peak is erased from the power spectrum. We will show the elimination of relaxation oscillation signature by ACF trace in the next subsection.
Figures 4(a) and 4(b) show the bandwidth and spectral flatness of the DSI signal (red filled squares) and chaotic laser (blue open squares) obtained experimentally as functions of feedback strength. In Fig. 4(a), as feedback strength increases, the bandwidth of the DSI signal is larger and grows faster than that of chaotic laser. The spectral flatness in Fig. 4(b) is approximately improved from ± 10 to ± 3 dB. Numerical results of the influences of feedback strength on bandwidth and flatness are shown in Figs. 4(c) and 4(d), respectively. The numerical tendencies are similar to the experimental results. Note that the difference in values is because of that the simulation parameters do not match well with experiments.

Fig. 4. Effects of feedback strength on the bandwidth and spectral flatness of chaotic OFSL and its DSI signal: (a), (b) experimental results with the same parameters in Fig. 3; (c), (d) numerical results with the same parameters in Fig. 2.

In addition, the spectrum flattening leads to redistribution of energy. Especially, the energy of low-frequency components increases greatly. To show this improvement quantitatively, we calculate the ratio of the energy in some frequency bands with width of 1GHz to the total spectral energy by integrating the experimental power spectra, and plot the results in Fig. 5. For the intensity chaos of the OFSL, shown in the blue open stars, the frequency band 5–6 GHz that includes relaxation oscillation occupies about 20% energy for all the feedback strength. In contrast, depicted by the blue open squares, the energy in the band 0.01–1 GHz is only about 0.6% even for strong feedback. For applications like time domain reflectometry which usually uses detecting bandwidth below 1GHz, the utilization of energy of the chaotic signal is seriously restricted. Even though increasing the detecting bandwidth to 3 GHz, the effective signal energy is only about 10% which is the energy sum of
the first three bands denoted by open squares, triangles and circles. For the DSI signal, as shown in red filled squares, the energy in the band 0.01–1 GHz greatly increases up to about 13.8% which is about 23 times that of the intensity chaos. The summed energy in the band 0.01–3 GHz also grows to about 36.6%. This increase of the energy of low-frequency parts is helpful to improve the signal-to-noise ratio of lidar and reflectometry. Note that, displayed by the red filled stars, the energy in the band 5–6 GHz decreases down to about 7.7% resulting from that the relaxation oscillation signature disappears.

3.2 Signatures suppression

Figure 6 plots the ACF traces of the chaotic laser and DSI signal of which spectra are shown in Fig. 3. These ACF traces are calculated using time series with length of 3 μs which is about 40 times feedback delay of 73.88 ns. As shown in the dotted blue line, the ACF trace of the chaotic laser has five side peaks separately at \( \tau_f \), \( 2\tau_f \), \( 3\tau_f \), \( 4\tau_f \), and \( 5\tau_f \) with gradually reduced height. In comparison, the ACF trace of the DSI signal has only two shortened peaks located at \( \tau_f \) and \( 2\tau_f \) with reduced height. The main peaks at zero point and the side peak at feedback delay are magnified in the insets. The length of time series for calculating is 3 μs which is about 40 times feedback delay.

Fig. 6. Experimental autocorrelation functions of the chaotic OFSL (blue) and DSI signal (red) shown in Fig. 3. The main peaks at zero point and the side peak at feedback delay are magnified in the insets. The length of time series for calculating is 3 μs which is about 40 times feedback delay.

Fig. 7. Experimental (a, c) and numerical (b, d) effects of feedback strength on the size of the ACF peak and valley. Open and filled squares represent chaotic laser and DSI signal, respectively. Experimental parameters are same as Fig. 3 and numerical parameters are same as Fig. 2. Correlation length equals to 40 times feedback delay time.
at $\tau$ and $2\tau$, depicted by the red solid line. This means the time-delay signature is depressed. Note that there is no peak appearing at 2.74ns in the red ACF trace, which means that ACF does not disclose the information about the OPD. In addition, as plotted with dotted line in the insets, the ACF trace of chaotic laser has an obvious valley located at about $\frac{T_{RG}}{2}$ after the peak. In contrast, the ACF trace of the DSI signal no longer has obvious valleys, that is, the relaxation oscillation signature is dispelled.

We use the height of the highest side peak located at $\tau$ to denote the level of the time-delay signature. Figure 7(a) shows the experimental peak height as function of feedback strength for chaotic laser (open squares) and DSI signal (filled squares). The crosses represent the three times standard deviation of the ACF background noise. We can find that the time-delay signature is depressed for any feedback state, the peak size decreased about 30-40%. Figure 7(b) displays the corresponding numerical results. Shown in open squares, the ACF peak size of chaotic laser decreases at first and then increases as feedback strength increases (similar results were found in [12]). The peak size of the DSI signal shown in filled squares is clearly reduced. For strong feedback levels, the tendency of peak size is similar to the experiments. The numerical results also indicate that, for chaotic laser light with weak time-delay signature under feedback strength in the range of $-30 - -20$ dB, the DSI can erase the time-delay signature. In addition, we use the ACF valley with maximum size to characterize the signature of the dominant component in chaos. Figures 7(c) and 7(d) separately plot the experimental and numerical results of the influences of feedback strength on the ACF valley size of chaotic OFSL and DSI signal. For the chaotic OFSL, the ACF valley size decreases as feedback strength grows as shown by open squares. We should mention that, strong feedback is not an optimum way to weaken the relaxation oscillation signature because it greatly intensifies the time delay signature, as shown in Figs. 7(a) and 7(b). As shown in the red filled squares, the DSI decreases the valley size below the noise level both in experiments and simulations. There is therefore no dominant component in the DSI signal.

### 3.3 Improvement on symmetry of probability distribution

Besides the bandwidth enhancement and signature suppression, the DSI can also improve the symmetry of the probability distribution. Figures 8(a) and 8(b) separately plot the time series of the chaotic laser and the DSI signal whose spectra and ACFs are shown in Fig. 3 and Fig. 6. The dash lines denote the mean value, and the red lines are the Gaussian fitted curves of probability distribution. (c) Experimentally obtained skewness of chaotic time series of OFSL (blue open squares) and DSI signal (red filled squares) as function of feedback strength.

Fig. 8. (a), (b) Experimental time series and (c), (d) probability distribution of the chaotic OFSL and DSI signal corresponding to Fig. 3 and Fig. 6. The dash lines denote the mean value, and the red lines are the Gaussian fitted curves of probability distribution. (e) Experimentally obtained skewness of chaotic time series of OFSL (blue open squares) and DSI signal (red filled squares) as function of feedback strength.

Besides the bandwidth enhancement and signature suppression, the DSI can also improve the symmetry of the probability distribution. Figures 8(a) and 8(b) separately plot the time series of the chaotic laser and the DSI signal whose spectra and ACFs are shown in Fig. 3 and Fig. 6. The corresponding probability distributions are shown in Figs. 8(c) and 8(d), in which the red lines are the Gaussian fitted curves and the dashed lines label the statistical mean value. As depicted in Fig. 8(c), the distribution of the chaotic laser light is right skewed, that is, the mass of the distribution is concentrated on the right of the figure. Its skewness is calculated as 0.4153. As shown in Fig. 8(d), the probability distribution of the DSI signal has a more
symmetrical profile almost agreeing with the Gaussian fitted curve of which the skewness is 0.0387. We further experimentally investigate the effects of feedback strength on the skewness of probability distribution of the chaotic OFSL and DSI signals. As displayed by blue open squares in Fig. 8(e), the skewness grows from about 0.15 up to 0.5 with the increase of feedback strength. This means that the chaotic intensity waveform of OFSL is usually skew, which will lead to a large bias ratio of 0 and 1 for RNG based on chaotic laser. In comparison, shown in filled squares, the skewness of DSI signal is improved by more than one order of magnitude, and is still nearly zero for strong feedback.

### 3.4 Demonstration of application in RNG

We now demonstrate the generation of random number using the DSI signal plotted in Fig. 8. The digitization procedure is realized by the 8bit ADC in the oscilloscope at a sampling rate of 40 GSa/s. We then extract points from the digitized series with an interval of 0.8 ns corresponding to a code rate of 1.25 Gbit/s. Note that at the lag equaling to the sampling interval, the ACF has a value of about $6.37 \times 10^{-3}$ indicating a low correlation. For comparison, we also extract random number from the chaotic laser light in Fig. 8 with the same digitization and extraction procedure. We then use the National Institute of Standards and Technology (NIST) battery of statistical tests [27] to evaluate the randomness of each significant bit. The tests are accomplished using 1000 samples of 1Mbit sequences and the significance level of 0.01 [27].

<table>
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<tr>
<th>NIST terms</th>
<th>Chaotic OFSL P-value</th>
<th>Chaotic OFSL Proportion</th>
<th>Chaotic OFSL Result</th>
<th>DSI P-value</th>
<th>DSI Proportion</th>
<th>DSI Result</th>
</tr>
</thead>
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<tr>
<td>Frequency</td>
<td>0.000000</td>
<td>0.967</td>
<td>Failure</td>
<td>0.699313</td>
<td>0.993</td>
<td>Success</td>
</tr>
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<td>Success</td>
<td>0.682823</td>
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<tr>
<td>Cumulative Sums</td>
<td>0.060000</td>
<td>0.968</td>
<td>Failure</td>
<td>0.288249</td>
<td>0.991</td>
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</tr>
<tr>
<td>Runs</td>
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<td>Success</td>
<td>0.589341</td>
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<td>Longest Run</td>
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<td>Failure</td>
<td>0.010570</td>
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<td>Success</td>
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<tr>
<td>Random Excursions</td>
<td>0.886375</td>
<td>0.987</td>
<td>Success</td>
<td>0.099855</td>
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For the extracted random sequence from the chaotic laser light, the 4 most significant bits (MSB) fail the NIST tests, similar to the results of [23] in which the 4 MSBs are suggested to be discarded. In addition, in our experiments, the last least significant bit (LSB) also fails two test terms ‘Frequency’ and ‘Cumulative Sums’, which may be caused by the skewed distribution. In comparison, the 5 LSBs of the random number digitized from the DSI signal can successfully pass the NIST test. For example, Table 1 comparatively lists the test results of the 5th LSB of two random sequences extracted from the chaotic OFSL and DSI signal. The three terms ‘Frequency’, ‘Cumulative Sums’ and ‘FFT’ are improved to pass the test by the DSI, benefiting from the improvement on symmetry of probability distribution and the suppression of time signatures. The results indicate that the total rate of RNG (combining all the LSBs passing test) can be increased by 1.67 times from 3.75 ($= 3\ \text{bit} \times 1.25\ \text{GSa/s}$) to 6.25 Gbit/s ($= 5\ \text{bit} \times 1.25\ \text{GSa/s}$) by using the DSI signal instead of chaotic laser. We should
mention that, because of the residual time-delay signature and the drift of mean value, the first 3 MSBs of the random sequence from the DSI signal hardly pass the NIST test.

4. Discussion and conclusion

In the proposed method, the delay time $\tau_d$ corresponding to the OPD between the two arms of MZI should obey the following two conditions. First, $\tau_d$ should be larger than the coherence time of the chaotic laser, because only incoherent DSI can effectively convert laser phase into intensity. For instance, in the case of $\tau_d = 0$, the DSI signal is just the laser intensity, which fails to improve. Our experiments found that the coherent DSI leads to an unstable chaotic signal of which waveform frequently jumps. Second, according to Eq. (1), $A(t)$ and $A(t-\tau_d)$ should be uncorrelated to suppress time delay signature effectively. As a result, for the chaotic laser light, the ACF value at lag of $\tau_d$ must be close to the background noise. Therefore, $\tau_d \neq m\tau_f$ is suggested, where $m$ is any low order integer corresponding to the ACF peaks (for example, $m = 1, 2, \ldots, 5$ for the chaotic laser in Fig. 6). As long as $\tau_d$ satisfies the conditions, the DSI can obtain improved chaotic signal. We note that the properties of the DSI signal are determined by the chaotic state of the OFSL and are little affected by the delay $\tau_d$. This implies that it makes no difference whether $\tau_d$ is larger than $\tau_f$ or not, and that the OPD can be shortened to a size making the setup capable of integration.

In summary, we present a method using the incoherent delayed self-interference of a chaotic light from a semiconductor laser with optical feedback to generate wideband chaotic signal with flattened spectrum and suppressed time-delay signature. Experiments and simulations demonstrate that the domination of laser relaxation oscillation is eliminated and then the power spectrum flatness is enhanced from $\pm 10$ to $\pm 3$ dB. The spectrum flattening also increases the energy in low-frequency band, which is helpful to improve the signal-to-noise ratio of radar [5] and reflectometry [8]. Furthermore, the DSI method depresses the time-delay signature induced by external feedback cavity and improves the symmetry of probability distribution of signal, which is beneficial to random number generation. The DSI method is also suitable for the chaotic light from lasers subject to optical injection or optoelectronic feedback. We therefore believe that this method is a promising candidate for producing wideband chaotic signal.

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