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<td><a href="http://hdl.handle.net/10220/46374">http://hdl.handle.net/10220/46374</a></td>
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Reproducible optical noise-like signal generation subjected by digital sequences

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Abstract: We experimentally demonstrate a reproducible broadband optical noise-like signal generation scheme whereby dispersion induced phase modulation to intensity modulation conversion and an electro-optic nonlinear transform are utilized to post process a binary random sequence. A flat spectrum and a symmetrical distribution of the generated analog noise-like signal can be observed. Moreover, Gaussian-like probability distribution function can be obtained by using the central limit theorem. The influences of the digital input and the analog parameters on complexity performance of the generated analogue noise are discussed in detail. Finally, the impact of key parameters on the reproducibility of the system is discussed. The proposed scheme could be a more controllable way to generate broadband optical noise-like signal, and has potential to be applied in various real world applications.

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OCIS codes: (060.4785) Optical security and encryption; (060.5060) Phase modulation; (070.1170) Analog optical signal processing; (280.5600) Radar.

References and links


https://doi.org/10.1364.OE.25.029189
1. Introduction

Noise signal or noise-like signal has become a popular research topic due to its valuable properties. Random or pseudo-random noise sources are widely used in various applications [1–5]. The characteristic of a noise source can be evaluated from several aspects, such as complexity, spectrum and distribution properties. These properties have gained considerable attention in different applications. In physical layer secure communication systems, noise-like signals such as the chaotic ones are used to mask the plaintext signals. The interest concentrates on the complexity and bandwidth of the generated noise. The security level and
transmission bit-rate strongly rely on the performance of the noise source [6, 7]. In radar applications, noise signal is a promising carrier owning to its good correlation property and broadband characteristic [8, 9], thus making noise radar prevalent in the current study. Noise source with specific probability distribution is an essential part in hardware based intensive modeling and simulation applications especially in many physic process researches [10–12]. Among these applications, a replica of the noise signal is expected to be generated at different places or occasions as a reference signal for different purposes. It is of significant importance to establish a robust reproduction of the original signal. Moreover, the reproducible broadband noise-like signal can provide additional benefits in some applications. For example, it could be propitious to the correlation-based time-domain reflectometry for enhancing signal-noise ratio by averaging [13,14].

Hitherto, most of the reproducible pseudo-random noise sources are designed in the digital way. Reproducible noise-like signals are generated by using an algorithm, which is established on computer software or hardware processor such as field programmable gate array [5, 15]. Owing to its easy reproduction property, the method based on the digital way to generate noise-like signals has been applied in extensive occasions [16, 17]. However, these works are performed by using electrical logical devices, where the generation rate is restricted by the limited calculation speed. This fact hinders it from broadband applications. Compared with the digital noise, analog noise has been a prior choice in many occasions on account for the unique advantage of broad bandwidth. In current applications, there are mainly two types of analog noise generator. One is based on physical processes with inherently random property, such as thermal noise or amplified spontaneous emission noise of an erbium-doped fiber amplifier [18]. However, it is nearly impossible to reproduce. The other is chaos system, which generates noise-like waveform based on deterministic dynamic processes [19]. A large number of studies are devoted to improving the dynamical complexity and bandwidth of chaotic signals [20–22]. Meanwhile, improving the distribution characteristic is also a concern of researchers. In [23, 24], the white chaos could be implemented by optical heterodyning technique. Nevertheless, it is still difficult to obtain a similar chaos signal in different places or occasions, as the chaos system is highly sensitive to its initial conditions and parameters.

The concept of generating a reproducible noise-like continuous signal from a pseudo-random binary sequence (PRBS) subjected to diverse filters is a creative outlet which links the digital sequence to analog noise. The early scheme is proposed by Robert et al. that the maximal-length linear binary sequence is applied as the input of a low-pass filter [25, 26]. As a result, the reproducible Gaussian-like electric noise can be obtained. Similar process can also be used to generate reverse-time chaos [27]. However, limited by the narrow bandwidth of electric devices, it cannot be directly applied in broadband applications. Recently, the optical version of reverse-time chaos is demonstrated to be feasible by designing a suitable microwave photonic filter [28]. However, such optical matched filter is still complicated and costly. Besides, the complexity of the obtained output signal is relatively low.

In [29], we have introduced a simpler way to generate the reproducible broadband noise, which is based on the phase modulation to intensity modulation (PM-to-IM) conversion. Compared with the scheme in [28], the reproducible noise-like signal owns a higher bandwidth and complexity. In this paper, the focus will be placed on the detailed discussion about complexity, bandwidth and distribution properties of the generated noise signal. Further, a method is proposed to make the distribution approach Gaussian. Besides, the effects of parameter mismatch on the reproducibility of system are verified by a simple experiment at the end of discussion.

2. Experimental setup

As depicted in Fig. 1, the noise generator consists of a pseudo-random binary sequence generator (PRBG), a PM-to-IM module, and a nonlinear transform module. The outputs of
these three parts are marked as $x_1$, $x_2$ and $x_3$, respectively. The optical carrier emitting from the laser diode (LD1) is phase modulated by a PRBS at the rate of 10 Gb/s through a phase modulator (PM). The mathematical model could be expressed as

$$E(t) = \sqrt{P_0} \exp[j(\omega_0 t + \phi_0)] \exp[jmx_1].$$

$E(t)$ is the electrical field of the output light. $P_0$ is the average power of the optical carrier. $\omega_0$ and $\phi_0$ denote the angular frequency and initial phase respectively. $m = \frac{V_s}{V_{\pi}}\pi$ is defined as the modulation index, where $V_s$ is input signal amplitude and $V_{\pi}$ is the half-wave voltage of the PM.

The phase modulated optical signal is then injected into a dispersive media which is performed by a fiber Bragg grating (FBG) to implement the conversion from PM-to-IM. Due to the different conversion efficiency at different frequencies [30], the PM-to-IM module could be considered as a generalized filter, thus the dichotomous sequence could be transformed to continuous analog signal. The transfer function of FBG in frequency domain is given as

$$H(\omega) = \exp\left[\frac{j}{2}d(\omega - \omega_0)^2\right],$$

where $d$ denotes the dispersion value.

Reflected from the FBG, the output optical field can be written as $E_1 = E(t) \ast h(t)$, where “$\ast$” denotes the convolution operation and $h(t)$ corresponds to the time-domain expression of $H(\omega)$. Sequentially, the optical signal is captured by a photo-detector (PD1) whose bandwidth is 16GHz. The output signal can be described by $x_2 = |E_1 \cdot E_1^*|$, where $E_1^*$ is the complex conjugate of $E_1$. Then the signal $x_2$ is processed by a nonlinear transform module, which is made up of a laser diode (LD2), a radio frequency amplifier (RFA2) and an intensity modulator (IM). After detected by a 16GHz PD (PD2), the relationship between the output $x_3$ and input $x_2$ could be expressed as

$$x_3 = \gamma P_1 \cos^2(m_1 N(x_2) + \phi_0).$$

$P_1$ is the average optical power and $\gamma$ is the responsibility of PD2. Through the function $N(\cdot)$, $x_2$ is normalized to $[0,1]$. $m_1 = \frac{V_{s1}}{V_{\pi1}}\pi$ is the modulation index, $V_{s1}$ and $V_{\pi1}$ represent the peak to peak value of the radio frequency input and the half-wave voltage of IM respectively, $\phi_0$ is the bias phase. To take full advantage of the nonlinear effect of the IM, $V_{s1}$ is required to be larger than $V_{\pi1}$. Finally, the generated optical noise can be observed through a 40GSa/s digital sampling oscilloscope (DSO).

![Fig. 1. Experimental setup of the optical noise generator.](image)

3. Results and discussions

A PRBS with length of $2^{31} - 1$ is used as the input and the modulation index of the PM is set as $m = 1.5$. The cumulative dispersion of the FBG is set as $d = 2000\text{ps/nm}$. The IM is biased on
the peak-point, namely \( \varphi_0 = 0 \). The peak to peak value of \( x_2 \) is amplified to 7V to drive the IM, where \( V_{\pi} \) is 5.5V. Finally, a duration of 5us data is sampled and recorded by using the DSO.

### 3.1 Power spectrum and autocorrelation function

The waveforms of \( x_1, x_2, \) and \( x_3 \) are shown in Fig. 2 and the corresponding power spectrums of \( x_1, x_2, \) and \( x_3 \) are shown in Figs. 3(a)-3(c) respectively. The peaks at 10GHz in Figs. 3(a)-3(c) correspond to the clock frequency of the PRBS. Firstly, the electrical signal \( x_1 \) is transformed from the optical phase to intensity through the dispersion media. As shown in Fig. 3(b), the frequency components lower than 2GHz seems to be filtered out after reflected from the FBG, which could be attributed to the low conversion efficiency at low frequencies [30]. As can be seen in Fig. 3(c), the spectrum is flattened after the nonlinear transformation. The effective bandwidth [31] of generated signal \( x_3 \) under the current operating condition could reach 9.82 GHz. The effective bandwidth is defined as the frequency including the range between DC to frequency that contains 80% of the whole spectrum power. The corresponding simulation results are consistent with the experiment, as shown in Figs. 3(d)-3(f).

![Fig. 2. (a), (b), (c) are the experimental waveforms of \( x_1, x_2, x_3 \).](image)

![Fig. 3. (a), (b), (c) are the experimental spectrums of \( x_1, x_2, x_3 \) and (d), (e), (f) are corresponding simulation results.](image)

Besides the power spectrum, we also investigate the autocorrelation function (ACF) of generated signal corresponding to Fig. 3(c). The ACF could be expressed by the equation

\[
\rho = \frac{\langle (y(t) - \langle y(t) \rangle)(y(t + \Delta t) - \langle y(t) \rangle) \rangle}{\sqrt{\langle (y(t) - \langle y(t) \rangle)^2 \rangle\langle (y(t + \Delta t) - \langle y(t) \rangle)^2 \rangle}},
\]

where \( \langle \cdot \rangle \) stands for the time average, \( y(t) \) represents the time series of signal and \( \Delta t \) denotes the time lag. The result is shown in Fig. 4. The correlation curve of the generated noise
decays quickly after the main peak at the origin point. The insert figure reveals side-lobe of
ACF is decaying within 0.2ns. It can be witnessed that the ACF is close to $\delta$ function which
could be benefit for communication and radar systems [32, 33].

![Fig. 4. The ACF of $x_3$.](image)

### 3.2 Probability Distribution

The distribution characteristic is an important aspect of a stochastic or pseudo-stochastic
process. Therefore, manipulation of the distribution of an artificial noise source is essential [5,
18]. The corresponding probability distribution function (PDF) of the generated noise $x_3$ is
shown in Fig. 5. To evaluate the asymmetry of the noise signal, the skewness is calculated
and measures 0.015, where a smaller value indicates a more symmetrical distribution [23].
With such a symmetrical distribution, the generated noise could approach the realistic
stochastic process.

![Fig. 5. The probability distribution of the amplitude of $x_3$.](image)

Moreover, in order to make the PDF Gaussian-like, a further step is taken to process the
generated noise. According to the central limit theorem, the sum of independent distributed
random variables tends toward a normal distribution. Similar methods are widely used in
electrical Gaussian noise generation [34, 35]. When it comes to optical versions, a high
generation rate could be easily obtained. A simulation is conducted to state its theoretical
feasibility. The optical output of the nonlinear transform is firstly divided into eight replicas
through a $1 \times 8$ optical splitter. Then it is delivered to an optical time-delay module, which
could be implemented by optical fibers with different lengths in practical application. In our
simulation, the time-delay for each channel are set as 1, 2, 3, 4, 5, 6, 7, and 8 ns respectively.
The correlation coefficient of adjacent channels measures 0.02, which could ensure the
independence of these channel signals. Combined by an optical coupler, the superposition of
the 8 optical noise signals can be obtained. The output waveform of electrical field is shown
in Fig. 6(a) and the corresponding PDF is demonstrated in Fig. 6(b). 200000 points of the
output data are used to construct the PDF. As can be seen, the distribution is close to an ideal
Gaussian shape. It could be a feasible way to generate the optical Gaussian noise.
However, the superposition operation brings about some additional correlation peaks in the autocorrelation trace of the generated signal, as shown in Fig. 7. Beside the main peak, there are several correlation peaks locating at $\Delta t = \pm 1$, $\pm 3$ and $\pm 4$ ns respectively. These correlation peaks indicate the local similarity of the obtained signal, which is brought by the superposition operation. However, the peak values are relatively low compared with the main peak at $\Delta t = 0$. Therefore, the ACF property is sacrificed in some degree to improve the distribution characteristic.

### 3.3 Complexity performance

The complexity of the generated analog noise signal is another fundamental characteristic in some applications, such as the secure communication. For a quantitative description, the complexity here is measured by permutation entropy (PE) [36] and approximate entropy (ApEn) [37]. The order and time delay parameters of PE are selected as 7 and 2 respectively. In the calculation program of ApEn, the length of the data segment is set as 2, and 0.2 times the standard deviation of the original time series is used as the similarity criterion.

Note that the input of the system is a digital sequence, while the output is a real valued analog signal. The relationship between the complexity of the binary sequences and the generated noise is investigated by means of simulation using the VPItransmissionMaker 9.0 software. The simulation duration time is 16384 ns and the step size is set as 1/160 ns. The binary input is specified by the linear feedback shift register (LFSR) with different orders, where a high order means a high linear complexity. The corresponding PE and ApEn of the generated noise are displayed in Fig. 8(a). The complexity of the analog noise grows linearly with the order of LFSR before reaching a saturation point. Having positive correlation with the complexity of binary sequences, the complexity of the generated noise could be determined by the binary input.
As shown in Fig. 1, a nonlinear transformation module performed by an IM is introduced in the system to flat the power spectrum of output signal, which could also help to improve the complexity of signal further. In our scheme, the strength of nonlinear effect introduced by the nonlinear transformation module could be described by the modulation index of IM, namely $m_1$ in Eq. (3). The influence of the nonlinear transformation on the complexity of output signal is investigated on the condition that the order of LFSR is set as 15. Figure 8(b) reveals the relationship curve between the signal complexity and the nonlinear factor $m_1$. As can be seen, the ApEn and PE of output signal could continue to get a raise with the enhancement of nonlinear effect.

Apart from binary sequence of LFSR, different format of digital signals can be used as the input. Here Lorenz chaotic oscillator [38] is adopted to produce $M$-ary digital sequences. The influence of $M$ on the complexity performance is also investigated. The time series of these chaotic models are generated by using the fourth-order Runge-Kutta algorithm [39] with an iteration time step of 0.01, and $M$-ary sequences can be obtained by the following process.

\[ x_i(t) = x_i(k), (k-1)T < t \leq kT \]  \hspace{1cm} (5) \\
\[ x_i(k) = g(y(k/f)), k = 1, 2, 3... \]  \hspace{1cm} (6) \\
\[ g(z) = \begin{cases} 
\text{ceil}(z \cdot M) - 1, & 0 < z \leq 1 \\
0, & z = 0
\end{cases} \]  \hspace{1cm} (7)

Here, $T$ is the duration time of unit pulse which is set as 0.1ns. $y(l)$ describes the chaotic series after being normalized to [0, 1], where $l$ denotes its serial number. The subsampling rate $f$ is set as 0.1. $g(z)$ is the quantification function. $\text{ceil}(\cdot)$ denotes the nearest integer larger than or equal to the variable. The number of quantified values is denoted by $M$. Figure 9 displays the relationship between the complexity of output noise and $M$. As can be seen, the complexity of output noise increases with $M$ in general trend. Therefore, the output complexity can be enhanced further by increasing the quantification resolution $M$ with regard to the same digital noise source.
From the discussions above, the conclusion is drawn that the output complexity could be improved by both digital and analog means. In the digital domain, improving the complexity of input signal source is an effective way to enhance the output complexity. However, from the practical point of view, the digital way may not be very easy to establish, since a high dynamical complexity digital source usually implies a high computational complexity. For example, the computational complexity of delayed-feedback optoelectronic chaos is much higher due to the delayed differential equation model. As a result, the calculation speed will be certainly restricted in real world applications. For the analog way, the nonlinear transform plays an important role. However, to realize a large value of $m_1$ in real applications, an IM with ultra-low half-wave voltage and a high performance RFA are indispensable. Such devices are usually costly. Besides, the complexity could be improved further through increasing the quantification resolution $M$. A higher quantification resolution usually means a higher computing resource or a higher demand of analog-to-digital converter. It will increase the system costs in the same way. Thus there will be a tradeoff between the complexity performance and implementation cost. Other forms of electro-optic or all optical nonlinear transformation will be explored in the future.

### 3.4 Robustness

Physical parameter mismatch is an important factor that influences the reproducibility of signal. In our system, slight differences in performance of PD, RF, IM and PM could both cause the differences on the modulation depth of IM and PM, which are depicted as $m$ and $m_1$. Here a proof-of-concept experiment is conducted to study their effects on the system’s reproducibility. A length of $2^9 - 1$ PRBS with the rate of 10 Gb/s is used as the digital input. Finally a duration of 0.3us data with a sample rate of 40GSample/s is recorded and stored through the DSO.

Figure 10 shows the effects of $m$ and $m_1$ on the system’s reproducibility separately. The correlation coefficients of output signals with different modulation depths are calculated to reflect their similarity, where $m$ and $m_1$ could be adjusted by adding attenuators after the RF. The output signal without attenuation is recorded as the reference signal. As displayed in Fig. 10, the outputs turns to be more sensitive to the fluctuation of $m$ compared with $m_1$. When the attenuation value is set as 1dB, namely 10% mismatch of $m$, the correlation coefficient could reach 0.85. The curve plotted in Fig. 10(b) shows a slow decay with the attenuating of $m_1$. A high correlation coefficient (~0.9) could be maintained even with 4dB attenuation of $m_1$. Based on these facts, it is convinced that similar outputs could be obtained by carefully choosing the devices and adjusting the parameters, as long as the input digital signal keeps same. Moreover, digital signal is easy to store, reconstruct, and suitable for long haul transmission. These facts may benefit the synchronous noise production at different places.
4. Conclusion

In this paper, we proposed a reproducible optical noise-like signal generator based on the effect of PM-to-IM conversion and a nonlinear transform. A flat spectrum and a symmetrical distribution can be observed in the generated noise signal. The distribution properties of the output noise have been discussed and a complement method is proposed to make it approach the Gaussian shape. We have also studied the complexity performance. There is a positive correlation between the complexity of input sequence and output noise. Since there is no noise interference, the complexity of a binary sequence is much easier to control and calculate than the analog signals. The complexity can be further enhanced by increasing the nonlinearity of the analog post process procedure. The analog noise can also be regenerated because the input binary sequence is relatively easier to generate or store in digital devices. Finally, the impact of key parameters on the reproducibility of the system is discussed. Therefore, the proposed scheme may be a more controllable way to generate broadband optical noise-like signal, which has the potential to be used in optical radar, secure communication systems and many other applications.

Funding

National Natural Science Foundation of China (NSFC) (61471179, 61505061, 61377073, 61675083); Fundamental Research Funds for the Central Universities’, HUST (2017KFYXJJ034); The 863 Program of China (2015AA016904).