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Ultrafast and real-time physical random bit extraction with all-optical quantization

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Abstract. Optical chaos generated by perturbing semiconductor lasers has been viewed, over recent decades, as an excellent entropy source for fast physical random bit generation (RBG) owing to its high bandwidth and large random fluctuations. However, most optical-chaos-based random bit generators perform their quantization process in the electrical domain using electrical analog-to-digital converters, so their real-time rates in a single channel are severely limited at the level of Gb/s due to the electronic bottleneck. Here, we propose and experimentally demonstrate an all-optical method for RBG where chaotic pulses are quantized into a physical random bit stream in the all-optical domain by means of a length of highly nonlinear fiber. In our proof-of-concept experiment, a 10-Gb/s random bit stream is successfully generated on-line using our method. Note that the single-channel real-time rate is limited only by the chaos bandwidth. Considering that the Kerr nonlinearity of silica fiber with an ultrafast response of few femtoseconds is exploited for composing the key part of quantizing laser chaos, this scheme thus may operate potentially at much higher real-time rates than 100 Gb/s provided that a chaotic entropy source of sufficient bandwidth is available.

Keywords: chaos; random number generation; semiconductor lasers; optical signal processing.

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1 Introduction

Physical random bits play crucial roles in cryptographic systems and information security.[1–4] Especially in the context of "one-time-pad" unconditional security, the real-time generation rate of physical random bits critically determines the secure communication rate.

Laser chaos has, over recent decades, attracted extensive attention to solve this problem of fast and real-time random bit generation (RBG) due to its high bandwidth and large random fluctuations in the past decades.[5–18] Typically, 1.7-Gb/s real-time RBG was first reported by Uchida et al. through binary digitization of the temporal fluctuations of two independent chaotic lasers using electrical 1-bit analog-to-digital converters (ADCs) in 2008.[5] In 2009, 12.5-Gb/s off-line RBG was demonstrated by Reidler et al. through a multiple-bit extraction approach, where the intensity fluctuations of a single chaotic laser were sampled by a virtual 8-bit ADC with least significant bits retention.[6] Shortly afterward, Kanter et al.[7] further improved the RBG rate using off-line high-order derivatives of the digitized chaotic signals. In parallel, numerous excellent RBG schemes have been proposed by increasing the chaotic bandwidth or optimizing the postprocessing methods.[8–19] Among them, Ugajin et al. typically reported a 21.1-Gb/s random bit throughput by retaining eight significant bits of the 12-bit ADC as the multiple parallel outputs through a sophisticated field programmable gate array, but it should be noticed that the real-time rates in each output channel are still 3.6 Gb/s determined by the ADC.[19] In sum, all the aforementioned RBG executes the quantization process by means of electrical ADCs, so the currently reported real-time

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rates in a single channel are severely limited to the level of Gb/s due to the electronic bottleneck.[17]

For this reason, we propose a method of RBG with all-optical quantization, where the optically sampled chaotic pulses can be digitized into a stream of random bits in real time by means of a length of highly nonlinear fiber (HNLF) with an optical filter. Specifically, the chaos is first all sampled into a train of optical pulses, whose peak power is proportional to the original chaos signal. Then, the obtained chaotic pulses are amplified and injected into the HNLF to generate a supercontinuum (SC) spectrum, whose spectral width depends on the peak power of the input chaotic pulse. Consequently, these optically sampled chaotic pulses can simply be digitized into binary bit sequences by an optical bandpass filter (BPF) with an appropriate central wavelength.

In our proof-of-concept experiment, the adopted optical chaos is generated by heterodyning two external-cavity laser diodes (ECLs), so-called white chaos.[20,21] Final results show that a 10-Gb/s random bit stream in a single channel can be continuously generated using our method. Note that the current real-time rate is mainly limited by the bandwidth of the chaotic source. Considering the Kerr nonlinearity of silica fiber with an ultrafast response of few femtoseconds, our proposed RBG method should have the potential to operate at the rate on the order of 100 Gb/s (even Tb/s) provided that a chaotic entropy source of sufficient bandwidth is available.

2 Experimental Setup and Results

2.1 Experimental Setup

Figure 1 shows the experimental setup, which includes three main parts: a broadband chaotic entropy source, an optical sampler consisting of an electro-optic modulator (EOM), and an optical quantizer containing a length of HNLF with an optical BPF. As shown in Fig. 1(a), the optical heterodyne technique is applied to produce the broadband chaos. Two external-cavity lasers ($ECL_{1,2}$) with adjacent central wavelengths are coupled into a 3-dB fiber coupler (FC) to interfere with each other. Their coupling outputs are injected into a balanced photodetector (BPD) to obtain white chaos. The chaotic signal is then optically sampled through the EOM triggered by a train of ultralow-jitter clock pulses from a mode-locked laser (MLL). Further, the sampled chaotic pulses are injected into the HNLF via an erbium-doped fiber amplifier (EDFA). In the HNLF, the optically sampled chaotic pulses with different amplitudes will experience different spectral broadening. The spectral broadening width is proportional to the amplitude of the sampled chaotic pulse. Based on this intensity-to-wavelength mapping, we finally can digitize these SC chaotic pulses into a stream of random bit sequences using the BPF with an appropriate central wavelength. This random bit quantization process is executed in the all-optical domain and thus eliminates the electrical bottleneck.

2.2 Experimental Results

Figure 2 characterizes the measured optical white chaos. In the experiment, the center wavelengths of ECL_1 and ECL_2 operate at 1553.178 and 1553.076 nm, as shown in the inset of Fig. 2(a). The feedback strengths are tuned to −9.8 dB for ECL_1 and −10.6 dB for ECL_2, while the associated feedback delays are $\tau_1 = 94.1$ ns and $\tau_2 = 111.9$ ns, respectively. Figure 2(a) shows the RF spectra of the final white chaos (blue line) and the original chaos from the ECL_1 and ECL_2 (red and violet lines), respectively. It is obvious that the RF spectra of white chaos are much wider and flatter than that of the ECLs due to the application of optical heterodyne. Figure 2(b) shows the autocorrelation function (ACF) of the white chaos, while its inset is the associated ACFs of the ECL_1 and ECL_2 outputs. From the inset of Fig. 2(b), one can observe that the ECL_1 and ECL_2 have obvious correlation peaks at their own feedback delays τ_1 and τ_2, called as the time-delay signatures (TDSs). Such TDSs will introduce some unwanted correlations in final random bits and thus must be eliminated. That is just the reason why we use the optical heterodyne process to generate the white chaos. Because of the nonresonant beatings between the two ECLs with disproportional feedback lengths, their external mode frequency intervals will also be disproportional. In consequence, the obtained white chaos has a noise-like RF spectrum and no TDS can be observed as shown in Fig. 2(b). Meanwhile, a symmetrical amplitude probability distribution can be ensured from Figs. 2(c) and 2(d), which is the base to generate unbiased random bits with no need of additional complex postprocessing. This symmetry is induced by the conversion of the fast phase chaos dynamics into intensity variations.

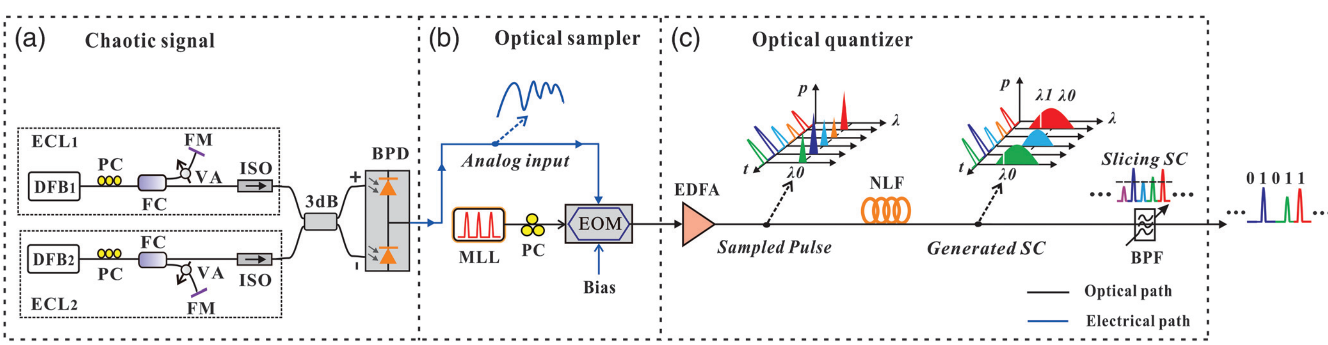

Fig. 1 Schematic of the proposed RBG with all-optical quantization: (a) optical chaos, (b) optical sampler, and (c) optical quantizer. DFB, distributed feedback semiconductor laser; PC, polarization controller; VA, variable optical attenuator; FM, fiber mirror; ISO, optical isolator; 3 dB, 3 dB FC; BPD, balanced photodiode; MLL, mode-locked laser; EOM, electro-optic modulator; EDFA, erbium-doped fiber amplifier; HNLF, highly nonlinear fiber; BPF, optical BPF.

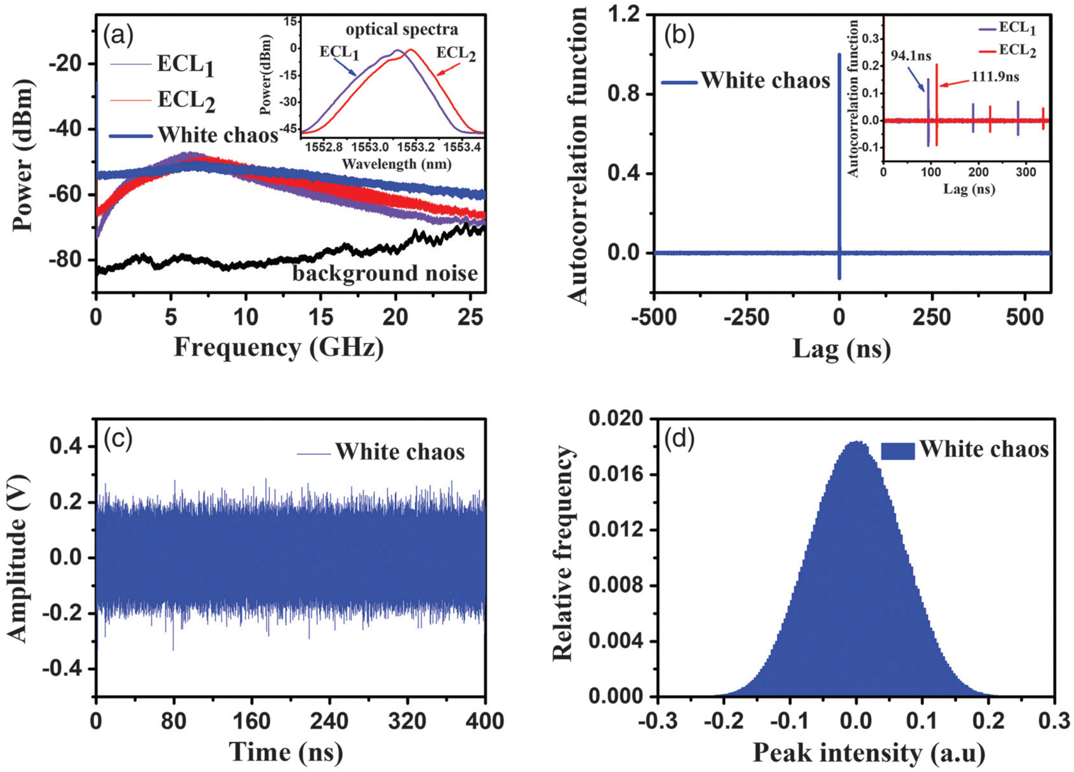

Fig. 2 (a) RF spectra of the white chaos and $ECL_{1,2}$ (the inset is the optical spectra of $ECL_{1,2}$); (b) ACF of the white chaos (the inset on right upper corner shows ACFs of the $ECL_{1,2}$); (c) temporal waveforms of the white chaos; (d) amplitude probability distribution of the white chaos.

Figure 3 shows the optical sampling results recorded by a real-time digital oscilloscope (OSC, Lecroy LabMaster10-36Zi, 36 GHz, 80 GS/s) via a 50-GHz photodiode (PD, Finisar XPDV2150R). In the experiment, the EOM with a 20-GHz input bandwidth (Photline, MX-LN-20) is biased at a voltage $V_{\mathrm{Bias}} = 5.5$ V, while the optical clock pulse train generated from the MLL (Pritel, UOC-05-14G-E) has a timing jitter less than 50 fs which works at a repetition rate of 10 GHz and a central wavelength of 1555.2 nm. Comparing the waveform before and after the optical sampler, it can be found that the continuous-time white chaos [Fig. 3(a)] matches very well with the peaks of the sample chaotic pulses [Fig. 3(b)]. Quantitatively, we calculate the normalized cross-correlation function (CCF) of the signal before and after the optical sampler to quantitatively evaluate the performance of the sampling system. Note, the signal here consists of a sequence of discrete sampled points and its size is 10^6 points. It can be clearly observed from Fig. 3(c) that the cross-correlation coefficient between the signals measured by the oscilloscope and the proposed method is as high as 0.997. Further calculation shows

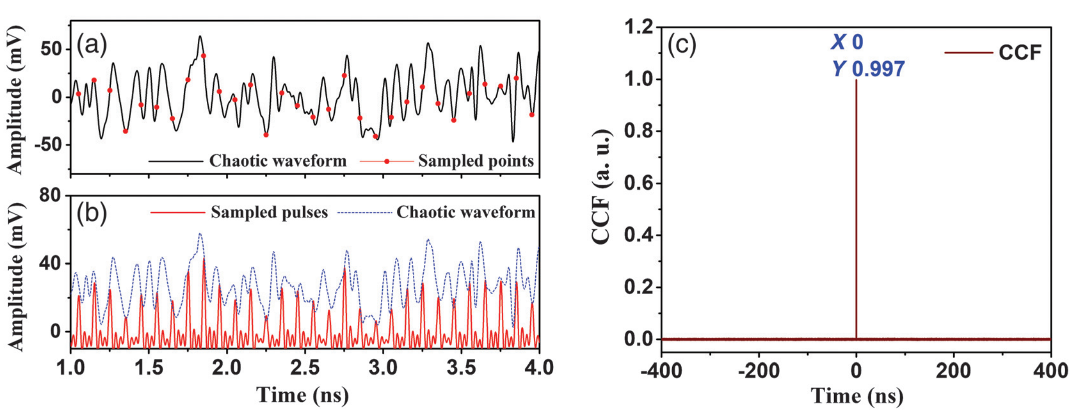

Fig. 3 Schematic optical sampling results. (a) Continuous-time white chaotic waveform to be sampled; (b) discrete-time chaotic pulses after the optical sampler; (c) normalized CCF of the signal before and after the optical sampler.

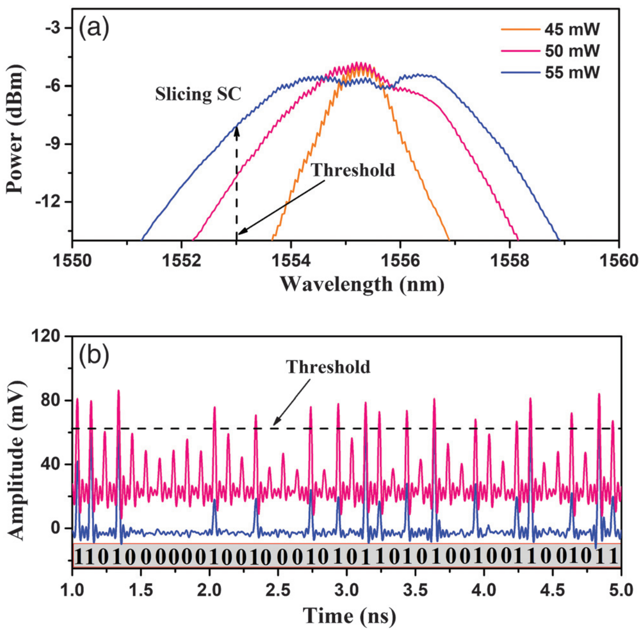

Fig. 4 (a) Measured optical spectra from three SC pulses with different powers (45, 50, and 55 mW); (b) measured pulse waveform before (red) and after (blue) the threshold/quantization operation.

that our optical sampling system has a high SNR of about 41.6 dB. All these results confirm that such an optical sampler has a high fidelity.

Figure 4 shows the optical quantizing results. As shown in Fig. 1(d), the optically sampled chaotic pulses are first amplified by the EDFA (KEOPSYS, PEFA-SP-C-SM-33-B2020-FA) and then used to pump a 400-m HNLF to generate the so-called SC pulse train. The typical parameters of the utilized HNLF are the nonlinear coefficient of 10 $W^{-1}\,km^{-1}$, the chromatic dispersion slope of 0.017 $ps\,nm^{-2}\,km^{-1}$, and the zero-dispersion wavelength of 1550 nm. Figure 4(a) shows typical optical spectra from three SC pulses with different powers (45, 50, and 55 mW) measured by an optical spectrum analyzer with a resolution of 0.02 nm (Yokogawa, AQ6370C). From it, one can see clearly that the optical spectrum width is broadened with increasing pulse power. In our experiment, we control the average optical power of the sampled SC chaotic pulse stream to be about 50 mW at the end of the HNLF, whose waveform is measured by the 36-GHz oscilloscope as shown in the pink line [Fig. 4(b)]. Then, the BPF (Yenista, XTM-50) on the anti-Stokes side lobe is used to threshold the generated SC chaotic pulses for real-time RBG. When the pulse power is higher than 50 mW, the associated optical spectrum will surpass the wavelength of 1553 nm [Fig. 4(a)]. Therefore, the filtering center of the BPF is experimentally set at $\lambda_0 = 1553$ nm with a 0.4-nm bandwidth. In this case, when the SC pulse is larger than the threshold, there is an output pulse in the end of the BPF. Otherwise, there is no output. The blue line in Fig. 4(b) shows the quantized output pulse waveform, which is further coded into the random bit stream in the stripe at the bottom of Fig. 4(b). When there is a pulse output, we code it as logical "1." Otherwise, we code it as logical "0." These results demonstrate that a 10-Gb/s random bit stream has been successfully and continuously generated.

As is well known, a physical random bit sequence should be unbiased and independent. Figures 5(a) and 5(b) show the statistical bias level and the autocorrelation (AC) coefficients of the generated 10 Gb/s binary random bit stream, estimated utilizing the normalized Gaussian distribution estimation $N\,(0, \sigma^2)$. It can be confirmed from Fig. 5 that both the bias and the serial AC coefficients are below their three-standard-deviations written as $3\sigma_e = (3N^{-1/2})/2$ and $3\sigma_c = 3N^{-1/2}$. Further, we use state-of-the-art National Institute of Standards and Technology (NIST SP800-22) test suite with 15 statistical test items to examine the obtained random bits.[22] Each test item is performed using 1000 samples of the 1-Mbit sequence, and the statistical significance level is set as $\alpha = 0.01$. The test criterion for success is that each P-value should be larger than 0.0001, and the proportion should be within the range of 0.99 ± 0.0094392. Figure 6 shows the test results. For tests that return multiple P-values and proportions, the worst case is given. All the results suggest that our generated random bits can be regarded to be unbiased and independent statistically.

3 Discussions

In this section, we discuss the robustness of our RBG. Specifically, the bias of the center wavelength of the BPF on the quality of the generated random bits is analyzed. Figure 7 shows the occurrence frequency of "1" in a random bit sequence and the number of passed NIST tests as a function of the

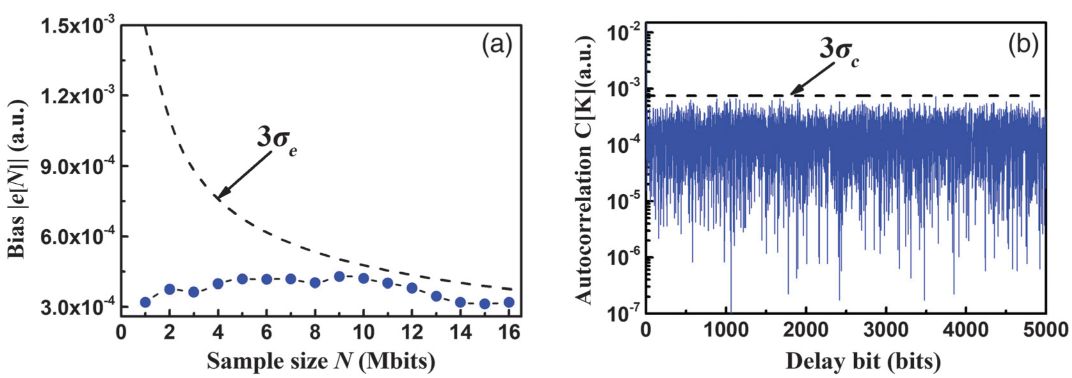

Fig. 5 (a) Bias $|e[N]|$ versus the sample size of the generated 10 Gb/s random bits stream. The black dotted line in (a) is its three-standard-deviation line, $3\sigma_e = (3N^{-1/2})/2$ where $N = 1, 2, 3, \ldots, 16$ Mbits. (b) AC coefficient $C[K]$ as a function of the delay bit K for 16 Mbits.

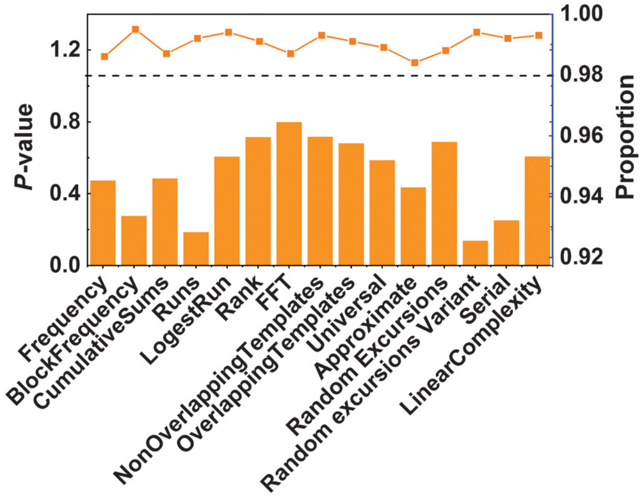

Fig. 6 NIST test results: *P*-value (left column) and proportion (right column). Note, the 15 test items are shown along the horizontal axis.

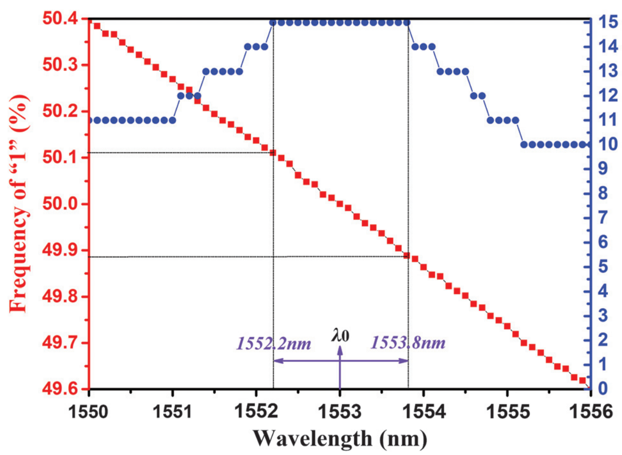

Fig. 7 Frequency of "1" in a random bit sequence (red squares) and the number of passed NIST tests (blue circles) as a function of the filtering center wavelength λ_0.

quantization threshold. It is obvious that the frequency of "1" decreases almost linearly with the increasing filtered center wavelength. Only the random sequences having a frequency of "1" in the range from 49.88% to 50.11% can pass all the NIST tests, where the center wavelengths are allowed in a range from 1552.2 to 1553.8 nm.

In addition, we want to point out that in the view of the portability, our current proof-of-principle experiment setup is relatively bulky due to the use of HNLF with weak nonlinear interaction ($\gamma = 10\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$). However, this issue may be solved by introducing the photonic integrated technology. To our knowledge, chip-based SCG has been investigated in several materials, such as silicon photonic nanowires,[23] chalcogenide waveguides,[24] and silicon nitride waveguides.[25] When these on-chip waveguides with high nonlinear coefficients are employed, the size of the SCG system can be greatly improved to the level of centimeters and the associated power consumption has the potential to be reduced by nearly 50%.

4 Conclusions and Outlook

In summary, we have proposed an all-optical approach for quantizing chaotic optical pulses into random bits. This scheme executes all the random bit extraction processes in the all-optical domain and therefore overcomes the bottleneck of electronic signal processing experienced by previous RBGs. As a proof-of-principle demonstration, a 10-Gb/s chaotic optical bit stream in a single channel is successfully generated using our method. The current real-time rate of 10 Gb/s is mainly limited by the bandwidth of the optical chaos used. Considering the ultrafast response of the HNLF used as the core unit for random bit extraction, our all-optical approach is expected to achieve a much faster real-time bit rate up to the order of 100 Gb/s if the bandwidth of the chaotic entropy source is sufficiently broad and the pulse generation speed of the used MLL is high enough. For instance, we notice that very recently a 315-GHz bandwidth of a chaotic light source has been reported using a particularly designed broad-area semiconductor laser.[18] Combining with pulse compressing and the optical time-delay multiplexing technique, the MLL pulse generation speed has the potential to be enhanced to above 300 GHz.[26]

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