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Wideband chaos generation using a VCSEL with intensity modulation optical injection for random number generation

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Physical random numbers have been widely used in modern network society, such as the generation of cryptographic keys for classical and quantum cryptography systems [1]. Among the many sources of physical entropy, chaotic semiconductor lasers have attracted wide attention due to their desired characteristics including larger bandwidth, low cost, and monolithic integration [2]. The modulated optical injected semiconductor laser is usually a method to investigate nonlinear dynamics. For example, Doumbia et al. [3] demonstrated a wideband chaos generation using a frequency comb optical injected distribution feedback (DFB) laser. Tseng et al. [4] experimentally generated a chaotic signal with a bandwidth of 33 GHz using an intensity modulation (IM) optical injected DFB laser. Very recently, our group predicted the possibility of the broadband chaos generated in vertical-cavity surface-emitting lasers (VCSELs) using IM optical injection [5]. Herein, we experimentally demonstrate a novel scheme for generating broadband chaos without time-delay signature (TDS) based on a VCSEL with IM optical injection. In the present work, by adjusting experimental parameters appropriately, we have experimentally captured a chaotic signal with a bandwidth exceeding 20 GHz, which surpasses the current chaos bandwidth achievable using VCSEL. Moreover, by adopting a simple multi-bit extraction method, we obtain 320 Gb/s random number sequences with verified randomness.

Figure 1 shows the experimental setup of wideband chaos generation in a VCSEL subject to IM optical injection. In this implementation, a typical master-slave laser framework is built, which is usually used in the generation of photonic microwave and chaotic signals. A tunable laser (TL, Newkey Photonics Inc.) is used as a master laser (ML) and its output is injected into the slave laser through polarization controllers (PC1 and PC2), a variable attenuator (VA), a Mach-Zehnder modulator (MZM, bandwidth: 40 GHz, $V_\pi = 1.8$), and an optical circulator (CIR). Herein, a commercially available 1550 nm VCSEL (SEOULVIOSYS) is employed as the slave laser (SL), which is driven by a high-stability and low-noise laser diode controller (laser diode controller, LDC, ILX-Lightwave LDC-3724C). Note that PC1 is adjusted to control the polarization states in the fiber link and to align with the modulation axis of the MZM. PC2 is used to match the direction of the X-polarization (XP) mode of the VCSEL. The injection power can be changed by the VA. Then, the output of the VCSEL is split by a polarization beam splitter (PBS) and the PC3 is applied to control the polarization state. In this experiment, the output of the VCSEL is split into two branches by the optical coupler (OC). One branch is sent to a photodetector (PD, bandwidth: 31 GHz) for photoelectric conversion followed by an oscilloscope (OSC, LeCroy WaveMaster 820Zi-B, bandwidth: 20 GHz, sampling rate: 80 GS/s) for data acquisition or by a 40 GHz electric spectrum analyzer (ESA, R& S FSV40) to observe the power spectra. Another branch is injected into an optical spectrometer analyzer (OSA, YOKOGAWA AQ6370D) to monitor optical spectral components.

Results and discussion. Herein, we consider using the IM optical injected VCSEL to generate a wideband chaotic signal, where only the XP mode of the VCSEL is discussed because the YP mode is suppressed. The polarization-resolved intensities for the free-running VCSEL are shown in Appendix B. The injection strength ξ_i is defined as the square root of the power ratio between the optical input and the free-running VCSEL. To begin with, sending the input carrier into the VCSEL excites the period-one (P1) dynamics at $(\xi_i, f_i) = (1, 26\text{ GHz})$, as shown in Figures 1(b1) and (b2). Note that the drive current of the VCSEL is fixed at 5 mA. A frequency difference of 26.8 GHz between the red-shifted cavity frequency and the regeneration frequency from the optical injection can be observed. After the frequency beating in PD, a microwave jittering around 26.8 GHz is obtained. To gain the chaotic dynamic, a microwave signal is modulated into the optical carrier and then injected into the XP mode of VCSEL. At the proper modulation pa-

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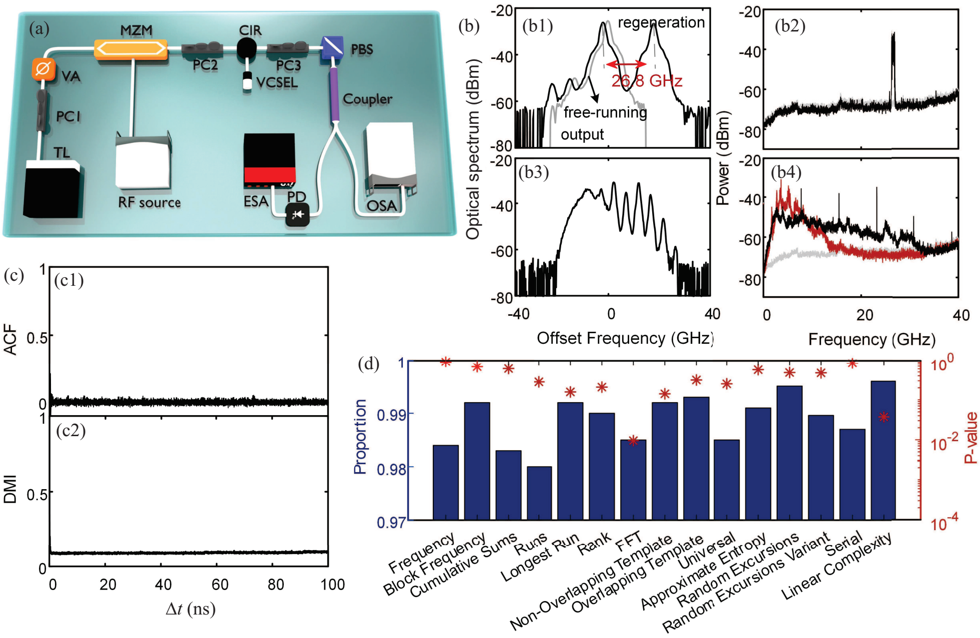

Figure 1 (Color online) (a) Experimental setup of broadband chaos generation in a VCSEL subject to IM optical injection; optical spectra of (b1) P1 oscillation and (b3) chaos; power spectra of (b2) P1 dynamic at a time instant (black curve) and (b4) chaos induced by IM modulation input (black curve) and CW input (red curve). The noise floor is indicated as the gray curve in Figures 1(b2) and (b4). (c1) ACF peak and (c2) DMI peak. (d) The results of NIST SP800-22 tests of chaos from VCSEL.

rameters (modulation depth m and modulation frequency f_m), the VCSEL will be destabilized into chaotic dynamics. For example, in Figures 1(b3) and (b4), modulating the microwave signal with $f_m = 14$ GHz by a 40 GHz optical modulator (Eospace AX-AV5-40) into the XP mode of VCSEL results in the chaotic behavior (i.e., the largest Lyapunov exponent is positive), where injection parameters are fixed at $(\xi_i, f_i) = (1, 26\text{ GHz})$. The complicated spectrum generation can be attributed to the mixing between the oscillation frequency and modulation frequency inside the laser cavity because of the nonlinearities of the laser. To quantitatively investigate the chaotic characteristic, we calculate the chaos bandwidth is 20.1 GHz. Furthermore, the evolution of chaotic bandwidth under various injection frequency detuning f_i is shown in Appendix C, where only maximum chaotic bandwidth is indicated for the given frequency detuning.

We calculate the autocorrelation function (ACF) and delay mutual information (DMI). The results show that no TDS occurs in the chaotic state and thus no postprocessing is needed to suppress/eliminate the periodicity (see Appendix C). Moreover, we calculate the skewness of time series to be 0.1054, which indicates a slightly asymmetrical amplitude distribution. To improve the uniformity and eliminate the residual correlation, we perform m least significant bits (LSBs) retention operation, as shown in Appendix D. One can see when the LSB decreases to 4, a uniformity and flat probability distribution can be obtained, which is one of the most important prerequisites for producing unbiased and reliable random bits. Furthermore, the physical random bit sequences can be passed 15 NIST tests, as shown in Figure 1(d). Finally, we calculate the random number generation rate at 320 Gb/s (80 GS/s×4 bit).

Conclusion. In conclusion, a scheme for broadband chaos generation is proposed and demonstrated based on a VCSEL with subharmonic modulation optical injection. A 1/2 subharmonic modulation signal is injected into the VCSEL to destabilize the P1 state and generate a complex chaos signal with a bandwidth above 20 GHz. Moreover, such a chaos signal has been used as a physical entropy source to produce the physical number. By adopting a 4-LSBs extraction method, we can realize a 320 Gb/s physical number stream with verified randomness. Our scheme may offer a new alternative solution for ultrafast physical number generation using a single VCSEL.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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