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Baicheng Yao

yaobaicheng@uestc.edu.cn

University of Electronic Science and Technology of China <https://orcid.org/0000-0001-8368-5815>

An-Ran Li

University of Electronic Science and Technology of China

Yong Geng

University of Electronic Science and Technology of China

Ning Jiang

University of Electronic Science and Technology of China

Hao-Nan Xu

University of Electronic Science and Technology of China

Guan-Qi Chen

University of Electronic Science and Technology of China

Yiqun Zhang

Institute of Optics and Electronics, Chinese Academy of Sciences <https://orcid.org/0000-0003-2055-787X>

Ying-Jun Fang

University of Electronic Science and Technology of China

Li-Lu Wang

University of Electronic Science and Technology of China

Qiang Zhou

University of Electronic Science and Technology of China <https://orcid.org/0000-0001-7099-1995>

Kun Qiu

University of Electronic Science and Technology of China

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Broadband radio-frequency chaos synthesis with Vernier chaotic microcombs

An-Ran Li^{1,#}, Yong Geng^{1,#}, Ning Jiang^{1,*}, Hao-Nan Xu¹, Guan-Qi Chen¹, Yi-Qun Zhang², Ying-Jun Fang¹, Li-Lu Wang¹, Qiang Zhou³, Kun Qiu^{1,*}, and Bai-Cheng Yao^{1,4,*}.

¹ *Key Laboratory of Optical Fiber Sensing and Communications (Education Ministry of China), University of Electronic Science and Technology of China, Chengdu, China.*

² *State Key Laboratory of Optical Field Manipulation Science and Technology, Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209, China*

³ *Institute of Fundamental and Frontier Sciences, University of Electronic Science and Technology of China, Chengdu 611731, China.*

⁴ *Engineering Center of Integrated Optoelectronic & Radio Meta-chips, University of Electronic Science and Technology of China, Chengdu, China.*

#These authors contributed equally.

***Corresponding author:** uestc_nj@uestc.edu.cn, kqiu@uestc.edu.cn, yaobaicheng@uestc.edu.cn

Abstract

Optical chaos is a powerful physical resource for secure communications, stochastic computing and photonic information processing owing to its intrinsic randomness and broadband dynamics. Among chaotic photonic platforms, Kerr microcomb-based sources are particularly attractive because they combine massive wavelength parallelism with broad spectral coverage, but the chaotic bandwidth of each comb tooth remains limited to the gigahertz scale by the cavity photon lifetime that governs the response speed of intracavity nonlinear dynamics. Here we develop a Vernier chaotic dual-microcomb platform in which multiheterodyne mapping reconstructs bandwidth-limited chaotic spectral elements into broadband radio-frequency (RF) chaos, thereby overcoming the single-tooth bandwidth bottleneck. The reconstructed RF chaotic bandwidth grows linearly with the number of mapped spectral-element pairs, thereby converting optical spectral parallelism into scalable electrical bandwidth. We experimentally generate RF chaotic states exceeding 40 GHz using only two mapped spectral-broadened spectral-element pairs, enabling single-channel offline random-bit generation at 3.072 Tbps and real-time extraction at 40 Gbps. Furthermore, the architecture offers a route towards controllable frequency translation and spectral tailoring of chaotic waveforms. These results establish Vernier chaotic microcombs as a platform for broadband chaos transduction and scalable RF-domain

chaotic waveform synthesis.

Introduction

Broadband stochastic dynamics in optical systems provide a physical basis for generating and processing random signals beyond the speed of conventional electronics. Optical chaos provides a powerful route to such dynamics, because it combines intrinsic unpredictability, with high-speed temporal fluctuations [1]. These properties have supported applications in secure communications [2], random bit generation (RBG) [3-5], key distribution [6], photonic decision making [7], optical fiber sensing [8] and reservoir computing [9]. Early optical-chaos platforms were predominantly based on semiconductor lasers, in which optical feedback, optical injection or optoelectronic feedback introduces additional coupling and delayed degrees of freedom into the carrier-photon dynamics. Although these systems enable high-speed chaotic waveform generation, their accessible bandwidth and channel dimensionality remain limited. Nonlinear feedback engineering [10,11] and laser-network coupling [12,13] have been explored to broaden the chaotic bandwidth and increase the number of output channels. However, these configurations often increase system complexity and are difficult to translate into compact integrated platforms. More fundamentally, semiconductor laser chaos remains governed by carrier-photon interactions and is typically constrained by the relaxation-oscillation timescale [1]. Accessing higher-dimensional chaotic dynamics therefore requires photonic platforms that go beyond the bandwidth and dimensionality of conventional laser-chaos systems.

Kerr microresonators (MRs) have emerged as an attractive platform for realizing high-dimensional spatiotemporal chaos [14]. Beyond their established role in coherent frequency comb generation [15,16], continuously pumped Kerr MR can enter chaotic regimes through modulation instability, nonlinear mode interactions and dissipative cavity evolution [17-19]. The resulting chaotic microcombs combine broad optical spectra with massive wavelength parallelism, offering many distributed stochastic spectral channels within an integrated photonic platform [20]. This parallelism has recently been used for ultrafast random bit generation [20-22], and parallel LiDAR [23,24]. Yet optical parallelism alone does not yield a broadband electrical chaotic waveform. The chaotic bandwidth carried by each comb tooth generally remains at the gigahertz scale, being constrained by the cavity linewidth and the photon-lifetime-limited response of intracavity Kerr dynamics which imposes a characteristic response and filtering timescale on the intracavity dynamics [21] (Fig. 1a). As a result, the full high-dimensional chaotic dynamics distributed across the microcomb spectrum are difficult to access through conventional single-comb photodetection, remaining an unresolved challenge.

Frequency-domain mapping offers a possible route beyond this limitation. Spectrally distributed chaotic components can, in principle, be translated to distinct carrier frequencies and assembled into a

broadband radio-frequency (RF) waveform (Fig. 1b). Dual-comb techniques provide a natural optical implementation of this concept, because multiheterodyne beating establishes a deterministic correspondence between optical mode pairs and RF frequencies [25-28]. This principle underpins dual-comb spectroscopy [29-32], precise ranging [33-36], and optical atomic clocks [37], where mutual coherence and phase stability are preserved to retain precise optical-frequency information. Whether the use of dual-comb mapping in an incoherent regime to reconstruct distributed optical chaos in the RF domain remains largely unexplored.

Here we demonstrate a Vernier chaotic dual-microcomb platform that reconstructs broadband RF chaos from distributed optical chaotic dynamics (Fig. 1b). Two free-running chaotic microcombs with slightly different repetition rates are generated on a monolithic Si₃N₄ platform, forming an incoherent Vernier dual-comb system (Fig. 1c). Multiheterodyne mapping translates bandwidth-limited chaotic spectral-element pairs into separated RF bands, such that each additional mapped pair contributes an incremental chaotic band and the reconstructed bandwidth increases linearly with the number of incorporated pairs (Fig. 1d). This mechanism shifts bandwidth scaling from the further broadening of an isolated comb tooth to the additive reconstruction of distributed chaotic resources. Spectral equalization suppresses low-frequency accumulation during multi-element synthesis, while element-level broadening increases the bandwidth contribution of each mapped pair and reduces spectral-resource consumption. Using only two broadened spectral-element pairs, we experimentally reconstruct RF chaotic states exceeding 40 GHz and demonstrate single-channel random-bit generation at 3.072 Tbps offline and 40 Gbps in real time. In principle, the pump-frequency offset provides a route to translating the reconstructed waveform across RF, microwave, millimeter-wave and potentially terahertz bands [38], whereas repetition-rate detuning offers an additional degree of freedom for tailoring its spectral distribution. These results establish Vernier chaotic microcombs as a platform for broadband chaos transduction and RF-domain stochastic waveform synthesis, with potential applications in high-speed random-bit generation, stochastic computing and reservoir computing.

Results

Multiheterodyne reconstruction of RF chaos

We first examined RF chaos synthesis in the incoherent Vernier dual-comb system. As illustrated in Fig. 1c, two independent continuous-wave (CW) lasers pumped a pair of Si₃N₄ MRs with a repetition-rate detuning Δf_{rep} of 2.5 GHz. By tuning the pump-resonance detuning, both resonators were driven into spatiotemporal chaotic states, generating two free-running chaotic microcombs. The resulting dual-comb spectrum spanned approximately 150 nm around 1550 nm and exhibited an

intrinsic pump-frequency offset Δf_p of 4 GHz (Fig. 2a). Owing to the Vernier relation between the two combs, stochastic dynamics carried by different optical spectral elements were shifted into discrete RF bands through multiheterodyne beating. The RF centre frequency of each mapped pair is set by the pump-frequency offset and an integer multiple of Δf_{rep} . Spectral-element pairs from the second to sixth modes on the long-wavelength side of the pump were selected for time-frequency characterization (Fig. 2b). The generated beat notes showed discrete frequency shifts separated by Δf_{rep} , forming a well-defined RF mapping grid. The corresponding temporal waveforms exhibited high-frequency oscillations modulated by slowly varying envelopes, a characteristic signature of multiheterodyne interference. This deterministic frequency translation allowed spectrally distributed chaotic dynamics to be reconstructed within electronically accessible RF sub-bands.

Efficient RF chaos reconstruction requires low correlation among the mapped spectral channels. Figure 2c shows the cross-correlation coefficient (CC) matrix calculated from six representative spectral-element pairs on the same side of the pump. The diagonal elements correspond to normalized autocorrelation peaks, whereas all off-diagonal coefficients remained below 0.05. These measurements indicate that the selected spectral-element pairs provide distinct stochastic waveforms for RF-domain reconstruction. Although symmetric comb modes within a single chaotic microcomb can exhibit intrinsic dynamical correlations [20], the Vernier dual-comb architecture allows different spectral regions to be used as separate mapping resources (Supplementary section I). These results show that distributed comb lines can provide statistically distinct stochastic channels for RF-domain reconstruction.

We next reconstructed broader RF chaotic waveforms by progressively aggregating mapped spectral channels. As the number of aggregated channels increased from one to five, the RF spectrum expanded towards higher frequencies, producing a clear broadening of the reconstructed RF chaotic bandwidth (Fig. 2d). Without spectral equalization, low-frequency components dominated the detected waveform and generated strong temporal envelopes and spectral power imbalance. This limited the efficiency of bandwidth scaling. To flatten the reconstructed spectrum, a reflective semiconductor optical amplifier (RSOA) was introduced before photodetection. Operated in the gain-saturation regime, the RSOA suppressed excessive low-frequency components and increased the relative contribution of high-frequency mapped components within the receiver dynamic range. (Supplementary section II). Consequently, the reconstructed RF spectrum became substantially flatter, and the effective RF chaotic bandwidth [39] increased from 5.52 GHz to 11.76 GHz for five aggregated channels.

The scalability of chaos transduction is quantified through the evolution of the effective bandwidth and spectral flatness as the number of aggregated spectral channels increases. Adjacent

channels were selected using an interleaved strategy to reduce RF spectral overlap. As shown in Fig. 2d, the effective RF chaotic bandwidth increased continuously with channel count, reaching 25.19 GHz for 10 aggregated channels. The spectral flatness also improved to 0.4769, where unity corresponds to an ideally flat spectrum. Numerical simulations further showed an approximately linear dependence between reconstructed bandwidth and the number of multiplexed spectral elements. This confirms that RF bandwidth scaling originates from distributed spectral aggregation rather than intrinsic broadening of individual comb teeth.

Bandwidth scaling through spectral aggregation alone, however, required an increasing number of mapped spectral elements. At higher aggregation levels, several beat notes approached the noise floor because of photodetector dynamic-range sharing and the non-uniform gain response of the erbium-doped fiber amplifier (EDFA) (Supplementary section II). These observations reveal a trade-off between RF bandwidth scaling and spectral-resource utilization. Further improvement in broadband RF chaos synthesis therefore requires increasing the bandwidth contribution of individual mapped spectral elements, rather than only increasing the number of aggregated channels.

Spectral broadening for efficient RF chaos synthesis

We introduced a spectral-broadening strategy to increase the chaotic bandwidth contribution of individual mapped spectral elements [40]. This approach addresses the limitation identified above: RF bandwidth scaling by spectral aggregation alone requires an increasing number of mapped spectral-element pairs. As illustrated in Fig. 3a, a broadband chaotic signal generated by an external-cavity laser was used to phase-modulate the chaotic microcomb before Vernier mapping. The imposed stochastic phase perturbations generated broadened sidebands around each comb tooth. Subsequent dispersive propagation through a single-mode fiber (SMF) converted these phase perturbations into intensity fluctuations. As a result, the originally discrete comb teeth evolved into broadened stochastic spectral envelopes (Fig. 3b). This process increased the spectral occupancy and chaotic bandwidth contribution of each mapped spectral element, allowing broadband RF chaos to be synthesized with fewer spectral-element pairs. In this configuration, spectral broadening serves as a pre-mapping bandwidth-expansion stage, whereas the Vernier dual-comb system performs the optical-to-RF reconstruction.

Figure 3c compares RF chaos synthesis using ten unbroadened spectral-element pairs and two spectrally broadened pairs. To reduce excessive overlap between adjacent broadened RF bands, spectral elements with larger mode spacing were selected. The broadened configuration generated richer temporal fluctuations and a substantially flatter RF spectrum. Despite using only two spectral-element pairs, the reconstructed RF chaotic waveform exhibited an effective bandwidth exceeding 40

GHz. This value is close to the summed bandwidth contributions of the two broadened mapped elements, consistent with additive RF-band synthesis through Vernier reconstruction (Supplementary section III). This bandwidth surpassed that obtained from ten unbroadened pairs in the same configuration, showing that efficient broadband RF chaos synthesis can be achieved by increasing the bandwidth contribution of individual mapped elements rather than only by increasing the number of aggregated pairs.

The scalability of the proposed architecture is further investigated through numerical simulations beyond the bandwidth limitations of the available experimental electronics. The free spectral ranges (FSR) of the two MRs were set to 300 GHz and 320 GHz, respectively, corresponding to a repetition rate detuning of 20 GHz, and the PD bandwidth was increased to 160 GHz. Figure 3d shows the synthesized RF spectra as the number of broadened spectral-element pairs increased from one to eight. The reconstructed RF chaotic bandwidth expanded continuously with increasing pair count and approached a device-limited ceiling of 128 GHz when seven pairs were incorporated. These results reveal that combining spectral broadening with Vernier multiheterodyne reconstruction provides an efficient route to ultra-broadband RF chaos synthesis with reduced spectral-resource requirements.

Ultrafast random bit generation

The random-bit experiments serve as a functional benchmark of the reconstructed RF chaos, linking its broadband stochastic dynamics to usable digital randomness. The application scenario and hardware implementation are illustrated in Fig. 4a, b. Before bit extraction, the temporal complexity of the reconstructed waveform was characterized using delayed mutual information (DMI) and permutation entropy (PE). As shown in Fig. 4c, the DMI remained below 0.1 for all non-zero delays and showed no observable periodic peaks, indicating the absence of pronounced residual temporal correlations or delay signatures. The PE consistently exceeded 0.9995, showing that the reconstructed dynamics retained a high degree of temporal complexity. These measurements confirm that the Vernier-reconstructed RF chaos provides stochastic dynamics suitable for physical random-bit extraction.

The reconstructed chaotic waveform was digitized using a high-speed digital phosphor oscilloscope operating at 256 GSa/s. Following the post-processing procedure described in Methods, the extracted bit streams were subjected to statistical evaluation. Figure 4d shows the probability distribution of the 12-bit symbols, where all 4096 possible states exhibited nearly uniform occurrence probabilities. This indicates efficient use of the digitized amplitude states after post-processing. The corresponding autocorrelation function (ACF) and statistical bias are shown in Fig. 4e. The ACF remained within the 3σ confidence interval for all non-zero bit shifts, confirming negligible residual

bit-level correlation. The bias $e[N]$ also remained below the $3\sigma_e$ threshold over the observation range, indicating no measurable bias accumulation in the extracted bit streams.

The extracted bit streams were further evaluated using the NIST SP800-22 statistical test suite. As summarized in the upper panel of Fig. 4f, all fifteen tests were passed. With a sampling rate of 256 GSa/s and 12 extracted bits per sample, the reconstructed RF chaotic waveform supported a single-channel offline random-bit rate of 3.072 Tbps. This value should be interpreted as an offline extraction benchmark under the adopted post-processing procedure. Practical operation was further examined using a real-time field-programmable gate array (FPGA)-based RBG prototype, following the real-time processing procedure described in Methods. The lower panel of Fig. 4f summarizes the corresponding NIST results, which also satisfied the statistical randomness criteria. The present real-time throughput was 40 Gbps, mainly limited by the acquisition bandwidth and FPGA processing clock. This demonstration verifies that the reconstructed RF chaotic waveform can be converted into statistically valid random bit streams in real time.

Finally, Fig. 4g compares the effective chaotic bandwidth and single-channel throughput of our approach with representative chaos-based entropy sources reported in the literature. Despite the bandwidth limitations of the current optoelectronic hardware, the proposed Vernier architecture achieves advanced performance in both effective chaotic bandwidth and single-channel random bit rate. More importantly, these performances enhancement originate from a different RF chaos transduction paradigm, in which distributed chaotic dynamics are reconstructed through incoherent Vernier mapping rather than relying solely on bandwidth enhancement of individual chaotic modes. Together, these results demonstrate that Vernier chaotic microcombs provide a scalable route toward ultrafast chaos generation and high-dimensional stochastic photonic information processing.

Discussion

This work demonstrates that the bandwidth bottleneck of individual chaotic comb teeth can be overcome by reconstructing broadband RF chaos from distributed optical stochastic dynamics. In the Vernier dual-microcomb architecture, two free-running chaotic microcombs with slightly detuned repetition rates form a multiheterodyne mapping grid, through which selected chaotic spectral-element pairs are translated into distinct RF bands. This process allows bandwidth-limited optical chaotic elements to be synthesized into a broadband RF chaotic waveform using a single photodetector. With spectral broadening of the mapped elements, RF chaotic bandwidths exceeding 40 GHz are reconstructed using only two spectral-element pairs, supporting 3.072 Tbps single-channel offline random-bit extraction and 40 Gbps real-time operation.

Table 1 compares this architecture with representative semiconductor-laser and microcomb-based

physical random-bit sources. Previous approaches have mainly increased accessible randomness by broadening an individual chaotic bandwidth [^{41,42}], suppressing delay signatures [⁴³], or multiplying parallel detection channels [⁴⁴⁻⁴⁷]. These strategies have enabled substantial progress, but the electrically accessible bandwidth remains closely tied to the dynamics of each emitter or to the complexity of parallel readout. The present work addresses a complementary problem: how stochastic dynamics that already exist across the optical spectrum can be reorganized into a broadband RF representation. In this sense, the architecture does not create additional stochastic dynamics, but maps and reconstructs distributed optical chaotic fluctuations into an electronically accessible waveform. The resulting RF chaotic bandwidth is therefore a collective property of the Vernier mapping process rather than a property of a single comb tooth. This distinction also changes the role of dual-comb physics in stochastic photonics. Conventional dual-comb systems rely on mutual coherence and phase determinism to preserve optical frequency information for spectroscopy, ranging and precision metrology. By contrast, the present system operates with free-running chaotic combs, where stochastic fluctuations are the information-bearing dynamics rather than noise to be removed. The Vernier repetition-rate detuning defines the spacing of the mapped RF bands, while the pump-frequency offset can shift the RF carrier position. These features suggest that incoherent dual-comb architectures can provide a flexible outlook for RF-domain stochastic waveform synthesis.

The present experiments define the current implementation scope of the proposed architecture. The >40 GHz RF chaotic bandwidth is obtained by combining Vernier multiheterodyne reconstruction with spectral broadening, which increases the stochastic bandwidth carried by each mapped spectral element and reduces spectral-resource consumption. The 3.072 Tbps result represents an offline extraction benchmark from the reconstructed broadband chaotic waveform, whereas the demonstrated 40 Gbps real-time output is limited primarily by the acquisition electronics and FPGA processing bandwidth. These distinctions indicate that the optical stochastic source and the real-time electronic backend are currently limited by different factors. Although the present system is implemented using a hybrid experimental platform, the key functions, including comb generation, modulation, dispersion engineering and photodetection, are compatible with heterogeneous photonic integration.

More broadly, Vernier reconstruction offers a route to access high-dimensional chaotic microcomb dynamics without requiring massively parallel electrical readout. By converting distributed optical stochastic channels into designable RF chaotic waveforms, this framework may support high-speed physical random-bit generation, stochastic photonic computing, neuromorphic information processing and other applications that exploit complex optical dynamics as a computational resource. These results extend chaotic microcombs from broadband optical stochastic sources toward programmable RF-domain stochastic waveform synthesis.

Methods

Generation of chaotic dual combs

The chaotic microcombs were generated using two Si₃N₄ MR co-integrated on a single photonic platform. To ensure high thermal stability and minimize relative frequency drift, both MRs were regulated by a shared temperature controller (Thorlabs MTD415L) maintained at a constant temperature of 26 °C. The MRs were designed with FSRs of 105 GHz and 102.5 GHz, respectively, yielding a repetition rate offset (Δf_{rep}) of 2.5 GHz. Stable chaotic dynamics were initiated by sweeping the frequency of two external pump lasers from blue to red detuning across the resonance, with a pump power of approximately 1 W. Following the suppression of residual pump components, the chaotic combs were coupled into a multiheterodyne dual comb architecture. Spectral element selection was performed using a C-band programmable wavelength selective switch (WSS, Finisar Waveshaper), where the bandwidth of each filtering window was set to 0.8 nm. The synthesized spectral elements were routed into a reflective semiconductor optical amplifier (RSOA, INPHENIX) for nonlinear amplification. The RSOA was utilized to leverage its gain saturation effect to suppress the dominant low-frequency intensity fluctuations and improve the spectral flatness of the chaotic signals.

For spectral broadening, we employed an electro-optic phase modulation (PM) scheme followed by dispersive stretching. Specifically, an electro-optic phase modulator was driven by an external chaotic source, and the modulated signals were subsequently transmitted through a segment of SMF. This configuration facilitated phase-to-intensity modulation (PM-to-IM) conversion through chromatic dispersion, effectively expanding the linewidth of each comb-tooth pair and bridging the spectral gaps in the RF domain to enhance extraction efficiency. The resulting chaotic RF signals were detected by a high-speed photodetector (PD, II-VI XPDV312, 75 GHz bandwidth). The temporal waveforms were captured by a high-performance real-time oscilloscope (Keysight UXR0594AP, 256 GSa/s, 59 GHz bandwidth).

Characterization of stochastic dynamics

To rigorously evaluate the orthogonality and randomness of the generated chaotic signals, several statistical metrics were employed:

Effective bandwidth: the effective bandwidth B_{eff} is defined as the cumulative bandwidth occupied by the discrete spectral segments accounting for 80% of the total RF spectral power. Specifically, the power spectral density components are sorted in descending order, and the minimum spectral subset satisfying:

$$\frac{\sum_{f_i \in \Omega_{80}} P(f_i)}{\sum_{i=1}^N P(f_i)} \geq 80\% \quad (1)$$

where $P(f_i)$ denotes the RF power spectral density at frequency f_i . The effective bandwidth is then calculated as:

$$B_{eff} = \sum_{f_i \in \Omega_{80}} \Delta f_i \quad (2)$$

where Δf_i is the frequency resolution of each spectral segment.

Cross correlation (CC): The inner-channel independence is quantified by the CC coefficient between two temporal trace $I_1(t)$ and $I_2(t)$:

$$CCF(\tau) = \frac{\langle (I_1(t) - \langle I_1(t) \rangle) (I_2(t - \tau) - \langle I_2(t - \tau) \rangle) \rangle}{\sqrt{\langle (I_1(t) - \langle I_1(t) \rangle)^2 \rangle \langle (I_2(t - \tau) - \langle I_2(t - \tau) \rangle)^2 \rangle}} \quad (3)$$

where $I_1(t)$ and $I_2(t)$ denote the two signals, τ is the time delay. The operator $\langle \cdot \rangle$ represents the mean of a discrete time series.

Spectral Flatness (SF): SF is used to evaluate the power spectral quality of chaotic signals, which is defined as:

$$SF = \frac{\prod_{n=1}^{N_s} PS(f_n)^{1/N_s}}{\frac{1}{N_s} \sum_{n=1}^{N_s} PS(f_n)} \quad (4)$$

where N_s is the number of sampling points, $PS(f_n)$ represents the magnitude of the n -th discrete frequency components f_n in the power spectrum. SF ranges between 0 and 1, with values closer to 1 indicating a flatter power spectrum.

Delayed Mutual Information (DMI): to assess temporal correlations, we calculate the DMI as:

$$DMI(\Delta t) = \sum_{I(t), I(t+\Delta t)} p[I(t), I(t+\Delta t)] \log \frac{p[I(t), I(t+\Delta t)]}{p[I(t)] \cdot p[I(t+\Delta t)]} \quad (5)$$

where $p[I(t)]$ and $p[I(t+\Delta t)]$ represent the probability density function of $I(t)$ and its delay version, $p[I(t), I(t+\Delta t)]$ represents the joint probability density function of $I(t)$ and $I(t+\Delta t)$.

Permutation Entropy (PE): The dynamical complexity of the chaotic entropy source is evaluated via the normalized PE. For a given time series $\{x(t), t = 1, 2, \dots, N\}$, we consider an embedding dimension m and a delay time τ . The sequence is partitioned into $N - (m-1)\tau$ overlapping segments, each defined as:

$$X_j^m = \{x(j), x(j + \tau), \dots, x(j + (m-1)\tau)\} \quad (6)$$

each segment X_j^m is mapped onto an ordinal pattern (or permutation) π_i by sorting its elements in

ascending order. There are $m!$ possible unique permutations for a dimension m . the term p_i represents the relative frequency (probability) of the i -th permutation π_i occurring within the entire sequence, defined as:

$$p_i = \frac{\text{number of segments of type } \pi_i}{N - (m-1)\tau} \quad (7)$$

the Shannon entropy is then calculated based on the distribution of these probabilities:

$$H_{PE} = \frac{-\sum_{i=1}^{m!} p_i \ln p_i}{\ln(m!)} \quad (8)$$

we set $m = 5$ to capture the dynamical fluctuations while maintaining statistical reliability.

Autocorrelation Functions (ACF) and Bias: For the generated bitstream, the ACF is calculated to ensure bits are independent, which can be defined as:

$$\text{ACF}(\Delta t) = \frac{\langle (I(t) - \langle I(t) \rangle) (I(t - \Delta t) - \langle I(t - \Delta t) \rangle) \rangle}{\sqrt{\langle (I(t) - \langle I(t) \rangle)^2 \rangle \langle (I(t - \Delta t) - \langle I(t - \Delta t) \rangle)^2 \rangle}} \quad (9)$$

while the statistical bias ε_N is defined as:

$$\varepsilon_N = \left| \frac{1}{N} \sum_{i=1}^N b_i - 0.5 \right| \quad (10)$$

where $b_i \in \{0,1\}$ and N is the sequence length.

Offline and Real-time random bit generation

The offline post-processing workflow is as follow: the raw chaotic entropy source first undergoes a fourth-order derivative operation to achieve a symmetric, bias-free amplitude distribution. Each sampled point is quantized into a 16-bit sequence, from which the 12 least significant bits (LSBs) are retained. To eliminate residual correlations between adjacent samples, a bitwise exclusive-OR (XOR) operation is performed between the current 12-bit segment and its delayed version, yielding the final random bitstream.

Following photodetection, the RF chaotic signals are fed into a high-performance field-programmable gate array (FPGA, Xilinx Virtex UltraScale+ XC7VU13P) platform for real-time extraction. The signal digitization and high-throughput data transmission are facilitated by a high-speed analog-to-digital converter (ADC, AAD08S040G) operating in conjunction with a shared precision clock distribution system (LMX2820). To ensure the statistical integrity of the output, the on-board digital logic is specifically engineered to mitigate physical amplitude biases and suppress residual temporal correlations. The hardware-level implementation of the processing pipeline is detailed as follows:

1) **Series-parallel conversion.** The high-speed serial output from the ADC is first deserialized into a 1024-bit wide parallel data stream. This module operates at a clock frequency of 312.5 MHz, where each clock cycle processes 128 consecutive 8-bit samples to meet the requirements for high-throughput real-time processing.

2) **Digital de-biasing.** To eliminate intrinsic physical biases and achieve a zero-mean distribution, a delay line with a depth of 29,952 points is implemented. This provides a 748.8 ns temporal offset, allowing for point-by-point subtraction between the real-time data and its delayed counterpart.

3) **Temporal de-correlation.** Residual correlations are further suppressed through a bitwise exclusive-OR (XOR) operation. This step utilizes a secondary delay line of 109925 points, corresponding to a 2748.8 ns delay, to ensure that the statistical independence of the bitstream is maximized.

4) **Bit extraction and data compression.** To optimize randomness while maintaining high efficiency, the second-to-last bit is extracted from each 8-bit sample. This process effectively compresses the 1024-bit raw input into a 128-bit sequence per clock cycle.

5) **Channel partitioning and output.** The 128-bit bitstream is partitioned into four parallel 32-bit channels. Driven by the 312.5 MHz clock, each channel delivers a data rate of 10 Gbps, resulting in an aggregate real-time throughput of 40 Gbps that matches the system interface bandwidth.

For digital output and subsequent characterization, the FPGA-generated data was captured in real-time utilizing the integrated hardware debugging tools within the Vivado 2021 design environment. The raw hexadecimal packets acquired from the FPGA registers were serialized and formatted into a continuous binary bitstream. This bitstream constitutes the final output of the high-speed true RBG, which was then exported for rigorous statistical verification and randomness performance analysis.

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Author contributions

A.R.L. and Y.G. contributed equally to this work. N.J. and B.C.Y. conceived and supervised the project. A.R.L., H.N.X., and G.Q.C. carried out the experiments. Y.G. and Q.Z. provided technical guidance and contributed to the system design. L.L.W. fabricated and characterized the microresonators. A.R.L. and Y.J.F. performed the numerical simulations. A.R.L. and N.J. developed the FPGA-based real-time random bit generation system. All authors contributed to data analysis and

interpretation. K.Q. provided financial support for the project. A.R.L., Y.G., and Y.Q.Z. prepared the manuscript with input from all authors.

Competing interests

Authors declare that they have no competing interests.

Data and materials availability

All data are available in the main text or the supplementary materials.

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Main Figures and Captions

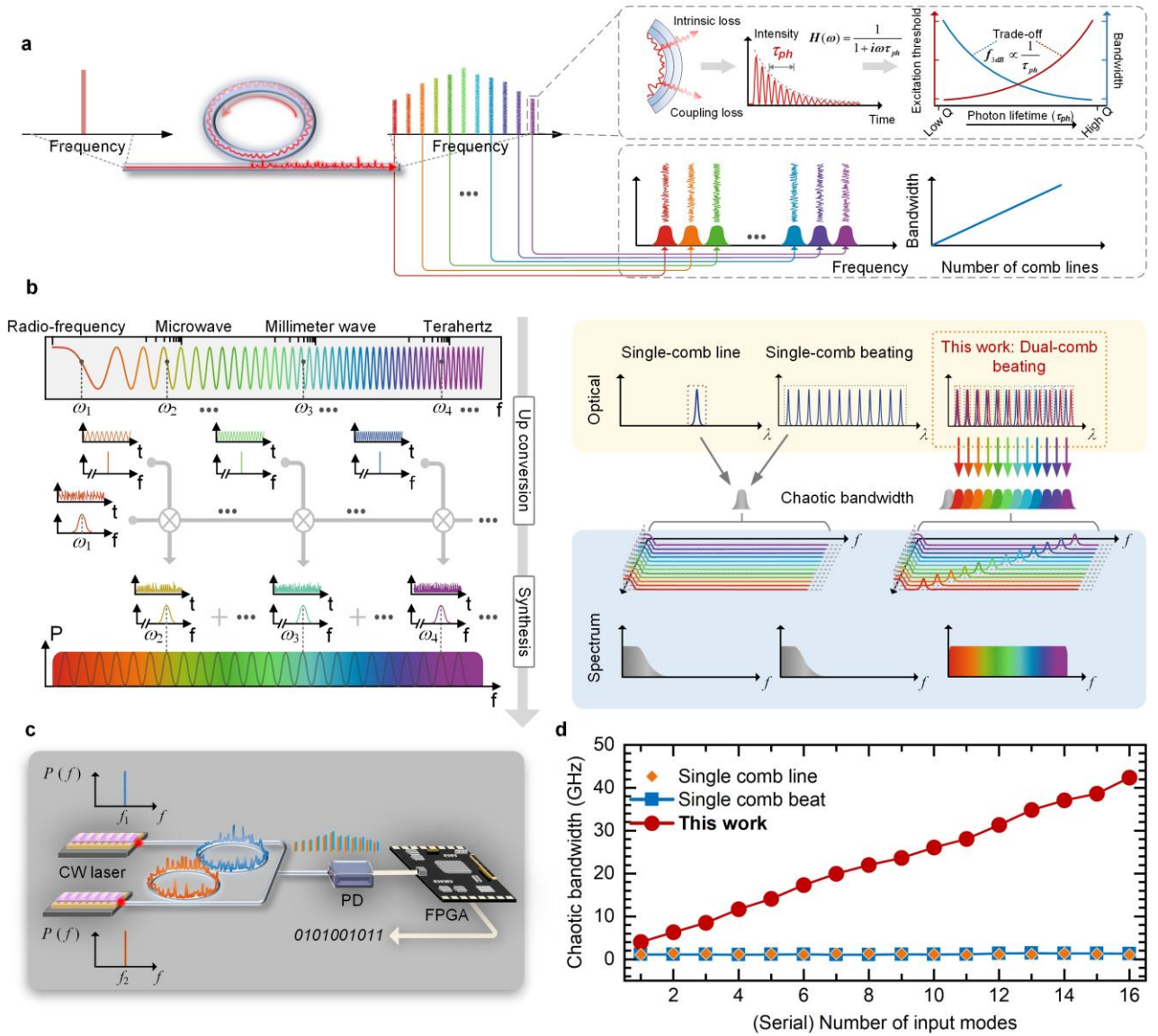


Fig. 1| Concept and architecture of broadband RF chaos synthesis with Vernier chaotic microcombs. a, Physical origin of the single-comb-tooth bandwidth bottleneck. In a Kerr microresonator (MR), the loaded cavity linewidth and photon lifetime set the response timescale of intracavity nonlinear dynamics. Increasing the photon lifetime lowers the nonlinear excitation threshold but narrows the cavity response bandwidth, limiting the chaotic bandwidth of each comb tooth. Distributed chaotic comb lines therefore provide spectral resources for bandwidth synthesis. **b,** Frequency translation and dual-comb synthesis. Bandwidth-limited chaotic spectral elements are translated to separated carrier frequencies and synthesized into a broadband chaotic waveform. The Vernier dual-comb implementation realizes this mapping optically and avoids the baseband crowding of single-comb self-beating. **c,** Experimental architecture. Two continuous-wave lasers pump co-integrated Si_3N_4 MRs to generate free-running chaotic microcombs with slightly detuned repetition rates. Their combined output is detected by a single photodetector, enabling parallel-to-serial reconstruction of distributed optical chaotic dynamics. **d,** Accessible chaotic bandwidth for single-comb-tooth detection, single-comb beating and Vernier dual-comb reconstruction, showing bandwidth scaling through RF-band synthesis.

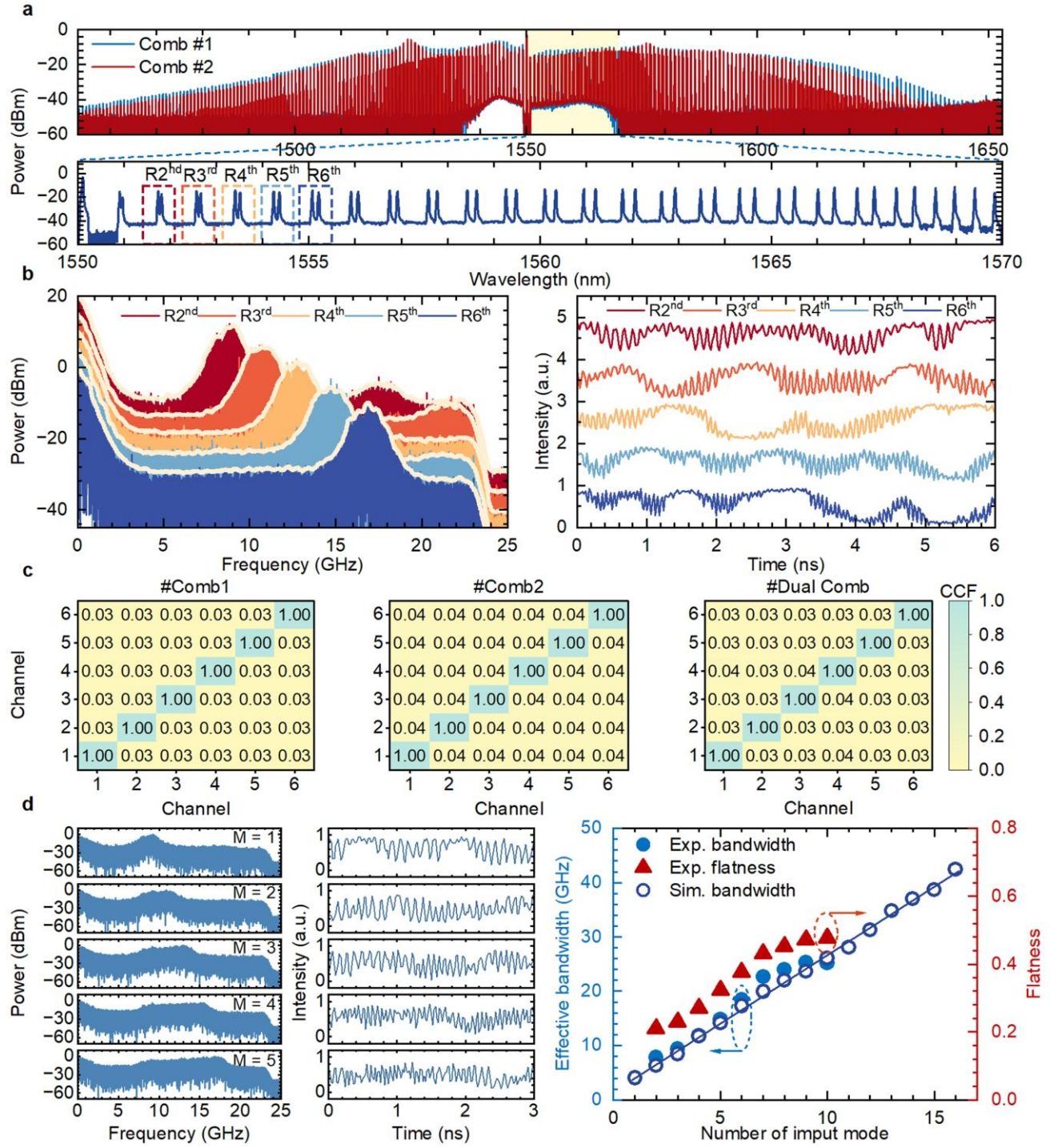


Fig. 2| Vernier multiheterodyne mapping of distributed optical chaos. **a**, Optical spectra of the two chaotic microcombs and the combined dual-comb state. The light-shaded region denotes the selected wavelength range from 1550 to 1570 nm. **b**, Representative dual-comb spectral segments with the corresponding down-converted RF spectra and temporal waveforms, showing Vernier frequency mapping with a repetition-rate detuning Δf_{rep} of 2.5 GHz. For visual clarity, the RF spectra and temporal traces are vertically offset by 5 dB and 1 a.u. per trace, respectively. **c**, Cross-correlation analysis of chaotic spectral elements in single-comb and dual-comb configurations, demonstrating the stochastic independence of the mapped RF channels. **d**, Evolution of RF spectrum and temporal waveforms as the number of mapped spectral-element pairs increases. The reconstructed RF chaotic bandwidth and spectral flatness increase with the number of multiplexed spectral elements, showing that broadband RF chaos can be synthesized from distributed optical chaotic channels through Vernier multiheterodyne mapping.

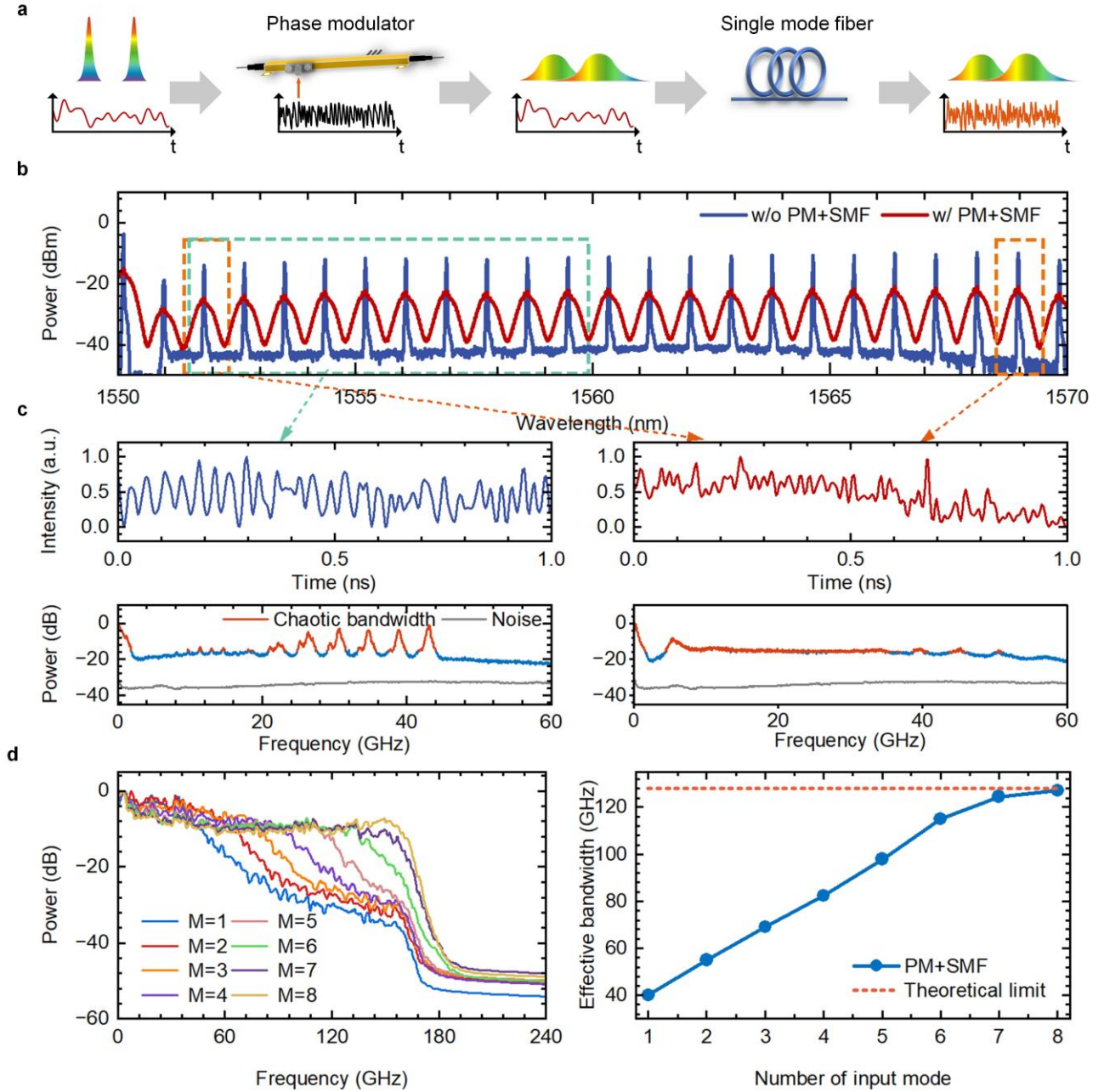


Fig. 3| Spectral broadening for efficient broadband RF chaos synthesis. **a**, Physical mechanism of chaotic spectral broadening. A phase modulator (PM) broadens the chaotic microcomb teeth, and subsequent propagation through a single-mode fibre (SMF) converts the induced phase fluctuations into intensity fluctuations. **b**, Optical spectra of the chaotic microcomb before and after spectral broadening, showing the increased spectral occupancy of individual comb teeth. **c**, Comparison of reconstructed RF chaotic waveforms generated using ten unbroadened spectral-element pairs and two spectrally broadened pairs. Spectral broadening increases the bandwidth contribution of each mapped spectral element, enabling RF chaotic bandwidths exceeding 40 GHz with substantially reduced spectral-resource consumption. **d**, Simulated scalability of the proposed architecture under enlarged detection bandwidth. Synthesized RF spectra are shown for increasing numbers of broadened spectral-element pairs, assuming a 160 GHz photodetector bandwidth and a 20 GHz repetition-rate detuning. The effective bandwidth approaches the device-limited ceiling of 128 GHz, suggesting a route towards ultra-broadband RF chaos synthesis.

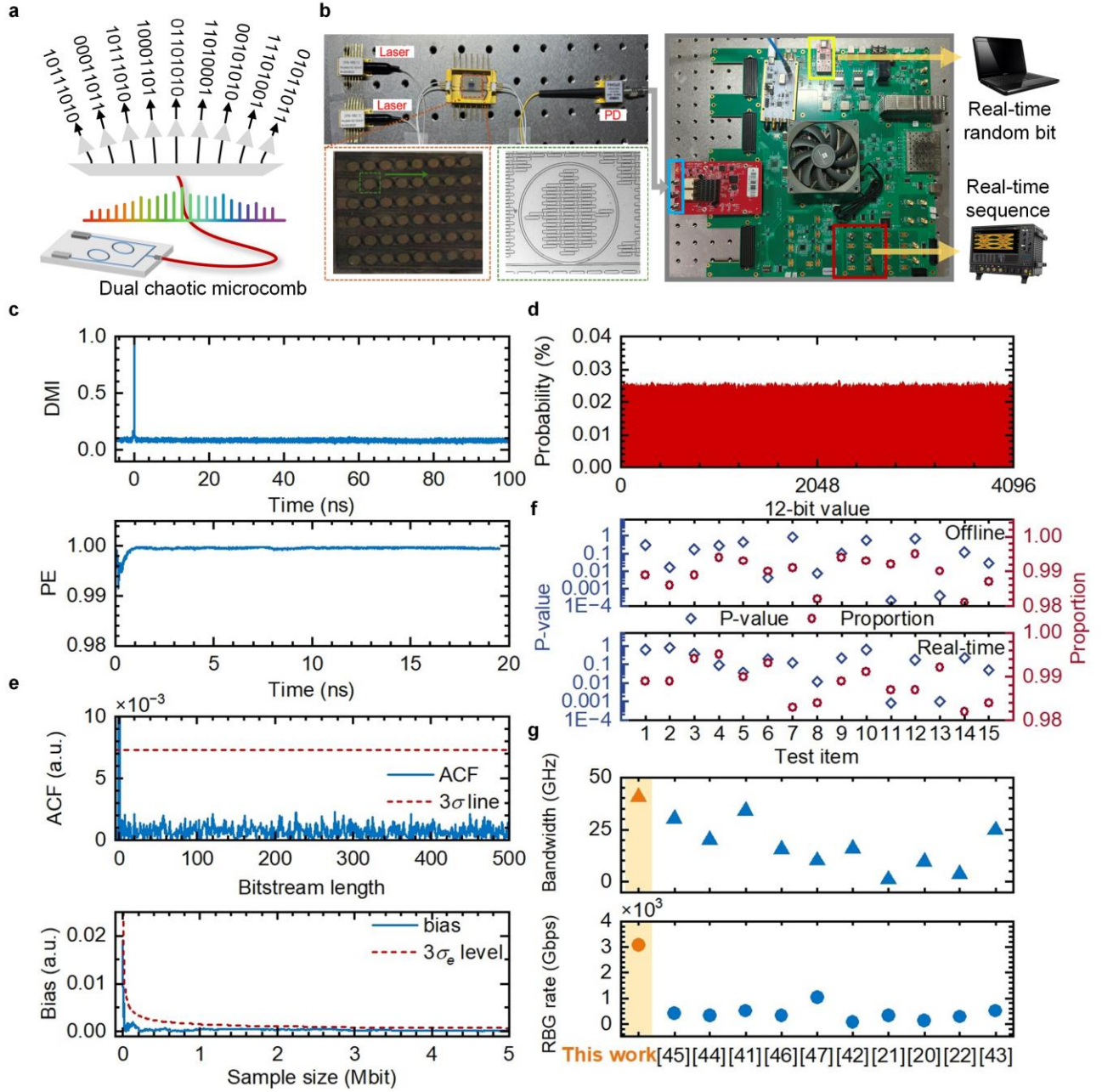


Fig. 4| Random-bit generation and performance benchmarking. **a**, Conceptual framework for random-bit generation (RBG) using the Vernier-reconstructed RF chaotic waveform. **b**, Main experimental hardware for real-time implementation. Representative optical and detection modules are shown for visual clarity, with the field-programmable gate array (FPGA) used for high-speed post-processing. **c**, Delayed mutual information (DMI) and permutation entropy (PE) of the reconstructed RF chaotic waveform. The absence of pronounced peaks in the DMI indicates no observable delay signature, whereas PE values exceeding 0.9995 indicate high temporal complexity. **d**, Symbol-distribution histogram under 12-bit analogue-to-digital quantization. The 4096 symbols show a nearly uniform probability distribution after post-processing. **e**, Autocorrelation function (ACF) and statistical bias of the generated random bit streams. The ACF and bias remain within their respective 3σ noise curve and the $3\sigma_e$ line, indicating negligible residual correlation and bias. **f**, NIST SP 800-22 statistical test results for the PC-based offline stream and the FPGA-based real-time output, corresponding to random-bit rates of 3.072 Tbps and 40 Gbps, respectively. The red dots and the blue dots represent the proportion and the P-value of the test items. **g**, Comparison of chaotic bandwidth and single-channel random-bit rate with representative chaos-based physical RBG schemes. The triangle represents the effective bandwidth, while the circle represents the RBG rate.

Table 1| Comparison with representative broadband chaotic/stochastic photonic platforms

Scheme	Effective bandwidth (GHz)	Offline random bit rate per channel (Gbps)
Chaotic semiconductor laser network ⁴⁴	~20 ^b	320
Array of 4 distributed feedback lasers ⁴⁵	>30 ^a	400
Self-chaotic microlaser ⁴¹	33.9 ^a	500
Weak-resonant-cavity F-P laser diode ⁴⁶	15.43 ^a	320
Cross-coupled laser ⁴⁷	~10 ^a	1040
Cascaded laser ⁴²	16 ^a	75
ASE noise of laser diode ⁴⁸	315 ^a	2000
Chaotic microcomb ²⁰	9.6 ^c	120
Chaotic microcomb ²¹	~1 ^a	320
AlGaAs microresonator ²²	3.7 ^a	280
This work	>40^a	3072
^a Effective bandwidth, defined as the width of spectral segment that accounts for 80% of the total power.		
^b The 90% bandwidth.		
^c 10dB bandwidth.		

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