

Programmable directional photonic spiking neuron based on a non-Hermitian silicon microresonator

Stefano Biasi*, Bülent Aslan, Stefano Gretter, Davide Olivieri, Alessandro Foradori, Riccardo Franchi and Lorenzo Pavesi

Citation: Biasi S, Aslan B, Gretter S et al. Programmable directional photonic spiking neuron based on a non-Hermitian silicon microresonator. *Opto-Electron Sci* **5**, 260038 (2026).

<https://doi.org/10.29026/oes.2026.260038>

Received: 24 June 2026; Accepted: 14 August 2026; Published online: 26 August 2026

Related articles

Integrated photonic synapses, neurons, memristors, and neural networks for photonic neuromorphic computing

Shufei Han, Weihong Shen, Min Gu, et al

Opto-Electronic Technology 2025, **1**(3): 250011 doi: [10.29026/oet.2025.250011](https://doi.org/10.29026/oet.2025.250011)

All-optical digital logic and neuromorphic computing based on multi-wavelength auxiliary and competition in a single microring resonator

Qiang Zhang, Yingjun Fang, Ning Jiang, et al

Opto-Electronic Science 2025, **4**(11): 250003 doi: [10.29026/oes.2025.250003](https://doi.org/10.29026/oes.2025.250003)

Photonic neuromorphic computing: from device classification to system reality

Lorenzo Pavesi

Opto-Electronic Advances 2026, **9**(8): 260199 doi: [10.29026/oea.2026.260199](https://doi.org/10.29026/oea.2026.260199)

Photonic spiking reinforcement learning for intelligent routing

Shuiying Xiang, Yonghang Chen, Ling Zheng, et al

Opto-Electronic Science 2026, **5**(5): 260005 doi: [10.29026/oes.2026.260005](https://doi.org/10.29026/oes.2026.260005)

More related articles in Opto-Electronic Journals Group website



Programmable directional photonic spiking neuron based on a non-Hermitian silicon microresonator

Stefano Biasi^{*†}, Bülent Aslan[†], Stefano Gretter, Davide Olivieri, Alessandro Foradori, Riccardo Franchi and Lorenzo Pavesi

Abstract: Traditional computing architectures are increasingly constrained by the “Von Neumann bottleneck”, motivating energy-efficient, brain-inspired neuromorphic systems. Silicon photonic microresonators can emulate key neuronal dynamics such as spiking and excitability. However, in reciprocal microresonators, forward spike emission and backward signals are intrinsically linked, limiting independent control of directionality, feedback and inter-node back-action. Here, we overcome this limitation by exploiting engineered intermodal coupling in non-Hermitian photonic resonators to realize directional excitability in all-optical neurons. First, we show that Taiji microresonators exhibit direction-dependent self-pulsing thresholds, enabling a single device to act as a spiking neuron in one direction while remaining quiescent in the opposite. Then, we introduce the dynamically reconfigurable unified microresonator (DRUM), which enables electrical control of intermodal coupling amplitude and phase. This allows independent control of forward spike emission and backward signals, suppression or enhancement of back-propagation, and active tuning of neuronal properties. We experimentally demonstrate directional spiking asymmetry alongside tunability of temporal integration and refractory period, establishing DRUM as a programmable photonic spiking neuron. Finally, network-level simulations show that controlled back-action can mediate synaptic-like behavior, including inhibition and synchronization. These results identify reconfigurable non-Hermitian silicon microresonators as promising building blocks for photonic spiking nodes with programmable directionality, back-action, and temporal response.

Keywords: neuromorphic photonics; microring resonator; non-Hermitian system; integrated photonics

DOI: [10.29026/oes.2026.260038](https://doi.org/10.29026/oes.2026.260038) | CSTR: [32246.14.oes.2026.260038](https://cstr.net/urn:nbn:de:hebis:3:5-64701-p0001-9)

Citation: Biasi S, Aslan B, Gretter S et al. Programmable directional photonic spiking neuron based on a non-Hermitian silicon microresonator. *Opto-Electron Sci* **5**, 260038 (2026).

1 Introduction

Von Neumann computing systems are inherently limited by the physical separation between processing (CPU) and memory units, giving rise to the well-known “Von Neumann bottleneck” that restricts both computational speed and energy efficiency¹. These limitations have motivated the development of alternative computing paradigms, particularly neuromorphic systems inspired by biological neural processing^{2,3}. In these architectures, computation and memory are co-located, mimicking the structure of biological

neural networks through artificial neurons and synapses, where information is encoded not only in binary states but also in the timing of discrete events, or “spikes”⁴. Spiking neural networks (SNNs) naturally arise from this paradigm, leveraging event-driven computation to achieve high energy efficiency, intrinsic parallelism, and enhanced computational scalability^{5–7}.

The behavior of a single neuron plays a fundamental role in SNNs, as network-level dynamics emerge from the collective interactions among individual spiking elements. Owing

Received: 24 June 2026

Accepted: 14 August 2026

Published online: 26 August 2026

Nanoscience Laboratory, Department of Physics, University of Trento, Trento 38123, Italy.

B Aslan. Present address: Nanoboyut Research Laboratory, Department of Physics, Eskişehir Technical University, Eskişehir 26470, Türkiye;

R Franchi. Present address: Nanomaterials & Nanostructure Optics, Department of Electrical and Computer Engineering, Boston University, Boston, Massachusetts 02215, USA.

[†]These authors contributed equally to this work.

^{*}Correspondence: S Biasi, E-mail: stefano.biasi@unitn.it

to their rich nonlinear and temporal processing capabilities, single-neuron models constitute the fundamental computational building blocks of neuromorphic systems⁸. Furthermore, precise control over the intrinsic properties of individual neurons—such as firing threshold, temporal response, and refractory periods—plays a key role in shaping network-level computation and facilitating learning in SNNs. Significant effort has been devoted to implementing artificial spiking neurons in both hybrid electro-optical and fully optical platforms⁹. Hybrid implementations, in which optical signals are interfaced with electronic control and readout, are explored due to their flexibility and compatibility with mature technological systems^{10,11}. Fully optical realizations are attracting growing interest, as neuronal dynamics and signal processing are performed entirely in the optical domain, often exploiting laser-based systems^{12–15} or integrated photonic nonlinearities to emulate spiking behavior¹⁶. Such approaches aim to minimize electro-optical conversion while enabling ultrafast operation and scalable neuromorphic architectures.

Passive photonic microresonators (MRs) have successfully demonstrated key neuronal behaviors—including excitability, refractory periods, spike-timing dynamics, and bursting^{16–18}—through the exploitation of thermal and free-carrier nonlinearities¹⁹. These demonstrations establish MRs as viable building blocks for photonic SNNs²⁰. However, a critical limitation remains: conventional MRs obey Lorentz reciprocity (i.e., they respond identically to forward and reverse excitation)²¹. This is in contrast to biological neurons, where action potentials propagate unidirectionally from dendrites to axon terminals and backward propagation is often inherently suppressed, preventing destabilizing feedback loops and enabling hierarchical information processing²². Here, backward propagation refers to the intrinsic backward response of a neuron not to the backward propagation of errors in ML algorithms²³. Achieving directional excitability in photonic neurons—where the device remains quiescent when excited from one direction yet becomes a spiking neuron when driven from the opposite direction—therefore represents a missing primitive for biologically plausible neuromorphic systems. More generally, in reciprocal photonic platforms, backward responses are intrinsically linked to forward excitation and cannot be independently controlled. Enabling the decoupling of forward spike emission from backward signals would allow the suppression or engineering of back-action, providing a closer analogy to biological neurons, where backward propagation is regulated rather than absent²⁴. Despite these challenges, the realization of such functionalities is critical for scalable photonic SNNs, where controlled signal directionality can mitigate crosstalk and stabilize network dynamics.

Recent research has explored nonreciprocity using non-Hermitian and PT-symmetric photonic structures, typically relying on active gain or complex bias control to break

symmetry^{25,26}. While successful in nonreciprocal continuous-wave (CW) transmission, these approaches often increase power consumption and integration complexity. By contrast, geometric design can intrinsically enforce non-Hermitian mode coupling between counterpropagating modes, offering a passive path to functional nonreciprocity^{27–31}. In the typical coupled-mode description, the clockwise and counterclockwise resonator modes are connected through the following effective Hamiltonian, which captures their mutual interaction and non-Hermitian dynamics²⁷:

$$\mathbf{H} = \begin{pmatrix} \omega_0 - i\gamma & -i\beta_{21} \\ -i\beta_{12} & \omega_0 - i\gamma \end{pmatrix}, \quad (1)$$

where ω_0 is the mode resonance angular frequency, γ is the loss rate, β_{12} and β_{21} are the intermodal coupling coefficients representing the energy transfer from clockwise mode (α_1) to counterclockwise mode (α_2) and vice versa. It is important to note that these generalized coupling coefficients are complex numbers; such that $\beta_{ij} = |\beta_{ij}|e^{-i\phi_{ij}}$. The nonreciprocity was achieved in our previous work where we showed that a Taiji MR exhibits nonlinearity-induced reciprocity breaking in CW transmission³². A Taiji MR is a microring resonator with an embedded S-shaped waveguide that induces asymmetric (non-Hermitian) intermodal coupling coefficients between the clockwise and counterclockwise optical modes (see top-central panel of Fig. 1), typically characterized by $|\beta_{12}| \gg |\beta_{21}|$ or vice versa^{33–35}. The Taiji MR exhibits direction-dependent intracavity energy storage, which in turn gives rise to direction-dependent nonlinear effects. Crucially, this nonreciprocity is absent in the linear (low-power) regime, where the device behaves reciprocally, and emerges only when nonlinear effects become significant³². The exploration of non-Hermitian-inspired photonic physics introduces new degrees of freedom for controlling dynamical responses, enabling functionality beyond static transmission asymmetry toward active, directional control of spike generation.

In this work, we leverage these non-Hermitian principles to map controllable intermodal coupling into programmable spiking-neuron dynamics. We first establish the principle of directional excitability using a geometry-defined intermodal coupling as in a Taiji MR (Section 2.1). Indeed, drawing inspiration from biological neurons, which receive stimuli through dendrites and propagate signals along the axon upon firing (Fig. 1, top-left), we demonstrate that silicon photonic microresonators can emulate a rich repertoire of neuronal behaviors. The key insight is that the same asymmetric intracavity energy storage that breaks reciprocity in CW transmission also creates direction-dependent thresholds for the onset of self-pulsing (SP) instabilities, which convert a CW input into a pulsed output^{36,37}. This gives rise to a qualitative difference in dynamical response: excitation from one direction (e.g., from port-1 in the upper inset of

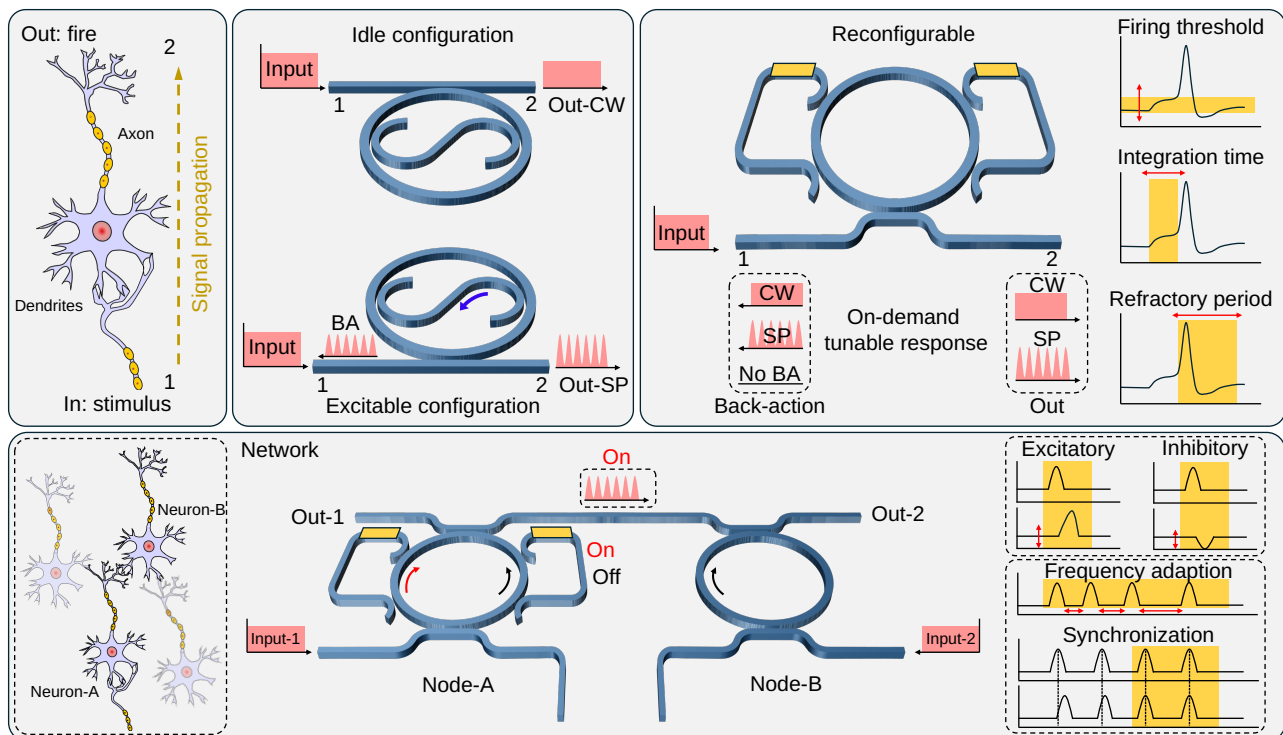


Fig. 1 | Schematic representation of a biological neuron (top-left) alongside the silicon integrated photonic devices studied in this work – the Taiji MR (top-center) and DRUM (top-right) – which emulate a wide range of neuronal response behaviors. Ports 1 and 2 denote the left and right terminals, each of which can serve as either input or output. Throughout this figure, the input and output fields are taken at ports 1 and 2, respectively, such that the primary propagation direction is from port-1 to port-2. SP, CW, and BA denote self-pulsing, continuous-wave, and structure-mediated back-action signal, respectively. In the *idle configuration*, no light is coupled into the S-shaped waveguide of an ideal Taiji MR, resulting in no BA and no modification in the form of the input field. In the *excitable configuration*, light couples into the S-shaped waveguide, and the resulting field enhancement within the microresonator drives it into SP. The SP signal then propagates in both directions along the bus waveguide. The DRUM architecture introduces reconfigurability: each side lobe waveguide enables independent control over both the amplitude and phase of the coupling between the clockwise and counterclockwise modes within the MR (see main text for details). This reconfigurability allows the output response of the device to be tailored; for a given CW input field, DRUM can produce either a CW or SP response at both ports 1 and 2, or exhibit unidirectional behavior. DRUM's on-demand tunable response enables emulation of a wide range of neuronal behaviors within a single device, with independently controllable firing threshold, integration time, and refractory period, as schematically illustrated in the rightmost panel of the figure. The lower panel illustrates a possible interconnection scheme for integrating these devices into a larger photonic neural network: DRUM enables such a network to reproduce excitatory and inhibitory neuronal behaviors, as well as frequency adaptation and synchronization.

Fig. 1 (top-center)), where the S-shaped waveguide does not couple light into the counterpropagating mode, yields a CW transmission up to a high input power threshold. We refer to this as the *idle configuration*, in which the Taiji MR remains quiescent with respect to SP. Excitation from the opposite direction, however—where the S-shaped waveguide actively couples light into the counterpropagating mode—triggers periodic optical spikes at low powers, yielding an SP threshold asymmetry. We refer to this as the *excitable configuration* (e.g., from port-1 in the lower inset of Fig. 1 (top-center)). These SP dynamics serve as the functional optical analogue of biological tonic spiking, which occurs in neurons under continuous excitation⁸.

To overcome the static constraints of geometry, we then introduce and experimentally characterize the DRUM (Dynamically Reconfigurable Unified Microresonator)³⁸

(Section 2.2). In fact, while the Taiji MR establishes the principle of directional excitability, it is limited to a single, fixed configuration determined by its geometry. A further practical limitation of conventional microresonators is the inevitable backscattering induced by surface roughness, which introduces uncontrolled coupling between the clockwise and counterclockwise modes and can significantly distort the intended device response^{39–41}. Moreover, the structure-mediated back-action signal (BA) is not independently regulated in the Taiji MR but is instead constrained by the device geometry. To overcome these limitations, the DRUM generalizes the Taiji MR and replaces the static S-shaped waveguide with two independently controllable side lobe circuits, each incorporating a Mach-Zehnder interferometer and a phase shifter. This architecture enables full, on-demand reconfiguration of the intermodal coupling,

allowing continuous and arbitrary control over both the amplitude and phase of the intermodal coupling coefficients (β_{ij}), as well as coherent suppression of spurious backscattering to restore the desired coupling state³⁸. As a result, the DRUM can not only reproduce the directional excitability of the Taiji MR in its excitable configuration, but can also be tuned into qualitatively distinct dynamical regimes within a single device (see Section 2.3). When neither lobe couples light into the counterpropagating mode, the device is similarly referred to as being in the idle configuration, remaining quiescent with respect to SP up to high input powers. Conversely, when both lobes are active and each mode is coupled into its counterpropagating counterpart, the device operates in the *sensitized configuration*. In this regime, the enhanced intracavity energy exchange increases the device's sensitivity to SP onset. This reconfigurability translates directly into control over key neuronal response parameters: the firing threshold, integration time, and refractory period, as schematically shown in Fig. 1 (top-right) and discussed in Section 2.4 and 2.5.

Finally, we theoretically investigate how these programmable units can support collective dynamics in coupled photonic spiking nodes (Fig. 1 bottom and Section 3.2). In such a network, Node-A (a DRUM device) receives an input at port-1, while Node-B (a simple MR) receives another input at port-2. The BA from Node-A, schematically depicted above the waveguide connecting the two MRs, mediates the coupling between the two nodes, enabling the network to reproduce fundamental neural network behaviors including excitatory and inhibitory responses, frequency adaptation, and synchronization.

2 Results

2.1 Directional excitability: Taiji microresonator

We first characterize a Taiji MR in the linear regime where the input powers are low ($P_{in} < 0.5$ mW), hence the free-carrier and thermo-optic effects are negligible. When excited from port-1 (see Fig. 1, top-center), the Taiji MR operates in its idle configuration, behaving as a simple MR in which only the clockwise mode is directly excited. The transmission spectrum consequently exhibits the characteristic Lorentzian lineshape while no reflection signal is generated⁴². The experimental spectral responses are shown in Fig. 2(a1) as a function of wavelength detuning $\Delta\lambda$, defined as the difference between the input laser wavelength and the cold microresonator's resonant wavelength. The presented resonance appears at $\lambda_0 \approx 1550.3$ nm with a loaded quality factor $Q_L \approx 5.3 \times 10^3$. Notice that the transmission and reflection spectra in Fig. 2 are shown with black and red lines, respectively. When the same Taiji MR is instead excited from port-2, it operates in its excitable configuration. In this case, the input light also enters the S-shaped waveguide and couples back into the microresonator, exciting both the clockwise and counterclockwise modes. The transmission spectrum retains its Lorentzian lineshape, but is now accompanied by a non-zero reflection signal, as shown in Fig. 2(b1). As expected from the Lorentz reciprocity theorem, the transmission spectra are similar in both configurations, while the reflection is strongly direction-dependent, establishing the Taiji microresonator as a passive, integrated unidirectional reflector³³. The broad oscillations observed in the reflection spectra, particularly in

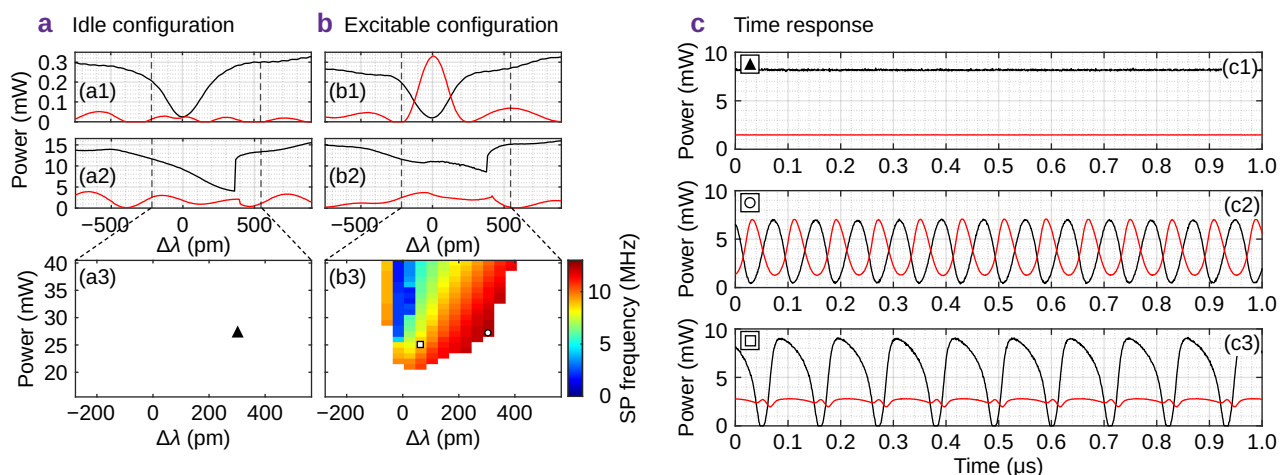


Fig. 2 | Experimental measurements for a Taiji MR in its (a) *idle configuration* and (b) *excitable configuration*. Spectral responses as a function of wavelength detuning $\Delta\lambda$, defined as the difference between the input laser wavelength and the cold microresonator's resonant wavelength, are shown in both the linear (a1, b1) and nonlinear (a2, b2) regimes. The color maps (a3, b3) display the SP frequency as a function of wavelength detuning and coupled laser power. Since the idle configuration exhibits no SP, it is represented by a white background. The color scale for the SP frequency is shown on the right. SP is observed above a threshold of about 20 mW in the excitable direction and is absent up to 40 mW in the idle direction. Temporal traces of the transmission (black lines) and reflection (red lines) signals are shown in (c) time response panel, corresponding to the states marked in (a3) and (b3) by filled triangle, circle, and square markers.

the off-resonance regions, are caused by Fabry–Perot oscillations in the bus waveguide between the coupling gratings at port-1 and port-2.

When the input power is increased to the nonlinear regime, the dynamics are governed by light-matter interactions dominated by two-photon absorption (TPA)⁴³. TPA generates free carriers (ΔN), whose relaxation produces a localized temperature increase (ΔT), shifting the effective resonance frequency of the microresonator. In this regime, both the transmission and reflection spectra are modified and the forward and backward nonlinear responses are no longer identical under the same operating conditions³². In its idle configuration, the Taiji MR exhibits the typical nonlinear response of a simple MR, with the characteristic triangular lineshape shown in Fig. 2(a2). The free-carrier and thermal relaxation processes operate on distinctly different timescales and their interplay can give rise to self-sustained oscillations, i.e., SP^{44,45}. Throughout the measured input power range of up to 40 mW, the transmitted signal shows no evidence of SP, appearing as a constant CW signal at all times, as shown in the SP frequency map of Fig. 2(a3) and the temporal trace of Fig. 2(c1) that corresponds to the point marked with a triangle in Fig. 2(a3). The SP frequency map displays the SP oscillation frequency as a function of wavelength detuning and input power. Frequency values are extracted from the dominant component of the Fourier transform of the time-domain optical transmission, and color-coded according to the scale shown on the right side of the panel; white regions correspond to steady states without oscillations. The absence of any colored region in Fig. 2(a3) confirms that the maximum optical power reached in the experiment is insufficient to trigger an SP response in the idle configuration.

In stark contrast, excitation from port-2, the excitable configuration, produces a markedly different response. The transmission spectrum (Fig. 2(b2)) differs noticeably from that of the idle configuration (Fig. 2(a2)), exhibiting spectral irregularities in the detuning range of approximately -40 to 360 pm due to the presence of SP. Note that both spectra (given in Fig. 2(a2) and 2(b2)) are collected under the same input optical power of 40 mW. As the input power exceeds $\simeq 20$ mW, the transmitted signal spontaneously transitions into an SP regime, as captured in the SP frequency map of Fig. 2(b3). It is worth noting that in this configuration, the light recirculated through the S-shaped waveguide enhances the intracavity energy storage sufficiently to trigger SP at a given input power. In contrast, in the idle configuration, the field coupled into the S-shaped waveguide is radiated away at its ends rather than being recirculated, resulting in no extra energy accumulation and consequently no SP. The SP onset occurs abruptly at a finite frequency of a few MHz – a characteristic signature of a Class II excitability⁴⁶ – and yields regular pulse trains with repetition frequencies ranging from 3 to 16 MHz, depending on the wavelength detuning. The continuous region of stable pulsing in Fig. 2(b3)

demonstrates that directional excitability persists over a broad range of input powers and detunings, suggesting that the functionality is tolerant to variations in operating conditions.

Temporal traces of the transmission and reflection signals for two representative operating points—marked by a circle and a square in Fig. 2(b3)—are shown in Fig. 2(c2) and 2(c3), respectively. At the circle point, a maximum SP frequency of ~ 12.4 MHz is observed with comparable power in both transmission and reflection. At the square point, a slower SP regime at ~ 8.9 MHz is observed, with SP predominantly in the transmission while the reflection remains nearly constant. Notably, the Taiji MR in its excitable configuration can support multiple SP states depending on the input laser frequency and power, similar to the behavior reported for a simple MR of a much smaller diameter³⁷.

2.2 On-demand directionality with DRUM

Having established directional excitability in the Taiji MR, we now demonstrate how DRUM extends this concept through full reconfigurability of the intermodal coupling. Figure 3 summarizes the three distinct configured states of a single DRUM device and their corresponding SP signatures. In the excitable configuration, the left lobe is deactivated ($|\beta_{12}| \ll |\beta_{21}|$) while the right lobe recirculates light from the counterclockwise mode (α_2) back into the MR as the clockwise mode (α_1). This increases the total intracavity energy for a given input power, lowering the effective SP threshold. The linear spectral response (Fig. 3(b), top) shows a non-zero reflection alongside a regular transmission profile, consistent with the asymmetric intermodal coupling. The experimental results for the DRUM device presented in this study were obtained for a cold resonance at $\lambda_0 \approx 1539.1$ nm. At $P_{\text{in}} \approx 61$ mW, SP is observed over a range of wavelength detunings, with frequencies reaching up to ~ 8.3 MHz and decreasing with increasing $\Delta\lambda$ (Fig. 3(c), red squares). When the right lobe is deactivated ($|\beta_{21}| \ll |\beta_{12}|$), however, only the counterclockwise mode circulates within the MR regardless of the left lobe's state, resulting in no extra energy accumulation. This is because the field coupled into the deactivated lobe is radiated away as loss rather than being recirculated back into the microresonator. The linear spectral response (Fig. 3(b), middle) shows a transmission profile similar to that of the excitable configuration, yet with negligible reflection. Consistent with this, no SP is observed at any wavelength detuning at the same input power of $P_{\text{in}} \approx 61$ mW (Fig. 3(c), blue triangle), confirming that the idle configuration effectively suppresses the SP instability.

In the default state of DRUM, no current is supplied to the micro-heaters in the lobes, resulting in a reciprocal intermodal coupling between the two counterpropagating modes of the MR ($|\beta_{12}| \approx |\beta_{21}| \neq 0$)³⁸. This bidirectional energy exchange further enhances the intracavity energy

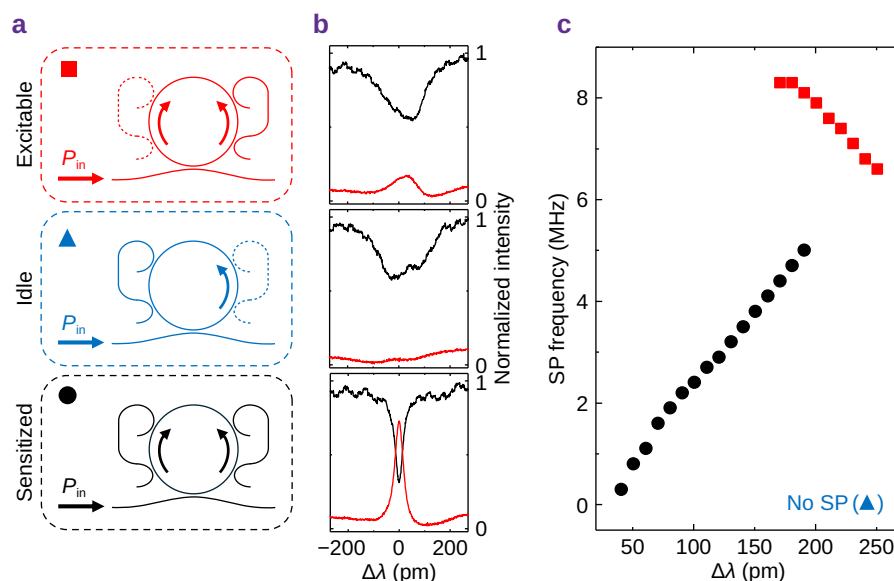


Fig. 3 | Three configured states of DRUM and their SP signatures. (a) Schematic representation of three distinct configured states of DRUM. Dashed lines indicate deactivated lobes. For a given input from the left port, in the *excitable configuration* (top), the left lobe is deactivated while the right lobe recirculates light from the counterclockwise mode back into the microresonator as the clockwise mode, causing an increase in the total energy stored within the microresonator. In the *idle configuration* (middle), the right lobe is deactivated. Regardless of the left lobe's state, only the counterclockwise mode circulates within the microresonator, resulting in no extra energy accumulation. In the *sensitized configuration* (bottom), both lobes are active, enabling recirculation of light between the counterclockwise and clockwise modes, and vice versa. Consequently, the energy accumulation within the microresonator is enhanced for the same input optical power. (b) Experimentally measured spectral responses as a function of wavelength detuning in the linear regime for the three configured states of DRUM shown in (a). Black and red lines correspond to the transmission and reflection signals, respectively. (c) Experimentally obtained SP frequency as a function of wavelength detuning for the three configured states of DRUM, for an input optical power of $P_{in} \approx 61$ mW. The idle configuration exhibits no SP at any wavelength detuning, as indicated. The same markers (both color and shape) as in (a) are used to identify the corresponding configured states.

accumulation compared to the excitable configuration, for the same input optical power. We then refer to this as the *sensitized configuration* (Fig. 3(a), bottom). The linear spectral response of this configuration exhibits a single Lorentzian-shaped spectrum with the smallest full width at half maximum value and with a pronounced reflection peak as presented in Fig. 3(b)-bottom. At the same input power of $P_{in} \approx 61$ mW, SP is observed at lower and broader wavelength detunings compared to the excitable configuration, with frequencies increasing gradually and approximately linearly from ~ 0.3 to ~ 5.0 MHz (Fig. 3(c), black circles), consistent with a lower effective SP threshold. Note that the DRUM demonstrates robustness against thermal crosstalk as a result of trenches on both sides of each micro-heater; therefore, switching the operating configuration introduces negligible resonance shifts⁴⁷.

Taken together, these three configurations demonstrate that DRUM can continuously transition between a non-spiking state, a moderately excitable state, and a highly sensitized spiking state—all within the same device and without any geometric modification. This on-demand tunability of the SP response, achieved here simply by switching the lobes between their fully active and fully deactivated states, already represents a key advance over the fixed

directional excitability of the Taiji MR. The broader reconfigurability of DRUM through the control of the phase of the intermodal coupling coefficients (in short coupling phase) will be explored in the following section, where we demonstrate an even richer repertoire of neuronal response behaviors.

2.3 Tuning the self-pulsing onset (firing threshold) in DRUM

Having demonstrated that DRUM can switch between qualitatively distinct dynamical regimes through binary lobe activation, we now explore its reconfigurability by tuning the coupling phase ϕ_{12} (phase shifter of the left-side lobe (PSL))^{38,47}. This allows fine control over the intermodal coupling conditions and, as we show, directly translates into a tunable SP firing threshold, a key neuronal response parameter.

Figure 4 presents the experimental characterization of the phase-dependent SP threshold in DRUM operating in its default sensitized configuration. The SP frequency map in Fig. 4(a) reveals that the SP region shifts significantly in both wavelength detuning and extent as ϕ_{12} is varied from 0 to 2π , at a fixed input power of $P_{in} \approx 32$ mW. This

demonstrates that the phase provides a powerful handle on the SP dynamics, independently of the input power. Experimentally, the phase scan is obtained by varying only the current applied to PSL. Note that the laser was turned off and on between successive phase points and during input wavelength tuning. Further details on the phase control mechanism and the associated non-Markovian hysteresis in the nonlinear regime are reported elsewhere⁴⁷.

To quantify this phase dependence, three representative phase values—marked by blue dashed lines with geometric markers (square, circle, and triangle) in Fig. 4(a)—are selected for a more detailed analysis. For each phase value, the SP frequency map as a function of wavelength detuning and input power is shown in Fig. 4(b), alongside the corresponding linear spectral response for reference. The SP maps reveal that both the minimum input power required to trigger SP and the detuning range over which SP is observed vary considerably across the three phase values, confirming that the coupling phase directly controls the SP threshold. This is further quantified in Fig. 4(c), which shows the mini-

mum input optical power at which SP is observed as a function of ϕ_{12} . The SP threshold increases monotonically as ϕ_{12} approaches π from both directions, reaching its highest values just below and above π : specifically, 27.8 mW at $\phi_{12} = 0.93\pi$ and 29.4 mW at $\phi_{12} = 1.15\pi$. Near $\phi_{12} = \pi$, no SP is detected up to the maximum input power of 32 mW used in this experiment. In fact, the gray shaded region in Fig. 4(c) denotes the range of input optical power for which no SP is detected. This defines a phase-dependent power floor below which the device remains quiescent in relation to the phase setting. Above this floor, SP is not immediately observed at all the phases—rather, for a given input power, there exists a phase window centered around π within which the device remains quiescent. This quiescent window narrows progressively as the input power increases, until SP becomes accessible across the full phase range at sufficiently high powers. This behavior can be understood from the linear spectral response at $\phi_{12} \approx \pi$, which exhibits a nearly perfectly balanced doublet splitting (see Fig. 4(b)—bottom obtained at $\phi_{12} = 0.93\pi$ as a reference). This is a hallmark of

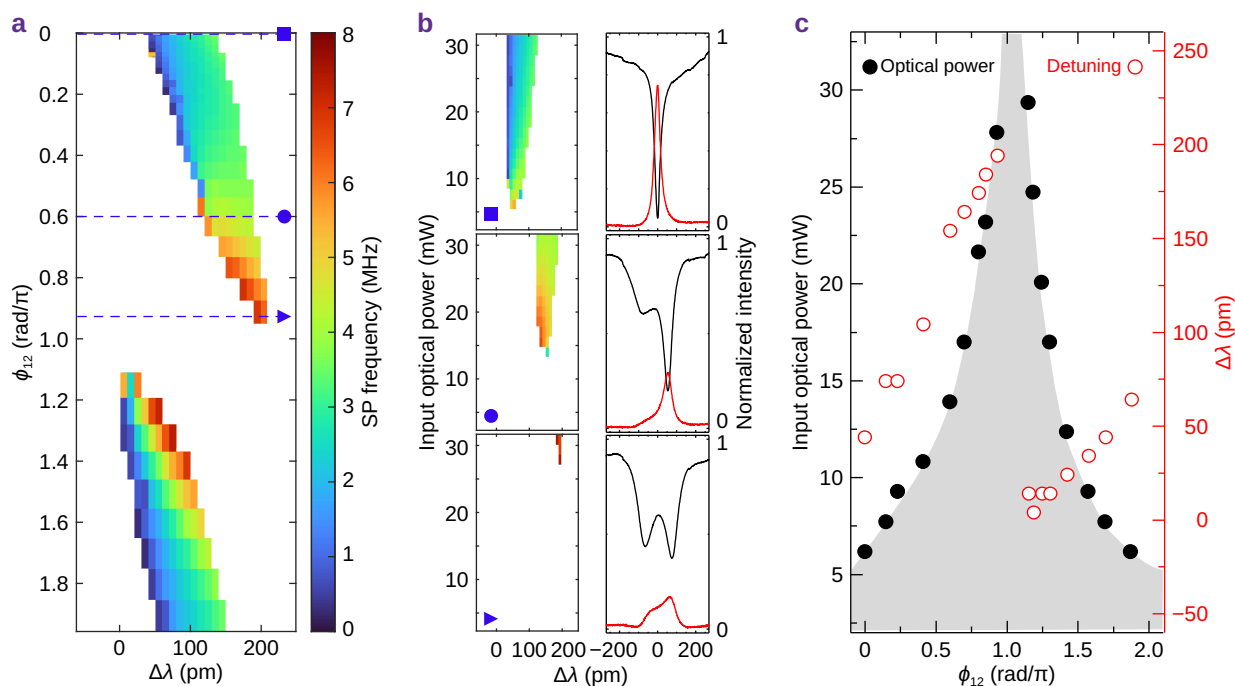


Fig. 4 | Experimental investigation of the tunable SP threshold in DRUM. (a) Experimentally obtained SP frequency map for DRUM in its default state (the *sensitized configuration*) as a function of wavelength detuning and phase ϕ_{12} , for an input optical power of $P_{in} \approx 32$ mW. The color scale for the SP frequency is shown on the right. Three representative phase values, marked by blue dashed lines with geometric markers (square, circle, and triangle), are selected for further analysis in (b). (b) SP frequency maps as a function of wavelength detuning and input optical power for three representative phase values marked in (a), identified by the corresponding geometric markers. The corresponding spectral responses in the linear regime, measured at the selected phase values, are provided in the right column as reference. (c) Minimum input optical power at which SP is observed, as a function of phase. The gray shaded region denotes the range of input optical power for which no SP is detected. The right axis shows the wavelength detuning corresponding to the minimum input optical power at which SP is observed. Error bars are omitted for clarity, as they are identical for all data points. The experimental uncertainty is estimated to be ± 250 μ W in the input optical power, mainly due to fiber-to-chip coupling variations, and ± 16 pm in the wavelength detuning, corresponding to the maximum uncertainty associated with tuning the integrated phase shifters of the lobes.

the Hermitian coupling condition where the counterclockwise and clockwise modes exchange energy symmetrically, with no preferred mode dominating the intracavity dynamics. Comprehensive analysis of the spectral lineshape and resonance splitting in the linear regime and their control by the coupling phase are reported elsewhere³⁸. As a result, neither mode accumulates sufficient energy to trigger SP at the available input power. Nevertheless, SP can still be induced at this phase by increasing the input power sufficiently; at $P_{\text{in}} \approx 45$ mW, SP is indeed observed at two distinct wavelength detuning values, though this regime is not shown here. The right axis shows the wavelength detuning at which SP first appears at the minimum threshold power, revealing that the optimal detuning also shifts with phase.

These results demonstrate that the coupling phase in DRUM provides continuous control over the SP firing threshold, analogous to the tunable firing threshold of a biological neuron, with the threshold spanning nearly one order of magnitude in input power.

2.4 Controlling the refractory period of the self-pulsing in DRUM

A defining characteristic of biological neurons is the refractory period—the finite recovery time following a spike during which the neuron cannot fire again regardless of the input stimulus⁴⁸. Here we demonstrate that DRUM can emulate this behavior and, crucially, that the refractory period can be continuously tuned via the intermodal coupling coefficient phase. We use the term refractory period operationally to denote the minimum delay after a triggered SP event for which a subsequent probe pulse can trigger another SP event.

To probe the refractory period experimentally, we design a set of four input waveforms, each consisting of a 100 ns excitatory pulse followed by a delay (i.e., the time in which the optical power is switched-off) and a 50 ns probe pulse, see Fig. 5(a). The delay time between the excitatory and probe pulses is systematically changed from 100 ns to 400 ns with 100 ns steps, while keeping the total period constant at 1 μ s as schematically shown in Fig. 5(a). In this operation, the excitatory pulse triggers an SP spike, after which the system enters a transient recovery state. The probe pulse then tests whether the system has recovered sufficiently to fire again. If the probe pulse arrives within the refractory period, no SP spike is generated; if it arrives after the system has recovered, an SP spike is observed. The long off state of 450–750 ns between the probe pulse and the subsequent excitatory input signal allows the initial state to be reset. We then collect temporal traces of both the transmission and reflection signals over a course of 50 μ s; i.e., 50 periods of the input waveform.

Figure 5(b) shows the experimentally obtained temporal traces of the reflection signal of DRUM for each input wave-

form at different ϕ_{12} values controlled by the PSL. For a given input power ($P_{\text{in}} \approx 21$ mW for CW input), there exists a phase window in which both the excitatory and probe pulses trigger an SP signal. An example is shown in the top panel of Fig. 5(b). The probe pulse response disappears at different phase values for different waveforms—that is, as ϕ_{12} is scanned towards 2π , the refractory period lengthens, and progressively later probe pulses fall within it. This phase-dependent suppression of the probe pulse response is a direct experimental signature of a tunable refractory period.

During the phase-scan measurements used to probe the refractory period, we observed an unexpected phenomenon: for certain phase values, the long off state between the probe pulse and the subsequent excitatory pulse was insufficient to reset DRUM to its initial state. Instead, the device exhibited a prolonged and reproducible SP regime whose periodicity was systematically dependent on the coupling phase. Figure 5(c) presents temporal traces of the reflection signal for input waveform #2 (where the aforementioned off state is 650 ns) over an extended time window spanning 12 periods, at several ϕ_{12} values ranging from $\sim \pi$ to 2π . At lower phase values, the system recovers rapidly and the probe pulse consistently triggers an SP spike (black line, $\phi_{12} = 0.96\pi$). At higher ϕ_{12} values, however, the recovery becomes significantly slower: not only the probe pulse (red line, $\phi_{12} = 1.18\pi$) but also the subsequent excitatory pulse falls within the refractory window (green and blue lines, $\phi_{12} = 1.49\pi$ and 1.56π , respectively). As ϕ_{12} is scanned further toward 2π , the refractory period extends even further, such that only every third (cyan line, $\phi_{12} = 1.76\pi$) and then every fourth (magenta line, $\phi_{12} = 1.81\pi$) excitatory pulse triggers an SP spike, until eventually the device no longer generates detectable SP events (orange line, $\phi_{12} = 1.92\pi$). Throughout this prolonged recovery regime, no SP spike is observed for the short probe pulses. It should be noted that the transitions between successive periodicities are not abrupt—rather, there exists a transitional phase range over which both periodicities are observed simultaneously. To further quantify the observed periodicities, the collected temporal traces are analyzed by identifying the times at which SP spikes are triggered. The periodicity is then extracted as the time interval between two successive SP signals: e.g., for the trace shown by the black line in Fig. 5(c)—where the device responds to both the excitatory and probe pulses—two periodicities are identified as 0.3 μ s and 0.7 μ s, consistent with the timing of the input waveform #2.

The periodicity analysis shown in the right column of Fig. 5(c), performed for three representative wavelength detuning values ($\Delta\lambda = 18, 38$, and 58 pm), confirms that the effective SP period—and hence the refractory period—increases substantially with ϕ_{12} , spanning from 0.3 μ s up to four times the total waveform period (4 μ s). Notably, the system enters a no-SP state for an intermediate phase range where the internal energy is insufficient to trigger SP; this phase range shifts toward higher ϕ_{12} values as the wavelength detuning

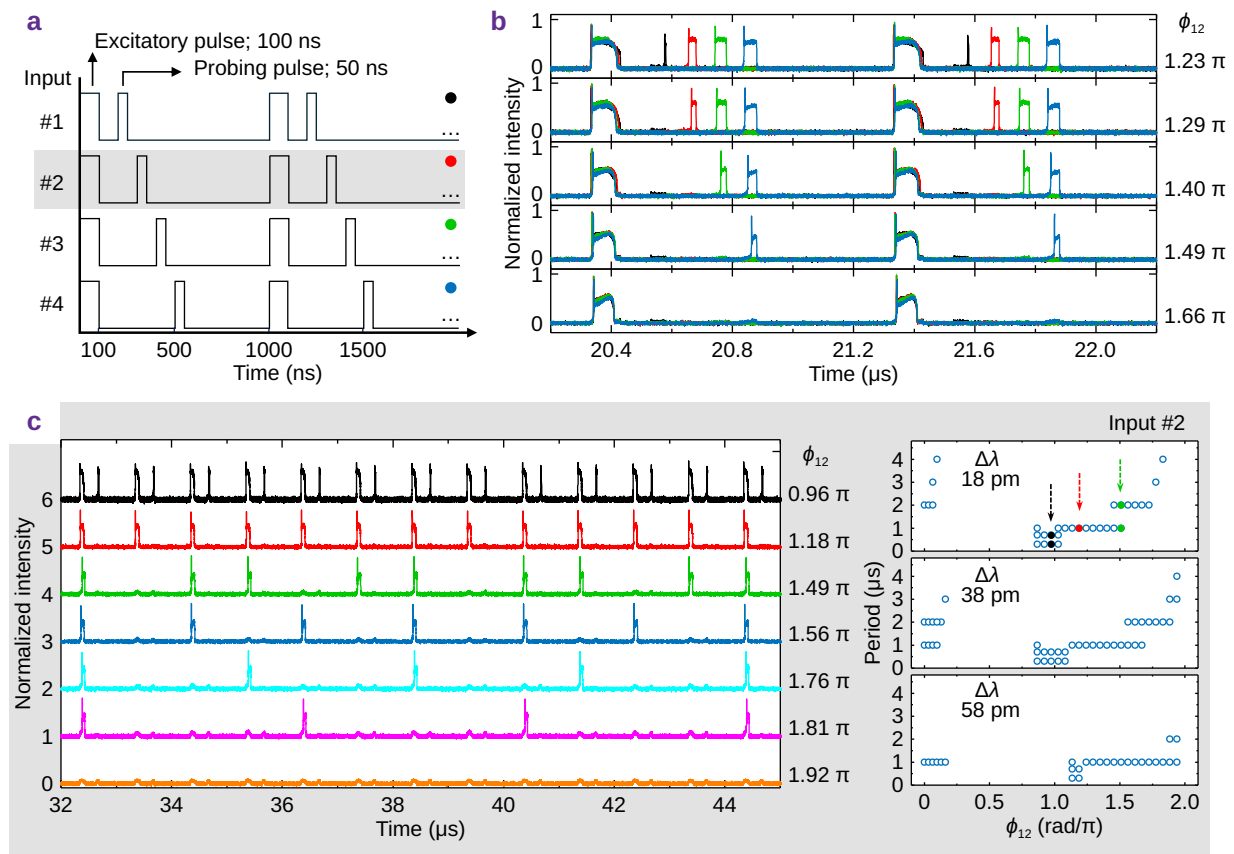


Fig. 5 | Demonstration of control over the refractory period. (a) Sketches of four input waveforms, each consisting of a 100 ns excitatory pulse followed by a 50 ns probe pulse. The probe pulse is systematically delayed relative to the excitatory pulse (from 100 ns to 400 ns in 100 ns steps) across the four waveforms, while the period is kept constant at 1 μ s. (b) Experimentally obtained temporal traces of the reflection signal of DRUM for each input waveform shown in (a), at different coupling phases controlled by the PSL. Different colors correspond to different input waveforms, as indicated by the filled circle markers in (a). As a signature of the refractory period, the probe pulse response disappears at different phase values for different waveforms. (c) Temporal traces of the reflection signal for input waveform #2 over an extended time window spanning 12 periods. The traces reveal significantly varying refractory periods as a function of coupling phase. Periodicity analysis performed for different wavelength detuning values as a function of phase is shown in the right column: the representative three periods are marked with arrows following the same color code as the traces given on the left. Temporal traces given in (b) and (c) were obtained for a wavelength detuning of $\Delta\lambda = 78$ pm and 18 pm, respectively.

increases. The extracted periods for three representative phase-periodicity combinations are indicated by arrows in the top panel of the right column, following the same color code (black, red, and green) as the corresponding temporal traces in Fig. 5(c).

Results demonstrate that the coupling phase in DRUM provides direct and continuous control over the refractory period of the SP spike. This tunability, spanning over an order of magnitude in recovery time, closely mirrors the variability in refractory behaviour observed across biological neuron types and represents a critical ingredient for programmable neuromorphic photonic circuits.

2.5 Observation of the phase-controlled spike-latency in DRUM

To gain deeper insight into the refractory period and its

underlying mechanism, we perform a more detailed investigation using a refined input waveform design. Instead of a single probe pulse, DRUM is now excited by a 100 ns excitatory pulse followed by a dense train of 36 probe pulses of 25 ns duration, separated by 25 ns off intervals, with a long (~ 1.43 μ s) off state introduced in each period to allow full recovery between periods, resulting in a total waveform period of 3.33 μ s (see inset of Fig. 6(b)). This design allows the refractory period to be mapped with much finer temporal resolution than the four-waveform approach of the previous section.

Figure 6(a) shows the temporal traces of the reflection signal for two representative coupling phase values. In both cases, the excitatory pulse triggers an immediate SP spike, followed by a train of probe pulse responses. The key observation is that the delay between the SP spike to the excitatory pulse and the first SP spike in the probe pulse train

differs significantly between the two phase values, confirming again that the refractory period is strongly phase-dependent. The dependence of this delay on coupling phase is quantified in Fig. 6(b), which shows a monotonically increasing trend as the phase approaches the quiescent window near $\phi_{12} \approx 1.6\pi$. Each data point represents the mean delay estimated from six temporal windows within the same excitation sequence, each separated by a recovery interval sufficient to restore the device to its initial operating conditions, while the error bars denote the corresponding standard deviation. The two phase values shown in Fig. 6(a) are marked accordingly, and the triangle marker identifies the phase value corresponding to the longest measurable refractory period within the experimental range of the pulse train.

A closer examination of the excitatory pulse region—highlighted by the gray shaded region in Fig. 6(a)

and enlarged in Fig. 6(c)—reveals a phase-dependent SP onset time which is defined as the delay between the excitatory pulse onset t_0 and the first observed SP signal. This latency to first spike, hereafter referred to as *spike latency*, increases systematically with coupling phase. This is visualized in Fig. 6(c), where representative traces at different phase values show the SP spike occurring progressively later after t_0 , with the system spending an increasingly long time in the subthreshold region before crossing the SP threshold (indicated by the horizontal dashed line). The inset quantifies this trend, showing that the spike latency increases from a few nanoseconds at low phase values to tens of nanoseconds in the quiescent window. The longer latency to spike means the system requires more time to integrate the input field before it goes to the first SP cycle. This also effectively extends the window during which subsequent probe pulses cannot trigger a response. To independently confirm this

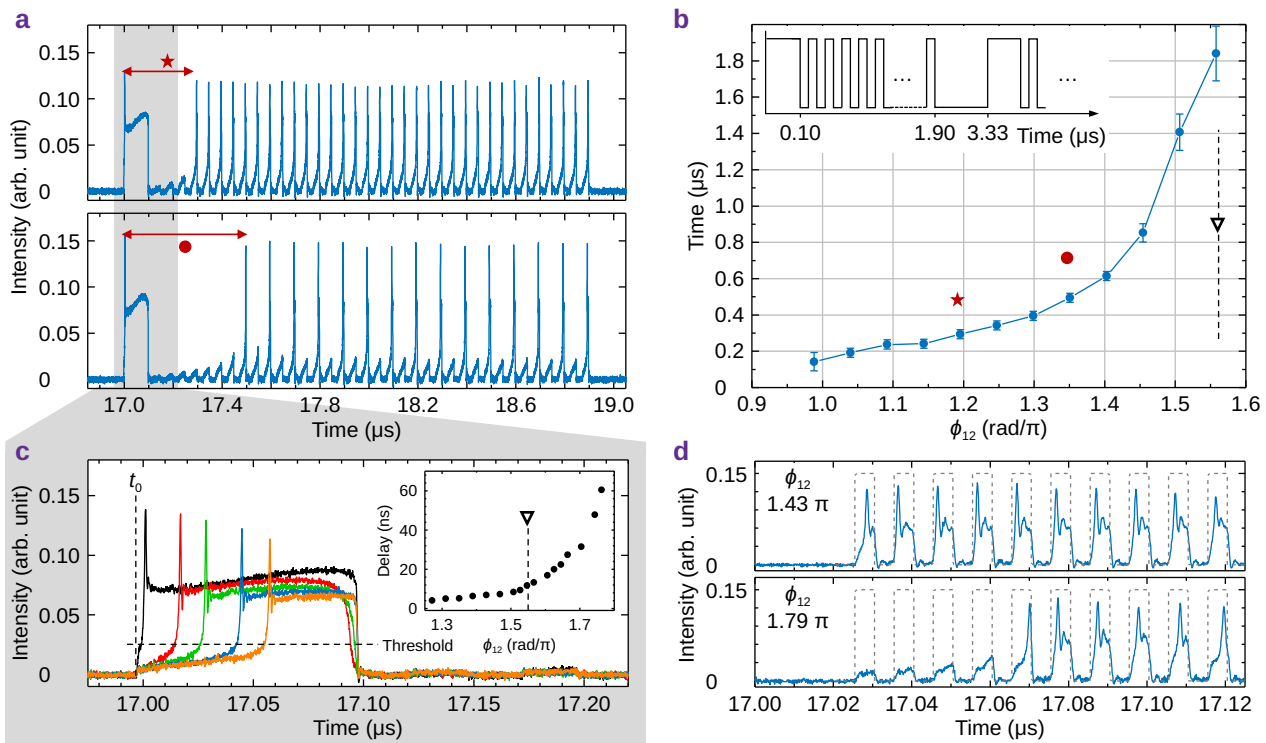


Fig. 6 | Detailed investigation of the refractory period. (a) Temporal traces of the reflection signal for an input waveform consisting of a 100 ns excitatory pulse followed by a train of 36 probe pulses of 25 ns duration, separated by 25 ns off intervals. A long (1.43 μs) off state is introduced in each period, resulting in a total waveform period of 3.33 μs , as schematically illustrated in the inset of (b). Results are shown for two representative phase values, illustrating a significant modification in the delay between the SP spike to the excitatory pulse and the first SP spike in the probe pulse train. The dependence of this delay (in μs) on coupling phase is shown in (b), where the two phase values from (a) are marked. (c) Enlarged view of the excitatory pulse region highlighted in (a) (gray shaded region) for five phase values ($\phi_{12} = 0.19\pi$, 1.14π , 1.35π , 1.45π , and 1.51π), color-coded from black to orange with increasing phase. The onset of the excitatory pulse is marked by a vertical dashed line and labeled as t_0 . The horizontal dashed line indicates the threshold above which the SP signal rapidly spikes. The SP onset time (delay between t_0 and the first observed SP signal; i.e., spike latency) increases as a function of phase, as shown in the inset. A vertical dashed line marked with a triangle indicates the longest refractory period, corresponding to the same marker in (b). (d) An alternative method to confirm the spike latency observed in (c): DRUM is excited by a continuous train of 5 ns pulses separated by 5 ns off intervals. The first SP spike is observed at varying time delays as the coupling phase is tuned: two representative coupling phase values given are $\phi_{12} = 1.43\pi$ (top) and $\phi_{12} = 1.79\pi$ (bottom). The results were obtained for a wavelength detuning of $\Delta\lambda = 38$ pm.

interpretation, Fig. 6(d) presents an alternative measurement in which DRUM is excited by a continuous train of 5 ns pulses separated by 5 ns off intervals. Under this excitation, the first SP spike is observed at varying time delays depending on the coupling phase. At $\phi_{12} = 1.43\pi$ (Fig. 6(d), top), the first SP spike appears within the first pulse (i.e., < 5 ns), consistent with a short spike latency. At $\phi_{12} = 1.79\pi$ (Fig. 6(d), bottom), the first SP spike is considerably delayed, consistent with a long spike latency discussed above. During this delay, a gradual buildup of intensity is observed in the pulses preceding the first SP spike, indicating that the device is accumulating energy from the input pulse train before reaching the SP threshold. This energy accumulation period is referred to as the *integration time*—another key neuronal response parameter that, as demonstrated here, is directly controlled by the coupling phase. This independent measurement corroborates the spike latency interpretation and confirms that the phase-dependent integration time is a robust and reproducible feature of DRUM's neuromorphic response.

3 Discussion

3.1 Modeling the nonlinear dynamics of the refractory period and integration time

The experimental observations suggest that the refractory period and integration time are governed by the nonlinear dynamics of the system, which we now theoretically explore by employing the nonlinear stability analysis of the system's evolution⁴⁷. The numerical model is not intended to reproduce each experimental operating point quantitatively, but rather to capture the dominant physical mechanisms governing the DRUM dynamics. In particular, the simulations include the nonlinear optical processes responsible for SP, namely two-photon absorption, free-carrier generation and relaxation, and thermo-optic dynamics, while treating the coupling phase and resonance detuning as effective control parameters. This approximation mainly affects the absolute detuning values. Experimentally, the effective detuning is influenced by the combined response of multiple coupled resonant elements, phase-controlled sections, residual backscattering, and static thermal shifts introduced by the integrated phase shifters. These contributions are not explicitly resolved in the reduced model. Therefore, although the operating point remains stable during each individual measurement, its absolute detuning can vary between different configurations and should not be compared one-to-one with the simulated detuning. The comparison below should instead be understood at the level of the underlying nonlinear mechanism and the resulting dynamical trends.

The phase portrait in Fig. 7(a) provides insight into the dynamics of DRUM under the time-dependent input waveform used in the experiments of Fig. 6. In the simulations, the laser excitation is switched on at the simulated time

$t = 0$ through a Heaviside step function. The initial condition of the temperature and carrier-concentration trajectories shown in the phase portrait is set to $(0, 0)$. The first SP spike in the temporal trace of the intracavity energy $|\alpha_2|^2$ is marked by blue arrowhead #1 in Fig. 7(b). After the start of the excitatory pulse at t_0 , $|\alpha_2|^2$ rises rapidly. This increase drives a rapid buildup of the free carrier population ΔN , while cavity temperature remains approximately constant ($\Delta T \sim 0$) during this initial transient. This sudden rise in ΔN is followed by an approximately linear co-evolution of both ΔN and ΔT , as evidenced by the straight segment of the phase portrait trajectory between blue arrowheads #1 and #2. We refer to the turning point where ΔN transitions from fast to slow evolution as the *spiking corner*, since the SP spike occurs at this moment. Note that the evolution of ΔN and ΔT is accompanied by a concurrent shift of the cavity resonance. The linear evolution of ΔN and ΔT persists until the thermally shifted hot resonance is pushed sufficiently far from the input wavelength that no light is coupled into the MR anymore, and the intracavity optical energy drops to almost zero. At this point, marked by blue arrowhead #2, the trajectory in the phase portrait changes direction and both ΔN and ΔT begin to decay with their respective relaxation timescales. In this condition, the system becomes effectively insensitive to the input state: the red trajectory (off state) originating at blue arrowhead #3 smoothly follows the preceding black trajectory (on state), and the intracavity optical energy remains negligibly small regardless of whether the input is on or off (Fig. 7(b)). The dynamics are thus governed primarily by thermal and free-carrier relaxation processes.

When the excitatory pulse is sufficiently long to drive the system past arrowhead #2, the system enters what we define as the *natural refractory regime*, highlighted in green in Fig. 7(a) and 7(b). In this regime, the system exhibits identical dynamical behavior regardless of the input state—no additional SP spike can be triggered until the system has sufficiently recovered. It is worth noting that if the excitatory pulse had been shorter than the time required to reach arrowhead #2, the trajectory would have turned earlier in phase space, with ΔN and ΔT beginning to decay sooner and leading to a qualitatively different dynamical response. The refractory period persists as long as the temperature remains above approximately 1.7 K for the given detuning. Once this threshold is crossed, the natural limit cycle associated with SP terminates, and the subsequent evolution depends on the input state: the system either relaxes toward $\Delta N = \Delta T = 0$ or is re-excited into a new cycle. The particular dynamical scenario that unfolds in this regime depends on the coupling phase and the repetition rate of the subsequent probe pulses, as explored experimentally in the previous section.

In the condition presented in Fig. 7(a), the probe pulse train arriving after the refractory regime drives the trajectory toward a new spiking corner. However, since both the individual pulses and the intervening off intervals are short,

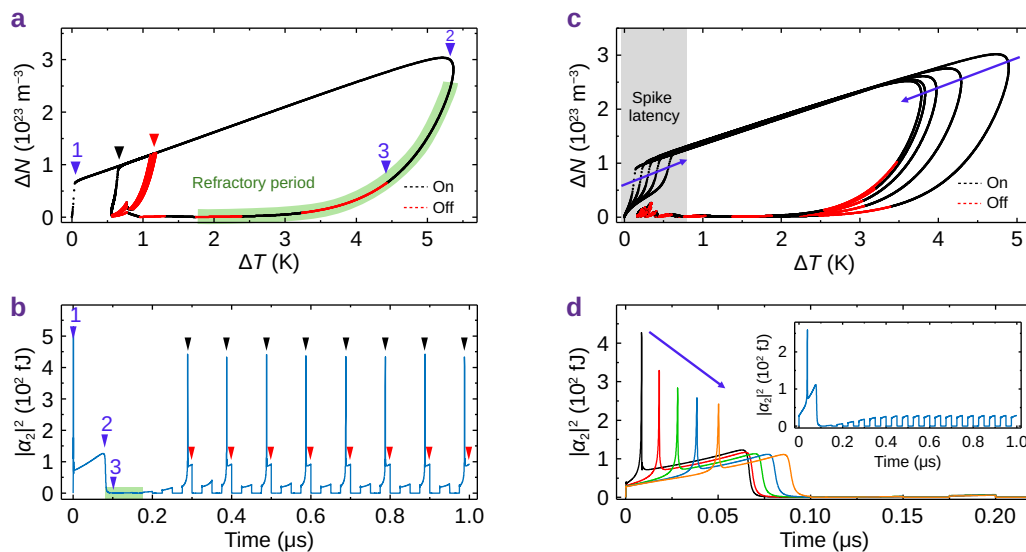


Fig. 7 | Phase portraits of DRUM in the ΔN – ΔT plane (top) and corresponding temporal traces of the intracavity energy $|\alpha_2|^2$ (bottom) for the input waveform used in the experiments presented in Fig. 6, at an input power of 25 mW and a wavelength detuning of -64 pm. Black and red dotted trajectories correspond to the *on* and *off* states of the input field, respectively. The first SP spike, the end of the SP cycle, and the end of the on-state corresponding to the excitatory pulse are marked with numbered blue arrowheads, both on the temporal traces (b) and on the phase portraits (a), for a given coupling phase value. SP spikes and the end of the on-state corresponding to the subsequent probe pulses are marked with black and red arrowheads, respectively. The green shaded region shown in both panels corresponds to the refractory period, during which the system cannot transition to the SP state regardless of the input signal. Phase portraits and corresponding temporal traces focusing on the excitatory pulse region for multiple coupling phase values—selected such that no SP spike is observed in the probe pulses, as shown in the inset—are shown in (c) and (d). The increasing spike latency as a function of coupling phase is indicated by a blue arrow in both panels, along which the phase values are $\phi_{12}=1.22\pi$, 1.31π , 1.34π , 1.36π , and 1.37π . The model captures the main dynamical trends observed experimentally in Fig. 6.

the system cannot reach the spiking corner within a single pulse. Instead, multiple pulses are required to accumulate sufficient energy to trigger an SP spike. This is the temporal integration of the input signal in this context. The off interval following each pulse is too short for ΔN and ΔT to fully relax to zero, so each subsequent pulse begins from a partially excited state that is progressively closer to the new spiking region, as marked by the black arrowhead. Once the spiking corner is reached and an SP spike is triggered, the system re-enters the approximately linear trajectory in phase space. This persists until the subsequent off interval; however, since the pulse duration is short, the system cannot follow the same trajectory as in the natural SP regime and instead diverges from it at an earlier point, as marked by the red arrowhead. At this point, the trajectory changes direction and both ΔN and ΔT begin to decay as the intracavity optical energy drops to zero. Full relaxation is again prevented by the arrival of the next pulse, which is itself too short to trigger a spike but brings the system closer to the spiking corner, and the cycle repeats. As a result, for the remainder of the probe pulse train, ΔN and ΔT become locked into a periodic state in which every second pulse triggers an SP (Fig. 7(b)), with the phase portrait cycling within the region bounded by the black and red arrowheads (Fig. 7(a)).

Since the intracavity energy depends strongly on the

interaction between the counterpropagating modes—and thus on the coupling phase ϕ_{12} —the SP dynamics depends significantly on the phase^{47,49}, modifying both the phase portrait trajectory and the corresponding temporal trace. Figure 7(c) and 7(d) present the phase portraits and corresponding temporal traces focusing on the excitatory pulse region for multiple coupling phase values, selected such that no SP spike is observed in the probe pulses (as shown in the inset). Results show that the coupling phase controls the onset of the first spiking corner and progressively delays it, resulting in an increasing spike latency indicated by the blue arrow in both panels. For the phase values presented, the mean intracavity energy is insufficient to sustain a complete SP cycle. Nevertheless, the excitatory pulse still drives the system along a trajectory reminiscent of SP dynamics before it converges toward a low-energy state. In this regime, the off intervals between pulses reduce ΔT and ΔN sufficiently that the subsequent short probe pulses cannot gradually accumulate enough energy to reach the spiking threshold. Although ΔN and ΔT remain close to zero during the probe pulse train, the intracavity energy still responds to the pulse repetition, as shown in the inset of Fig. 7(d). Considering only this first incomplete SP cycle, phase tuning enables the SP peak to be delayed by hundreds of nanoseconds while simultaneously reducing both the maximum intracavity energy and the extent of the phase portrait trajectory.

The results presented in Fig. 7 constitute the theoretical counterpart of the experimental observations in Fig. 6, with the model capturing the main dynamical trends and revealing the physical origin of the observed refractory and integration behavior. One notable difference is visible in Fig. 6(c), where the SP cycle is clearly truncated at the end of the 100 ns excitatory pulse. This truncation is absent in the theoretical results of Fig. 7(d) because, for the parameters used in the simulations (section 4.2), the SP cycle is shorter than the excitatory pulse duration. As a result, the system completes its SP cycle and enters the natural refractory regime within the excitatory pulse window, which manifests as a drop of the intracavity optical energy to zero at varying times within this interval.

3.2 Simulated auto-synchronization in a two-node photonic network

Having demonstrated the rich repertoire of single-node neuromorphic behaviors accessible in DRUM, we now turn to the emergent dynamics when two such nodes are coupled into a simple photonic neural network. We simulate a two-node system consisting of two DRUM devices coupled through a shared bus waveguide (Fig. 8(a)). The first DRUM is configured in the excitable regime by deactivating one of its lobes, effectively operating it as a Taiji MR—hereafter referred to as DTMR (Node-A). The second DRUM has both lobes deactivated, reducing it to a simple MR—hereafter referred to as DSMR (Node-B). Note that while the experimental realization of such a network is not yet available, the theoretical modeling presented here supports the concept and will inform the design of future neuromorphic networks. Node-A receives a varying input at port-1 (Input-1), while Node-B receives a fixed input at port-2 (Input-2), both at the same wavelength. The key coupling mechanism between the two nodes is the BA generated by the nonlinear DTMR, which propagates rightward along the bus waveguide and serves as an effective driving signal for Node-B. To establish a reference, we first characterize the SP behavior of each node in isolation. When the BA is absent, the DSMR operates autonomously, exhibiting an intrinsic SP frequency determined solely by its own detuning and input power. Since Input-2 is fixed, the DSMR oscillates at a single SP frequency of 6.9 ± 0.1 MHz regardless of the DTMR's operating conditions. This is reflected in Fig. 8(b1), which shows a uniform SP frequency throughout the map—plotted as a function of the DTMR's detuning and input power—confirming that the DSMR is completely decoupled from Node-A in the absence of BA. On the other hand, the DTMR alone exhibits its characteristic SP map as shown in Fig. 8(b2) with frequencies spanning approximately 4 to 10 MHz over the explored range of detuning and input power. When the BA is switched on, the SP map of the DSMR is significantly modified (Fig. 8(b3)), reflecting the influence of the periodic driving signal from Node-A. The comparison of

the maps in Fig. 8(b) immediately reveals that the BA substantially alters the dynamical landscape of Node-B, creating the conditions for synchronization. It is worth noting that in our model, the frequency detuning of the DTMR is varied not by tuning the input laser wavelength but by shifting the cold resonance of the mode—this could, for instance, be realized via a thermal phase shifter integrated on the ring. This approach preserves the coherence between the two nodes, which would otherwise be compromised by a change in the input wavelength.

The collective behavior of the coupled network is summarized in the behavioral map of Fig. 8(c1), constructed from the SP frequency ratio $f_{\text{Out-2}}/f_{\text{Out-1}}$ as a function of frequency detuning $\Delta\omega_{\text{DTMR}}$ and input power $P_{\text{in-1}}$. Four distinct behavioral regimes are identified: (i) synchronized (blue), where both nodes oscillate at the same frequency; (ii) unsynchronized (red), where the nodes oscillate at different or undefinable frequencies; (iii) inhibitory (black), where the BA from Node-A suppresses SP in Node-B; and (iv) free-running (gray), where Node-B oscillates at a frequency that is at most slightly shifted from its intrinsic SP frequency due to the non-oscillating Node-A. The numbered boxes in Fig. 8(c1) identify representative network states, whose dependence on the phase acquired by the field when it propagates through the right lobe of DTMR is shown in Fig. 8(c2). Notably, the behavioral regime of each network state is phase-dependent. For instance, state #3 transitions between unsynchronized and synchronized regimes as the phase is varied, demonstrating that the coupling phase can alter the collective network dynamics. In contrast, state #1 exhibits a strong robustness against phase variations, remaining synchronized across the entire phase range.

Figure 8(d) illustrates the temporal traces of the three distinct behavioral regimes as indicated by the geometric markers in Fig. 8(c1) and 8(b2). In the inhibitory regime (d1), the non-self-pulsing BA from Node-A interacts with the intrinsically oscillating field in Node-B (6.9 MHz), represented by the black line, and suppresses it, driving Node-B into a CW state. As a result, both Out-1 (blue line) and Out-2 (red line) carry CW signals, albeit at different intensities. This is a direct photonic analog of inhibitory synaptic behavior. In the synchronized regime (d2), both Out-1 and Out-2 oscillate at the same frequency of 8.1 MHz, demonstrating robust injection locking of Node-B—whose free-running SP frequency is 6.9 MHz—to the periodic driving signal provided by the BA from Node-A. Thus, both Out-1 and Out-2 carry the same SP frequency. In the unsynchronized regime (d3), the BA from Node-A interacts with the intrinsically oscillating field in Node-B (6.9 MHz), but fails to establish a stable locking condition. Consequently, Out-1 oscillates at 7.8 MHz while the signal at Out-2 exhibits no well-defined frequency.

These results demonstrate that a minimal two-node photonic network built from passive silicon microresonators can exhibit a rich repertoire of collective behaviors

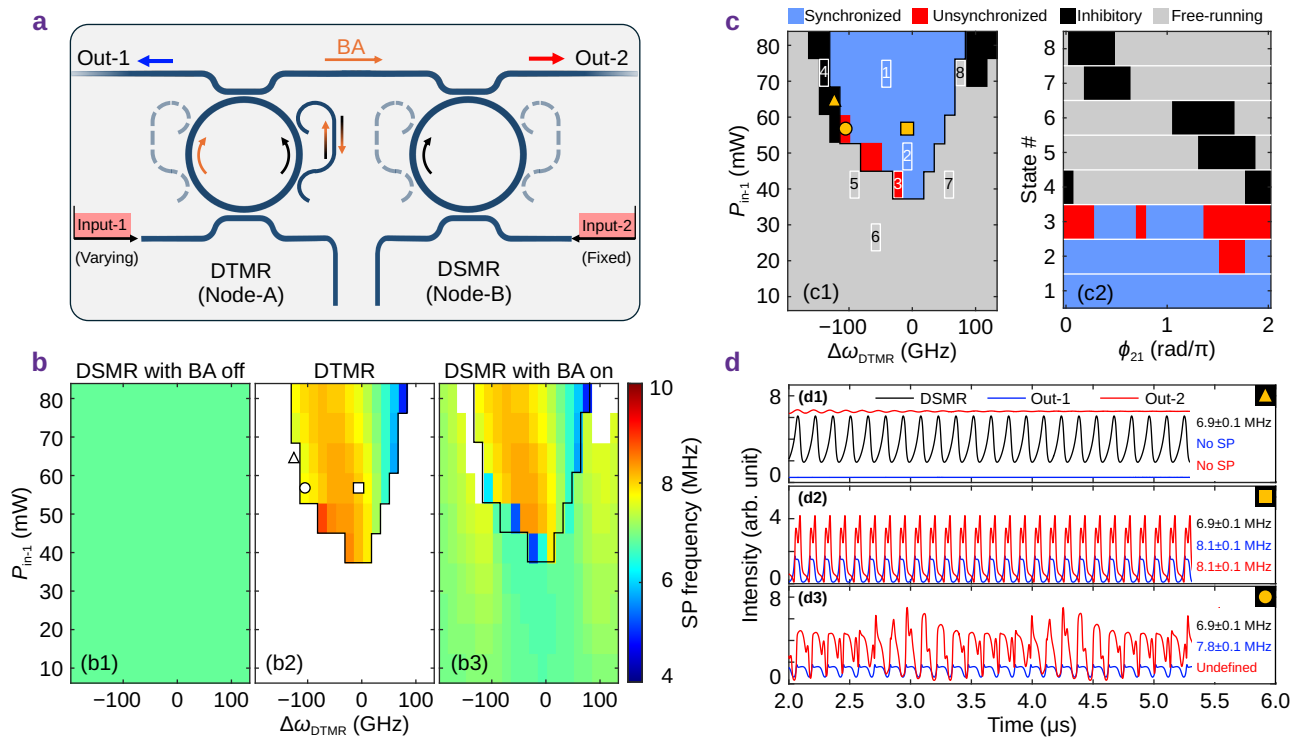


Fig. 8 | Theoretical investigation of synchronization in a two-node photonic network. (a) Schematic of the network consisting of a DTMR (Node-A) and a DSMR (Node-B) coupled through a shared bus waveguide. Input-1 (varying) and Input-2 (fixed, at 80 mW) are injected from the left and right ports, respectively. The BA from Node-A, indicated by the orange arrow, mediates the coupling between the two nodes. Out-1 and Out-2 denote the left and right output ports, respectively. (b) SP frequency maps, obtained from the simulated intracavity fields, as a function of frequency detuning $\Delta\omega_{\text{DTMR}}$ and input optical power $P_{\text{in-1}}$ for the DSMR with BA off (b1), the DTMR alone (b2), and the DSMR with BA on (b3). Detuning and input power for DSMR were kept at $2\pi \cdot 6.8$ GHz and 80 mW, respectively. The color scale indicates the SP frequency in MHz. (c) Behavioral map of the network as a function of $\Delta\omega_{\text{DTMR}}$ and $P_{\text{in-1}}$ (c1), constructed from the SP frequency ratio $f_{\text{Out-2}}/f_{\text{Out-1}}$. Four distinct behavioral regimes are identified: synchronized (blue), unsynchronized (red), inhibitory (black), and free-running (gray). The numbered boxes in (c1) denote representative states of the network. (c2) shows the behavioral regime of each numbered state as a function of the phase acquired by the field propagating in the right lobe of the DTMR, revealing the phase-dependent tunability of the network behavior. Geometric markers indicate the specific states whose temporal traces are shown in (d). (d) Temporal traces at Out-1 (blue) and Out-2 (red) for three representative states marked in (c1): inhibitory behavior (d1), synchronized behavior (d2), and unsynchronized behavior (d3). The black line shows the Out-2 signal of the DSMR in the absence of BA, serving as a reference. The corresponding SP frequencies are indicated on the right.

analogous to those observed in biological neural networks, including inhibition, synchronization, and desynchronization. Moreover, they suggest that the phase control could provide a useful programming handle in a larger photonic neural networks. While the numerical results demonstrate the feasibility of the proposed architecture, its experimental implementation in large cascaded networks will require addressing resonance-wavelength mismatch between neighboring rings arising from fabrication tolerances and thermal crosstalk between neighboring devices; the former is not expected to be critical for quality factors on the order of $10^3 - 10^4$, as demonstrated in our previous work on coupled microring arrays for reservoir computing^{50,51}, while the latter can be mitigated through strategic trench placement or, as discussed in Section 3.3, through carrier-depletion-based control.

3.3 Comparison and outlook

To situate our work within the broader landscape of hardware implementation of artificial neurons, we provide a comparative analysis of existing integrated platforms in Table 1. Signal propagation is classified into four categories: *one-directional*, in which propagation is architecturally constrained to either the forward or reverse direction; *bi-directional reciprocal*, in which the response is identical for forward and reverse excitation; *bi-directional non-reciprocal*, in which the response differs depending on the excitation direction; and *bi-directional (non-)reciprocal*, in which the response can be reconfigured on demand between reciprocal and non-reciprocal operation. BA is similarly classified into four categories, where backward refers to the direction opposite to that of the input excitation: *not present*, in which no backward signal exists by design; *present but unregulated*,

in which backward signals arise but cannot be independently controlled; *ideally absent, practically unregulated*, in which backward responses are suppressed under ideal conditions but emerge in practice due to fabrication imperfections such as backscattering; and *present and regulated*, in which backward signals exist and can be actively controlled on demand. We further distinguish between hybrid electro-optical systems and fully optical implementations.

Hybrid platforms encompass a broad class of opto-elec-

tronic neurons, including photodiode–microring systems¹⁰, resonant tunneling diode (RTD)-based neurons^{11,52}, and phototransistor–memristor architectures⁵³. These systems offer good control over neuronal properties through electronic control and enforce one-directional signal propagation at the system level via electronic isolation. As a result, BA between neurons is not present by design, rather than intrinsically regulated at the device level. Within this class, two distinct mechanisms can be identified: extrinsic and

Table 1 | Comparison of neuromorphic photonic spiking systems.

System		Firing process					Functionality			Key reference
		Spiking (output)	Spiking control	Mechanism	Time scale	Tunability	Signal propagation	Back action	Reconfigurability	
Hybrid: opto-electronic	PD + pn-MR	Optical	Optical-to-electrical signal	Extrinsic: RC constant	ns	High	One-directional	Ideally absent Practically unregulated	No	ref. ¹⁰
	(PD) + RTD	Electrical	Optical-to-electrical or optical signal	Intrinsic: Nonlinearity of the RTD	μs to ns	Limited	One-directional	Not present	No	ref. ¹¹ ref. ⁵⁴
	RTD + Laser diode	Optical	Optical-to-electrical signal	Intrinsic: Nonlinearity of the RTD + material response	μs to ns	Limited	One-directional	Not present	No	ref. ⁵²
	Phototransistor + Memristor	Electrical	Optical-to-electrical signal	Extrinsic: Optical modulation Intrinsic: Material response	μs	Moderate	One-directional	Not present	No	ref. ⁵³
All-optical	VCSEL	Optical	Optical excitability	Intrinsic: Laser relaxation oscillation	ns to ps	Moderate	One-directional	Not present	No	ref. ¹³
	FP-SA / DFB-SA	Optical	Optical excitability	Intrinsic: gain-absorption dynamics	ps to ns	Moderate	One-directional	Not present	No	ref. ¹⁴ ref. ¹⁵
	Passive MR	Optical	Nonlinear instability	Intrinsic: Free-carrier and thermal relaxation	μs	Limited	Bi-directional Reciprocal	Ideally absent Practically unregulated	No	ref. ¹⁶
	PCM-integrated MR	Optical	Optical power	Structural: Phase change material	μs to ns	Limited	One-directional	Not present *	No	ref. ⁵⁵
	SIL laser (DFB laser + MR)	Optical	Electronic stimulation and MR detuning	Extrinsic: Electrical modulation of the laser	μs to ns	High	One-directional	Not present *	No	ref. ⁵⁶
	Non-Hermitian Taiji MR	Optical	Nonlinear instability	Intrinsic: Free-carrier and thermal relaxation	μs	Limited	Bi-directional Non-reciprocal	Present but slightly regulated	No	Our work
	Non-Hermitian DRUM	Optical	Nonlinear Instability	Intrinsic: Free-carrier and thermal relaxation	μs	Fully (with some interdependency)	Bi-directional (Non)-reciprocal	Present and regulated	Yes	Our Work

* Feedback is present by design rather than arising naturally from the back-propagation of a primitive element. PD, photodiode; LD, laser diode; RTD, resonant tunneling diode; VCSEL, vertical-cavity surface-emitting laser; FP, Fabry-Pérot; SA, saturable absorber; SIL, self-injection-locked; DFB, distributed feedback laser; PCM, phase change material.

intrinsic control of firing process. In photodiode–microring and phototransistor–memristor systems, neuronal dynamics are extrinsic, arising from electro-optical feedback loops governed by circuit-level time constants (e.g., RC time constant). Consequently, the observed spiking behavior is externally implemented, rather than emerging from intrinsic nonlinear dynamics of the optical device. In contrast, RTD-based neurons exhibit intrinsic excitability originating from the nonlinear properties of the device, enabling ultra-fast spiking dynamics in the ns to sub-ns regime. A recent demonstration has further shown resonate-and-fire dynamics, tunable resonance and spike-based temporal encoding functionalities in optically sensitive RTD neuron⁵⁴. However, despite this physically grounded spiking mechanism, signal routing and directionality in RTD-based systems remain architecturally enforced, and BA is still absent by design rather than a controllable degree of freedom.

All-optical platforms, on the other hand, including laser-based excitable systems^{13,56}, passive microresonators (MRs)^{16–18}, and phase-change material (PCM)-integrated devices⁵⁵, exploit intrinsic material nonlinearities to emulate neuronal behavior. While these approaches enable event-driven dynamics, they face fundamental limitations in the control of signal flow and network-level directionality. Conventional MRs operate in a bi-directional reciprocal regime governed by Lorentz symmetry without any type of control on the propagation direction. In idealized conditions, backward signals do not exist as independent degrees of freedom; in practice, however, they emerge due to fabrication imperfections, such as surface-roughness-induced backscattering, and remain unregulated. PCM-integrated devices and the self-injection-locked (SIL) laser (distributed feedback (DFB) laser coupled to an MR)⁵⁶, can exhibit effective one-directional behavior depending on the device architecture; however, this directionality is geometrically defined rather than actively controlled. Laser-based excitable systems, such as vertical-cavity surface-emitting lasers (VCSEL)¹³ and integrated laser neurons with saturable absorbers, based on either Fabry–Pérot¹⁴ or distributed-feedback¹⁵ cavities, support intrinsic optical spiking through nonlinear cavity dynamics, but do not enforce directionality at the device level; instead, their effective directionality arises from network topology and injection conditions rather than from an intrinsic physical asymmetry. As a result, BA occurs across these platforms but remains unregulated. Consequently, neither signal directionality nor control over BA is an intrinsic neuron-level property. The class of laser-based neurons has recently been extended to network-scale hardware demonstrations, including nonlinear photonic chips for spiking reinforcement learning¹⁵, hardware-aware light-weight SNNs for pattern classification⁵⁷, and photonic spiking reinforcement learning for intelligent routing⁵⁸.

Our work addresses the *missing primitive* of directional excitability in all-photonic neurons through the non-Hermitian DRUM architecture. Building on the Taiji MR concept,

which demonstrated bidirectional asymmetric response via geometry-induced intermodal coupling, DRUM extends this principle into a reconfigurable regime. Unlike conventional passive microresonators, whose forward and backward responses are constrained by reciprocity and uncontrolled backscattering, Taiji and DRUM devices exploit engineered coupling between counterpropagating modes to realize direction-dependent nonlinear dynamics. Crucially, DRUM adds active control over both the amplitude and phase of this coupling, allowing forward spike emission and backward signal pathways to be tailored and, when desired, suppressed. In this framework, BA is not merely an unwanted parasitic response, but becomes a tunable degree of freedom, providing a functional analogue to biological neurons, where back-propagation is not absent but regulated. By combining intrinsic all-optical nonlinear dynamics with device-level control of directionality and feedback, DRUM bridges the gap between the architectural controllability of hybrid systems and the compact, passive nature of resonator-based photonic neurons.

More broadly, this programmability opens a route toward heterogeneous spiking photonic neural networks in which neuronal diversity is engineered rather than inherited from fabrication disorder. Biological neural circuits rely on populations of neurons with different firing thresholds, spike latencies, integration times, refractory periods, and feedback sensitivities; similarly, photonic networks could exploit DRUM nodes to introduce controlled variations in excitability, temporal response, and back-propagation. In conventional integrated photonic implementations, achieving such heterogeneity would typically require either device-to-device fabrication variations or distinct neuron designs. DRUM offers an alternative strategy: programmable nodes can be selectively embedded within a network of simpler spiking elements. In this architecture, not every node needs to be reconfigurable. DRUM neurons could be placed only where tunability, feedback control, or directional response is required, while simpler microring neurons could implement fixed-function spiking nodes with smaller footprint and lower power consumption. For example, such networks could combine fast-spiking, low-threshold nodes for rapid transient processing with slow-integrating, high-threshold nodes for longer temporal memory or sequence processing. Such a hybrid network would combine the compactness and efficiency of passive microrings with the programmability of DRUM, enabling scalable heterogeneous photonic spiking circuits in which diversity becomes an addressable design parameter rather than a fabrication constraint. Here, we have not addressed learning in these networks, i.e., the way information flows or is shared among different neurons to perform a specific task. Typically, this is governed by synaptic connections between the network nodes. Within the DRUM, synaptic weighting can be achieved intrinsically by exploiting programmable non-Hermitian lobes and resonance detuning to tailor its nonlinear response. This

approach provides a compact solution and enables task-dependent optimization of its dynamics. Alternatively, synaptic weights could be implemented using dedicated programmable photonic components, such as microring weight banks or cascaded MZIs. By providing individually addressable weights, these architectures could also enable local learning rules, such as spike-timing-dependent plasticity directly in hardware.

Our proof-of-concept implementation of the DRUM as a reconfigurable artificial photonic neuron exhibits three main limitations: energy consumption, device footprint, and potential crosstalk in large-scale integrated networks. Regarding energy consumption, the passive DRUM operates under CW optical pumping. In the sensitized configuration, an optical power of approximately 5 mW in the bus waveguide is sufficient to trigger SP at a frequency of 6 MHz. Considering only the optical power delivered to the bus waveguide and neglecting static heater consumption, this corresponds to an energy scale of approximately 0.8 nJ per spike. It should be noted that this value represents the optical energy associated with one period of the autonomous SP dynamics under continuous optical excitation, rather than the energy required for a task-defined computational event; a meaningful energy-per-inference metric can only be established once the neuron is integrated into a trained, weighted network performing a specific computational task. Furthermore, this value accounts only for the optical energy delivered to the bus waveguide and excludes the power consumption of auxiliary laboratory equipment, such as the pump laser, EDFA, modulator drivers, thermal stabilization, and detection electronics, as well as the static power required to maintain the operating point through the phase shifters. Under this definition, the energy remains higher than that reported for several hardware spiking-neuron implementations, including a passive microring-resonator-based neuron with an energy of approximately 6 pJ per spike⁵⁹, and active laser-based neurons employing a saturable absorber, for which an input activation-energy threshold as low as 18.5 fJ/spike and an output spike energy of approximately 116 fJ/spike have been reported¹⁵. This substantially lower energy consumption of the laser-based neurons reflects a fundamentally different physical mechanism: they rely on an active gain medium, in which a small perturbation triggers a self-sustained lasing transition. In contrast, both the passive microring-resonator neuron and the DRUM exploit the same underlying thermal and free-carrier nonlinearity. The DRUM architecture can be further optimized to significantly reduce its energy consumption, potentially reaching or even surpassing the performance of the passive microring-resonator neuron. Increasing the quality factor of the DRUM could reduce the SP threshold below 1 mW, while free carrier control through p-n junctions could increase the SP frequency up to hundreds MHz⁶⁰. Although the incorporation of a p-n junction introduces a modest additional propagation loss, reverse-bias

carrier depletion effectively suppresses free-carrier absorption even at high intracavity power⁶¹. As a result, SP has been demonstrated at input powers of 2.6 mW in doped p-i-n microrings⁶², while the SP frequency can be increased to approximately 30 MHz by applying a reverse bias of only 100 mV. The main trade-off is a narrower laser-cavity detuning window, with the SP regime eventually disappearing at higher reverse bias. Together, these improvements could reduce the optical energy per spike towards the few-pJ regime. Moreover, the current DRUM design occupies an area of approximately $560 \times 160 \mu\text{m}^2$, substantially larger than that of a conventional microring resonator neuron ($16 \times 16 \mu\text{m}^2$ ⁵⁹). However, the footprint is dominated by the Mach-Zehnder interferometers and phase shifters used to control the coupling coefficients. Dedicated layouts based on compact interferometric structures and optimized phase shifters could reduce the overall footprint without altering the operating principle. Reducing the length of the lobes is not expected to compromise the non-Hermitian response, which is mainly governed by the microring-lobe coupling condition. Since the nonlinear dynamics are dominated by the intracavity field enhancement in the main microring, footprint optimization can reduce the device size while preserving the SP mechanism. Finally, large-scale integration might be affected by thermal crosstalk between neighboring DRUMs. This effect is partially mitigated by the use of trenches, as evidenced by the limited resonance shift observed under maximum heater power⁴⁷. Nevertheless, replacing thermo-optic control with carrier-based tuning through p-n junctions would largely reduce thermal crosstalk, enabling independent programming of multiple DRUM neurons and potentially supporting online training schemes without requiring thermal stabilization delays or crosstalk-compensation algorithms.

4 Materials and methods

4.1 Experimental setup and samples

Figure 9 shows a schematic of the experimental setup. A fiber-coupled continuous-wave tunable laser (CWTL, Yenista Optics, TUNICS-T100S) is connected to a fiber switch that configures the setup in two operating modes: CW and modulated excitation. In CW mode, the laser output is sent directly to an erbium-doped fiber amplifier (EDFA, IPG Photonics). In modulated mode, the optical signal first passes through an electro-optic modulator (EOM, ixblue MXAN-LN-10) driven by an arbitrary waveform generator (AWG, Teledyne T3AFG500). Throughout the setup, optical signals are monitored using three detection units (DUs) consisting of a 99/1 fiber coupler whose 1% port feeds a low-bandwidth photodetector (PD, 30 kHz) to measure the average power, and whose 99% port feeds a high-bandwidth photodetector (PD, 1.2 GHz) to record the temporal trace. The amplified optical signal exiting the

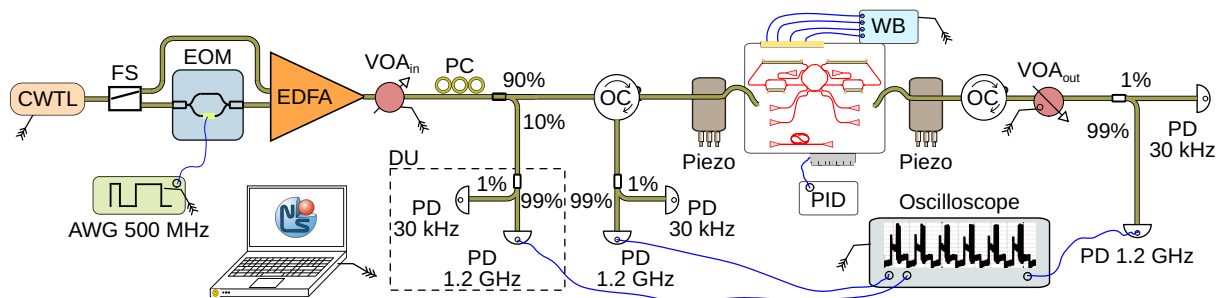


Fig. 9 | Schematic diagram of the experimental setup. A fiber-coupled tunable laser provides continuous-wave or modulated excitation via an electro-optic modulator (EOM) driven by an arbitrary waveform generator (AWG). After amplification and polarization control, light is coupled into the sample through a fiber on a piezoelectric stage. Optical circulators (OCs) separate forward and backward signals, which are monitored by photodetectors (low- and high-bandwidth) and recorded with an oscilloscope. Phase shifters are electrically controlled via a write board (WB), and the chip temperature is stabilized using a PID-controlled Peltier system. All symbols are defined in the text.

EDFA is controlled in power and polarization by an input variable optical attenuator (VOA_{in}) and a polarization controller (PC). A 10% optical tap is used to monitor the average input power and the temporal response using a first DU. The remaining 90% of the signal is sent to an optical circulator (OC), which routes the light to a stripped optical fiber mounted on a three-axis piezoelectric stage. This fiber couples light into the device under test (DUT) through the input grating coupler. The light reflected by the DUT into the input fiber is redirected by the circulator to a second DU to record the backward-propagating optical signal. At the output grating coupler, a second stripped optical fiber, also mounted on a three-axis piezoelectric stage, collects the transmitted signal and sends it to a second OC, a variable optical attenuator (VOA_{out}) and a third DU. The electrical signals generated by the high-bandwidth PDs of the DUs are recorded with an oscilloscope (LeCroy WavePro 7300A, 3 GHz). The oscilloscope and all instruments connected by black arrow tails in Fig. 9 are controlled by a personal computer. The currents applied to the phase shifters of the DUT are supplied by a write board (WB, NI CompactDAQ). The photonic chip is mounted on a temperature-controlled holder. The temperature is stabilized by a proportional-integral-derivative (PID) controller (Stanford Research Systems SIM960) connected to a Peltier element and a 10 k Ω thermistor.

The first DUT is a Taiji microresonator featuring a race-track geometry. It is formed by connecting four 15 μm radius, 90° Euler bends with two straight sections measuring 758 μm and 3.106 μm respectively, giving a total perimeter of approximately 196.22 μm . The inner S-shaped waveguide is also based on Euler curves. The central sections have a radius of 10 μm and an angle of 135°, while the end sections have a radius of 10 μm and an angle of 75°. Inverse tapers are implemented at both ends of the S waveguide to suppress back reflections. The devices were fabricated at the IMEC/Europpractice multi-project wafer facility. The Taiji was designed on a silicon-on-insulator platform with a silicon waveguide cross section of 450 $\times$ 220 nm² embedded in

a silicon cladding. Further details can be found in ref.²⁷.

The second DUT is a DRUM. The central microresonator is a deformed ring that combines straight and curved sections, measuring 328.5 μm in total length. It is coupled to a bus waveguide via a short, straight coupling section. Similarly, the coupling between the microresonator and the side lobes uses straight sections designed to provide a stronger interaction than the bus waveguide. Each lobe spans 574.6 μm in length between its two coupling regions with the central microresonator. Symmetric Mach-Zehnder interferometers are integrated within the lobes, with arm lengths of 122.8 μm , including 60 μm of straight waveguide. The phase shifters and Mach-Zehnder interferometers incorporate 2 μm -wide titanium nitride (TiN) micro-heaters for thermo-optic tuning. The devices were fabricated by AMF Europpractice within a multi-project wafer run. The DRUM were designed on a silicon-on-insulator platform with a silicon waveguide cross section of 500 $\times$ 220 nm² embedded in a silicon cladding. Further details can be found in ref.³⁸.

4.2 Nonlinear dynamics: equations for a two-node photonic network

The time-dependent nonlinear behavior of an MR can in general be represented by a set of four coupled ordinary differential equations⁶³. These equations describe the evolution of the optical fields (clockwise α_1 and counterclockwise α_2) within the MR, the free carrier concentration (ΔN) and the temperature difference between the waveguide core and the cladding (ΔT)^{63,64}. A two-node photonic network is constructed by connecting two DRUM devices as illustrated in Fig. 10. The two nodes are configured as a Taiji MR on the left (i.e., DTMR) and a simple MR on the right (i.e., DSMR), achieved by deactivating one lobe in the left DRUM and both lobes in the right DRUM, as indicated by the dashed outlines. The dynamics of this system are described by seven coupled equations given below. Note that the number of equations is reduced from eight to seven, as the DSMR supports only the clockwise propagating mode, and

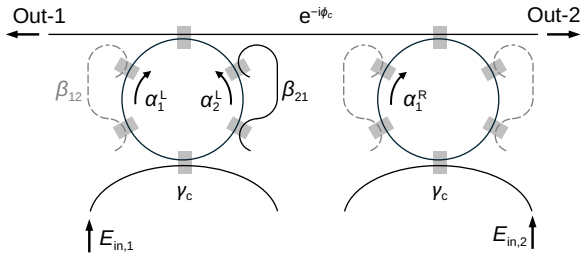


Fig. 10 | Schematic of the two-node photonic network showing the parameters used in the equations.

the counterclockwise mode equation vanishes identically. All the quantities are labeled with a superscript L if they refer to the DTMR or R if they refer to the DSMR. In addition, the internal energies in the two resonators are defined as $E_L = |\alpha_1^L|^2 + |\alpha_2^L|^2$ and $E_R = |\alpha_1^R|^2$.

$$\frac{d\alpha_1^R}{dt} = \left[i\Delta\omega^R - \frac{\gamma_i(E_R, \Delta N^R)}{2} \right] \alpha_1^R - \gamma_c e^{-i\phi_c} \alpha_1^L + i\sqrt{\gamma_c} E_{in,2}, \quad (2)$$

$$\frac{d\alpha_1^L}{dt} = \left[i\Delta\omega^L - \frac{\gamma_i(E_L, \Delta N^L)}{2} \right] \alpha_1^L - \beta_{21}^L \alpha_2^L, \quad (3)$$

$$\frac{d\alpha_2^L}{dt} = \left[i\Delta\omega^L - \frac{\gamma_i(E_L, \Delta N^L)}{2} \right] \alpha_2^L + i\sqrt{\gamma_c} E_{in,1}, \quad (4)$$

$$\frac{d\Delta N^R}{dt} = -\frac{\Delta N^R}{\tau_{fc}} + E_R^2 \mathcal{N}, \quad (5)$$

$$\frac{d\Delta T^R}{dt} = -\frac{\Delta T^R}{\tau_{th}} + E_R \mathcal{T}(E_R, \Delta N^R), \quad (6)$$

$$\frac{d\Delta N^L}{dt} = -\frac{\Delta N^L}{\tau_{fc}} + E_L^2 \mathcal{N}, \quad (7)$$

$$\frac{d\Delta T^L}{dt} = -\frac{\Delta T^L}{\tau_{th}} + E_L \mathcal{T}(E_L, \Delta N^L), \quad (8)$$

where the total losses γ_i , the function $\mathcal{T}$ and the coefficient $\mathcal{N}$ are written as

$$\begin{aligned} \gamma_i(E, \Delta N) &= 6\gamma_c + \gamma_{rad} + \gamma_{abs}(E, \Delta N) \\ \mathcal{T}(E, \Delta N) &= \frac{\gamma_{th} \gamma_{abs}(E, \Delta N)}{\rho c_p V_{th}} \\ \mathcal{N} &= \frac{\gamma_{FCA} \beta_{Si} c^2}{2\hbar\omega_0^R V_{FCA}^2 n_g^2} \end{aligned}, \quad (9)$$

with

$$\begin{aligned} \gamma_{abs}(E, \Delta N) &= \gamma_{abs,lin} + gE + g_N \Delta N \\ g &= \frac{\gamma_{TPA} \beta_{Si} c^2}{n_g^2 V_{TPA}}, \quad g_N = \frac{\gamma_{FCA} \sigma_N c}{n_g} \end{aligned}, \quad (10)$$

The frequency detuning functions that are used as variables in the simulations are given as

$$\Delta\omega^R(\omega, \Delta N, \Delta T) = (\omega_0^R - \omega) + \delta\omega_T \Delta T + \delta\omega_N \Delta N, \quad (11)$$

$$\Delta\omega^L(\omega, \Delta N, \Delta T) = (\omega_0^L - \omega) + \delta\omega_T \Delta T + \delta\omega_N \Delta N, \quad (12)$$

where ω_0^R and ω_0^L are the cold resonance angular frequencies of DSMR and DTMR, respectively.

The synchronization results presented in Section 3.2 were obtained for a network in which Node-A is a DTMR operating in its excitable regime. To maintain coherence between the two nodes, the input laser frequency ω in Eqs. (11–12) is held constant while the cold resonance frequency ω_0^L of the DTMR is varied. The output fields at ports Out-1 and Out-2 are then given by the following expressions, which are used to produce Fig. 8(c) and 8(d):

$$P_{out,1} = |i\sqrt{\gamma_c} \alpha_2^L|^2, \quad (13)$$

$$P_{out,2} = |i\sqrt{\gamma_c} (\alpha_1^R + e^{-i\phi_c} \alpha_1^L)|^2, \quad (14)$$

here, ϕ_c denotes the phase acquired by the field propagating in the DTMR and, then, in the bus waveguide between the two coupling regions of the two nodes, as indicated in Fig. 10. It should be noted that the phase-dependent network response can equivalently be investigated by varying the phase acquired either in the bus waveguide between the two nodes or within the lobe of the DTMR. The physical constants and parameters appearing in Eqs. (2–12), along with their values used in the simulations, are listed in Table 2. These parameters were taken primarily from ref.¹⁶ and subsequently fine-tuned using experimental data.

4.3 Numerical simulations using PRECISE

The model described in section 4.2 is based on temporal coupled-mode theory (TCMT) and does not explicitly account for the physical dimensions and propagation paths of the photonic circuit⁶⁵. Thus, the coupling coefficients between the counterpropagating modes (β_{ij}) and the bus waveguide connecting the two DRUM devices do not explicitly account for the phase accumulated along the optical paths. This phase depends on the propagation of the optical signal through these regions and may consequently affect the DRUM's response^{32,38}. To validate the model and extend the analysis to an all-pass spiking-neuron configuration, we employed the MATLAB-based Photonic hybRid EleCtro-magnetIc SolvEr (PRECISE)⁶⁶. Using PRECISE, we simulated the time evolution of the complex optical fields in the photonic circuit using its physical dimensions, including two-photon absorption (TPA), free-carrier effects (FCA and FCD), and thermo-optic nonlinearities.

Based on the two-node scheme reported in Fig. 10, the microresonators feature six equidistant and identical coupling ports with a field transmittance $t_c = 0.932$. The circumference of each ring is 328.5 μm , and their coupling is ensured by a 100.2 μm long bus waveguide. The individual lobe length is fixed at 138.5 μm . For the numerical modeling, propagation losses are set to 2 dB/cm and $\omega_0^R = 2\pi 191.257$ THz is used. Throughout the simulations, the

Table 2 | Physical constants and parameters of the nonlinear microring model.

Symbol	Description	Value	Unit
β_{Si}	TPA coefficient (Si)	8.4×10^{-12}	m/W
$\delta\omega_T$	Frequency displacement factor due to temperature	-0.065	THz K ⁻¹
$\delta\omega_N$	Frequency displacement factor due to free-carriers	1.208×10^{-24}	THz m ³
σ_N	Absorption cross-section	1.5×10^{-21}	m ²
ρ	Silicon density	2.33×10^6	g/m ³
c_p	Specific heat capacity (Si)	0.7×10^{-21}	m ² /(ps ² ·K)
n_{Si}	Refractive index (= n_g , group index)	3.476	–
τ_{th}	Thermal lifetime	80×10^3	ps
τ_{fc}	Free-carrier lifetime	12×10^3	ps
ω_0^{R}	Resonance angular frequency	$2\pi \cdot 193.0695$	THz
β_{21}	Intermodal coupling coefficient	55×10^{-3}	THz
$\gamma_{\text{abs,lin}}$	Linear absorption rate	3.90×10^{-3}	THz
γ_{rad}	Linear radiative loss rate	5.85×10^{-3}	THz
γ_c	Coupling rate	26×10^{-3}	THz
γ_{th}	Thermal overlap factor	0.9355	–
γ_{TPA}	TPA overlap factor	0.9964	–
γ_{FCA}	FCA overlap factor	0.9996	–
V_{th}	Thermal mode volume	4.466×10^{-17}	m ³
V_{TPA}	TPA mode volume	3.626×10^{-17}	m ³
V_{FCA}	FCA mode volume	3.304×10^{-17}	m ³

detuning and input power of the DSMR were fixed at 0 GHz and 98.9 mW, respectively. The results obtained via PRECISE are in good agreement with those presented above, confirming the validity of our model. In a similar manner, the collective behavior of the network is summarized in the behavioral map of Fig. 11(a), constructed from the SP frequency ratio $f_{\text{Out-2}}/f_{\text{Out-1}}$ as a function of frequency detuning $\Delta\omega_{\text{DTMR}}$ and input power $P_{\text{in-1}}$. The figure adopts the same color code and definitions as Fig. 8(c1). Figure 11(a) reproduces the same synchronized (blue), inhibitory (black), and free-running (gray) regimes, albeit with slightly different relative weights in the parameter space. This discrepancy is due to the inherent approximations of the TCMT framework, where the full dispersive and geometric complexity of the device fold into a small set of effective parameters as described above. In contrast, PRECISE employs the transfer matrix method with exact device parameters, capturing the complete interference structure, wavelength-dependent dispersion, and precise field profiles at each interface. As a result, minor quantitative shifts in the regime boundaries are expected and do not undermine the physical picture conveyed by our model.

Temporal traces recorded at Out-1 (blue) and Out-2 (red) for three representative operating points marked in Fig. 11(a) are illustrated in Fig. 11(b). As shown in Fig. 11(b1), 11(b2), and 11(b3), the intrinsically oscillating DSMR is suppressed (inhibitory regime), locked to a different SP

frequency (synchronized regime), and left nearly unperturbed (free-running regime), respectively. The corresponding steady-state SP frequencies are indicated in each panel. The traces further reveal the transient dynamics during the first ~ 1 μs , reflecting the time required for the coupled system to settle into its steady state.

4.3.1 Simulated all-pass network response and synaptic feedback analogy

To extend the analogy with biological neural networks, we now consider an all-pass photonic configuration in which the DTMR plays the role of the "post" neuron and the DSMR acts as the "pre" neuron, as illustrated in Fig. 12(a). In this setting, the DSMR fires first and its output propagates forward to drive the DTMR. The right lobe of the DTMR recirculates a portion of the intracavity field back toward the DSMR, thereby implementing a BA mechanism that modifies the initial state of the pre-neuron. This provides a photonic analogue of feedback-mediated synaptic modulation in biological systems. It should be noted that this is not a photonic implementation of a Hebbian learning rule, since no persistent update of the coupling strength is implemented.

The effect of this bidirectional interaction is captured in the SP frequency maps of Fig. 12(b), constructed from the simulated intracavity fields as a function of frequency detuning $\Delta\omega_{\text{DTMR}}$ and input optical power P_{in} , while the DSMR detuning was kept fixed at $\Delta\omega_{\text{DSMR}} = 0$ GHz throughout.

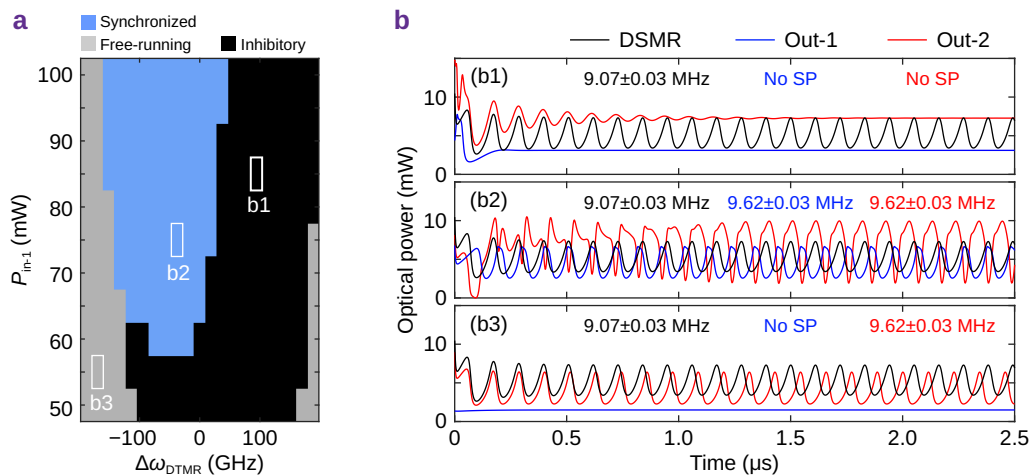


Fig. 11 | PRECISE simulation confirming the distinct dynamical regimes of a two-node photonic neural network, in analogy with Fig. 8: (a) Behavioral map of the network as a function of the DTMR detuning and input power P_{in-1} , constructed from the SP frequency ratio f_{Out-2}/f_{Out-1} . (b) Temporal traces of Out-1 (blue), Out-2 (red), and the free-running DSMR reference (black) corresponding to the three representative operating points marked by white rectangles in (a), with panels (b1), (b2), and (b3) depicting the inhibitory, synchronized, and free-running regimes, respectively. The dominant SP frequency extracted from each steady-state trace is indicated in the corresponding panel.

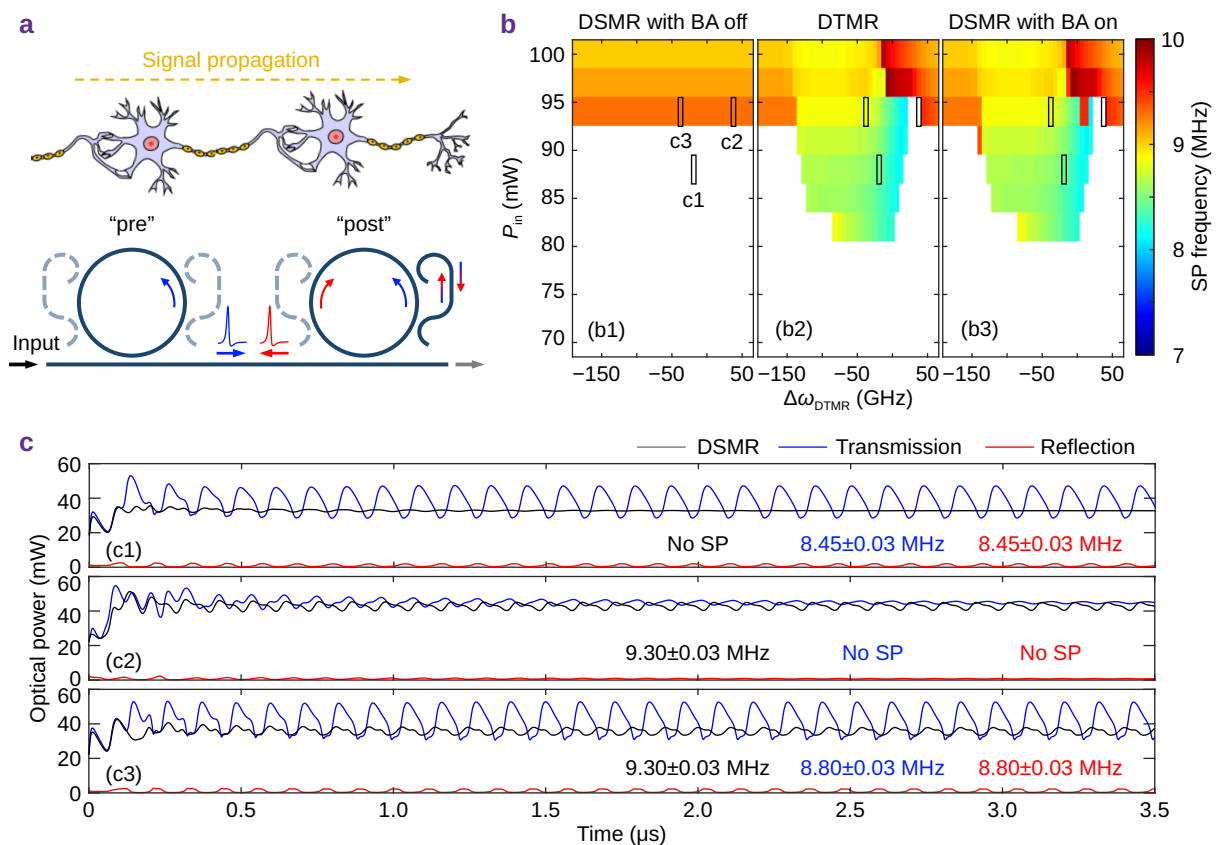


Fig. 12 | (a) Schematic analogy between the all-pass photonic configuration and a biological neural pair, where the DSMR and DTMR play the roles of the "pre" and "post" neurons, respectively. (b) SP frequency maps constructed from the simulated intracavity fields as a function of frequency detuning $\Delta\omega_{DTMR}$ and input optical power P_{in} , while keeping $\Delta\omega_{DSMR}$ fixed at 0 GHz, for: the isolated DSMR driven by the input field alone (b1), the DTMR (b2), and the DSMR after receiving the BA from the DTMR (b3). The color scale indicates the SP frequency in MHz. Three representative operating points are marked by white rectangles. (c) Temporal traces of the transmission (blue), reflection (red), and free-running DSMR reference (black) signals for the three representative states marked in (b), corresponding to excitatory (c1), inhibitory (c2), and synchronized (c3) behaviors. The dominant SP frequency extracted from each steady-state trace is indicated in the corresponding panel.

Figure 12(b1) shows the SP frequency map of the isolated DSMR driven solely by the input field, where SP states are confined to a relatively narrow region at high input powers. In contrast, the DTMR operating in its excitable configuration exhibits SP states over a significantly broader range of input powers, lowering the threshold for SP, as shown in Fig. 12(b2). Crucially, the clockwise-propagating mode generated by the right lobe couples back into the DSMR and modifies its dynamical state. Consequently, its SP map shifts toward a configuration closely resembling that of the DTMR, as evidenced by the expanded SP region visible in Fig. 12(b3). The network therefore exhibits feedback-mediated back-action, in which the post-neuron reshapes the dynamical response of the pre-neuron.

The dynamical range enabled by this configuration is further illustrated by the temporal traces in Fig. 12(c), recorded at the transmission (blue) and reflection (red) ports for three representative operating points marked in Fig. 12(b). The black trace in each panel shows the transmission of a free-running DSMR in the absence of BA, serving as a reference. In the excitatory regime (Fig. 12(c1)), the DSMR remains quiescent while the transmission and reflection signals both oscillate at 8.45 ± 0.03 MHz, indicating that the DTMR drives the network into a SP state. In the inhibitory regime (Fig. 12(c2)), the DSMR self-pulses initially at 9.30 ± 0.03 MHz, yet both the transmission and reflection signals show no SP activity, demonstrating that the BA from the DTMR suppresses the oscillation at the output ports. Finally, in the synchronized regime (Fig. 12(c3)), the transmission and reflection signals lock to a common frequency of 8.80 ± 0.03 MHz, distinct from the free-running DSMR frequency, confirming frequency synchronization mediated by the BA field.

Taken together, these simulations show that the all-pass inter-node connection can support excitatory, inhibitory, and synchronized dynamical regimes reminiscent of coupled biological neurons, with the DTMR-mediated BA acting as an effective synaptic-like coupling between the two nodes.

References

- Wulf WA, McKee SA. Hitting the memory wall: implications of the obvious. *ACM SIGARCH Comput Archit News* **23**, 20–24 (1995).
- Christensen DV, Dittmann R, Linares-Barranco B et al. 2022 roadmap on neuromorphic computing and engineering. *Neuromorph Comput Eng* **2**, 022501 (2022).
- Brunner D, Shastri BJ, Al Qadasi MA et al. Roadmap on neuromorphic photonics. arXiv. (2025-01-16). <https://arxiv.org/abs/2501.07917>.
- Schuman CD, Kulkarni SR, Parsa M et al. Opportunities for neuromorphic computing algorithms and applications. *Nat Comput Sci* **2**, 10–19 (2022).
- Nunes JD, Carvalho M, Carneiro D et al. Spiking neural networks: a survey. *IEEE Access* **10**, 60738–60764 (2022).
- Lobo JL, Del Ser J, Bifet A et al. Spiking neural networks and online learning: an overview and perspectives. *Neural Netw* **121**, 88–100 (2020).
- Shastri BJ, Tait AN, de Lima TF et al. Photonics for artificial intelligence and neuromorphic computing. *Nat Photonics* **15**, 102–114 (2021).
- Gerstner W, Kistler WM. *Spiking Neuron Models: Single Neurons, Populations, Plasticity* (Cambridge University Press, Cambridge, 2002).
- Han SF, Shen WH, Gu M et al. Integrated photonic synapses, neurons, memristors, and neural networks for photonic neuromorphic computing. *Opto-Electron Technol* **1**, 250011 (2025).
- Tait AN, de Lima TF, Nahmias MA et al. Silicon photonic modulator neuron. *Phys Rev Appl* **11**, 064043 (2019).
- Robertson J, Black D, Donati G et al. Ultrafast and compact photonic-electronic leaky integrate-and-fire circuits based upon resonant tunnelling diodes. arXiv. (2025-01-28). <https://arxiv.org/abs/2501.17133>.
- Nahmias MA, Shastri BJ, Tait AN et al. A leaky integrate-and-fire laser neuron for ultrafast cognitive computing. *IEEE J Sel Top Quantum Electron* **19**, 1800212 (2013).
- Robertson J, Hejda M, Bueno J et al. Ultrafast optical integration and pattern classification for neuromorphic photonics based on spiking VCSEL neurons. *Sci Rep* **10**, 6098 (2020).
- Xiang SY, Shi YC, Guo XX et al. Hardware-algorithm collaborative computing with photonic spiking neuron chip based on an integrated Fabry-Perot laser with a saturable absorber. *Optica* **10**, 162–171 (2023).
- Xiang SY, Chen YH, Zhao HW et al. Nonlinear photonic neuromorphic chips for spiking reinforcement learning. *Optica* **13**, 457–468 (2026).
- Van Vaerenbergh T, Fiers M, Mechet P et al. Cascadable excitability in microrings. *Opt Express* **20**, 20292–20308 (2012).
- Zhang Q, Jiang N, Zhang YQ et al. On-chip spiking neural networks based on add-drop ring microresonators and electrically reconfigurable phase-change material photonic switches. *Photonics Res* **12**, 755–766 (2024).
- Xiang JL, Zhang YJ, Zhao YT et al. All-optical silicon microring spiking neuron. *Photonics Res* **10**, 939–946 (2022).
- Biasi S, Donati G, Lugnan A et al. Photonic neural networks based on integrated silicon microresonators. *Intell Comput* **3**, 0067 (2024).
- Donati G, Biasi S, Pavesi L et al. All-optical spiking processing and reservoir computing with a passive silicon microring and wavelength-time division multiplexing. *Photonics Res* **13**, 2641–2653 (2025).
- Jalas D, Petrov A, Eich M et al. What is—and what is not—an optical isolator. *Nat Photonics* **7**, 579–582 (2013).
- Kandel ER, Schwartz JH, Jessell TM. *Principles of Neural Science* 4th ed (McGraw-Hill, New York, 2000).
- Rumelhart DE, Hinton GE, Williams RJ. Learning representations by back-propagating errors. *Nature* **323**, 533–536 (1986).
- Stuart GJ, Sakmann B. Active propagation of somatic action potentials into neocortical pyramidal cell dendrites. *Nature* **367**, 69–72 (1994).
- Feng L, El-Ganainy R, Ge L. Non-Hermitian photonics based on parity-time symmetry. *Nat Photonics* **11**, 752–762 (2017).
- Wang CQ, Fu ZT, Mao WB et al. Non-Hermitian optics and photonics: from classical to quantum. *Adv Opt Photonics* **15**, 442–523 (2023).
- Biasi S, Franchi R, Mione F et al. Interferometric method to estimate the eigenvalues of a non-Hermitian two-level optical system. *Photonics Res* **10**, 1134–1145 (2022).
- Franchi R, Biasi S, Picciocchi D et al. The infinity-loop microresonator: a new integrated photonic structure working on an exceptional surface. *APL Photonics* **8**, 056111 (2023).
- Chen YH, Li J, Xu K et al. Electrically reconfigurable mode chirality

- in integrated microring resonators. *Laser Photonics Rev* **18**, 2301289 (2024).
30. Li JW, Li WX, Feng Y et al. On-chip fabrication-tolerant exceptional points based on dual-scatterer engineering. *Nano Lett* **24**, 3906–3913 (2024).
31. Lee H, Chang L, Kecebas A et al. Chiral exceptional point enhanced active tuning and nonreciprocity in micro-resonators. *Light Sci Appl* **14**, 45 (2025).
32. de las Heras AM, Franchi R, Biassi S et al. Nonlinearity-induced reciprocity breaking in a single nonmagnetic Taiji resonator. *Phys Rev Appl* **15**, 054044 (2021).
33. Calabrese A, Ramiro-Manzano F, Price HM et al. Unidirectional reflection from an integrated “taiji” microresonator. *Photonics Res* **8**, 1333–1341 (2020).
34. Fan HB, Fan HW, Fan HL. Multiple Fano resonance refractive index sensor based on a plasmonic metal-insulator-metal based Taiji resonator. *J Opt Soc Am B* **39**, 32–39 (2022).
35. Zeng SW, Zhao XL, Sweatt L et al. Unidirectional hybrid diode laser through the integration of a hook-shaped traveling-wave semiconductor optical amplifier and Taiji ring resonator. *Opt Lett* **48**, 1132–1135 (2023).
36. Chen SW, Zhang LB, Fei YH et al. Bistability and self-pulsation phenomena in silicon microring resonators based on nonlinear optical effects. *Opt Express* **20**, 7454–7468 (2012).
37. Biassi S, Lugnan A, Micheli D et al. Exploring the potential of self-pulsing optical microresonators for spiking neural networks and sensing. *Commun Phys* **7**, 380 (2024).
38. Aslan B, Franchi R, Biassi S et al. Coherent control of (non-)Hermitian mode coupling: tunable chirality and exceptional point dynamics in photonic microresonators. *Light Sci Appl* **15**, 150 (2026).
39. Li A, Van Vaerenbergh T, De Heyn P et al. Backscattering in silicon microring resonators: a quantitative analysis. *Laser Photonics Rev* **10**, 420–431 (2016).
40. Biassi S, Ramiro-Manzano F, Turri F et al. Hermitian and non-Hermitian mode coupling in a microdisk resonator due to stochastic surface roughness scattering. *IEEE Photonics J* **11**, 6101114 (2019).
41. McCutcheon W. Backscattering in nonlinear microring resonators via a Gaussian treatment of coupled cavity modes. *APL Photonics* **6**, 066103 (2021).
42. Bogaerts W, De Heyn P, Van Vaerenbergh T et al. Silicon microring resonators. *Laser Photonics Rev* **6**, 47–73 (2012).
43. Borghi M, Bazzanella D, Mancinelli M et al. On the modeling of thermal and free carrier nonlinearities in silicon-on-insulator microring resonators. *Opt Express* **29**, 4363–4377 (2021).
44. Van Vaerenbergh T, Fiers M, Dambre J et al. Simplified description of self-pulsation and excitability by thermal and free-carrier effects in semiconductor microcavities. *Phys Rev A* **86**, 063808 (2012).
45. Priem G, Dumon P, Bogaerts W et al. Optical bistability and pulsating behaviour in Silicon-On-Insulator ring resonator structures. *Opt Express* **13**, 9623–9628 (2005).
46. Hodgkin AL. The local electric changes associated with repetitive action in a non-medullated axon. *J Physiol* **107**, 165–181 (1948).
47. Biassi S, Grotter S, Aslan B et al. Phase-controlled non-Markovian hysteresis in a nonlinear, non-Hermitian silicon microresonator. *Phys Rev Appl* **25**, 024041 (2026).
48. Izhikevich EM. *Dynamical Systems in Neuroscience* (MIT Press, Cambridge, 2007).
49. Davide O. Study of a reconfigurable non-hermitian optical microresonator: from linear response to nonlinear dynamics (University of Trento, Trento, 2024).
50. Lugnan A, Biassi S, Foradori A et al. Reservoir computing with all-optical non-fading memory in a self-pulsing microresonator network. *Adv Opt Mater* **13**, 2403133 (2025).
51. Biassi S, Franchi R, Cerini L et al. An array of microresonators as a photonic extreme learning machine. *APL Photonics* **8**, 096105 (2023).
52. Romeira B, Javaloyes J, Ironside CN et al. Excitability and optical pulse generation in semiconductor lasers driven by resonant tunneling diode photo-detectors. *Opt Express* **21**, 20931–20940 (2013).
53. Li FF, Li DW, Wang CQ et al. An artificial visual neuron with multiplexed rate and time-to-first-spike coding. *Nat Commun* **15**, 3689 (2024).
54. Adair A, Owen-Newns D, Donati G et al. Resonate-and-fire photonic-electronic spiking neurons for fast and efficient light-enabled neuromorphic processing systems. *Commun Phys* **9**, 271 (2026).
55. Feldmann J, Youngblood N, Wright CD et al. All-optical spiking neuromorphic networks with self-learning capabilities. *Nature* **569**, 208–214 (2019).
56. Lan D, Ma BW, Guo YY et al. Heterogeneous nonlinear photonic spiking neuron based on a self-injection-locked laser. *Photonics Res* **14**, 2199–2209 (2026).
57. Xiang SY, Zhang YH, Shi SX et al. Hardware-aware lightweight photonic spiking neural network for pattern classification. *Opto-Electron Adv* **9**, 250319 (2026).
58. Xiang SY, Chen YH, Zheng L et al. Photonic spiking reinforcement learning for intelligent routing. *Opto-Electron Sci* **5**, 260005 (2026).
59. Zhang Q, Fang YJ, Jiang N et al. All-optical digital logic and neuromorphic computing based on multi-wavelength auxiliary and competition in a single microring resonator. *Opto-Electron Sci* **4**, 250003 (2025).
60. Xiang JL, Zhao YT, He A et al. Photonic neuromorphic processing with on-chip electrically-driven microring spiking neuron. *Laser Photonics Rev* **19**, 2400604 (2025).
61. He ML, Hamerly R, Shetewy AE et al. Active nonlinear silicon microring resonators tomography: modeling and characterization. *J Lightwave Technol* **44**, 5059–5070 (2026).
62. Shetewy AE, Catuneanu MT, He ML et al. Demonstration of high-frequency self-pulsing oscillations in an active silicon micro-ring cavity. *Sci Rep* **14**, 23823 (2024).
63. Johnson TJ, Borselli M, Painter O. Self-induced optical modulation of the transmission through a high-Q silicon microdisk resonator. *Opt Express* **14**, 817–831 (2006).
64. Biassi S, Franchi R, Bazzanella D et al. On the effect of the thermal cross-talk in a photonic feed-forward neural network based on silicon microresonators. *Front Phys* **10**, 1093191 (2022).
65. Suh W, Wang Z, Fan SH. Temporal coupled-mode theory and the presence of non-orthogonal modes in lossless multimode cavities. *IEEE J Quantum Electron* **40**, 1511–1518 (2004).
66. Bazzanella D, Mancinelli M, Borghi M et al. Precise photonic hybrid electromagnetic solver. *IEEE Photonics J* **14**, 3026310 (2022).

Acknowledgements

We gratefully thank Dr. Alessio Lugnan and Prof. Peter Bienstman for useful suggestions and interesting discussions. This project has received funding from the European Union under MINDnet 101226674.

Author contributions

S.B., B.A. and L. P. conceived the concept of this study. B.A. performed the experiments of the DRUM with the help of D.O.. S.B. and A.F. performed the experiments of the Taiji MR with the help of R.F.. B.A. and S.B. analyzed the data with support from S.G. and D.O.. S.G. performed the theoretical simulations (TCM) with the help of S.B. and B.A.. D.O. performed the theoretical simulation (PRECISE) with the help of S.B. and B.A.. B.A. and S.B. wrote the manuscript with contributions from all co-authors. L.P. supervised the work. All authors discussed the results and agreed on the final version of the manuscript.

Competing interests

The authors declare no competing interests.

Data availability

The data supporting the results of this study are available from the corresponding author upon reasonable request.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>

©The Author(s) 2026.

Published by Editorial Office of *Opto-Electronic Science*, Institute of Optics and Electronics, Chinese Academy of Sciences.

