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Phys. Rev. Lett. **120**, 203902 — Published 16 May 2018

DOI: [10.1103/PhysRevLett.120.203902](https://doi.org/10.1103/PhysRevLett.120.203902)

All-Optical control of linear and nonlinear energy transfer via Zeno effect

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Microresonator-based nonlinear processes are fundamental to applications including microcomb generation, parametric frequency conversion, and harmonics generation. While nonlinear processes involving either second- ($\chi^{(2)}$) or third- ($\chi^{(3)}$) order nonlinearity have been extensively studied, the interaction between these two basic nonlinear processes has seldom been reported. In this paper we demonstrate a coherent interplay between second- and third- order nonlinear processes. The parametric ($\chi^{(2)}$) coupling to a lossy ancillary mode shortens the lifetime of the target photonic mode and suppresses its density of states, preventing the photon emissions into the target photonic mode via Zeno effect. Such effect is then used to control the stimulated four-wave mixing process and realize a suppression ratio of 34.5.

Introduction.- The ancient Zeno's arrow paradox describes that a flying arrow seems to be not moving if it is instantly observed. Such concept is generalized to quantum Zeno effect (QZE) by Sudarshan et al. [1], which states that the evolution of a quantum system can be frozen by the frequent measurement. In theory, the measurement of a system will have effect on the dynamics of that system, shifting the effective energy level of a quantum system or changing its decay rate. Zeno effects inherently result from such measurement back-action. Apart from the frequent measurement, Zeno effect can be equivalently realized by a continuous strong coupling to an ancillary system, which has been proved theoretically and experimentally [2–4]. Such effects have been widely applied in quantum system control and engineering, including quantum state preparation [5–11], entanglement generation [10], autonomous quantum error correction [12, 13], and even counter-factual quantum communication [14].

In recent years, cavity nonlinear optical processes have been widely explored due to their important applications on Kerr comb generation [15–20], frequency conversion [21–24], new wavelength generation [25–28], and correlated photon pair generation [29–31]. As an analogue of a quantum system, a photonic mode in the micro-cavity can be treated as an energy level that allows multiple excitation. Therefore, we could expect the similar engineering and control of photonic mode by the Zeno effect [32, 33]. It is proposed and demonstrated that the optical switching based on Zeno effect can be realized by cavity nonlinear optical effects [34–38]. However, only one optical nonlinear process is involved in previous experiments and only the linear energy transfer in the system is controlled by the Zeno effect.

In this Letter, we demonstrate a coherent interaction between second- ($\chi^{(2)}$) and third- ($\chi^{(3)}$) order nonlinear process in an aluminum nitride (AlN) microring resonator. We show that not only the linear coupling, but also the nonlinear frequency conversion process, can be greatly suppressed by Zeno effect. Specifically, we utilize the strong second-order optical nonlinearity in AlN microring resonator to coherently couple the target high- Q

photonic mode to a low- Q ancillary mode. The coherent coupling to a lossy ancillary mode shortens the lifetime of the target photonic mode and suppresses its density of states, preventing the photon emissions into the target photonic mode via Zeno effect. We first verify the Zeno effect by probing the suppressed linear energy transfer between the external waveguide and the micro-cavity. Such Zeno effect is then used to control the nonlinear frequency conversion process inside the cavity, where the photon generated in the target mode through the stimulated four-wave mixing (FWM) process is suppressed by a factor of 34.5.

System and model.- As a material possessing both $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearity [39], AlN has been used to realize high-efficiency second-harmonic generation [28] (using $\chi^{(2)}$) and third-harmonic generation [40] (using $\chi^{(3)}$). It is worth noting that simultaneous generation of both second- and third- harmonics has also been observed in the case of extreme nonlinear optics [41], where both nonlinear optical processes originate from $\chi^{(3)}$ nonlinearity. Our experimental system contains a waveguide coupled AlN microring resonator [23, 28], which supports a variety of optical modes of different wavelengths. In the following study, we focus on three optical modes located in the telecom band (a, b, c) and one optical mode in the visible band (d). When the microring is cold, i.e. not pumped by any laser, the density of states of all these optical modes are shown in Fig. 1(a). The telecom optical modes (a, b, c) have a higher and narrower density of states because of their longer lifetime (~ 210 ps) compared to the visible mode d (~ 45 ps). The third-order nonlinear interaction leads to FWM process where two photons in mode b are converted to a pair of photons in mode a and c ($b + b \rightarrow a + c$), as illustrated in Fig. 1(a). Due to the second-order nonlinear effect, modes b, c are also participating in the three-wave mixing (TWM) process ($b + c \rightarrow d$) which involves the high-loss visible mode d . Under a pump at mode b , the system can be described

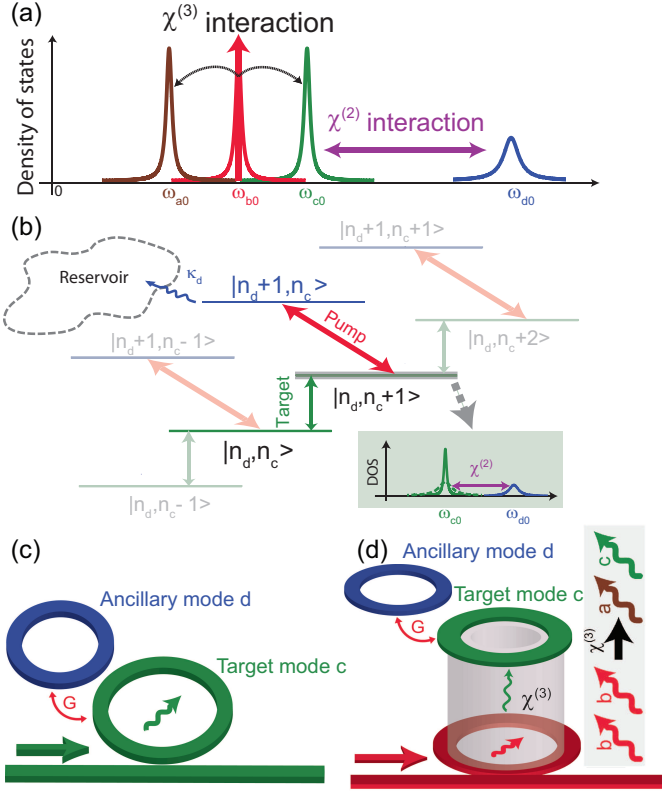


FIG. 1: Schematic and the energy diagram of optical modes coupling through $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearity. (a) The linear density of states of the system. Optical modes a , b , and c are coupled through $\chi^{(3)}$ process while b , c , and d are coupled through $\chi^{(2)}$ process. (b) The energy diagram describing the nonlinear coupling between the target photonic mode c and the ancillary photonic mode d via three-wave mixing process. $n_c(n_d)$ stands for the cavity photon number for mode c (d). Inset: the dramatically suppressed density of states for the target mode when coherently coupled to the ancillary mode. (c) Probing the Zeno effect with linear waveguide-to-microring coupling scheme. (d) Controlling nonlinear wavelength conversion process the via Zeno effect. The photon emissions into the targeted optical mode via four-wave mixing process are suppressed when the target optical mode is coupled to the dissipative ancillary mode.

by the Hamiltonian [42]

$$\frac{H}{\hbar} = \sum_{o \in \{a, b, c, d\}} \omega_{o,0} \hat{o}^\dagger \hat{o} + g_2 (\hat{b}^\dagger \hat{c}^\dagger \hat{d} + c.c.) + g_3 \left[(\hat{b}^\dagger)^2 \hat{a} \hat{c} + c.c. \right] + \epsilon_b (i \hat{b}^\dagger e^{-i\omega_b t} + c.c.) \quad (1)$$

Here, \hat{o} is the Bosonic operator for mode o with $o \in \{a, b, c, d\}$, and $\omega_{o,0}$ is the angular frequency of mode o . The intrinsic, external and total loss rate of mode o are denoted as $\kappa_{o,0}$, $\kappa_{o,1}$ and $\kappa_o = \kappa_{o,0} + \kappa_{o,1}$, respectively. The input pump field $\epsilon_b = \sqrt{2\kappa_{b,1} P_b / \hbar \omega_b}$, where P_b and ω_b are the power and frequency of the pump laser, respectively. g_2 and g_3 are the single-photon nonlinear coupling

strength for the TWM and FWM processes, respectively. The numerical values for all the relevant parameters are summarized in the supplementary materials.

Under a strong coherent pump field in mode b , the photons in mode c can be coherently converted to the high-loss mode d and get dissipated to the environment (Fig. 1(b)). For the sake of convenience, in the following context we name the long-lifetime mode c as the ‘‘target’’ photonic mode and the short-lifetime mode d as the ‘‘ancillary’’ mode. This coherent coupling between the target mode c and the ancillary mode d can be regarded as a continuous measurement of mode c . And the backaction of such measurement leads to a counter-factual result that the ability for the photons to couple into the target mode c is suppressed. This is an analogue to the Zeno effect where frequent measurement inhibits the occupation of an energy level. Alternatively, we can understand the Zeno effect as the reduction of the density of states, as shown in the inset of Fig. 1(b), due to coupling with the dissipative ancillary mode.

Linear probe of the Zeno effect.— To experimentally verify the Zeno effect induced by the TWM, we directly probe the linear energy transfer from the external waveguide to the target mode c , which has been employed in previous related works [34–38]. This linear probe scheme is shown in Fig. 1(c), where a bus waveguide is used to send photons into the target photonic mode through the evanescent coupling between waveguide and the microring.

When the dissipative ancillary mode is parametrically coupled with the target mode via the TWM process, the photons remain in the bus waveguide with suppressed coupling into the microring. Quantitatively, when scanning the frequency of the probe laser (ω_c) across the resonance of the target mode c , the transmission spectrum can be calculated as [42]

$$t_c = \left| 1 + \frac{2\kappa_{c,1}}{-i\delta_c - \kappa_c + \frac{g_2^2 |\beta|^2}{(-i\delta_d - \kappa_d)}} \right|^2. \quad (2)$$

Here, $\delta_c = \omega_{c0} - \omega_c$ and $\delta_d = \omega_{d0} - \omega_b - \omega_c$ are the frequency detunings for mode c and d , respectively, which are expressed in terms of the pump frequency ω_b and probe frequency ω_c . $\beta = \epsilon_b / [-i(\omega_{b,0} - \omega_b) - \kappa_b]$ represents the pump mode field under the non-depletion approximation. Compared with the transmission spectrum of c without the pump ($\beta = 0$) that $t_c = |1 + 2\kappa_{c,1}/(-i\delta_c - \kappa_c)|^2$, a maximum modification of the target mode’s transmission will happen when the phase-matching condition for the TWM process is fulfilled, i.e. $\delta_{pm} \triangleq \omega_{d0} - (\omega_b + \omega_{c0}) = 0$, which physically mean that mode c (with a resonant frequency ω_{c0}) and d (with a resonant frequency ω_{d0}) are resonant coupled to each other in the rotating frame of the pump laser frequency ω_b . When phase matched, the coherent coupling to the ancillary mode d introduces an extra loss term $\gamma = g_2^2 |\beta|^2 / \kappa_d$ to κ_c . When the coupling to the ancillary mode is very

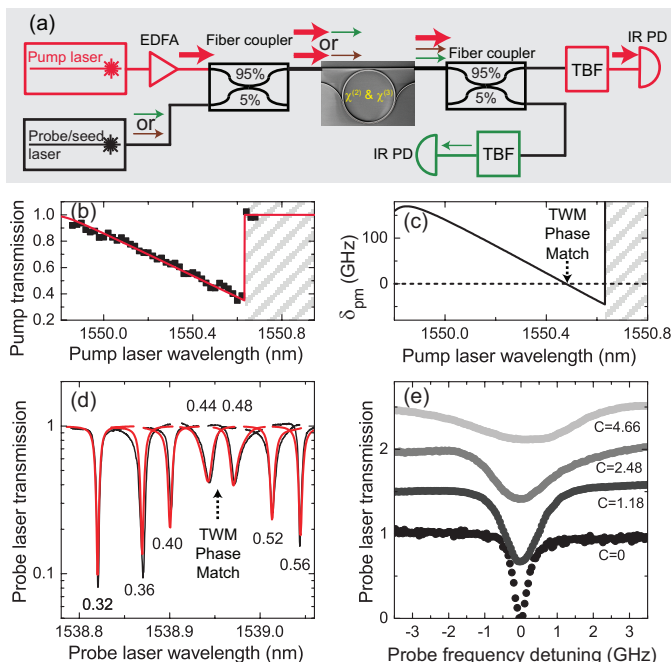


FIG. 2: Probing the Zeno effect with linear coupling scheme. (a) Experimental setup. A strong laser is used to coherently drive the optical mode b . A probe laser can either directly probe the Zeno effect using linear coupling scheme by scanning across the resonance of target photonic mode c or using nonlinear scheme by scanning across the resonance of mode a . TBF: tunable bandpass filter. (b) The transmitted power of the strong pump laser when scanning across the resonance of mode b . A triangle-like shape is observed due to the thermal effect. (c) The tuning of phase mismatch δ_{pm} during the pump laser wavelength scan. At a certain pump wavelength the phase-match condition is fulfilled. (d) The measured transmission spectra of the target photonic mode c under different pump laser wavelength. The pump laser wavelength ($\lambda_b - 1550$ nm) is labeled near each curve. When the phase mismatch gradually approaches 0, a much lower-extinction resonance dip is observed. The black curves are experimental data, which agree with the red theoretical curves. (e) The measured transmission of the target photonic mode c with phase-matching condition $\delta_{pm} = 0$ satisfied. With larger pump laser photon number (hence larger cooperativity C), the mode c 's extinction is reduced and the Zeno effect is more prominent.

strong, i.e. $\gamma \gg \kappa_c$, the coherent coupling will quickly dissipate any photons that couple into the target photonic mode c . This leads to a counter-factual result that the ability for the photons to couple into the target mode c is suppressed and results in a much larger transmission t_c , as we will show next.

The experimental setup is illustrated in Fig. 2(a). One pump laser is used to coherently drive the optical mode b , acting as the pump for the TWM process. The on-chip power of the pump laser varies from 0 to around 180 mW. In experiment, we scan the frequency of pump laser ω_b across the resonance of the pump mode b . Since the value of δ_{pm} is very important for observing the Zeno

effect, we first explain the tuning of δ_{pm} during the pump laser scan. Due to the thermal effects, a frequency red shift will happen when scanning the pump laser, which results in an extended transmission spectrum with a triangle shape [43]. Figure 2(b) shows a typical pump laser transmission spectrum. The thermal effects induced by the pump would also affect the other resonances in the same microring cavity, albeit at different rate. As a result, the value of δ_{pm} will also change during the pump laser scanning process (Fig. 2(c)). It is indicated that at a certain pump wavelength, the phase-matching condition $\delta_{pm} = 0$ is satisfied. In this condition, the target mode c will be *resonantly* coupled to the ancillary mode d and the effect of TWM will be prominent.

In the experiment, we measure the transmission spectrum of the target mode c during each scanning step of pump laser ω_b . Each step corresponds to a different phase mismatch δ_{pm} and pump laser field β . The on-chip probe laser power was set to be 0.1 mW, much weaker than the pump laser power. In the measured transmission spectra of the target mode c (Fig. 2(d)), we can see that originally the transmission is of normal Lorentzian shape, which corresponds to the situation where the TWM is not prominent due to an unsatisfied phase-matching condition ($\delta_{pm} \gg \kappa_c$). The photons from bus waveguide can be efficiently coupled to the target photonic mode, leading to a high-extinction dip in the transmission spectrum. At a certain point, when the phase mismatch $\delta_{pm} = 0$ and β is considerably large, a broadened transmission spectrum of the target mode c is observed. Noticeably, the much shallower extinction dip manifests itself as an indication of Zeno effect, with suppressed coupling between the bus waveguide and the microring. As the the pump laser wavelength changes further, the coupling to the ancillary mode gets lost due to unsatisfied phase-matching condition ($\delta_{pm} \neq 0$) and the spectrum of target mode c returns to the high-extinction Lorentzian shape. We observe in Fig. 2(d) that the simulated transmission spectra (red) of mode c matches very well with the measured curve (black), indicating a good theoretical understanding of this process. By increasing the power of the pump laser, the cooperativity [23] $C = \frac{g_2^2 |\beta|^2}{\kappa_c \kappa_d}$ of the TWM process will increase proportionally. We can therefore observe the suppression of the linear coupling with increasing fidelity, as shown in Fig. 2(e).

Controlling FWM via Zeno effect.- As the Zeno effect by TWM is confirmed by measuring the linear energy transfer in the system, we then investigate how the Zeno effect can be used to control the nonlinear processes in the cavity. Specifically, we study the suppression of photon generation in the target mode through the stimulated FWM, which is a nonlinear energy transfer process, as depicted in Fig. 1(d). By controlling the temperature of the photonic chip, we can determine whether the phase-matching condition of the TWM process can be fulfilled [28]. As we show next, by switching on and off the TWM process, we can control the FWM efficiency by more than one order of magnitude.

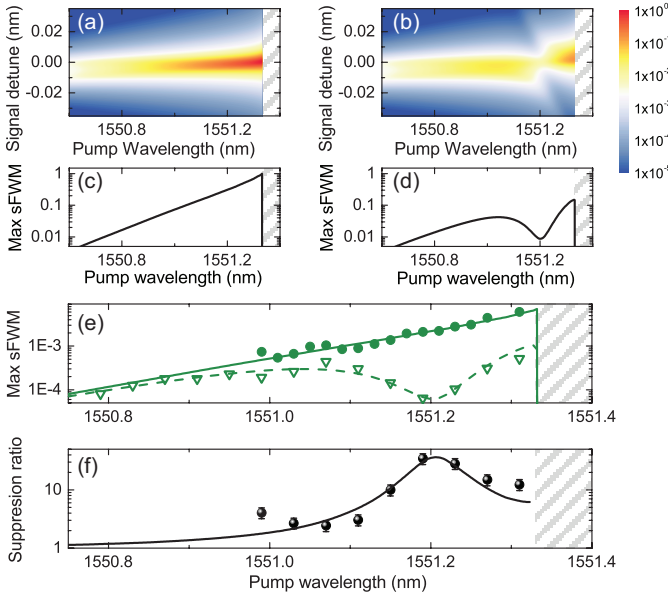


FIG. 3: Numerical simulation and experimental measurement of the suppressed four-wave mixing efficiency due to Zeno effect. (a-b) The intensity of stimulated four-wave mixing in target mode c (a) with or (b) without $\chi^{(2)}$ process. The signal laser is scanning across mode a while the pump laser is scanning across mode b . (c-d) The maximum stimulated four-wave mixing intensity as the pump laser scanning across mode b when $\chi^{(2)}$ interaction (c) does not show up (d) shows up. (e) Experimental result of the stimulated four-wave mixing efficiency with and without $\chi^{(2)}$ interaction. The solid circles (without $\chi^{(2)}$) and open triangles (with $\chi^{(2)}$) represent the experimental measurements while the solid (without $\chi^{(2)}$) and dashed (with $\chi^{(2)}$) lines corresponds to theoretical fitting. (f) The suppression ratio of four-wave mixing efficiency as a function of pump wavelength.

At certain temperature, the phase-matching condition is not fulfilled, i.e. $g_2^2 |\beta|^2 / \delta_d \ll \kappa_c$, and TWM's effect is negligible. In this case, we can study the pure FWM process, i.e. ignoring the $\chi^{(2)}$ related term in the system's Hamiltonian. As mode b is strongly pumped by a pump laser with frequency ω_b , we stimulate the FWM process by sending a seed laser around mode a and record the generated light intensity in the target mode c . The nonlinear energy transfer to the target mode c through the FWM process can be calculated by [42]

$$P_{c,out} = \frac{2\kappa_{a,1}}{\delta_a^2 + \kappa_a^2} \frac{2\kappa_{c,1}}{\delta_c^2 + \kappa_c^2} \frac{\omega_c}{\omega_a} |\beta^4| g_3^2 P_{a,in}, \quad (3)$$

where $P_{a,in}$ is the input power of the seed laser around mode a . During the scanning of pump laser ω_b , the pump laser frequency gradually approach the resonance of mode b and suddenly jump out of resonance due to thermal bistability, which is already explained and shown in Fig. 2(b). By considering the thermal induced frequency shift into Eq. (3), the normalized efficiency of the stimulated FWM as a function of both pump laser wavelength and seed laser wavelength can be es-

timated, as shown in Fig. 3(a). By extracting the maximum stimulated FWM efficiency at each pump wavelength [Fig. 3(c)], we observe that the photon emissions in the target mode c through stimulated FWM increases monotonically with the pump wavelength approaching the resonance of mode b .

By tuning the device's temperature, we can fulfill the phase-matching condition for TWM process. We then consider the case when the TWM exists and couples the target mode c with an ancillary mode d . In this case, the nonlinear energy transfer to the target mode is modified as

$$P'_{c,out} = P_{c,out} / \left| 1 + \frac{g_2^2 |\beta|^2}{(-i\delta_d - \kappa_d)(-i\delta_c - \kappa_c)} \right|^2. \quad (4)$$

The additional term $\frac{g_2^2 |\beta|^2}{(-i\delta_d - \kappa_d)(-i\delta_c - \kappa_c)}$ due to coherent coupling between mode c and d can lead to a dramatic decrease of the nonlinear energy transfer efficiency. The numerical simulation of the stimulated FWM process when the TWM is involved is shown in Fig. 3(b). Compared to Fig. 3(a), a clear suppression of the efficiency is observed when the phase-matching condition ($\delta_{pm} = 0$) of TWM process is satisfied. Again we extract the maximum stimulated FWM efficiency at each pump wavelength, as shown in Fig. 3(d). A clear dip of FWM efficiency appears when the phase-matching condition is satisfied. This suppressed FWM efficiency signifies the appearance of Zeno effect in the nonlinear energy transfer process.

The experimental results about such suppression of stimulated FWM are summarized in Figs. 3(e) and (f). When the TWM is negligible, the measured stimulated FWM efficiency depends on the pump wavelength as shown by the solid circles in Fig. 3(e). In contrast, when the phase-matching condition of TWM process is fulfilled, a clear suppression of FWM efficiency is shown by the open triangles as depicted in Fig. 3(e). The solid and dashed lines come from the theoretical fitting and the used fitting parameters are summarized in the supplementary materials. To quantify the suppression of nonlinear frequency conversion process induced by the Zeno effect, we plot the suppression ratio against the pump wavelength, as shown in Fig. 3(f). It can be observed that at a certain pump wavelength, when the phase-matching of TWM is satisfied, the highest suppression ratio of 34.5 is achieved. This large suppression ratio clearly demonstrates the control of the system's nonlinear dynamics utilizing the Zeno effect. Note that the experimental result deviates slightly from the theoretical curve at the pump wavelength close to 1551.0 nm. This could be induced by the weak back-scattering inside the microring, which is not considered in the theoretical model.

Conclusion.- We have investigated the all-optical control of linear and nonlinear energy transfer in a nonlinear microring cavity by combining the TWM and FWM processes. We show that the efficiency of stimulated four-wave mixing is suppressed by a factor of 34.5 through

Zeno control, which is implemented by coherently coupling the target photonic mode to the high-loss ancillary mode. The demonstrated Zeno control on a photonic chip can be a useful tool for tailoring the local mode's density of state and the dispersion, suppressing or enhancing the nonlinear optics process. The ample nonlinear effects in the micro-cavity may also lead to potential applications in quantum nonlinear optics, such as entangled photon pairs generation [44, 45] and *in-situ* frequency conversion [23, 24, 46] into other wavelength bands.

Acknowledgments

Facilities used for device fabrication were supported by Yale SEAS cleanroom and Yale Institute for Nanoscience

and Quantum Engineering. The authors thank Michael Power and Dr. Michael Rooks for assistance in device fabrication. We acknowledge funding support from an AFOSR MURI grants (FA9550-15-1-0029, FA9550-15-1-0015), LPS/ARO grant (W911NF-14-1-0563), NSF EFRI grant (EFMA-1640959), DARPA SCOUT program and the Packard Foundation. L.J. acknowledges support from the Alfred P. Sloan Foundation (BR2013-049) and the Packard Foundation (2013-39273).

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- [1] B. Misra and E. C. G. Sudarshan, *The Zeno's paradox in quantum theory*, *Journal of Mathematical Physics* **18**, 756 (1977).
- [2] A. G. Kofman and G. Kurizki, *Universal Dynamical Control of Quantum Mechanical Decay: Modulation of the Coupling to the Continuum*, *Physical Review Letters* **87**, 270405 (2001), [arXiv:0107076 \[quant-ph\]](#).
- [3] P. Facchi, D. A. Lidar, and S. Pascazio, *Unification of dynamical decoupling and the quantum Zeno effect*, *Physical Review A* **69**, 032314 (2004), [arXiv:0303132 \[quant-ph\]](#).
- [4] F. Schäfer, I. Herrera, S. Cherukattil, C. Lovecchio, F. Cataliotti, F. Caruso, and A. Smerzi, *Experimental realization of quantum zeno dynamics*, *Nature Communications* **5**, 3194 (2014), [arXiv:1309.1552](#).
- [5] G. J. Milburn, *Quantum Zeno effect and motional narrowing in a two-level system*, *Journal of the Optical Society of America B* **5**, 1317 (1988).
- [6] W. M. Itano, D. J. Heinzen, J. J. Bollinger, and D. J. Wineland, *Quantum Zeno effect*, *Physical Review A* **41**, 2295 (1990).
- [7] A. G. Kofman and G. Kurizki, *Quantum Zeno effect on atomic excitation decay in resonators*, *Physical Review A* **54**, R3750 (1996).
- [8] J. M. Raimond, C. Sayrin, S. Gleyzes, I. Dotsenko, M. Brune, S. Haroche, P. Facchi, and S. Pascazio, *Phase Space Tweezers for Tailoring Cavity Fields by Quantum Zeno Dynamics*, *Physical Review Letters* **105**, 213601 (2010), [arXiv:1007.4942](#).
- [9] A. Signoles, A. Facon, D. Grosso, I. Dotsenko, S. Haroche, J.-M. Raimond, M. Brune, and S. Gleyzes, *Confined quantum Zeno dynamics of a watched atomic arrow*, *Nature Physics* **10**, 715 (2014).
- [10] G. Barontini, L. Hohmann, F. Haas, J. Esteve, and J. Reichel, *Deterministic generation of multiparticle entanglement by quantum Zeno dynamics*, *Science* **349**, 1317 (2015).
- [11] L. Bretheau, P. Campagne-Ibarcq, E. Flurin, F. Mallet, and B. Huard, *Quantum dynamics of an electromagnetic mode that cannot contain N photons*, *Science* **348**, 776 (2015), [arXiv:1505.04238](#).
- [12] N. Erez, Y. Aharonov, B. Reznik, and L. Vaidman, *Correcting quantum errors with the Zeno effect*, *Phys. Rev. A* **69**, 062315 (2004), [arXiv:0309162 \[quant-ph\]](#).
- [13] G. a. Paz-Silva, a. T. Rezakhani, J. M. Dominy, and D. a. Lidar, *Zeno Effect for Quantum Computation and Control*, *Phys. Rev. Lett.* **108**, 080501 (2012).
- [14] Y. Cao, Y.-H. Li, Z. Cao, J. Yin, Y.-A. Chen, H.-L. Yin, T.-Y. Chen, X. Ma, C.-Z. Peng, and J.-W. Pan, *Direct counterfactual communication via quantum Zeno effect*, *Proceedings of the National Academy of Sciences* **114**, 4920 (2017).
- [15] P. Del'Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth, and T. J. Kippenberg, *Optical frequency comb generation from a monolithic microresonator*, *Nature* **450**, 1214 (2007), [arXiv:0708.0611](#).
- [16] T. Herr, V. Brasch, J. D. Jost, C. Y. Wang, N. M. Kondratiev, M. L. Gorodetsky, and T. J. Kippenberg, *Temporal solitons in optical microresonators*, *Nature Photonics* **8**, 145 (2013), [arXiv:1211.0733](#).
- [17] X. Xue, Y. Xuan, Y. Liu, P.-H. Wang, S. Chen, J. Wang, D. E. Leaird, M. Qi, and A. M. Weiner, *Mode-locked dark pulse Kerr combs in normal-dispersion microresonators*, *Nature Photonics* **9**, 594 (2015).
- [18] Q.-F. Yang, X. Yi, K. Y. Yang, and K. Vahala, *Stokes solitons in optical microcavities*, *Nature Physics* **1**, 1 (2016), [arXiv:1606.05259](#).
- [19] M. Yu, Y. Okawachi, A. G. Griffith, M. Lipson, and A. L. Gaeta, *Mode-locked mid-infrared frequency combs in a silicon microresonator*, *Optica* **3**, 854 (2016), [arXiv:1604.06501](#).
- [20] X. Guo, C.-L. Zou, H. Jung, Z. Gong, A. Bruch, L. Jiang, and H. X. Tang, *Efficient visible frequency comb generation via Cherenkov radiation from a Kerr microcomb*, *Arxiv:1704.04264* (2017), [arXiv:1704.04264](#).
- [21] J. Huang and P. Kumar, *Observation of quantum frequency conversion*, *Physical Review Letters* **68**, 2153 (1992).
- [22] K. De Greve, L. Yu, P. L. McMahon, J. S. Pelc, C. M. Natarajan, N. Y. Kim, E. Abe, S. Maier, C. Schneider, M. Kamp, S. Höfling, R. H. Hadfield, A. Forchel, M. M. Fejer, and Y. Yamamoto, *Quantum-dot spin-photon entanglement via frequency downconversion to telecom wavelength*, *Nature* **491**, 421 (2012).
- [23] X. Guo, C.-L. Zou, H. Jung, and H. X. Tang, *On-Chip*

- Strong Coupling and Efficient Frequency Conversion between Telecom and Visible Optical Modes*, *Physical Review Letters* **117**, 123902 (2016).
- [24] Q. Li, M. Davanço, and K. Srinivasan, *Efficient and low-noise single-photon-level frequency conversion interfaces using silicon nanophotonics*, *Nature Photonics* **10**, 406 (2016).
- [25] S. M. Spillane, T. J. Kippenberg, and K. J. Vahala, *Ultralow-threshold Raman laser using a spherical dielectric microcavity*, *Nature* **415**, 621 (2002).
- [26] T. Carmon and K. J. Vahala, *Visible continuous emission from a silica microphotonic device by third-harmonic generation*, *Nature Physics* **3**, 430 (2007).
- [27] J. U. Fürst, D. V. Strelakov, D. Elser, M. Lassen, U. L. Andersen, C. Marquardt, and G. Leuchs, *Naturally Phase-Matched Second-Harmonic Generation in a Whispering-Gallery-Mode Resonator*, *Physical Review Letters* **104**, 153901 (2010), arXiv:0912.3864 .
- [28] X. Guo, C.-L. Zou, and H. X. Tang, *Second-harmonic generation in aluminum nitride microrings with 2500%/W conversion efficiency*, *Optica* **3**, 1126 (2016).
- [29] S. Clemmen, K. P. Huy, W. Bogaerts, R. G. Baets, P. Emplit, and S. Massar, *Continuous wave photon pair generation in silicon-on-insulator waveguides and ring resonators*, *Optics Express* **17**, 16558 (2009).
- [30] J. W. Silverstone, D. Bonneau, K. Ohira, N. Suzuki, H. Yoshida, N. Iizuka, M. Ezaki, C. M. Natarajan, M. G. Tanner, R. H. Hadfield, V. Zwiller, G. D. Marshall, J. G. Rarity, J. L. O'Brien, and M. G. Thompson, *On-chip quantum interference between silicon photon-pair sources*, *Nature Photonics* **8**, 104 (2013).
- [31] X. Guo, C.-l. Zou, C. Schuck, H. Jung, R. Cheng, and H. X. Tang, *Parametric down-conversion photon-pair source on a nanophotonic chip*, *Light Sci Appl.* **6**, e16249 (2017), arXiv:1603.03726 .
- [32] C.-L. Zou, X.-D. Chen, X. Xiong, F.-W. Sun, X.-B. Zou, Z.-F. Han, and G.-C. Guo, *Photonic simulation of system-environment interaction: Non-Markovian processes and dynamical decoupling*, *Physical Review A* **88**, 063806 (2013), arXiv:1303.2811 .
- [33] X.-s. Ma, X. Guo, C. Schuck, K. Y. Fong, L. Jiang, and H. X. Tang, *On-chip interaction-free measurements via the quantum Zeno effect*, *Physical Review A* **90**, 042109 (2014).
- [34] Y. H. Wen, O. Kuzucu, M. Fridman, A. L. Gaeta, L.-W. Luo, and M. Lipson, *All-Optical Control of an Individual Resonance in a Silicon Microresonator*, *Physical Review Letters* **108**, 223907 (2012).
- [35] K. T. McCusker, Y.-P. Huang, A. S. Kowligy, and P. Kumar, *Experimental Demonstration of Interaction-Free All-Optical Switching via the Quantum Zeno Effect*, *Physical Review Letters* **110**, 240403 (2013), arXiv:1301.7631 .
- [36] S. M. Hendrickson, C. N. Weiler, R. M. Camacho, P. T. Rakich, A. I. Young, M. J. Shaw, T. B. Pittman, J. D. Franson, and B. C. Jacobs, *All-optical-switching demonstration using two-photon absorption and the Zeno effect*, *Physical Review A* **87**, 023808 (2013).
- [37] Y.-Z. Sun, Y.-P. Huang, and P. Kumar, *Photonic Nonlinearities via Quantum Zeno Blockade*, *Phys. Rev. Lett.* **110**, 223901 (2013).
- [38] J.-Y. Chen, Y. M. Sua, Z.-T. Zhao, M. Li, and Y.-P. Huang, *Observation of Quantum Zeno Blockade on Chip*, *Sci. Rep.* **7**, 14831 (2017), arXiv:1703.09830 .
- [39] H. Jung, R. Stoll, X. Guo, D. Fischer, and H. X. Tang, *Green, red, and IR frequency comb line generation from single IR pump in AlN microring resonator*, *Optica* **1**, 396 (2014), arXiv:1410.5018 .
- [40] J. B. Surya, X. Guo, C.-L. Zou, and H. X. Tang, *Efficient third-harmonic generation in composite aluminum nitride/silicon nitride microrings*, *Optica* **5**, 103 (2018), arXiv:1712.00059 .
- [41] T. Tritschler, O. D. Mücke, M. Wegener, U. Morgner, and F. X. Kärtner, *Evidence for Third-Harmonic Generation in Disguise of Second-Harmonic Generation in Extreme Nonlinear Optics*, *Physical Review Letters* **90**, 217404 (2003).
- [42] See Supplemental Material for detailed theoretical derivation and experimental parameters.
- [43] T. Carmon, L. Yang, and K. Vahala, *Dynamical thermal behavior and thermal self-stability of microcavities*. *Optics express* **12**, 4742 (2004).
- [44] D. Grassani, S. Azzini, M. Liscidini, M. Galli, M. J. Strain, M. Sorel, J. E. Sipe, and D. Bajoni, *Micrometer-scale integrated silicon source of time-energy entangled photons*, *Optica* **2**, 88 (2015).
- [45] J. W. Silverstone, R. Santagati, D. Bonneau, M. J. Strain, M. Sorel, J. L. O'Brien, and M. G. Thompson, *Qubit entanglement between ring-resonator photon-pair sources on a silicon chip*, *Nature Communications* **6**, 7948 (2015).
- [46] Z. Vernon, M. Liscidini, and J. E. Sipe, *Quantum frequency conversion and strong coupling of photonic modes using four-wave mixing in integrated microresonators*, *Physical Review A* **94**, 023810 (2016), arXiv:1606.01582 .