Stochastic and quantum phenomena in microcombs

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***Abstract*— Optical microresonators have the capability to trap laser light by total internal reflection for a duration higher than a microsecond. In these ultra-high Q optical cavities, the small volume of confinement, high photon density and long photon lifetime ensures a strong light-matter interaction, which can trigger various effects mediated by optical nonlinearities. In this communication, we report some of the latest advances related to the understanding of stochastic and quantum phenomena in optical microresonators, and we relate them as well to some of the main applications in photonic engineering.**

Keywords—Microcombs, whispering-gallery mode resonators, nonlinear photonics, microwave photonics, quantum photonics.

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I. INTRODUCTION

In recent years, the optical frequency comb technology has been the focus an intense research activity [1-3]. In the most basic configuration, a continuous wave laser pumps a whispering-gallery mode resonator with ultra-high quality factor at the near-infrared wavelength of 1550 nm. The long photon lifetime and small modal volume permit strong nonlinear interactions of photons via four-wave mixing. As a consequence, a definite set of eigenmodes is excited in the spectral domain, yielding a quasi-equidistant set of frequencies – a Kerr optical frequency comb, or *microcomb* – whose properties differ as a function of the system parameters. Their intermodal spectral spacing generally corresponds to the free-spectral range (FSR), or a multiple. Both stochastic and quantum noise plays a major role for the technological applications of these combs.

II. STOCHASTIC AND QUANTUM NOISE

Kerr optical frequency combs are generated in resonators with eigenfrequencies $\omega_l \cong \omega_0 + l\Omega_R$, where ω_0 is the eigenfrequency of the pumped mode and Ω_R is the free-spectral range of the chipscale resonator. The grid spacing can range from 1 GHz to 1 THz depending on the size of the resonator. The pumped mode is labeled with the eigenumber $l = 0$, while the neighboring sidemodes are expanded as $l = \pm 1, \pm 2, \pm 3$. Two equivalent approaches to describe the deterministic dynamics of these combs are coupled mode (or spectrotemporal) equations and the Lugiato-Lefever (or spatiotemporal) formalism. Both evidence the emergence of various dissipative intracavity patterns such as Turing rolls, as well as various types of bright, dark, and breather solitons. When these combs are designed for metrology purposes, the stochastic perturbations of the comb have to be accounted for to evaluate the stability of the phase coherence across the comb. In particular, it is known that after photodetection, the output signal is a microwave with a frequency that corresponds to the intermodal spectral spacing of the comb, and its harmonics. The phase noise properties of this microwave are essentially defined by those of the comb, compounded by the noise generated by the photodetection process. The analysis of these phenomena requires the use of stochastic differential equations (SDE) techniques.

Kerr optical frequency combs involve interactions among individual photons, and therefore, can feature genuinely quantum properties when pumped below or above threshold [4]. Indeed, quantum Kerr combs arose in recent years as one of the leading platform for quantum photonics. In the literature, there are several experimental works that evidenced a plethora of quantum phenomena, such as squeezing [5], generation of multiphoton entangled quantum states [6], energy-time entanglement covering multiple resonances [7], high-dimensional entangled quantum states [8], high-dimensional one-way quantum processing implemented on D-level cluster states [9], or entangled photon pair source for optical quantum communications networks [10].These experimental results provide some of the most convincing examples of the kind of quantum states that are needed in quantum communications. In particular, the most noteworthy benefits of quantum optical combs are high-dimensionality, operation at room-temperature, operation at standard telecom wavelengths, and operation with off-the shelf, readily available components.

The eigenfrequencies are resonant, and these resonances are narrow enough such that they can be redefined as frequency bins, which are orthonormal eigenstates that can be defined as $|l\rangle$ with the orthonormalization condition $\langle l|l'\rangle = \delta_{l,l'}$. Once a pair of photons is converted into a pair of twin photons via the interaction $2\hbar\omega_0 \rightarrow \hbar\omega_l + \hbar\omega_{-l}$, the photon pair is entangled as $|\psi\rangle = \sum_{l=1}^{L} c_l |-l\rangle|+l\rangle$ with $\sum_{l=1}^{L} |c_l|^2 = 1$, where $|-l\rangle|+l\rangle$ is the quantum state consisting of one photon being in the eigenmode $-l$ and its twin being in the eigenmode l.

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It therefore appears that one of the main advantages of microresonator-based twin-photon generation is their capability to create quantum superposition in very high-dimensional Hilbert spaces, since here l can be as high as $L = 100$. An important area of current research is therefore to gain a deeper understanding of the generation of this quantum state, as well as its processing via computing protocols.

III. Conclusion

The study of the nonlinear, stochastic and quantum properties of microcombs is one of the most active topic in contemporary photonics. In particular, understanding how to tame stochastic noise while harnessing the quantum one is arising as one of the main challenge in the field. Applications in the areas of time-frequency metrology and quantum communication systems are generating a strong technological incentive that justifies sustained interest in this research area.

References

[1] Y. K. Chembo, "Kerr optical frequency combs: Theory, applications and perspectives", Nanophotonics 5, 214 (2016).

[2] G. Lin, A. Coillet and Y. K. Chembo, "Nonlinear phenomena in ultra-high Q optical whispering gallery mode resonators," Adv. Opt. Phot. 9, 828 (2017).

[3] A. Pasquazi, M. Peccianti, L. Razzari, D. J. Moss, S. Coen, M. Erkintalo, Y. K. Chembo, T. Hansson, S. Wabnitz, P. Del'Haye, X. Xue, A. M. Weiner, and R. Morandotti, "Micro-Combs: a Novel Generation of Optical Sources," Phys. Rep. 729, 1 (2018)

[4] Y. K. Chembo, "Quantum dynamics of Kerr optical frequency combs below and above threshold: Spontaneous four-wave mixing, entanglement, and squeezed states of light", Phys. Rev. A 93, 033820 (2016).

[5] A. Dutt, K. Luke, S. Manipatruni, A. L. Gaeta, P. Nussenzveig, and M. Lipson, "On-Chip Optical Squeezing," Phys. Rev. Applied 3, 044005 (2015).

[6] C. Reimer, M. Kues, P. Roztocki, B. Wetzel, F. Grazioso, B. E. Little, S. T. Chu, T. Johnston, Y. Bromberg, L. Caspani, D. J. Moss, and R. Morandotti, "Generation of multiphoton entangled quantum states by means of integrated frequency combs," Science 351, 1176 (2016).

[7] J. A. Jaramillo-Villegas, P. Imany, O. D. Odele, D. E. Leaird, Z.-Y. Ou, M. Qi, and A. M. Weiner, "Persistent energy–time entanglement covering multiple resonances of an on-chip biphoton frequency comb," Optica 4, 655 (2017)

[8] M. Kues, C. Reimer, P. Roztocki, L. Romero Cortes, S. Sciara, B. Wetzel, Y. Zhang, A. Cino, S. T. Chu, B. E. Little, D. J. Moss, L. Caspani, J. Azana, and R. Morandotti, "On-chip generation of high-dimensional entangled quantum states and their coherent control," Nature 546, 622 (2017).

[9] C. Reimer, S. Sciara, P. Roztocki, M. Islam, L. Romero Cortes, Y. Zhang, B. Fischer, S. Loranger, R. Kashyap, A. Cino, S. T Chu, B. E Little, D. J Moss, L. Caspani, W. J Munro, J. Azana, M. Kues, and R. Morandotti, "High-dimensional one-way quantum processing implemented on d-level cluster states," Nat. Phys. 15, 148 (2019).

[10] X. Lu, Q. Li, D. A. Westly, G. Moille, A. Singh, V. Anant and K. Srinivasan, "Chip-integrated visible–telecom entangled photon pair source for quantum communication," Nat. Physics 15, 373 (2019).