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Ultra-miniaturized non-classical light sources for quantum devices

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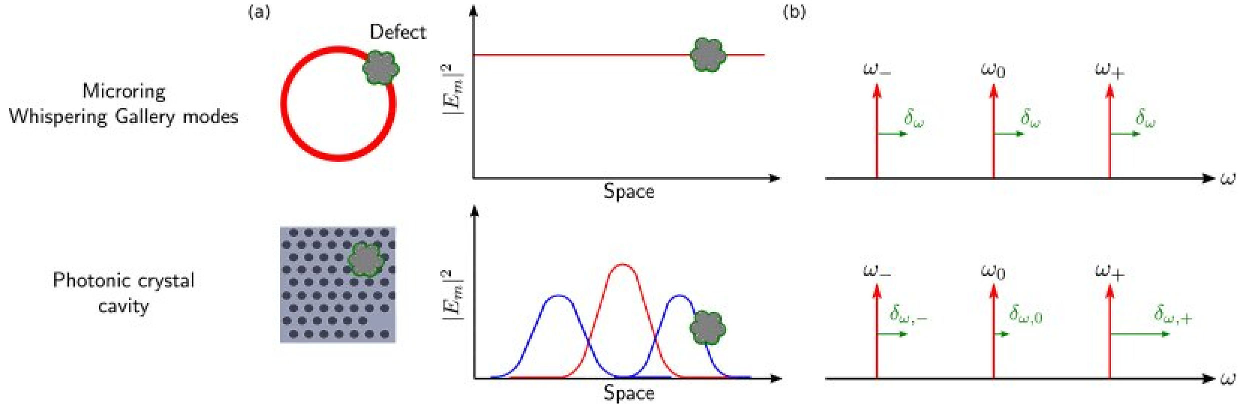

Effect of a defect on the cavity eigenfrequencies. (a) Schematics of a microring resonator and a 2D photonic crystal cavity and corresponding mode field intensities in the azimuthal/longitudinal directions. The gray "cloud" represents a defect. (b) Consequence on the eigenfrequencies ω (red arrows). Horizontal green lines show the same (different) spectral shift δω (δω,k) in the resonance frequencies for ring resonators (PhC) caused by the defect on the top (bottom) figure, depending on the spatial profile of the modes. Credit: *IEEE Journal of Selected Topics in Quantum Electronics* (2022). DOI: 10.1109/JSTQE.2022.3229164

Non-classical states of light such as single photons and entangled photons are key ingredients for chips dedicated to quantum computation, quantum sensing, quantum measurement, etc. Fabrication of a traditional chip is hard, but with billions of dollars of specialized equipment (and guys in white bunny suits) it can be done. Fabrication of a quantum chip is even harder. In addition, sources of non-linear light are needed, and making these light sources fabricable is essential.

Construction of ≈ 20 µm non-classical light sources is demonstrated in "Canonical Resonant Four-Wave-Mixing in Photonic Crystal Cavities: Tuning, Tolerances and Scaling." The paper hails from the four corners of France plus the US National Institute of Standards and Technology (NIST) in Maryland. They start by discussing quantum resonators that generate non-classical states of light, like the microring and photonic crystal (PhC) cavity.

The researchers had made the "exotic" choice, the photonic crystal, and developed the first Optical Parametric Oscillator (OPO) operating at room temperature with a microwatt-level continuous wave pump. Indium Gallium Phosphide (InGaP) is used, rather than silicon. The test vehicle was designed to operate in the telecom spectral range though the emission spectrum can be engineered easily. They demonstrated repeatability in the fabrication process and the ability to reach efficient parametric conversion using very low pump power (≈ 40 µW), a key to conserving energy.

The device emits correlated photons, and quadrature-squeezed vacuum below, and while below and approaching a threshold, both being resources for quantum information. Above the threshold, the OPO emits correlated beams of coherent light by efficiently converting the power of the pump. This is the point where this publication starts. It is a "Chapter 2" as it were, providing more measurements on the OPO and examining issues like tuning, quality, tolerances, and scaling.

The paper, published in the *IEEE Journal of Selected Topics in Quantum Electronics*, is quite a read. Photons from the pump decay, squeezed light, whispering gallery modes, degenerate cases—classic science fiction. But wait, a plot twist: time-energy entangled photon pairs and conditions of "gentle" confinement. Woah.

The delightful language of photonic integrated circuits for quantum computing belies its seriousness. There's a reason that NIST, the Commerce Department Lab, is involved. NIST oversees cybersecurity technology. If bad actors get their quantum chips made before we do, then they can break any code. As the authors explain, the quantum advantage vis-a-vis today's digital chips is that quantum mechanics within a crystal allows for non-exponential scaling where fantastically complex math is concerned.

So back to photonic crystal cavities we go.

The paper's Section II is a deep-dive into the concept of canonical resonant Four-Wave-Mixing (FWM), meaning FWM occurs in a cavity allowing the interaction of only three modes (four in the non-degenerate case). The use of "canonical" here refers to the details of a Hamiltonian matrix transformation (math).

They defend their choice of a PhC cavity visa vie ring resonators, when considering structural disorder. They show how to create a resonator with a prescribed number of modes, and not more. This is important because extra modes imply a larger volume for the resonator. More importantly, each of these modes can be controlled independently, i.e., their frequency spacing, and quality factor can be designed to be different.

This translates into a superior control over the parametric processes, ensuring that only the desired interactions efficiently take place, thereby suppressing parasitic effects. Admitted, practically achieving this degree of control is extremely challenging.

In Section III the authors compare the properties of three geometries of PhC multimode resonators. The photonic crystal is made of a 200 nm thin layer of $In_{0.5}Ga_{0.5}P$ with a two-dimensional pattern of holes.

Section IV reports on a detailed statistical analysis of a batch of new devices. The authors show that structural disorder induces uncorrelated fluctuations of the modes of the same resonator. Here is where the tuning mechanism is discussed in detail. In Section V the authors compare theory and experiment on parametric oscillation in 11 OPOs, with good agreement on threshold and slope efficiency.

More information: Alexandre Chopin et al, Canonical Resonant Four-Wave-Mixing in Photonic Crystal Cavities : tuning, tolerances and scaling, *IEEE Journal of Selected Topics in Quantum Electronics* (2022). DOI: 10.1109/JSTQE.2022.3229164

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