Rabi-Like Oscillations in Photon Pair Correlations

CNF Project Number: 1997-11
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Primary CNF Tools Used: JEOL 9500, UNAXIS 770, YES Asher

Abstract:

We have produced a new quantum coherence phenomenon via photon generation within ultra-high-*Q* silicon microdisks. The Rayleigh-scattering-induced strong coupling of counterpropagating modes opens up discrete energy pathways for pair creation, leading to Rabi-like oscillations in the biphoton second-order coherence. Additionally, the pump resonance splitting may be used to coherently control the internal structure of the oscillations by enabling the quantum interference between multiple creation pathways.

Summary of Research:

Optical microresonators have proven to be excellent chip-scale sources of heralded single photons and entangled photon pairs [1-3]. In this report, we will show that they possess a new and fascinating functionality not seen in any other system to date. We propose and demonstrate that the Rayleigh-scattering-induced strong coupling between counterpropagating cavity modes within microresonators can be used to achieve Rabi-like oscillations in the biphoton second-order coherence.

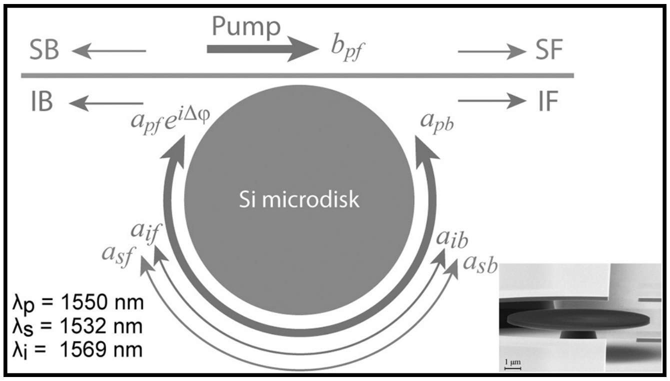


Figure 1: Illustration of the intracavity physics leading to oscillations in the biphoton correlations. The input pump field is evanescently coupled into intracavity pump mode, leading to spontaneous four-wave mixing. The intracavity fields are labeled as, a_{jk}, where j = p, s, i for pump, signal and idler, respectively, and k = f, b denotes forward and backward. Signal (S) and idler (I) photons are coupled from the optical cavity into the waveguide in the forward (F) and backward (B) directions, resulting in four path configurations for cross-correlations. The inset depicts a scanning electron microscope image of the suspended silicon microdisk.

Figure 1 illustrates the system and the intracavity processes that lead to this phenomenon. A scanning electron microscope image of the actual silicon microdisk is shown in the inset, with a radius of 4.5 µm, thickness of 260 nm and average intrinsic optical *Q*s above one million. The device pattern was defined using the JEOL 9500 electron beam lithography system and transferred to the silicon layer using the UNAXIS 770 etcher. A pump laser is evanescently coupled into the microdisk, wherein cavity-enhanced spontaneous four-wave mixing (SFWM) occurs between the pump (p), signal (s) and idler (i) modes. In the absence of a coupling mechanism, each cavity mode admits two degenerate eigenmodes, forward and backward traveling. However, the extreme enhancement of the light-matter interaction strength in our system enables the small Rayleigh scattering at the boundary of the cavity to induce a strong coupling between the forward and backward modes, which manifests as the well-known resonance splitting [4]. Thus, the single photons may coherently cycle between forward and backward modes, as depicted by the use of bidirectional arrows in Figure 1. The photons are coupled out of the cavity and detected by superconducting nanowire single-photon detectors. A coincidence counter histograms the detection of photon pairs as a function of their arrival time differences, which yields the biphoton coherence waveforms, $g^{(2)}(\tau)$, seen in Figures 2-4.

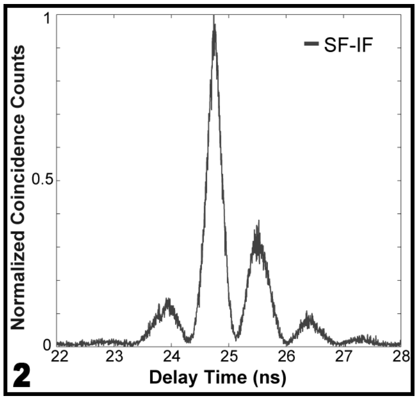
In analogy to the formation of dressed states in an atom-cavity system [5], the strong coupling between counterpropagating modes implies that it is no longer possible to describe forward or backward independently. And given that the biphoton coherence properties are established by the cavity [6], we expect that the strong coupling must be imprinted on the biphoton correlations. This is precisely what we observe in Figures 2-4.

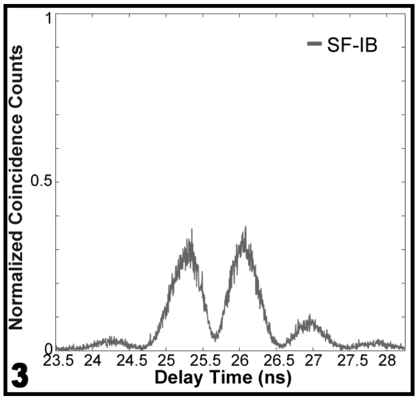
The measured biphoton correlations display a stunning difference compared with other chip-scale sources, which exhibit monotonically decaying profiles. In Figure 2, we see that at certain delay times the photon pairs in the signal forward-idler forward (SF-IF) channels are highly correlated, then diminish to nearly zero, before being revived in an oscillatory manner.

Figure 3 depicts the biphoton correlations between the signal forward-idler backward (SF-IB) channels. Here, we clearly see a complementary effect compared to Figure 2. Taken together, we understand that as the correlations are diminishing in the copropagating configuration they are intensifying in the counterpropagating configuration, and vice versa. Thus biphoton correlations oscillate between configurations, and an estimate of the modulation period infers that the process originates from a resonance splitting of approximately 1 GHz, which is in good agreement with the measured splitting of the signal and idler resonances.

In Figure 4, we measure the biphoton correlations for the SF-IB configuration using two different values of pump-cavity frequency detuning. Although we are measuring the same channel configuration, we are able to achieve oscillatory features that are completely out of phase with each other. Varying the detuning causes the counterpropagating intracavity pump fields to develop different relative phases (see Figure 1), which may be used to conveniently control the oscillations.

We have shown for the first time that optical microresonators can be used to achieve Rabi-like oscillations in photon pair correlations. We have also demonstrated that the oscillations may be controlled by varying the relative phase of the counterpropagating intracavity pump fields. Given the vital role that second-order coherence assumes in many quantum photonic systems [7], we expect that this new phenomenon will have a broad impact. Photon pairs produced by SFWM are intrinsically time-energy entangled, and we have demonstrated that their correlation properties may be highly coupled to the path configuration of our system. Consequently, we envision that our device may be used to explore quantum state generation and new entanglement properties, as well as the potential for quantum logic operations.





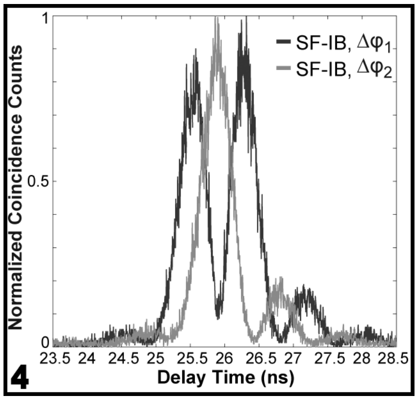


Figure 2, top: Cross-correlation between signal forward (SF) and idler forward (IF). Figure 3, middle: Cross-correlation between signal forward (SF) and idler backward (IB). Figure 4, bottom: Cross-correlation between signal forward (SF) and idler backward (IB), with the black data taken with the counterpropagating intracavity pump modes in phase and the light gray data taken with a relative phase shift of nearly 180 degrees.

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