Non-Markovian delay in the formation of coherence in quantum-dot nanolasers operating in the cavity-QED regime

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I. Introduction

The quest for miniaturization of integrable optoelectronic devices has led to the development of smaller and smaller nanolasers. Optical microcavities are used to confine the electromagnetic field on the extent of the wavelength itself, culminating in photonic-crystal cavities that combine small mode volumes with long storage time of photons. The small mode volume in particular puts a limit on the amount of gain material that can be brought in spatial overlap with the mode. In order to acquire sufficient gain to sustain lasing operation, spontaneous emission itself is enhanced via the Purcell effect, pushing the concept of lasing into a quantum-cavity-QED regime that is governed by correlation and fluctuation effects.

The presence of correlation effects is not easily revealed. Often they manifest themselves in the dynamical properties of the emission, such as following a short excitation pulse. Here, we combine photon correlation spectroscopy with a microscopic semiconductor laser theory to map out non-Markovian effects in the emission dynamics of a quantum-dot (QD) photonic-crystal nanolaser that cause a delay in the build-up of coherence during the emission pulse.

II. Coherence Dynamics

When a semiconductor laser system is excited with a short pulse, charge carriers are promoted into energetically higher states. Emission takes place following carrier relaxation in the form of a pulse such as shown in Fig. 1. Below the threshold, the pulse duration is determined by the spontaneous emission time. When a sufficient number of intracavity photons are present at the maximum of the emission pulse, stimulated emission sets in. While the onset of lasing is already difficult to assess in high-β nanolasers under cw excitation due to the absence of a kink in the input-output curve [1], it is even harder to attribute under pulsed excitation. The photon autocorrelation function $g^{(2)}(\tau=0)$ is often used in such systems to uniquely identify the threshold, which is given by the transition from a value of 2 (thermal light) to a value of 1 (coherent light). Fig. 1 illustrates that the onset of coherence typically coincides with the onset of stimulated emission at the emission-pulse peak. When the output pulse ceases, emission becomes thermal again.

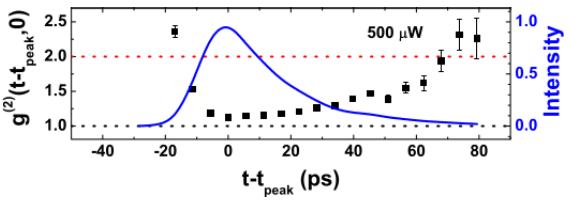

Figure 1 Time-resolved emission intensity (solid) and second-order photon correlation function $g^{(2)}(t,\tau=0)$ (dots) as measured on a quantum-dot micropillar laser. Adapted from [2].

III. Two-time photon correlation dynamics

Our study on a high-Q photonic-crystal nanolaser involves two-photon correlation spectroscopy using a Hanbury Brown and Twiss-type setup with a 70ps time resolution that is used to access the full two-time autocorrelation function $g^{(2)}(t_1,t_2)$. The sample contains an ensemble of QDs that can be temperature-tuned into resonance, allowing to control the emitter number in the cavity and to tune from LED to room-temperature laser operation in one and the same device.

A typical result is shown in the left panel of Fig. 2, where the transition from thermal to coherent and back to thermal emission in found on the diagonal $t_1=t_2$ (i.e. the delay τ between arrival of two photons at the two detector arms is zero).

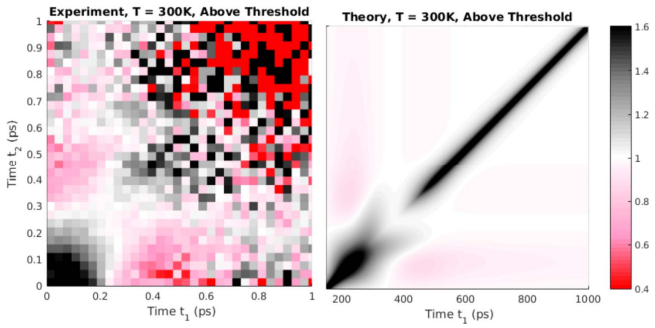

Figure 2 Two-time map of the second-order photon correlation function $g^{(2)}(t_1,t_2)$ for a nanolaser under pulsed excitation. The diagonal corresponds to $\tau=0$. Left: Measurement on a high-Q photonic-crystal nanolaser at room temperature. Right: Microscopic laser theory.

This time-resolved equal-time correlation function is shown in Fig. 3 (dots) together with the emission intensity (solid line). Strikingly, in contrast to the results shown in Fig. 1, the formation of coherence is delayed with respect to the emission-pulse peak by more than 100ps, leading to the fact that the high-intensity part of the emission pulse is largely thermal even though the system operates in the regime of stimulated emission.

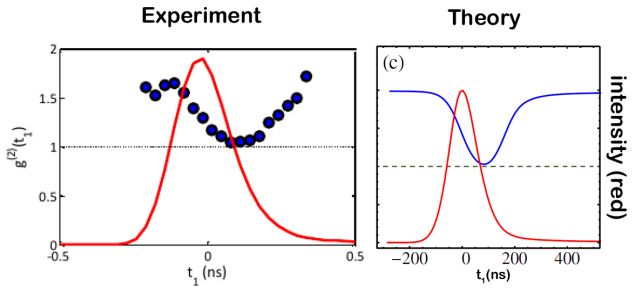

Figure 3 Time diagonal of $g^{(2)}(t_1,t_2)$, providing the time-resolved autocorrelation fuction $g^{(2)}(t,\tau=0)$ in blue, together with the emission intensity (red). Left: Experiment. Right: Microscopic laser theory.

IV. Microscopic Laser Theory

An understanding of the origin of this effect is facilitated by a microscopic semiconductor laser model. Based on the approach established in [3], equations of motion are used to formulate coupled dynamical equations for the carrier- and photon populations, which are driven by the photon-assisted polarization describing the interaction of carriers with the quantized electromagnetic field, such as the annihilation of an electron-hole pair via the emission of a photon. These polarization-like terms are eliminated in the derivation of rate-equation models, but are kept in our theory. In addition, higher-order carrier-photon and photon-photon correlation functions are derived in order to calculate the second-order photon-correlation function $g^{(2)}(t,\tau=0)$. The two-time quantity $g^{(2)}(t_1,t_2)$ is calculated by means of an adapted quantum-regression theorem as outlined in [4]. While previous studies were focused on cw excitation, here we access the full two-time two-photon correlation function as required due to the pulsed excitation scheme.

An application of the microscopic theory with the parameters of the QD-photonic-crystal nanolaser produces results that are in excellent agreement with the intricate emission and correlation dynamics observed in the experiment, as can be seen for the room temperature case by comparing the left and right panels in Figs. 2 and 3. Moreover, the model allows us to expose the origin of the delay in the formation of coherence observed in the nanolaser. The non-Markovian time evolution of carrier-photon correlations, such as the photon-assisted polarization, but also similar quantum-mechanical expectation values involving higher-order photon contributions, have a particular impact in the cavity-QED regime, where spontaneous emission is enhanced, and a high Q factor fosters the storage of photons in the cavity mode. This is revealed by expressing these quantities in a Markovian way so that their time evolution adiabatically follows the carrier occupations and photon intensity as it is the case in rate-equation therories. In this case, the delay disappears, as shown in Fig. 4.

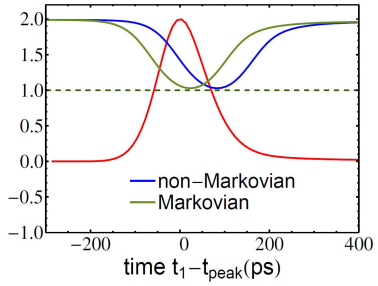

Figure 4 Reproduction of the right panel of Fig. 3, comparing the influence of non-Markovian effects in the theory.

V. Summary

By combining an advanced laser theory with photon-correlation spectroscopy on a tunable state-of-the-art nanolaser, we provide new insight into lasing deep in the cavity-QED regime. Our findings have particular implications for the modulation response of future devices based on high-Q nanolasers.

References

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