Quantum-dot nanolasers – From control of spontaneous emission to superradiance

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I. Lasing in the cavity-QED regime

CONTROL of spontaneous emission itself is amongst the most intriguing and, at the same time, application-defining aspects of cavity-quantum electrodynamics (QED). In tailored dielectric structures, such as photonic crystal or micropillar cavities, light is confined to the cubic wavelength. Gain material embedded in such tiny mode volume interacts much more strongly with the electromagnetic field. The resulting enhancement of the spontaneous emission rate, in combination with small losses, put the realization of lasing with a single quantum-emitter in the solid-state within close reach. At the same time, a large ratio of coupling strength to dissipation rates is the requirement for strong light-matter coupling, the ultimate demonstration of which are vacuum Rabi oscillations— the temporal reflection of a coherent energy exchange between a single photon and a single electronic excitation [1].

In addition to the presence of strong coupling, the formation of radiatively mediated correlations between several emitters to one and the same cavity mode is fostered in the cavity-QED regime. These correlations are the origin of superradiance, which is emission at an enhanced rate, in which emitters do not participate individually, but synchronize in phase and act as a collective.

The need for integrable and power efficient nanolasers is the driving force behind the ongoing miniaturization of semiconductor lasers. This quest is taking the concept of lasing into regimes, where new paradigms dictated by cavity-QED effects are responsible for device characteristics that can strongly differ from that of conventional lasers.

II. Identification of lasing

One consequence of strongly enhanced spontaneous emission is that radiative losses can be made almost irrelevant in quantum-dot nanolasers. This regime is defined by the absence of a visible threshold in the input-output curve and a β factor close to unity *("thresholdless laser")*. Distinguishing such a laser from a LED requires the analysis of fluctuations in the emission as given by the second-order photon autocorrelation function $g^{(2)}(\tau=0)$. For a LED, it takes on a value of 2, for a coherent laser a value of 1, and smaller values indicate non-classical emission. Fig. 1 illustrates how $g^{(2)}(\tau=0)$ allows the identification of the laser threshold in a seemingly "thresholdless laser". For this reason, both the measurement of $g^{(2)}(\tau=0)$ via an Hanbury-Brown and Twiss setup and the calculation in theories beyond rate-equation approximations have become an important tool in the development of new nanolaser devices [2].

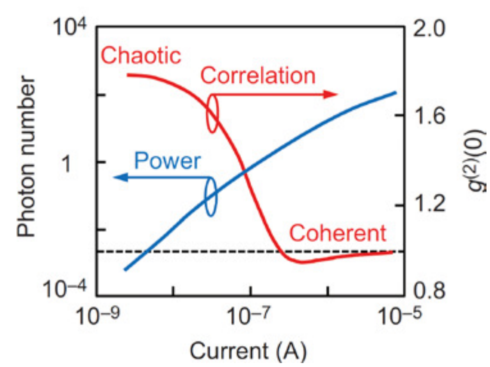

Figure 1 Input-output characteristics in terms of mean photon number (left axis) and autocorrelation function (right axis) versus pump current for a thresholdless (β=1) nanolaser. Figure reprinted from [3].

III. Strong coupling and lasing

Small mode volumes of nanocavities can accommodate only few solid-state emitters. To achieve lasing with few or even a single emitter, their emission into the laser mode must be enhanced so that gain is sufficient to compensate losses. This typically implies laser operation in or close to the regime of strong light-matter coupling.

Strong coupling and lasing are usually observed in different operational regimes. The regime where both effects intermingle is widely unexplored, but has stirred interest since it was first reported in a semiconductor nanolaser [4]. Strong coupling is generally identified by the occurrence of two well-separated peaks in the emission spectrum, the so-called vacuum Rabi doublet. In the presence of stimulated emission, the vacuum-Rabi doublet is modified and the established criterion for strong coupling no longer applies. In [5] we have provided a generalized criterion for strong coupling and the corresponding emission spectrum, which

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includes the influence of higher Jaynes-Cummings states.

A combination of this criterion with numerical results from a microscopic laser theory is the foundation of the parameter-space diagram for a single-emitter laser shown in Fig. 2. Four regimes can be distinguished, in which either strong coupling, lasing, neither, or both are realized. Lasing with only a single emitter is possible for $g/\kappa \gtrsim 2.5$. At these large coupling strengths, lasing takes generally place in the presence of strong coupling, and "conventional lasing" in the weak-coupling regime ($g \ll \kappa$) is only realized if the excitation power is increased further than the threshold value.

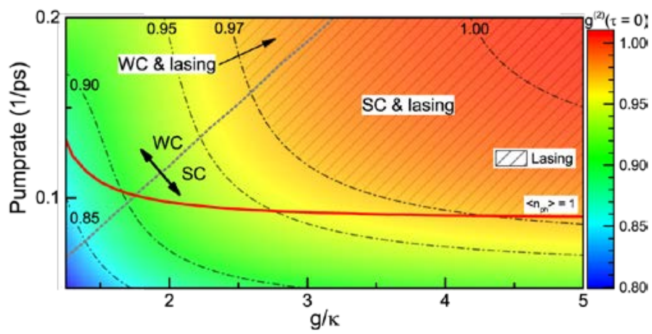

Figure 2 Parameter-space diagram relating the conditions for strong coupling (dotted line) and lasing (red: $\langle n \rangle = 1$, $g^{(2)}(\tau=0)$ as colormap) to the dimensionless light-matter coupling g (κ is the cavity loss rate) and excitation strength. Figure reprinted from [5].

IV. Superradiance as Source of Coherence in Nanolasers

It is commonly known that spontaneous emission is determined by the excited-state population and the emission rate (the Einstein A-coefficient). The derivation of this result from a microscopic theory involves, however, the neglect of dipole correlations between *distant* emitters. The resulting assumption of a gain material consisting of *individual emitters* is the foundation for most laser theories. In a cavity-QED enhanced single-mode nanolaser, such correlations can be present and strongly modify both the spontaneous emission rate and the statistical properties of the emission [6].

The emission dynamics are altered in a way that is familiar from Dicke superradiance [7]. In a QD micropillar nanolaser, a superradiant emission burst has been observed with ten-fold increase of the Purcell-enhanced emission rate. Since the β factor is defined as the fraction of the total spontaneous emission that is directed into the laser mode, it directly reflects such modifications. This is visualized in Fig. 3, where the β factor is shown for a photonic crystal nanolaser operating with only four solid-state emitters. As radiative coupling between emitters depends on the excitation regime, β itself becomes pump-rate dependent. Comparing the steady-state properties of a cw-driven laser with and without inter-emitter correlations reveals that radiative coupling leads to a strong inhibition of spontaneous emission at low excitation (i.e. subradiance) and an enhancement of spontaneous emission above the laser threshold (i.e. superradiance).

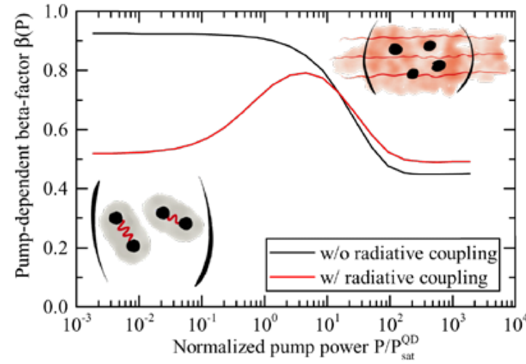

Figure 3 Pump-rate dependent β factor obtained from a microscopic laser theory including radiative coupling (red curve). Calculation suppressing radiative coupling effects between emitters that are responsible for sub- and superradiant effects are shown as black curve. Sketches illustrate the operational regime of radiative coupling (below threshold) and stimulated emission (above threshold). Figure reprinted from [8].

V. Summary

The miniaturization of solid-state nanolasers relies on exploiting cavity-QED effects to control and funnel spontaneous emission into a single confined mode. Sustaining lasing in this regime fosters correlation effects that manifest themselves in a variety of signatures, such as strong-coupling spectra that behave unconventionally at the onset of stimulated emission, and severe modifications of the spontaneous-emission rate due to inter-emitter coupling that carry over to the β factor and to the coherence properties. Microscopic laser theories can account for such effects and aid the design and development of the next generation of nanolaser devices.

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