有限少数個量子ドットを利得媒質とするナノレーザの理論解析

Theoretical analysis of nanolaser with a few quantum dot gain

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Recent developments in high quality nanocavities have opened up possibilities in creating lasers with gain from a single or few solid state emitters, operating with ultra-low energy consumption [1,2]. Such systems have been theoretically analyzed using models extended from simple two-level atom laser [3]; however, these were largely simplified in many cases. Especially, the incorporation of pure emitter dephasing, which inherently exists in most solid state emitters, and an extension to a model incorporating additional energy states or carrier injection details, will be inevitably required for a deeper understanding of the laser performance. In this work, we studied the dynamics and steady-state operation of a few emitter nanolaser modelled as a four-level system under the influence of pure dephasing processes, in particular from the view point of the laser dynamics. We find the fast-carrier-relaxation-induced dephasing and pure dephasing have a significant detrimental effect on lasing operation.

We modeled our system as artificial atoms (i.e. quantum dots) with four discrete energy levels (see the inset in Fig. 1). N identical atoms are coupled at a rate \( g \) to a single cavity mode. The upper state \( |4 \rangle \) is pumped at a rate \( P \), and carriers can relax from state \( |4 \rangle \) to \( |3 \rangle \) and from state \( |2 \rangle \) to \( |1 \rangle \) at rates \( \gamma_{34} \) and \( \gamma_{12} \) respectively. The atoms can spontaneously emit into the environment at a rate \( \gamma_\text{esc} \), while cavity photons escape at a rate \( \kappa \propto Q^{-1} \) where \( Q \) is the cavity quality factor. We incorporated pure dephasing of the atom energy levels, at rate \( \kappa_\text{ph} \), (assumed to be induced by phonon-carrier and carrier-carrier interaction), driving towards classical behavior by clenching the coherent exchange of quanta. In our methods, we apply a rate equation approximation from the quantum master equation, intuitively explaining the reduction in emission rates due to increased dephasing of the photon assisted polarization.

Figure 1 shows the steady-state input-output characteristics of our nanolaser system, as a function of carrier injection pumping rate, where we set the parameters as \( g=200\,\text{ns}^{-1}, \kappa=100\,\text{ns}^{-1}, \gamma_{12}=y_{34}=1000\,\text{ns}^{-1}, \gamma_{23}=1\,\text{ns}^{-1} \), and the number of atoms \( N=10 \). \( y_{34}=4000\,\text{ns}^{-1} \) reflects a typical room temperature phonon induced pure dephasing rate [4]. When the system reaches the lasing regime and the intracavity photon number surpasses unity, we note a strong influence of the pure dephasing rate on the photon number due to a reduction of the Purcell enhanced emission rates. Saturation occurs because effective carrier injection into the \( |3 \rangle \) state is limited by the relaxation from the \( |4 \rangle \) state.

Figure 2 shows the small-signal modulation transfer amplitude calculated by rate-equation analysis and using the same parameters as in Fig. 1. The response is unity at low modulation frequency and diminishes rapidly for frequencies approaching \( \kappa \); this can be explained by noting that our system emission rates are higher than \( \kappa \) and \( \kappa > N\gamma_{23} \). Therefore, the cavity decay is the limiting decay channel for the system to relax back to steady state after a small amplitude change. We note a significant decrease in modulation bandwidth at pure dephasing rates typical for room-temperature operation. Our results motivate for a deeper investigation into quantum dot interactions with environment and with each other in a nanolaser based on a few quantum dots.

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