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

°V. E. Elfving[1], 太田泰友 [1], 上出健仁 [1], 岩本敏 [1,2], 荒川泰彦 [1,2] (1. 東大生研, 2. 東大ナノ量子機構)
°V. E. Elfving[1], Y. Ota[1], K. Kamide[1], S. Iwamoto[1,2], Y. Arakawa[1,2](1.IIS 2.NanoQuine, Univ. of Tokyo)
E-mail: elfving@iis.u-tokyo.ac.jp

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 from state $|1\rangle$ 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 γ_{34} and γ_{12} respectively. The atoms can spontaneously emit into the environment at a rate γ_{23}, 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 γ_ϕ, (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 ns^{-1}, κ=100 ns^{-1}, $\gamma_{12} = \gamma_{34}$=1000 ns^{-1}, γ_{23}=1 ns^{-1}, and the number of atoms N=10. γ_ϕ=4000 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 κ; this can be explained by noting that our system emission rates are higher than κ 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.

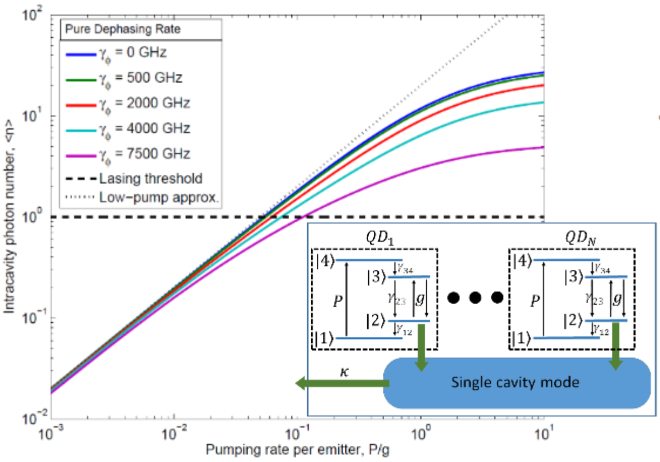

Figure 1: Intracavity photon number as a function of input pumping rate. Inset: schematic diagram of the four-level QD-cavity model.

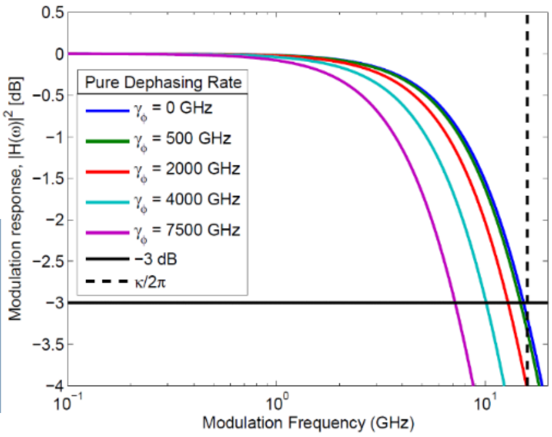

Figure 2: Normalized modulation transfer function as a function of small-signal modulation frequency. Pump rate is modulated around a bias pump rate P=g.

Acknowledgement: This work was supported by Project for Developing Innovation Systems of MEXT and NEDO

References: [1] M. Nomura, *et al.*, Nat. Phys., **6**, 279283 (2010). [2] B. Ellis, *et al.*, Nat. Photonics **5**, 297 (2011).
[3] A. Moelbjerg, *et al.*, IEEE J. Quantum Electron. **49**, 945 (2013). [4] P. Borri *et al.*, Phys. Rev. B 71, 115328, (2005)