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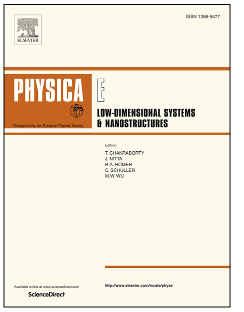

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Markov model of quantum fluctuations at the transition to lasing of semiconductor nanolasers

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Abstract

A Markov model of semiconductor nanolaser is constructed in order to describe finely the effects of quantum fluctuations in the dynamics of the laser, in particular by considering the transition to lasing. Nanolasers are expected to contain only a small number of emitters, whose semiconductor bands are simulated using true carrier energy states. The model takes into account carrier-carrier interactions in the conduction and valence bands, but the result is a huge Markov chain that is often too demanding for direct Monte-Carlo simulation. We introduce here a technique to split the whole chain into two subchains, one referring to thermalization events within the bands and the other to laser photonic events of interest. The model is applied to the analysis of laser transition and enlightens the coexistence of a pulse regime triggered by the quantum nature of the photon with the birth of the known coherent cw regime. This conclusion is highlighted by calculated time traces. We show that on the ultrasmall scale of nanolasers, we are unable to define perfectly the threshold.

Keywords: Nanolaser, Semiconductor laser, Markov chain, Laser threshold

1. Introduction

Nanolasers are becoming increasingly important in the scientific and technical community. Their potential applications for high-bit-rate optical interconnections can solve the need for an exponential increase in information flow, even in microelectronics at inter or intra-chip levels, for example. Regardless of the application and due to their ultra-small size, nanolasers have unique advantages for this type of requirement as low consumption becomes an essential need. Their realization relies historically on semiconductor technologies based on heterostructures [1, 2], but was extended recently to spasers [3] whose plasmonic effects allow resonant cavities of a volume much lower than λ^3, with λ the wavelength of operation in vacuum [4–6]. Because of these small ultimate sizes, only a few individual emitters can be involved in a single device, which results in a very small number of photons emitted and an increasing importance of the fluctuations due to the quantum nature of processes, either optical or electrical. In semiconductor laser technology, the tiny number of emitters is either reached with quantum dots or with very small VCSELs, although even some commercial VCSELs behave like nanolasers [7]. Laser models must then account for this quantization to move from continuous variable descriptions like rate equations [8] toward a quantum microscopic description of the device [9]. The expected physical answers are then a better description of the transition from incoherent to coherent emission [10, 11] and the associated ultimate noise performances of a device [12, 13].

One class of very accurate models able to describe nanolasers relies purely on quantum mechanics [14]. It numerically includes only very few two-levels emitters ($N_e \leq 5$) in the optical cavity [15, 16] because the numerical complexity of the density matrix increases exponentially with N_e. However, in spite of this limitation these models have shown that coherence effects between excited atoms are smoothed as soon as their count exceeds a few units. The consequence is that the extensive consideration of these coherences is not necessary to give a detailed account of a real nanolaser.

If an accurate description of the quantum-well (QW) active medium is required, a quantum-mechanical nonequilibrium theory for the coupled carrier-photon system in semiconductor micro cavity lasers was built to