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Nonequilibrium Green's function approach to simulations of active photonic nanostructures

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A reliable simulation of photonic devices requires good understanding of numerous physical aspects. The analyzed device can be considered as an inhomogeneous system of carriers, that interact with themselves, the lattice and the optical field. While in some situations, the quantum properties of the carriers play crucial role, in others they can be accurately described by classical physics. Commonly used approaches rely on classical models, often called the drift-diffusion approach, see for example [1], [2]. The main attraction of those models is the speed of calculations and the simplicity of incorporating physical effects. They are useful for researchers who need to get quick estimates of the characteristics of a design that is not too dissimilar from current designs. As the dimensions of semiconductor and photonic devices scale down to nano-scale dimensions (of the orders of hundreds of angstroms), kinetic and quantum effects in the carrier transport become crucial for the device's operation.

In those circumstances, more fundamental approaches are necessary. Such approaches treat carriers as quantum many-body system with all possible interactions. The operation of active photonic devices combines electrical transport of carriers along with optical field interacting with those carriers. In those devices spontaneous and stimulated emissions play an important role. To consistently describe spontaneous emission, the light field must also be quantified. The description of such carrier-photon system in principle is described by the many-particle Schroedinger equation.

In the present work we summarize the applications of nonequilibrium Green's function (NEGF) approach to simulations of photonic nanostructures, with the emphasis on active devices [3]. We provide theoretical foundations of simulations of those devices where four types of quasi-particles (electrons, holes, phonons and photons) play an important role in the underlying physics. In this work we do not consider other types of quasi-particles, like excitons or plasmons.

General equations for photon Green's functions and polarizations will be established as well as their coupling to electron Green's functions through self-energies. Series of approximations are done to photon Green's function to allow for efficient numerical approach. All equations will be written in the non-orthogonal basis suitable for numerical calculations. As an example, the theory will be applied to analyze $Al_{0.2}Ga_{0.8}As/GaAs$ quantum well laser with the effective mass Hamiltonian. Major laser characteristics such as material and modal gain, threshold parameters, carrier and current densities are determined.

References

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