QUANTUM THEORY OF DIPOLE NANOLASERS

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Abstract

We generalize the semiclassical model of the dipole nanolaser (DNL) based on the Heisenberg–Langevin approach, taking into account spontaneous emission of plasmons into the generation mode, nonlinearity of generation, and noises. We find a “thresholdless” smooth transition from the spontaneous emission to the stimulated emission and the threshold conditions for such a transition and determine the spectrum of generation and its linewidth. We show that, in spite of the very low quality of the DNL generation mode, the linewidth of a DNL with many $M \sim 10^4 - 10^5$ emitters decreases, with the pump increase, to quite small values $\sim 10^{-2}$ of the width $2\Gamma_2$ of the lasing transition at modest pump rates, about 30 times larger than the decay rate of the emitter upper lasing state. This fact confirms the practical possibilities of realizing DNLs with narrow-line stimulated emission. Otherwise, the linewidth of DNLs with small $M \sim 1$ number of emitters is larger than $2\Gamma_2$ and increases with the pump rate. In addition, our results on DNLs can be applied to other lasers, such as nanolasers, microlasers, and LEDs for lighting, also with a low-quality cavity and strong spontaneous emission into the generation mode.

Keywords: nanolasers, plasmons.

1. Introduction

Miniature lasers find many applications in microelectronics, information processing, and telecommunications [1]. Several microlasers have been suggested such as, for example, polymer-thin-film lasers [2], microwire lasers [3], and Bregg-mirror-cavity lasers [4]. Microlasers have the Fabry–Perot or a whispering gallery-mode cavity [3], so their size cannot be smaller than $\lambda/(2n)$, where $\lambda$ is the wavelength of the cavity mode and $n$ is the refractive index of the lasing medium.

Spasers and dipole nanolasers (DNLs) have been suggested in [5, 6]; their size may be smaller than $\lambda/(2n)$, and they generate not photons but other bosonic particles – plasmons.* Small sizes of spasers and DNLs are important for applications such as, for example, in chip-scale optical interconnects [7], but not only the small sizes are interesting features of DNLs and spasers. Many phenomena of laser physics, quantum optics, and plasmonics appear in these devices — the self-phasing of arrays of DNLs or spasers [8], superradiance and bistability [9, 10], local field effects, and thresholdless generation.

*The possibility of laser generation of bosons different from photons has been pointed out, for example, in [11].
DNLs and spasers consist of resonant emitters of light (molecules, atoms, q-dots, etc.) placed at small, ∝ λ, distance near the metal nanoparticle, and they are incoherently pumped by some energy source: broad-band light, injection current, etc. Emitters and the nanoparticle interact with each other through the electric field, and the delay in this interaction is negligibly small, so that the electric field is assumed to be adiabatically eliminated [12], and only all dipole momenta and the population inversion of emitters are considered as dynamical variables. The emitter resonant transition frequency is close to the plasmon resonance frequency of the nanoparticle, so that resonant oscillations of the electron density of the nanoparticle–plasmons can be excited. The resonant generation of surface plasmons takes place in spasers, that is, surface plasmon amplification by stimulated emission of radiation [13]. The resonant generation of localized plasmons takes place in DNLs. Localized plasmons of small metal nanoparticles are oscillations of the nanoparticle dipole momentum; this is why DNL is a dipole nanolaser. Surface plasmons are guided electromagnetic waves that do not propagate into free space far from the guiding surface [14]; thus, the spaser described in [13] generates a near field confined near the surface of the metal particle. DNLs emit as dipoles and generate both near and far fields.

A DNL is a D class laser [15] with a “bad cavity” having a large linewidth 2Γ of the generation mode – localized plasmon resonance (LPR): 2Γ ≫ 2Γ2 and τ −1, where 2Γ2 and τ −1 are the width and lifetime of the upper energy state of the resonant transition of the emitter near the nanoparticle. Class D is “unpopulated” with respect to classes A, B, and C of usual lasers with 2Γ < 2Γ2 and τ −1. Only some beam masers belong to class D [15] besides DNLs and spasers; that is why D-type lasers are rather poorly studied theoretically. Meanwhile, the theory of D-type lasers is, in general, more complicated that the theory of ordinary lasers. Quantum and classical noise along with the spontaneous emission into the generation mode are important in D-lasers. For correct modeling, the semiclassical approach [16] for DNLs has to be replaced by quantum Heisenberg–Langevin equations. The strong fluctuations of the field and polarization cannot be treated as perturbations, so that the usual procedure of linearizing the equations with respect to a fluctuating part of the variables is, in general, not valid. Nevertheless, the nonlinear properties of lasers must be preserved. All these facts make the analytical modeling of DNLs difficult, and complete analysis is possible only numerically. However, in some approximations, quasi-nonlinear analytical approaches of the quantum theory of the thresholdless lasers [17] can be used.

The first goal of this paper is the formulation of the nonlinear model of DNLs with noise following [17]. The second goal is the estimation of DNL characteristics, in particular, the conditions necessary for the stimulated emission (lasing) of plasmons and the generation linewidth. We answer the question when a considerable narrowing of the laser linewidth is possible at reasonable values of the pump rate and other parameters in DNLs with a low-quality cavity at a high contribution of the spontaneous emission into the generation mode.

Quantum properties of the micromaser and calculations of its linewidth were described in [18], and the linewidth of the laser with a bad cavity and inhomogeneous broadening was studied in [19], but in both papers using the linear approach, which is, in general, not applicable to DNLs with strong spontaneous emission into the generation mode. Quantum properties of DNLs have been taken into account and estimations of their linewidth have been carried out in [20], assuming that the stationary population inversion of emitters in the DNL did not depend on the generation. Here we take a step forward with respect to [20], taking into account the dependence of the population inversion on the number of generating plasmons in the DNL with noise. This dependence is quite important since the generation of plasmons strongly de-populates upper levels of emitters. We do not consider here noise properties of the DNL in the external field, which was the subject of [10], leaving the application of our