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Quantum-Kinetic Approach to Deriving Optical Bloch Equations for Light Emitters in a Weakly Absorbing Dielectric

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Abstract. We obtained the system of Maxwell-Bloch equations (MB) that describe the interaction of cw laser with optically active impurity centers (particles) embedded in a dielectric material. The dielectric material is considered as a continuous medium with sufficient laser detuning from its absorption lines. The model takes into account the effects associated with both the real and the imaginary part of the dielectric constant of the material. MB equations were derived within a many-particle quantum-kinetic formalism, which is based on Bogolyubov-Born-Green-Kirkwood-Yvon (BBGKY) hierarchy for reduced density matrices and correlation operators of material particles and the quantized radiation field modes. It is shown that this method is beneficial to describe the effects of individual and collective behavior of the light emitters and requires no phenomenological procedures. It automatically takes into account the characteristics associated with the presence of non-resonant and resonant particles filling the space between the optical centers.

Keywords: local field, impurity center, resonance fluorescence, collective phenomena

The problem of light emission by a quantum system modified by its environment has a long history, but it has not lost its relevance thanks to development of new optical materials, the methods of diagnostics and miniaturization of light sources. Experimental data suggest that the properties of the emitter are determined by its interaction with other quantum objects and properties of the host medium at the micro and macro scales. The existing theories provide radiative corrections applicable to different situations. The majority of approaches are aimed at determining the change in the rate of spontaneous decay of an excited single particle in a given environment compared to its spontaneous emission in a vacuum. In the literature, these approaches are conventionally divided into "microscopic" and "macroscopic" models. The common points in the models are to take into account the following: modifications of intrinsic properties of the emitting center, the structure of the local field and the change in density of photonic states.

Of particular interest is the problem of studying the properties of optical centers in a host medium in the presence of an external laser radiation. The mathematical apparatus used in laser physics, nonlinear and quantum optics, and other research in the area of interaction of radiation with the matter is largely based on an analysis of Maxwell-Bloch (MB) equations. To date, there is limited number of papers (for example, [1-4]) giving MB equations, which take into account in a consistent manner the effective values of all parameters: Rabi frequency, frequency shifts and the rates of relaxation mechanisms (including spontaneous emission). It should be noted that competing theories lead to inconsistent results regarding the effective values of the parameters and their dependency on the characteristics of the environment. In many cases, the modifications are performed phenomenologically. Comparisons with the experimental data, as a rule, are based on the variation of the other constants so it is not always possible to determine the correctness or universality of the approach [4, 5].

In this work, we derived a generalized master equation for two-level emitters forming an ensemble of motionless optical centers in a dielectric medium, non-resonant to the external light. The master equation was used to build the material part of MB, i.e., the system of optical Bloch equations. It takes into account the effective rates of individual and collective radiative damping of optical centers, the Rabi frequency, and frequency shifts of the optical transition caused by the presence of a dielectric host. The MB parameters were found to be functions of the real and imaginary parts of the host permittivity. It was shown that the equations are flexible to adopting Lorentz and Onsager local field concepts.

The complete system of MB equations was obtained using a many-particle quantum-kinetic formalism, which is based on the Bogolyubov-Born-Green-Kirkwood-Yvon (BBGKY) hierarchy for reduced density matrices and correlation operators of material particles and the quantized radiation field modes accurate to the generalized polarization approximation. This approximation of BBGKY provides accounting for all two-particle correlations as well as certain types of three-particle correlations. It fully corresponds to the case when the material quantum objects interact with each other via the photonic subsystems with the electric dipole approximation applicable. This approach takes into account the relaxation processes and the effects of dynamic polarization in the material subsystem. The self-consistent effects of the particles on each other is an intrinsic property of BBGKY that allows one to calculate the local field acting on the light emitter, produced by its discrete and continuous environments.

The lifetime of the excited state of the emitter as a function of the refractive index of the host obtained in MB was shown to be in agreement with the experimental data [4, 5]. Finally, we discuss the similarities and differences with other existing approaches to derivations of effective MB.

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