Chapter 8
Photon Transport

1. OVERVIEW AND CHAPTER OBJECTIVES

Photons are amazing information carriers that travel with the speed of light! The science of photonics is large and encompasses the generation, conversion, transport, guiding and detection of photons. Accurate modeling of photonic devices is essential for the development of high performance optical components required by current and future communication systems. In fact, the light speed and low noise properties make photons indispensable for telecommunications and information processing. Therefore, the modeling and simulation of photon transport, together with charge-carrier and phonon-heat transport, is of high interest for optoelectronic and photonic device design. In addition, the band structure calculation of the conveying medium and other quantization effects should be carried out, in order to obtain correct results. Figure 1 shows how transport models of charge carriers, phonons and photons should be integrated in the simulation process of a laser diode.

The description of photon transport in photonic semiconductor devices in general, and semiconductor lasers in particular, is important to generate improved designs. Laser Light is generated in a semiconductor laser by radiative recombination of electrons and holes. In order to generate more light by stimulated emission than is lost by absorption, the system has to be inverted. Inversion population is carried out electrically or by optical pumping. A laser is, thus, always a high carrier density system that entails many-body interactions. The operation of laser, as well as other photonic devices, involves an interaction between electrons and light waves (photons) as well as lattice vibrations (phonons). Also, the so-called excitons (bound electron-hole pairs) emerge in photo-excited semiconductors and strongly influence the carrier transport process. All these interactions cannot be taken into account exactly because of the high number of involved carriers and quasi particles. Therefore, the following approximations are usually adopted:

1. Free Carrier Model: In this model, many-particle interactions are neglected approximated phenomenologically. To take the effect of carrier interactions into consideration, a phenomenological
scattering time is introduced. Simple models for the gain coefficient are then used to obtain a system of laser rate equations, to calculate the time-dependent laser response.

2. **Hartree-Fock Approximation**: Here, the semiconductor Bloch equations (SBEs) are employed. To describe the carrier interactions, the Hartree–Fock approximation is utilized. In this case, carrier–carrier interaction leads to re-normalization terms for carrier energy and electric field. The collision terms, i.e., the terms describing carrier–carrier scattering have to be introduced phenomenologically using a relaxation time for the polarization field.

3. **Correlation Effects**: This microscopic approach takes the collision terms in the SBEs into account explicitly. Therefore, the collision terms in the SBEs can be included in the second-Born approximation. This model yields the correct laser linewidth for any excitation density or temperature. In the other models, the relaxation time has to be extracted from experiment.

Figure 2 depicts the different models of photon/exciton transport and electromagnetic field propagation. The electromagnetic field analysis of photonic devices may be carried out by classical or quantum models. The classical models are all about solving the Maxwell equations inside the device active region. The quantum approaches are based on some sort of dynamic wave equations (Schrodinger-like or Heisenberg-like) in the microscopic level or the SBEs in the macroscopic level. The so-called dynamics-controlled truncation (DCT) formalism is another successful microscopic approach that describes coherent correlations in optically excited semiconductors. On the other hand, the most successful approach to study incoherent effects and correlations in highly excited semiconductors is the nonequilibrium Green’s functions (NEGF) approach.