Chapter 7: Matter-Light Interaction

The laser, LED and photodetector all share the same basic physical principles. The rate equations provide a fundamental description of optical emission and absorption. However, as in Chapter 2, the gain and spontaneous recombination terms often appear as phenomenological terms. Maxwell's equations and the Poynting vector explain emission, absorption and transport in terms of the classical theory of the microscopic dipoles. While quite successful, the description does not account for the quantum nature of matter and light and does not explain basic phenomena such as the spontaneous emission.

We now explore the matter-light interaction culminating in a quantum description of gain and the rate equations. The study begins with the time-dependent perturbation theory and the semiclassical approach to Fermi's golden rule for optical transitions. Fermi's golden rule relates the transition rate to the optical power, frequency and dipole moment. The time-dependent perturbation theory for electromagnetic interactions uses a Hamiltonian $\hat{\mathscr{H}} = \hat{\mathscr{H}}_o + \hat{\mathscr{V}}$ with $\hat{\mathscr{H}}_o$ representing the atomic system such as an atom or a quantum well for example. The interaction Hamiltonian $\hat{\mathscr{V}}$ describes the effect of the electromagnetic wave interacting with the atomic system. The theory assumes that $\hat{\mathscr{V}}$ does not change the energy basis states obtained from $\hat{\mathscr{H}}_o$ but rather induces particle transitions between them. The semiclassical approach does not use the quantized form of the electromagnetic field and, for this reason, the full Hamiltonian $\hat{\mathscr{H}}$ does not include the free-field Hamiltonian $\hat{\mathscr{H}}_{em}$. The semiclassical approach does not account for spectral broadening and gain saturation due to the interaction of the radiating system with its environment. Sections 7.4 through 7.6 discuss Hamilton's and Lagrange's classical formulation for the EM interaction and shows how the vector potential modifies Schrodinger's equation and produces the dipole moment.

The density operator describes the quantum and classical state of the particle and field system. This operator lives in the tensor product space consisting of (at minimum) the product of the spaces for the matter and field. The number of spaces can increase depending on the number of degrees of freedom. For example, the wave functions and density operator describing the state of the reservoirs reside in their own Hilbert space. The combination of the matter, fields and reservoirs constitutes a complete system. The density operator appears in both the semiclassical and the full quantum theory.

The motion of the density operator in its direct product space describes the system transitions. An atom, for example, might have an electron in the first excited state but, through the matter-field interaction, it transitions to the lower state thereby exciting one of the optical modes. A first order partial differential equation, known as the Liouville equation or the master equation, describes the system dynamics. Rather than working with complicated evironmental Hamiltonians, the Liouville equation uses uses phenomenological terms for the environmental relaxation effects while retaining the semiclassical theory for the matter-field interaction. The relaxation terms do not maintain phase coherence in the wavefunction and produce spectral broadening (homogeneous broadening) and naturally lead to gain saturation.

The remainder of chapter discusses the Jaynes-Cummings model and begins to explore the fully quantized model for the electromagnetic interaction. This material treats the interactions in terms of reservoirs and derives the Liouville equation.