The past two decades have seen an explosion in the types and configurations of novel laser systems. This development has been fueled by advances in microfabrication techniques and motivated by applications to integrated on-chip optics, more efficient optical communications, as well as basic scientific interest. Many of these advances are driven by the use of new gain media, such as semiconductor lasers, quantum cascade lasers, and rotationally excited gases, for which the typical two level atomic system approximation is poorly suited. For example, though the band structure of the semiconductor gain medium can be approximated as a series of two level atomic transitions, multiple transitions are required to represent the effects of Pauli blocking [1]. Cascaded-transition quantum cascade lasers are designed with two lasing transitions to operate at longer wavelengths [2, 3]. Additionally, for both rotationally excited gases and semiconductor media the carriers are allowed to diffuse through the cavity, an effect that is not addressed in the Maxwell-Bloch equations [4].

In this poster we derive and test a substantial generalization of Steady-State Ab Initio Laser Theory (SALT) to treat such complex gain media [5]. This generalized theory is able to treat atomic and molecular gain media with diffusion and multiple lasing transitions, and semiconductor gain medium in the free carrier approximation including fully the effect of Pauli blocking. The key assumption of the theory is stationary level populations, which leads to coupled self-consistent equations for the level populations and lasing modes in the presence of spatial hole-burning. These equations can be solved efficiently for the steady-state properties by a similar non-linear iteration procedure as in previous versions of SALT, in which only the modal equations need be solved self-consistently. The theory is tested by comparison to much less efficient Finite Difference Time Domain (FDTD) methods and excellent agreement is found, as shown in Fig. 1. Using the generalization to include gain diffusion, the transition is demonstrated between the regime of strong spatial hole burning with multimode lasing, to the regime of negligible spatial hole burning, gain-clamping, and single mode lasing. The effect of spatially inhomogeneous pumping combined with diffusion is also evaluated and a relevant length scale for spatial inhomogeneity to persist is determined. For the semiconductor gain model, the frequency shift with pump due to Pauli blocking is demonstrated.

FIG. 1: Plot of modal intensities as a function of pump strength for a cavity with $n = 1.5$ and a gain medium consisting of atoms with two different atomic transitions, $\omega_{a,1} = 40$, $\omega_{a,2} = 38$ and 6 atomic levels in total, with decay rates as indicated in the schematic. Results from SALT using the stationary population approximation are shown as straight lines, results from FDTD simulations are shown as triangles. The different colors indicate different modes. Inset shows the modal frequencies and their intensities at $P = .0035$ with the gain curves of both lasing transitions shown behind. All values are reported in units of $c/L$.