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Nonlinear Gain Saturation in Active Slow Light Photonic Crystal Waveguides

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Abstract: We present a quantitative three-dimensional analysis of slow-light enhanced traveling wave amplification in an active semiconductor photonic crystal waveguides. The impact of slow-light propagation on the nonlinear gain saturation of the device is investigated.

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A major advantage in combining photonic crystal (PhC) waveguides and active III-V semiconductors is the possibility to drastically decrease the component length via enhanced light-matter interaction enabled by slow-light (SL) propagation [1]. The investigation of group velocity related gain enhancement was initiated in Bragg slabs [2]. It is natural to extend such ideas to PhC line defect waveguides with guided modes within the bandgap [3]. Comparing with the successful demonstrations of PhC Lasers [4], the attempts of realizing PhC travelling wave semiconductor optical amplifiers (SOAs) [5] are confronted by various challenges, e.g. excessive propagation losses due to mode leakage into substrate as well as heating issues.

From the simulation perspective, the finite-difference time-domain (FDTD) method has been used to simulate the properties of an active material, often described by Maxwell-Bloch equations, embedded in a photonic crystal waveguide [6] and fiber bragg gratings [7]. However, this is a computationally demanding task and not suitable for systematically investigating, e.g., the dynamical saturation properties. Thus what is missing is an effective model equivalent to the traveling wave model of an active ridge waveguide, which has been so successful in understanding the properties of SOAs, e.g. saturable gain and small-signal modulation response. A one-dimensional rate equation analysis [5] with heuristic inclusion of group velocity was suggested previously, but not compared to full simulation to qualitatively investigate the gain characteristics of PhC traveling wave SOAs. In this paper, we present a rigorous three-dimensional frequency-domain finite-element simulation (www.comsol.com) and suggest a modified effective rate equation analysis, that well accounts for the carrier-depletion-induced modal gain saturation in a slow-light enhanced active photonic crystal waveguide.

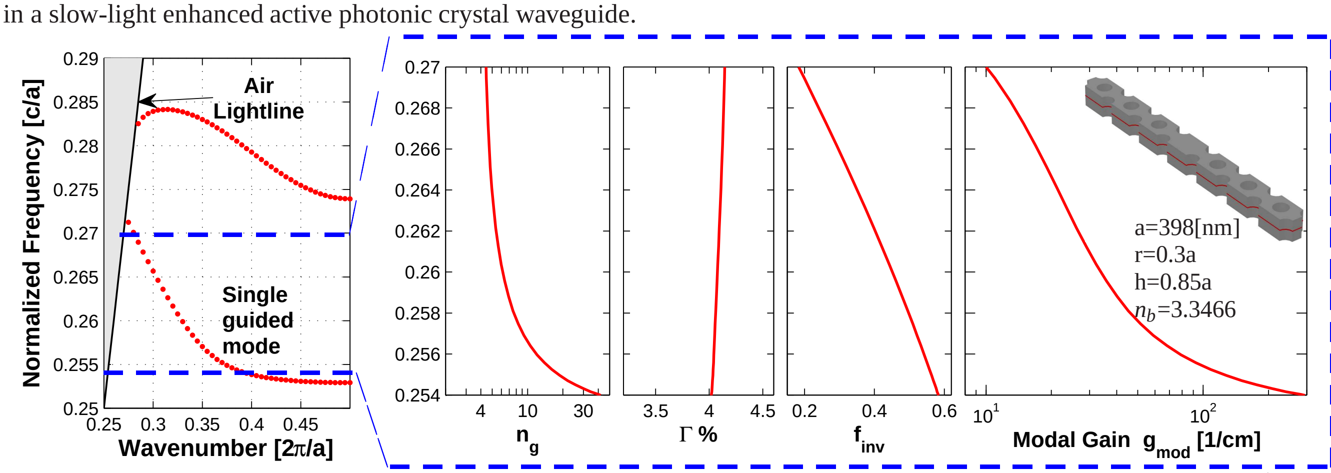

Fig. 1: Slow-light enhanced small-signal modal gain in a W1-defect PhC membrane with a single QW layer ($g_{mat} = 1000cm^{-1}$).

In the weak perturbation limit, we approximate the exact solution of Maxwell equations as a principal TE-like guided Bloch wave, $\frac{1}{2}[\mathbf{e}(r), \mathbf{h}(r)]\exp(i\beta z - i\omega t)$, multiplied with a forward amplitude $\psi(z)$ along propagation direction z. $\mathbf{e}(r)$, $\mathbf{h}(r)$ are the the normalized electric and magnetic fields of the periodic Bloch mode of passive structure. For simplicity, we only consider the carrier-induced material gain, as the product of maximum material gain g_{mat}, active material distribution function $F(r)$ and distributed population inversion factor $f_{inv}(r)$. We only investigate the stationary quasi-equilibrium solution of carrier dynamics by introducing a distributed balance equation of carrier density $N(r)$ in the active region:

$$0 = R_p(r) - R_{st}(r) - \frac{F(r)N(r)}{\tau_s},\ R_{st}(r) = \frac{\Gamma g_{mat} a}{\hbar\omega}\frac{n_g}{n_b}\frac{\varepsilon_0 n_b^2 F(r)|\mathbf{e}(r)|^2 f_{inv}(r)}{\langle \varepsilon_0 n_b^2 F(r)|\mathbf{e}(r)|^2\rangle}|\psi(z)|^2 P_z,\ \Gamma = \frac{n_b^2\langle \varepsilon_0 F(r)|\mathbf{e}(r)|^2\rangle}{\langle \varepsilon_0 n_b^2(r)|\mathbf{e}(r)|^2\rangle} \qquad (1)$$

Here, τ_s is carrier lifetime, R_P is the injection rate of carriers by optical/electrical pumping, R_{st} is the SL-enhanced stimulated emission rate based on principal guided Bloch wave expansion. n_g is the group index, n_b is background refractive index, ε_0 electric permittivity. $\langle\rangle$ is a volume-integral operator over a supercell. a is the lattice constant, P_z is the unit rms power flux over the transverse section. Γ is a confinement factor for stored electric energy inside the active region. Based on the slowly-varying envelope assumption, $\psi(z)$ is considered constant over the period of PhC structure a. The modal gain per unit length is

$g_{mod} = \frac{\hbar\omega\langle R_{st}(r)\rangle}{a|\psi(0)|^2 P_z} = \Gamma g_{mat}\frac{n_g}{n_b}\bar{f}_{inv}$. $\bar{f}_{inv} = \frac{\langle n_b^2 F(r)|\mathbf{e}(r)|^2 f_{inv}(r)\rangle}{\langle n_b^2 F(r)|\mathbf{e}(r)|^2\rangle}$ is a volume-averaged population inversion factor. In the small-signal limit, $f_{inv}(r)$ as a function of Fermi-Dirac distribution, is constant within the active region under uniform pumping. Fig. 1 illustrates the corresponding contributions to SL-enhanced modal gain in a 3D PhC waveguide with a single QW layer. As the frequency decreases towards the band-edge region, the enhancement of modal gain is dominated by the increased group index.

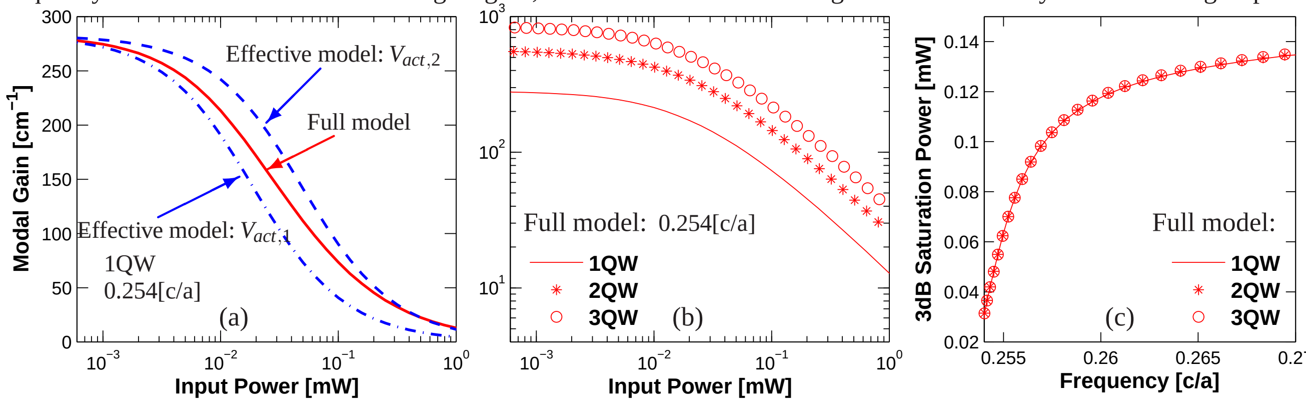

Fig. 2: SL-enhanced modal gain saturation in a W1-defect PhC membrane. (a) Comparison of modal gain as a function of input power between full and effective model determined by Eq. (1)&(2). $V_{act,1} = (\sqrt{3}a^2 - \pi r^2)h_{QW}$,$V_{act,2} = (3\sqrt{3}a^2 - 5\pi r^2)h_{QW}$. (b) Gain saturation with different QW layer numbers based on full model. (c) 3dB saturation power as a function of frequency based on full model.

In the saturation regime, $f_{inv}(r)$ and $N(r)$ in the active material are implicitly determined by a Fermi-Dirac integral under quasi-equilibrium condition. Based on Eq. (1), we might still derive a balance equation for averaged carrier density $\langle N\rangle/V_{act}$ in a supercell:

$$0 = \frac{\langle R_P\rangle}{V_{act}} - \frac{\langle R_{st}\rangle}{V_{act}} - \frac{\langle F(r)N\rangle}{V_{act}\tau_s}, \qquad \frac{\langle R_{st}\rangle}{V_{act}} = \frac{g_{mat}}{\hbar\omega}\frac{\Gamma a}{V_{act}}\frac{n_g}{n_b}\bar{f}_{inv}|\psi(z)|^2 P_z = g_{mat}\frac{c}{n_b}\frac{\Gamma V_{opt}}{V_{act}}|\psi(z)|^2 N_P \tag{2}$$

here V_{act} and V_{opt} is the active material and optical mode volume. c is the speed of light in vacuum. $N_p = \frac{n_g a}{c}\frac{P_z}{\hbar\omega V_{opt}}$ is the averaged photon density corresponding to the unit rms power flux P_z. Eq. (2) is equivalent to the stationary form of conventional laser dynamics rate equation analysis. The confinement factor in the stimulated emission term as a function of photon density [5] is corrected by $\frac{\Gamma V_{opt}}{V_{act}}$. Fig. 2 quantitatively illustrates the SL-enhanced modal gain saturation in PhC waveguides. In comparison with the full model results based on Eq. (1) in Fig. 2(a), the effective model results based on Eq. (2) display qualitatively similar gain saturation as a function of input power. However, different active material volumes lead to deviations at either low or high input power region, as it is difficult to characterize the highly non-uniformly depleted carrier density with a universal active material volume and averaged carrier density. Fig. 2(b) illustrates the gain saturation with different QW layers. By increasing the QW layer numbers, the confinement factor is increased proportionally. Hence, larger modal gain is provided for traveling wave amplification. On the other hand, the corresponding 3dB saturation power shown in Fig. 2(c) has negligible dependence on QW layer numbers. As V_{act} is also proportional to QW layers, the factors $\frac{\Gamma a}{V_{act}}$ and $\frac{\Gamma V_{opt}}{V_{act}}$ are hardly changed. As the operation frequency moves deeper into the slow-light region, the saturation power further decreases. Considering such low saturation power, PhC SOAs with SL enhancement appears attractive for nonlinear signal processing, e.g., four-wave mixing, rather than linear optical amplification [5].

In conclusion, we compared rigorous three-dimensional simulations of gain saturation in photonic crystal active waveguides to the predictions of an effective rate-equation-based model. The simple rate equation model is shown to provide good quantitative results as long as the parameters entering the model are carefully evaluated. Simulations indicate that a SL-enhanced PhC traveling-wave amplifier has a high small-signal modal gain at the expense of low saturation power, making it promising for nonlinear optical signal processing.

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