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Theoretical Analysis of Four Wave Mixing in Quantum Dot Optical Amplifiers

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Abstract: The four wave mixing properties of semiconductor quantum dot amplifiers have been investigated. The combination of strong non-equilibrium depletion of dot levels and a small linewidth enhancement factor results in efficient and symmetric four wave mixing.
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Quantum Dot (QD) amplifiers have a number of properties that render them likely candidates for signal processing [1] and low-noise linear amplification [2] in future communication systems. Recent experiments [3,4] have indicated that the Four Wave Mixing (FWM) properties of QD amplifiers are very different from bulk and Quantum Well (QW) devices. Thus, the FWM efficiency is independent of the sign of the detuning and decreases by less than 20dB/decade with detuning. Here, based on a simple 2-level model, we explain these properties. The model includes carrier capture from a Wetting Layer (WL) with finite QD capture time, τ_{cap}.

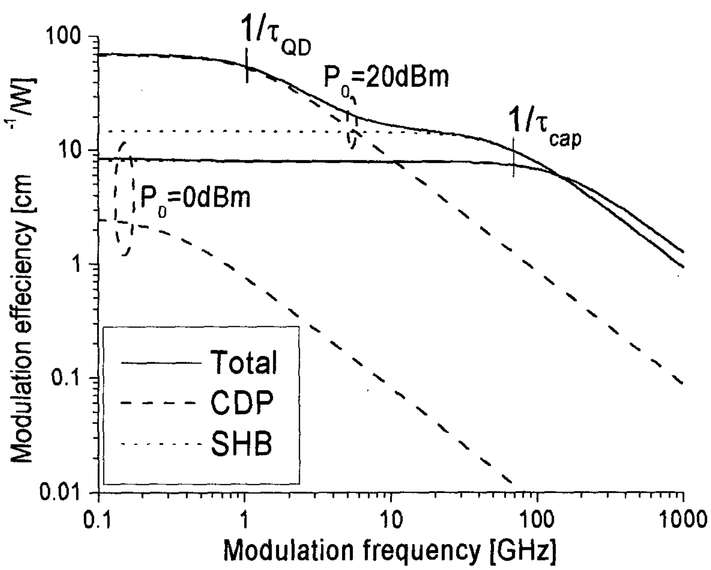

Fig. 1: Calculated optical modulation response for two different optical power levels.

The FWM efficiency depends on the efficiency by which the complex material susceptibility can be modulated through beating of the pump and probe signals. Fig.1 shows the modulation efficiency of the local gain. For an average power of P_0=1mW the device is strongly inverted, due to strong electrical pumping, and the response is dominated by non-equilibrium dynamics between QD and WL levels, referred to here as Spectral Hole Burning (SHB), which is limited by τ_{cap} . For P_0=100mW the device is forced towards transparency and, as a consequence, the response becomes dominated by Carrier Density Pulsation (CDP), which is limited instead by the much slower QD carrier lifetime. If we inject a 1mW pump signal into a 4mm long amplifier (corresponding to a gain of 20dB), the output power will reach 100mW. As a result, the FWM signals will, along the length of the amplifier, experience responses ranging between the two limiting cases shown in Fig.1.

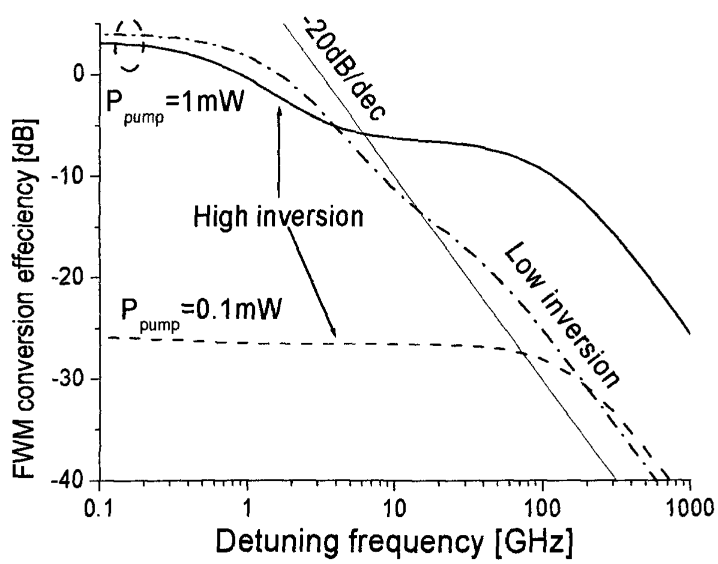

Fig. 2: Conversion efficiency of a 4mm long device with 20dB small signal gain and linewidth enhancement factors $\alpha=\beta=0$.

The calculated FWM conversion efficiency, Fig.2, shows that for a 1mW pump and under high inversion (solid line), CDP dominate at frequencies below 1GHz. SHB dominates for larger detunings and results in a conversion efficiency that drops off by less than -20 dB/decade. This is in good agreement with recent experimental observations [4]. For a weaker pump of 0.1mW (dashed line), the FWM process is dominated by SHB for all detunings simply because the device never reaches saturation and the CDP component remains small. Finally, if the inversion is reduced (dash-dotted line), the device is saturated throughout its length by a 1mW pump and CDP, therefore, dominates for all detunings and the conversion efficiency decreases by approximately 20dB/decade. This case thus resembles that of a typical bulk/(QW) device, where complete inversion of the active states is difficult to reach.

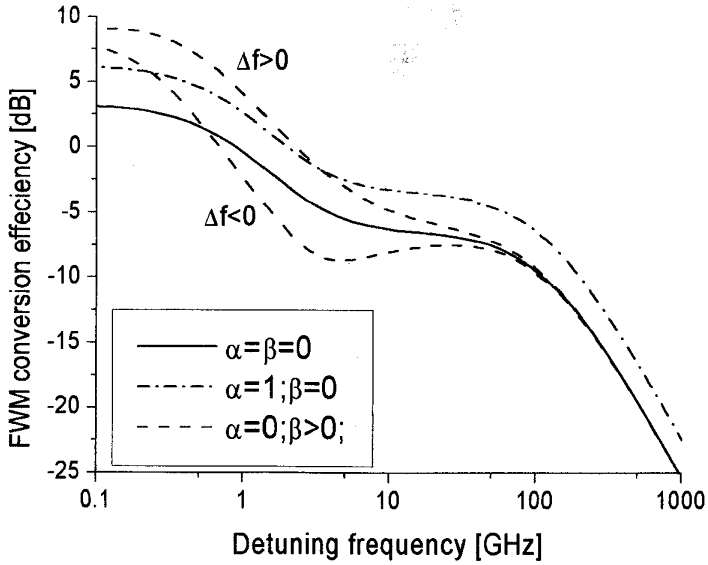

Fig. 3: Conversion efficiency for non-zero linewidth enhancement factors α and β.

The contribution of refractive index gratings is illustrated in Fig.3. We distinguish here between resonant contributions (referred to as α) and non-resonant contributions from the WL states (referred to as β). The case of $\alpha=\beta=0$ (solid line) is shown for reference. A resonant index grating (dash-dotted line) leads to an increased, but still symmetric, conversion efficiency. A non-resonant grating arising from modulation of WL carriers results in an asymmetry between positive and negative detunings, similar to the case of non-zero α-parameter in a bulk/QW amplifier. Such behavior has not yet, to our knowledge, been experimentally observed, but could be expected in case of strong inversion, where the WL becomes significantly populated. The WL has been shown to give a large dynamical contribution to the index under strong inversion [5].

In conclusion, we have investigated the FWM properties of QD amplifiers and find that the presence of effective SHB leads to a flatter frequency response compared with bulk/QW devices. Finally the presence of a highly inverted WL could be expected to lead to breakdown of the symmetry between positive and negative detuning frequencies.

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