Direct Observation of Slow Light in the Noise Spectrum of a Laser

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Abstract: The role of coherent population oscillations is evidenced in the noise spectrum of an ultra-low noise laser. The coherent population oscillations manifest themselves through their associated dispersion probed by the non-lasing side modes.

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1. Introduction

Slow and fast light (SFL) have been the subject of considerable research efforts. To control the group velocity of light, various approaches have been proposed and demonstrated, such as, e. g., electromagnetically induced transparency [1, 2], coherent population oscillations (CPO) [3], and stimulated Brillouin scattering [4]. CPO, an ubiquitous mechanism inducing SFL, is present in any active medium provided that a strong optical beam saturates this medium. Thus, CPO must be present in any single frequency laser since the oscillating beam acts as a strong pump which, by definition, saturates the active medium. This effect could be observed using an external probe whose angular frequency is detuned with respect to the oscillating mode, by less than the inverse of the population inversion lifetime $1/\tau_c$. Consequently, this effect should be also visible in the laser excess noise, using the spontaneous emission present in the non-lasing side longitudinal modes of a single-frequency laser as probe of the CPO effect. In semiconductor lasers τ_c is in the ns range, and then the CPO effects are efficient at offset frequencies below a few GHz from the lasing mode [5]. However, class-A vertical external cavity surface emitting semiconductor lasers (VECSELs) [6] recently developed for their low noise characteristics exhibit i) single-frequency operation, ii) ultra-narrow linewidth, iii) shot-noise limited intensity noise, and iv) a FSR in the GHz range. All these characteristics make them perfectly suited for the observation of CPO induced SFL in their noise spectrum.

2. Experimental setup and results

The laser used in our experiment is a VECSEL which operates at $\sim 1\ \mu$m. The 1/2-VCSEL gain chip is a multi-layered stack of semiconductors materials. Gain is produced by six InGaAs/GaAsP strained quantum wells grown on a high reflectivity Bragg mirror. The top of the gain structure is covered by an anti-reflection coating. The output mirror is placed at $L \lesssim 10$ cm from the gain structure. In these conditions, $1/2\pi\tau_c$ is not negligible compared with the FSR ($\Delta \gtrsim 1.5$ GHz). The laser is optically pumped at 808 nm. A thick glass etalon is inserted inside the cavity to make the laser single mode. The noise spectrum is measured using a wide bandwidth photodiode and a low noise radio-frequency amplifier. We focus on the excess noise due to the beat notes between the laser line and the spontaneous emission noise at neighboring longitudinal mode frequencies [7, 8]. At the p^{th} FSR frequency $p\Delta$, the noise spectrum is thus the sum of two Lorentzian peaks due to the beat notes of the lasing mode with the corresponding sidebands (p^{th} and $-p^{\text{th}}$ modes). When the pumping rate is increased, we found experimentally that the excess noise consists of two peaks separated by $\delta f = f_p - f_{-p} \sim 100$ kHz (inset of Fig. 1). This frequency shift is given by

$$\delta f \approx \nu_0 \frac{L_m}{L + n_0 L_m} (\delta n_p + \delta n_{-p}), \tag{1}$$

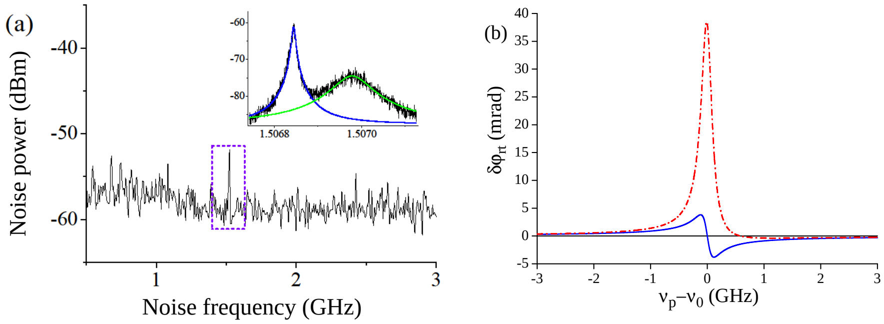

Fig. 1. (a) Typical laser intensity noise spectrum. For a cavity length $L \approx 10$ cm, the beat note frequency appear at the first harmonic of the resonator FSR $\Delta \approx 1.5$ GHz. The inset is a zoom of the excess noise in the region around Δ. (b) Round-trip phase modification experienced by the side modes for $\alpha = 0$ (full line) and $\alpha = 5$ (dotted-dashed line).

where n_0 is the bulk refractive index of the semiconductor structure and L_m is the length of the gain medium. $\delta n_{\pm p}$ are the modifications of the refractive index of the structure experienced by the $\pm p$ side modes and induced by the dispersion associated with the CPO effect. In a semiconductor active medium, thanks to the Bogatov effect [10], the dispersion is not an odd function of the frequency detuning with respect to ν_0. Thus, $\delta n_p \neq -\delta n_{-p}$ and the two beat note frequencies f_p and f_{-p} corresponding to the p and $-p$ modes occur at slightly different frequencies, as evidenced by the double peak of Fig. 1(a). This CPO induced index modification can be derived from the gain medium rate equation including the phase-intensity coupling coefficient α (Henry's factor) that is responsible for the Bogatov effect [11]. This CPO effect is also responsible for the modification of the refractive index seen by the side modes which modifies the round-trip phase accumulated by each side mode Fig. 1(b). Finally, notice also that since the cavity FSR Δ is sufficiently large that we are probe the wings of the dispersion profile of Fig. 1(b), i. e., in the slow light regime.

3. Conclusion

In conclusion, we experimentally evidenced the existence of intracavity slow light effects in a laser induced by the CPO mechanism. These effects are probed by the laser spontaneous emission noise present in the non lasing modes. We have shown that this noise is a very efficient probe to explore the intracavity CPO effects.

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