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

Abdelkrim El Amili, B.-X. Miranda, Fabienne Goldfarb, Ghaya Baili, Grégoire Beaudoin, Isabelle Sagnes, Fabien Bretenaker, Mehdi Alouini

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

A. El Amili[1], B.-X. Miranda[1,2], F. Goldfarb[1], G. Baili[3], G. Beaudoin[4], I. Sagnes[4], F. Bretenaker[1], and M. Alouini[2,3]

1. Laboratoire Aimé Cotton, CNRS-Université Paris Sud 11, 91405 Orsay Cedex, France
2. Institut de Physique de Rennes, CNRS-Universit de Rennes I, 35042 Rennes Cedex, France
3. Thales Research and Technology, Campus Polytechnique, 91127 Palaiseau Cedex, France
4. Laboratoire de Photonique et Nanostructures, CNRS, Route de Nozay, 91460 Marcoussis, France

Coherent population oscillations (CPO), an ubiquitous mechanism inducing slow and fast light (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 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. This effect should be 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. Class-A vertical external cavity surface emitting semiconductor lasers (VECSELs) [1] recently developed for their low noise characteristics make them perfectly suited for the observation of CPO induced SFL in their noise spectrum. The single-frequency laser used in our experiment is a VECSEL which operates at $\sim 1\ \mu$m. 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 [2,3]. 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(a)). This frequency shift is given by: $\delta f \approx \nu_0 \frac{L_m}{L+n_0 L_m}(\delta n_p + \delta n_{-p})$, where n_0 is the bulk refractive index of the semiconductor structure, L and L_m are the length of the cavity and the gain medium respectively. $\delta n_{\pm p}$ 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 [4], 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. 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). 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. 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.

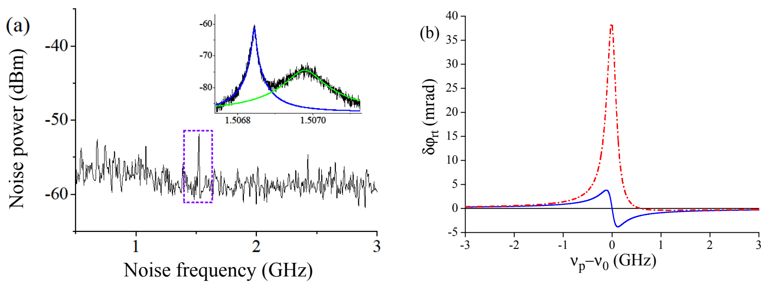

Fig. 1 (a) Typical laser intensity noise spectrum. For a cavity length $L \approx 10$ cm, the beat note frequency appear at the first harmonic of the resonator FSR $\Delta \approx 1.5$ GHz. The inset is a zoom of the excess noise in the region around Δ. (b) Round-trip phase modification experienced by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

References

[1] A. Laurain, M. Myara, G. Beaudoin, I. Sagnes, and A. Garnache, "High Power SingleFrequency ContinuouslyTunable Compact Extended-Cavity Semiconductor Laser", Opt. Expr. **17**, 9503-9508 (2009).
[2] M. P. van Exter, R. F. M. Hendriks, J. P. Woerdman, and C. J. van der Poel, "Explanation of Double-peaked Intensity Noise Spectrum of an External-Cavity Semiconductor Laser", Opt. Comm. **110**, 137-140 (1994).
[3] G. Baili, F. Bretenaker, M. Alouini, L. Morvan, D. Dolfi, and I. Sagnes, "Experimental Investigation and Analytical Modeling of Excess Intensity Noise in Semiconductor Class-A Lasers", J. Lightwave Technol. **26**, 952-961 (2008).
[4] A. P. Bogatov, P. G. Eliseev, and B. N. Sverdlov, "Anomalous Interaction of Spectral Modes in a Semiconductor Laser", IEEE J. Quantum Electron. **11**, 510-515 (1975).