Amplitude squeezing with a Fabry–Perot semiconductor laser: existence of an optimum biasing condition

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The effect of gain suppression on amplitude squeezing with a Fabry–Perot semiconductor laser is studied with a semiclassical model. A strong decrease of the internal amplitude noise and an optimum biasing point with minimum amplitude noise are demonstrated. Small gain nonlinearities improve external compression.

For the past few years attention has been paid to amplitude squeezing with semiconductor lasers. Several models have been developed, based on a quantum-mechanical approach,[1] traveling waves,[2] or semiclassical approaches.[3] A model[4] based on a semiclassical analysis with a Green's function analysis and including nonlinear gain[5] has been developed. This model enables us to take into account structural dependences such as spatial hole burning and other phenomena such as gain suppression. In a first step, this model has been applied to study the effect of only gain suppression on squeezing performances.

The Helmholtz equation for the internal field is solved with a Green's function method. Noise forces associated with the transmitted vacuum forces and the structure internal losses are added to this equation. The incoming vacuum fluctuations are given by

$$f_0(t) = \sqrt{1 - R_1}\sqrt{\tau/V} f_{\mathrm{vac}}(t),$$

$$f_L(t) = \sqrt{1 - R_2}\sqrt{\tau/V} f_{\mathrm{vac}}(t), \qquad (1)$$

with $\langle f_{\mathrm{vac}}(t) f_{\mathrm{vac}}(t')^* \rangle = \delta(t - t')$, where R_1 and R_2 are the power reflection coefficients of the laser facets as defined in Fig. 1, τ is the light's round-trip time inside the cavity, and V is the volume of the active section.

For a Fabry–Perot structure as shown in Fig. 1 with the facet reflectivity R_2 not too small, these forces induce changes in the Langevin diffusion coefficient associated with the average photon density $\overline{P}$, which is written as

$$2D_{PP} = \left(2n_{\mathrm{sp}}\nu_g g\overline{P} + \frac{2\overline{P}}{\tau_P}\right)\Big/ V, \qquad (2)$$

where τ_P is the photon lifetime and ν_g is the group velocity.

After linearization of the rate equations deduced from a Green's function analysis[5] around the linear gain operation point, internal noise spectra are obtained with a Fourier-transform analysis. For a Fabry–Perot laser, in which spatial hole burning may be not considered, many simplifications occur and simple analytical results are obtained. The internal amplitude noise spectra are

$$S_{A_{\mathrm{int}}}(\Omega) = \frac{A_{\mathrm{int}P}\Omega^2 + B_{\mathrm{int}P}}{(\Omega_0{}^2 - \Omega^2)^2 + \dfrac{\Omega^2}{\tau_r{}^2}}, \qquad (3a)$$

where

$$A_{\mathrm{int}P} = 2D_{PP},$$

$$B_{\mathrm{int}P} = \frac{2D_{PP}}{\tau_r{}^2} + 2D_{NN}(\overline{P}\nu_g g_d)^2 + 4\overline{P}D_{NP}\frac{\nu_g g_d}{\tau_r}, \qquad (3b)$$

and $\Omega_0{}^2 = \overline{P}\nu_g{}^2 g g_d$, with the same notation as in Ref. 5. External amplitude noise spectra are then deduced from the boundary condition at the laser's right facet, including the reflected vacuum forces. This leads to

$$S_{A\mathrm{ext}}(\Omega) = \frac{\omega}{Q_e}\left[\frac{A_{\mathrm{int}P}\Omega^2 + B_{\mathrm{int}P}}{\left(\Omega_0{}^2 - \Omega^2\right)^2 + \dfrac{\Omega^2}{\tau_r{}^2}}\right] \times V + \frac{1}{2} - \frac{\omega}{\tau_R Q_e}\frac{\Omega_0{}^2}{\left(\Omega_0{}^2 - \Omega^2\right)^2 + \dfrac{\Omega^2}{\tau_r{}^2}}, \qquad (4)$$

where $\omega/Q_e = -(\nu_g/2L)\ln(R_2)$ represents the contribution of the mirror loss to the photon lifetime.

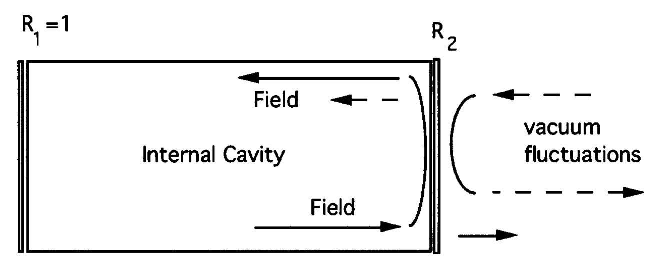

Fig. 1. Fabry–Perot laser structure scheme with field and noise force reflections.

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The use of a pump-noise-suppressed laser is modeled by a change in the diffusion coefficient of the Langevin force associated with the carriers D_{NN}, which is then given by

$$2D_{NN} = \left[\nu_g g\left(n_{\rm sp} - \frac{1}{2}\right)\overline{P} + \frac{\overline{N}}{2\tau_e}\right]\Big/V, \qquad (5)$$

with $\overline{N}$ the carrier density, g the gain, τ_e the spontaneous electron lifetime, and $n_{\rm sp}$ the population inversion coefficient. For a high pump level $R = I/I_{\rm th} - 1$ and quiet pumping, total amplitude squeezing is obtained for a laser without internal losses as demonstrated previously.[1,4]

We take the gain suppression into account, using the equation

$$g = g_{\rm linear}(1 - \varepsilon\overline{P}), \qquad (6)$$

where ε is the gain suppression factor. This equation is one of many existing in the literature.[3,6]

With or without a quiet source the internal amplitude noise becomes very small for a very high pumping rate, as shown in Fig. 2, because of the clamping of the amplitude of the internal field for a high pump level. Only a slight discrepancy exists between pumping with and without a quiet source. Concerning the external amplitude noise, the effects of nonlinear gain are important. Without a quiet source, amplitude squeezing is possible, down to 25% under the shot-noise value. This has been pointed out by Arnaud.[3]

Under an assumption of linear gain, the use of quiet source permits substantial noise compression. The gain suppression leads to an optimum biasing point, for which a maximum of amplitude squeezing may be obtained, as shown in Fig. 3. For low pump rates, significant differences do not exist between linear and nonlinear gain assumptions. The external amplitude noise decreases and gets below the shot-noise value.

At high pump rates, a major difference appears: as the internal amplitude noise decreases and becomes very small because of gain suppression, the vacuum fluctuations reflected at the facets become the major contribution to the external noise. In such conditions the external amplitude noise increases and tends to the shot-noise level, but it does not reach zero as in the linear gain case.

Consequently, an optimum biasing point for squeezing exists. This optimum performance is strongly dependent on the gain suppression factor, as shown in Fig. 4. Gain suppression factors used for these simulations correspond to usual values for bulk lasers. As reported by Nilsson *et al.*,[7] a reduction of the relaxation peak has also been found. They demonstrated a limitation in the amount of squeezing permitted but not an increase in the noise at high pump levels.

The use of other gain suppression expressions[3,6] does not change the conclusions, as $\varepsilon\overline{P}$ is close to 0.1 in the minimum external amplitude noise region. The only existing difference is the limit value for high pump rates, which becomes below the shot-noise level for other expressions similar to the one used here.

Such a minimum external amplitude noise can be demonstrated for a laser pumped with a Poissonian current source. This would explain experimental re-

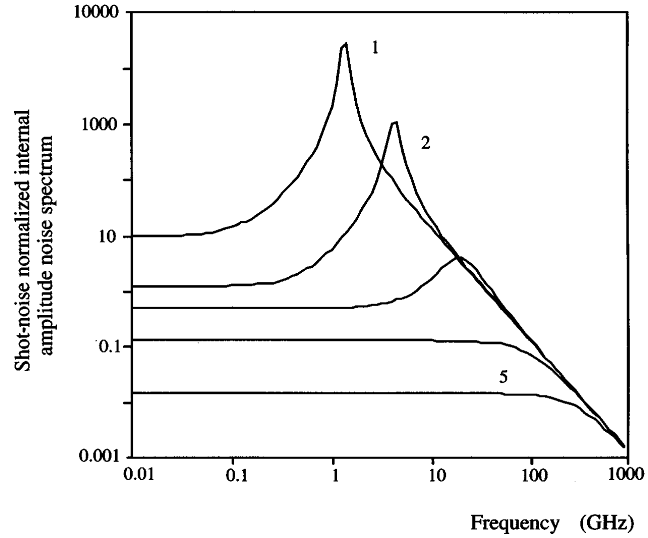

Fig. 2. Internal amplitude noise normalized by the shot-noise level for $\varepsilon = 10^{-18}$ cm^3 at biasing levels $R = I/I_{\rm th} - 1$ of 1 (curve 1), 10 (curve 2), and 400 (curve 5).

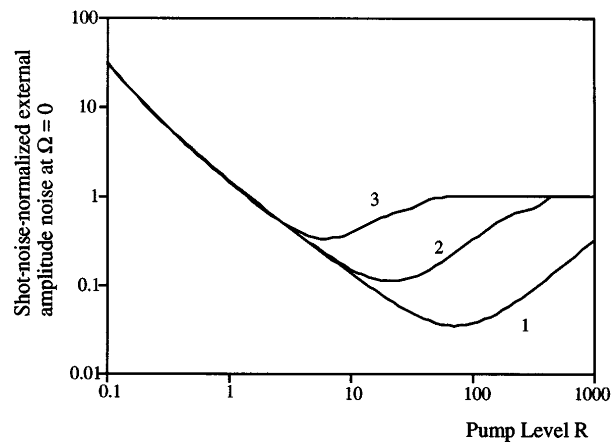

Fig. 3. External amplitude noise at zero frequency normalized by the shot-noise level with quiet source pumping for nonlinear gain coefficients of 10^{-19} cm^3 (curve 1), 10^{-18} cm^3 (curve 2), and 10^{-17} cm^3 (curve 3).

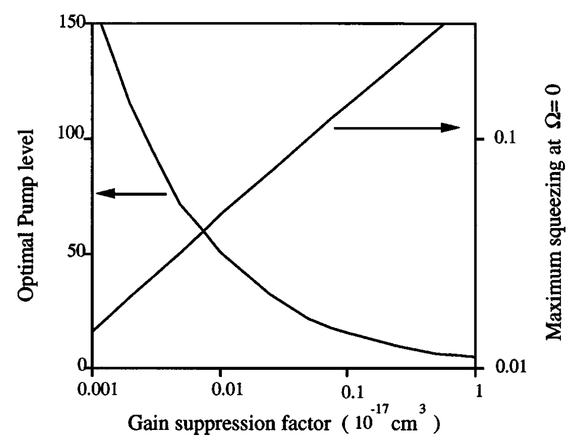

Fig. 4. Minimum external noise value obtainable and optimum biasing current as functions of the gain suppression factor ε.

sults already obtained, in which a minimum value of the relative internal noise was found[8,9] when the pumping current was varied.

A new method pointing out the influence of gain suppression has been reported. It shows that quantum-well lasers, with low threshold currents but high nonlinearity, may not be optimum for squeezing. An optimum longitudinal structure for squeezing that uses a distributed-feedback or distributed-Bragg-reflector section is under study.

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