Modulation of Nanolaser Output for Information Encoding

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Abstract— We analyze some of the fundamental issues concerning the suitability of high-β laser devices for information encoding by using a Stochastic Simulator. Modulating the pump in a square-wave fashion, to encode sequences of 0 and 1 levels, we study the influence of offset (or bias) and modulation amplitude on the fidelity of the nanolaser output. The impact of the cavity relaxation rate is also discussed.

1. INTRODUCTION

In recent years, nanolasers have gained much attention and a significant amount of work has been carried out to explore and develop them, given their potential as sources for data transmission and storage, intra-chip connections and generically for their use as on-chip light sources [1–3].

Nanoscale lasers, in the limit of $\beta = 1$ (where β represents the fraction of spontaneous emission coupled into the lasing mode) offer the advantage of allowing a unique electromagnetic cavity mode to interact with the "atoms" of the gain material (where "atoms" is to be intended as the generic quantum element transforming internal energy into electromagnetic radiation). This way, the coupling efficiency from spontaneous emission to the lasing mode approaches unity, thereby allowing for high efficiency and very low threshold [4]. In addition, their extremely small cavity size offers the potential for a short cavity lifetime (even though photons need to be *recycled* more than in a conventional laser to achieve stimulated emission), thus allowing for higher modulation bandwidth, a significant advantage for high volume information processing.

So far, different kinds of nanoscale lasers have been manufactured, and very low-threshold performance has been demonstrated, at least with optical pumping. Electrical injection is actively pursued, because of its obvious advantages, and some results in this direction have been obtained [5]. One important hurdle has so far hampered the development of these devices: the competition between the efficient fabrication of a gain medium and the manufacturing of suitable cavity "mirrors". Indeed, the two requirements tend to impose conflicting restrictions, as particularly clear in the case of photonic crystal structures, where the "damage" inflicted on the material by the holes renders the achievement of strong gain difficult. A very recent breakthrough, decoupling the problem of achieving adequate optical gain from the construction of the cavity "mirrors", has been obtained by accurately positioning a monolayer gain medium on top of a photonic crystal cavity [6]. This innovative configuration brings nanolasers one step closer to their actual deployment as practical devices. Thus, it is time to start asking under which conditions nanolasers may be used for effective information encoding.

Theoretically, since only a limited number of emitters is enclosed inside the cavity and therefore the number of photons is not very large, we cannot consider the *thermodynamic limit* commonly assumed for the laser [7]; thus, the quantum fluctuations in the number of inverted *atoms* and in the intracavity (as well as emitted) photons cannot be ignored [8]. Hence, the traditional rate equations [9] are no longer suitable to model such small lasers. Although sophisticated modeling has been conducted up until now on the basis of greatly enhanced rate equations which take into account the physical characteristics of the semiconducting structure both for nanolasers [10, 11] and for nanoLEDs [11], the device's sensitivity to the intrinsic noise cannot be easily tested with these numerical approaches. Further, doubts about the suitability of nanosources for optical communications, and for information encoding and handling have been raised due to the larger intrinsic fluctuations and to the appearance of population cycles (noise-induced relaxation oscillations) in high-β devices [8].

The failure of the simplest, standard modeling choice of reliably predicting the response of a nanolaser under parameter (pump) modulation represents a serious obstacle for determining suitable operating conditions for optical encoding. More sophisticated modelling choices [12, 13] suffer from the disadvantage of requiring large computing times and/or from not allowing for dynamical investigations [14]. In order to obtain efficient predictions on the expected nanolaser response to pump modulation for data encoding, we are going to use a recently introduced Stochastic Simulator (SS) [15], which extends an idea adopted in [8]. The model predicts the physical response of a nanolaser, taking into account the *granularity* of the processes (number of photons and of excited *atoms*) without pretending to specifically consider the construction details of any device, which would vary according to the materials, construction techniques, etc. No external noise is applied (e.g., pump noise) at the present time, since the sole *stochasticity* of the lasing process is sufficient to induce deviations — substantial for particular operating parameters — from the pattern imposed by the pump. Different regimes are considered, changing biasing, modulation amplitude and cavity quality factor.

2. STOCHASTIC SIMULATOR

The Stochastic Simulator mimics a sequence of events as a succession of possible occurrences taking place at discrete times, with a time discretization small enough compared to the fastest time scale [15]. This scheme describes the process of spontaneous or stimulated photons emitted by an excited *atom* as a random process. The individual processes considered in the SS, which in their collective interaction produce lasing or incoherent emission, are: 1. excitation of an *atom* by the pumping mechanism; 2. disexcitation of an *atom* with emission of an off-axis (i.e., in an e.m. cavity mode other than the lasing mode) spontaneous photon; 3. disexcitation of an *atom* with emission of an on-axis (i.e., in the lasing mode) spontaneous photon; 4. disexcitation of an *atom* with emission of a stimulated photon; 5. leakage (out of the cavity volume) of an off-axis spontaneous photon; 6. transmission of an on-axis spontaneous photon through the cavity output mirror; 7. transmission of a stimulated photon through the cavity output mirror [15]. The spontaneous photons emitted off-axis are collected into a single ensemble, to which we assign a (somewhat arbitrarily) same, average leakage rate, due to their low impact onto the overall dynamics. The distinction of photons into three categories is indispensable in a photon number modeling approach, since it is the most efficient way of numerically following the different populations. A Poissonian probability distribution is used for the pump, while all other processes are simulated with a binomial probability distribution. Details about the SS rules can be found in [15]. The dynamical response to the modulation of the pump is simply obtained by applying a square-wave modulation, with variable frequency and amplitude (as well as offset), to the dynamical evolution of the SS.

The parameters we used for the simulations are: material relaxation constant $\gamma_{\parallel} = 2.5 \times 10^9\,\mathrm{s}^{-1}$, and losses for off-axis spontaneous photons $\Gamma_0 = 5 \times 10^{13}\,\mathrm{s}^{-1}$. As in [15], the value of the parameter of tuning the probability of a spontaneous photon generating a stimulated photon is set at $K = 0.05$. The time step used to follow the process is set to $\triangle\tau = 2 \times 10^{-15}\,\mathrm{s}$, allowing for a good sampling of the fastest evolution (off-axis spontaneous photons). The cavity losses for the on-axis mode (describing the transmission by the output mirror for both kinds of photons: spontaneous or stimulated) are typically assumed to be $\Gamma_c = 1 \times 10^{11}\,\mathrm{s}^{-1}$, unless otherwise noted (i.e., when changing the resonator's quality factor).

3. RESULTS AND DISCUSSION

The Stochastic Simulator is a very useful tool for predicting the laser dynamics with fast computations thus allowing for a quantification of the intrinsic noise (i.e., the spontaneous emission). The self-consistent inclusion of both populations of spontaneous photons (on- and off-axis) in addition to the traditional quantities (inverted *atoms* and stimulated photons) allows for obtaining meaningful predictions of the laser's response irrespectively of the modulation amplitude and bias (i.e., even in a region where the laser is not "properly above threshold"). In addition, the choice of stochastically simulating the discrete physical processes without introducing a differential description removes the assumptions which are normally necessary for the latter, and preserves the *granular* description of the interaction, thereby delivering predictions which maintain the strongly stochastic character typical of small-sized systems [16]. Thus, the resulting dynamical output will reflect the concomitance of the stochastic processes which contribute to the onset of lasing action even in regimes where the pump is modulated at a high rate even across the threshold region [15].

Here, we show an example of modulation in a high-β nanocavity laser, where the *lasing transition* becomes nearly linear (cf. Fig. 1, inset, $\beta = 0.9$) [17]. Since we are working with a model based on physical principles, rather than on a practical device, the parameter values are relative and do not have a direct quantitative equivalence in physical units. The region of input-output response depicted in the inset corresponds to predominantly spontaneous photons emitted for the smallest values of the pump, and to predominantly stimulated ones for the largest ones [16]. The five output

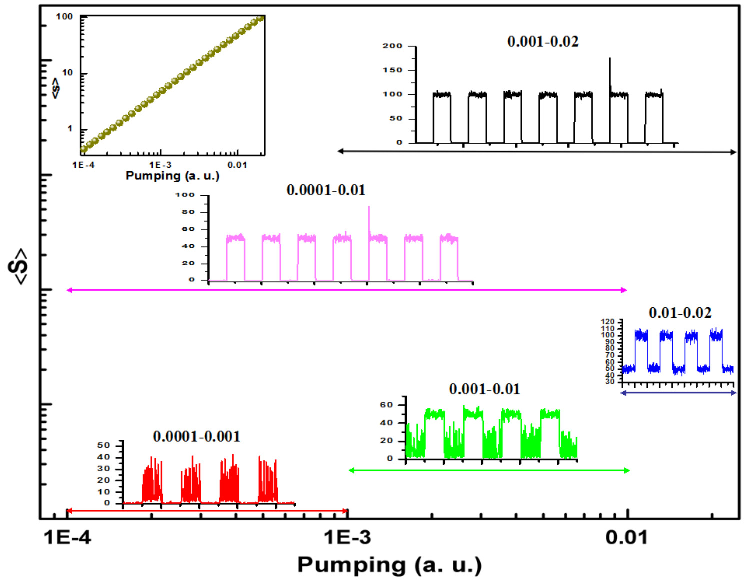

Figure 1: Illustration of principle of direct current modulation in a nanolaser with $\beta = 0.9$ computed by the SS. Inset (upper left corner): average output intensity as a function of pump. The color traces show the predicted output for a few 0–1 bit sequences for different modulation amplitude and offset. Their position is marked by color dots in the response curve (inset).

samples in the body of Fig. 1 illustrate the laser output for different values of the modulation amplitude (cf. reflected qualitatively by the horizontal placement of each graph in the figure). The exact pump values are given for each figure as a set of two numbers indicating (lower–upper) pump value, respectively, and the colored arrows give a visual representation of the modulation offset and amplitude (on the horizontal axis). The signal is computed with an integration time (0.2 ns) simulating the detector response.

First, we notice that the scale for the (total: spontaneous plus stimulated) photon number exiting the cavity does not vary more than a factor approximately 2 over the whole range explored. What changes drastically is the response of the laser to the modulation. The frequency chosen is quite low here, to highlight the different regimes (the frequency response will be analyzed elsewhere). For the lowest excitations (red curve, bottom left in the figure), the logical 1 level corresponds to a sequence of spikes corresponding to a signal whose *noise* is as large as the average (thus an entirely closed eye diagram). This is not unexpected since in the threshold region the laser operates as a sequence of spikes [15]. Moving the offset upwards one order of magnitude (green curve), we find that the lower level is extremely noisy, due to the same spiking operating regime just discussed. A large modulation amplitude (purple curve, pump driven between 10^{-4} and 10^{-2}) provides a sequence of bits which are usable, even though one remarks the presence of a spurious, large spike at the beginning of the fifth 1-level. The same occurs when the pump corresponding to the 1-level is doubled (black curve). Finally, when driving the nanolaser between two above-threshold levels one obtains a noisy, but usably encoded output (blue curve).

The cavity losses (alternately, the cavity quality factor) also play an important role in determining the encoding fidelity, as shown in Fig. 2. For large losses ($\Gamma_c = 10^{12}\,\mathrm{s}^{-1}$) the number of photons output is very small and the intrinsic fluctuations render the signal unusable (black curve). The 1-level is reminiscent of coherent oscillations [8], found also with the SS [15] (the 0-level is almost always devoid of photons, for all three values of cavity losses considered in this figure). This is plausible since for lower pump values one expects to find (less-damped) relaxation oscillations which can strongly be excited by the intrinsic fluctuations proper to the stochastic process.

Reducing the losses by one order of magnitude (red curve) the average number of photons increases by one order of magnitude and the relative fluctuations are strongly reduced, for the same pump values (from 10^{-4} to 10^{-2}). Further reduction of the cavity losses ($\Gamma_c = 10^{-10}\,\mathrm{s}^{-1}$, blue curve) provides a much stronger signal with small fluctuations. It is important to remark that occasional "errors" survive, in the form of spikes, not only for the intermediate, but also for the smaller losses (cf. initial value of the fourth 1-level). Given that the number of bits computed here is very small, it is not impossible that fidelity may be affected even under the best conditions shown here for moderately long bit sequences.

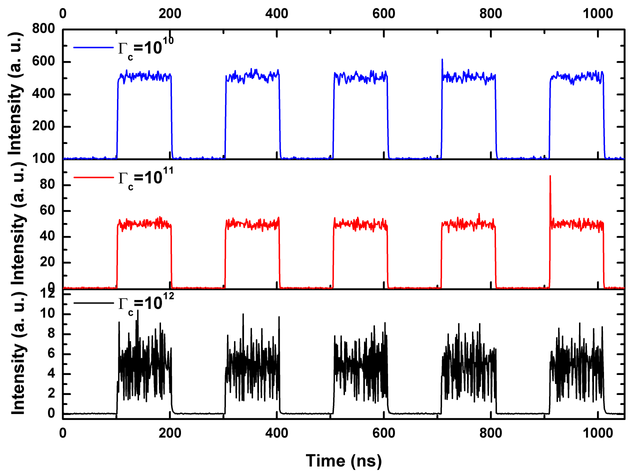

Figure 2: Laser output for a square modulation of the pump between 10^{-4} and 10^{-2} in a 0-1 level repetitive sequence for three different values of cavity losses Γ_c. Notice that the threshold is lowered as Γ_c is decreased, whence the larger output and higher-quality encoding.

The enhanced spontaneous emission, coupled with a high Q cavity (low Γ_c), is expected to result in a reduction of the laser turn-on delay, in addition to a threshold reduction. This comes from the fact that dynamically (i.e., in a rate-equation kind of analysis) the saddle point moves closer to threshold [18] and therefore can be reached faster. In the limit of $\beta = 1$ this would amount to reducing the turn-on delay to zero. However, a strong increase in cavity quality factor is accompanied by a strong reduction of the modulation bandwidth (easily checked even with a SS), thus offsetting entirely the advantage originating from the disappearence of the turn-on delay — which limits the modulation bandwidth — by an even stronger limitation on bandwidth. In addition, it is possible that the coherent oscillation conditions may worsen when the threshold is strongly lowered [8], thus calling again into question the desirability of high Q cavities. Work is under way to clarify this point.

4. CONCLUSION

With the help of a Stochastic Simulator we have analyzed some fundamental aspects of the issues which concern the suitability of a nanolaser for information encoding. Fundamental concerns raised by other authors appear to be realistic, but it seems possible to find parameter regimes in which very small devices should prove usable for digital applications.

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