Signatures of non-classical light emission from semiconductor lasers

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I. Introduction

Nowadays, single-photon sources can be generated experimentally through a wide variety of platforms [1]. Semiconductor quantum dots [2] have demonstrated impressive performance in terms of photon purity and indistinguishability, particularly in Hong-Ou-Mandel experiments. Another widely used method involves nonlinear crystals, which can generate entangled photon pairs via nonlinear processes such as spontaneous parametric down-conversion (SPDC) or spontaneous four-wave mixing (SFWM). These are heralded single-photon sources, rather than deterministic ones, yet they remain essential tools in quantum optics [3]. Moreover, among the most commonly used single photon sources, there are NV centres in diamonds [4]. These single-photon sources emit quantum states of light, i.e., those that have no classical counterpart.

In the realm of semiconductor lasers, the seminal work of Yamamoto et al. [5] demonstrated the possibility of reducing the noise of light emission in a quantum well laser below the classical shot noise limit, also known as the standard quantum limit, a clear signature of the quantum nature of the emitted light [6], [7]. This was achieved by minimising noise in the input stream of pumped electrons through the use of high-impedance suppression, resulting in a more regular, so-called ”quiet” electron pumping. Recent experimental studies have shown that this effect can also be realised in quantum dot lasers and appears to be more robust in the presence of optical feedback [8], [9].

These developments hold promise for applications in quantum communication, such as continuous-variable quantum key distribution (CV-QKD), by leveraging the mature fabrication capabilities of the semiconductor industry—thus enhancing the commercial feasibility of these platforms [10].

In this work, we will introduce a theoretical framework to study the dynamics of semiconductor lasers based on stochastic rate equations, along with an efficient numerical approach for their simulation. In particular, we will focus on the role of pumping noise in shaping the relative intensity noise (RIN) spectrum, and we will examine the conditions under which this spectrum can be suppressed below the standard quantum limit.

II. Semiclassical Rate Equations

The behaviour of semiconductor lasers can be described using a set of coupled stochastic differential equations (SDEs) for the dynamical variables $\vec{X}(t)$ -namely, the carrier densities and the single mode of the electromagnetic field [7]. These equations take the general form:

$$\frac{d\vec{X}}{dt} = \vec{a}(\vec{X}) + \vec{F}(\vec{X}), \tag{1}$$

where $\vec{a}(\vec{X})$ represents the deterministic drift term and $\vec{F}(\vec{X})$ denotes the noise vector.

In the case of quantum dot lasers, we employ a three-level carrier model, following the approach in [11]. The dynamical material variables include the carrier densities in the wetting layer (resonant level), as well as the excited and ground states of the quantum dots, respectively, denoted as (N_{RS}, N_{ES}, N_{GS}). Photon emission is assumed to occur exclusively from the ground state.

The correlation matrix associated with the noise vector is ultimately derived from the application of the fluctuation-dissipation theorem at the microscopic level, where the laser dynamics are governed by quantum Langevin equations [12].

Within the finite-dimensional dynamical models considered, it is possible to obtain an exact solution of the linearized system for small-signal analysis. This allows for an analytical expression of the relative intensity noise (RIN) spectrum, defined as

$$\mathrm{RIN} = \frac{\delta S_{II}}{I^2}, \tag{2}$$

where

$$\delta S_{II} = |\delta I(\omega)|^2 \tag{3}$$

is given in terms of the Fourier transform $\delta I(\omega)$ of the intensity fluctuations around the stationary solution I.

However, our main interest lies in the output RIN [7], which accounts for the partition noise introduced by the cavity mirrors. This additional noise must be considered to accurately describe the Poissonian photon statistics and thus properly define the standard quantum limit (SQL). The fluctuation of the output power, incorporating the correlated noise term F_0, is given by

$$\delta P = (\eta_0 h\nu)\delta I + F_0, \tag{4}$$

where η_0 is the output coupling efficiency and ν is the laser frequency.

III. Numerical Simulation Techniques

We have developed and implemented an algorithm to simulate the laser dynamics by numerically integrating the system of stochastic differential equations (Eq. 1). The method is an extension of the classical second-order Runge-Kutta algorithm [13], adapted to rigorously account for noise correlations.

The algorithm takes as input the drift vector $\vec{a}(\vec{X})$ and the correlation matrix $\mathbf{C}(\vec{X})$, where each element is given by $\mathbf{C}_{ij} = \langle F_i F_j \rangle$. The square root of this matrix, $\mathbf{B}(\vec{X})$, is computed at each time step to construct the noise term and multiplied by the vector of random variables $\Delta\vec{W}_k$. Once the

Algorithm 1 Stochastic Runge-Kutta 2nd Order (SRK2)

procedure SRK2($\vec{X}_0, \vec{a}, C, T, \Delta t$)
  $n_{\text{steps}} \leftarrow \text{int}(T/\Delta t)$
  $\vec{X} \leftarrow \vec{X}_0$
  for $k = 0$ to $n_{\text{steps}} - 1$ **do**
    $\Delta\vec{W}_k \leftarrow \text{vec}(\mathcal{N}(0, \sqrt{\Delta t}), \text{dim} = n_W)$
    $\mathbf{B}(\vec{X}_k) \leftarrow \text{sqrtm}(C(\vec{X}_k))$
    $\vec{K}_1 \leftarrow \vec{a}(\vec{X}_k)\Delta t + \mathbf{B}(\vec{X}_k) \cdot \Delta\vec{W}_k$
    $\mathbf{B}(\vec{X}_k + \vec{K}_1) \leftarrow \text{sqrtm}(C(\vec{X}_k + \vec{K}_1))$
    $\vec{K}_2 \leftarrow \vec{a}(\vec{X}_k + \vec{K}_1)\Delta t + \mathbf{B}(\vec{X}_k + \vec{K}_1) \cdot \Delta\vec{W}_k$
    $\vec{X}_{k+1} \leftarrow \vec{X}_k + \frac{1}{2}(\vec{K}_1 + \vec{K}_2)$
  end for
  return $\vec{X} = (\vec{X}_0, \ldots, \vec{X}_{n_{\text{steps}}})$
end procedure

stationary state is identified from the rate equations, we verify that it corresponds to a stable fixed point of the dynamics. Post-processing of the resulting trajectories is then used to compute the RIN spectrum, according to Eq. (3).

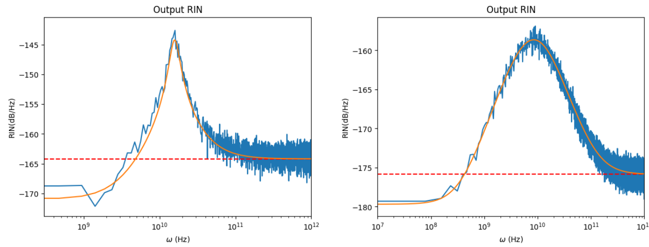
IV. Results

We analyse both theoretically and numerically the effect of pumping noise on output power fluctuations, considering quantum dot lasers with quantum well lasers. To identify the standard quantum limit (SQL), we assume that the variance of the output power is proportional to its mean value, corresponding to Poissonian statistics. This sets the RIN level at high frequency where shot noise dominates [7] at $\frac{h\nu}{P_{st}}$, where P_{st} is the stationary output power.

In Fig. 1a, we show that for the quantum well laser, the RIN spectrum drops below the SQL in the low-frequency region due to quiet pumping, in agreement with the literature [7]. A similar result for the quantum dot laser is shown in Fig. 1b. Also in this case, our results qualitatively match the recent experimental evidence reported in [8], [9]. In both cases, the high frequency region of the spectrum aligns with the SQL level after the peak associated with relaxation oscillations, while the low frequency region reveals a noise reduction of up to 5–6 dB/Hz.

V. Conclusion and Outlook

In this work, we have theoretically shown that a regular input stream of electrons (quiet pumping regime) can lead to a reduction in relative intensity noise in the low-frequency region, falling below the shot noise level—i.e., below the



(a) Quantum well laser at 17 mW. (b) Quantum dot laser at 256 mW.

Fig. 1. RIN spectra in the quiet pumping regime using parameters respectively from [7] and [11].

classical detection limit, both in quantum dot and quantum well lasers.

While the RIN spectrum offers a signature of non-classical light emission, a more definitive indicator for the emission of quantum states of light is the second-order correlation function at zero delay. Future work will aim to study the effect of optical feedback on sub-shot noise emission and possibly assess directly the sub-Poissonian statistics of the detected photons through numerical simulations.

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