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Quantum Photonics with Interband Cascade Lasers

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Abstract— Quantum photonics with interband cascade lasers (ICLs) is an emerging research field that investigates the use of ICLs for quantum communication, quantum cryptography, and other applications that require the generation and manipulation of quantum states. In this work, we explore the possibility of generating amplitude-squeezed light with high quantum efficiency ICLs through theoretical investigations. Based on two different modelling approaches, we demonstrate that this mid-infrared semiconductor device can operate with significant amplitude squeezing over a large bandwidth of several GHz when driven by low-noise constant current sources. Our findings could accelerate the development of original quantum hardware in the mid-infrared range, which is currently not available but could have numerous applications, including laser-based free-space secure communication systems.

1. Introduction

Noise considerations play a pivotal role in defining the quality and reliability of communication applications. Since the inception of laser oscillators, understanding noise has been of tremendous significance, encompassing fundamental physical principles and design considerations. Key phenomena such as the shot noise limit and the Schawlow-Townes linewidth have been recognized as crucial milestones in the evolution of semiconductor lasers. However, recent decades have witnessed remarkable progress in comprehending the noise properties in photonics [1], allowing semiconductor lasers to surpass previously presumed limitations in terms of intensity noise and linewidth, entering the quantum regime. These advancements have propelled the performance of semiconductor lasers to unprecedented levels, hence opening up new possibilities for a wide range of quantum applications. Moreover, the maturity of the semiconductor fabrication process, combined with fresh concepts, has facilitated the realization of those fundamental theories, further enhancing the practicality and applicability of semiconductor lasers in real-world scenarios.

In this work, we investigate a novel category of quiet-light optoelectronic sources designed for operation in the mid-infrared window, which is highly relevant for numerous applications in free-space communication. Our focus is on interband cascade lasers (ICLs) emitting in a broad wavelength range of 3-6 μm. These lasers employ an active region consisting of multiple-stage cascade periods comprising type-II quantum wells (QWs). The distinctive feature of ICLs is their ability to combine a relatively long upper-level recombination lifetime with an efficient cascading mechanism, enabling the generation of coherent light through interband transitions [2]. This stands in contrast to quantum cascade lasers (QCLs), where photons are emitted via intersubband transitions.

Hereinafter, we show that ICLs are eligible sources for the generation of amplitude-squeezed light, exhibiting suppressed photon-number fluctuations below the shot noise limit and sub-Poissonian output photon statistics. The concept of amplitude-squeezed light from semiconductor lasers was initially proposed by Yamamoto *et al.* [3,4]. They provided theoretical and experimental evidence that squeezed light in lasers can be achieved through a suppressed pump-noise configuration. In this scheme, the sub-Poissonian pumping statistics of the electron current are directly converted into nonclassical photon statistics. This approach offers numerous advantages, including a wide range of wavelengths, broad squeezing bandwidth, high output power, and compactness of laser diodes. We investigate this phenomenon using two distinct modelling approaches: semiclassical Langevin equations [5] and stochastic simulation algorithms [6]. Our findings offer valuable insights that can accelerate the development of quantum hardware in the mid-infrared range which remains an unexplored domain. This technique holds immense potential for various applications, including laser-based free-space quantum communication systems.

2. Modelling

2.1. ICL band structure

In our modelling of ICLs, it is assumed that all cascading stages within the ICL are identical, as depicted in Figure. 1. Each stage comprises a W-shaped active region, an electron injector, and a hole injector [13]. When a forward bias is applied, electrons (holes) from the electron (hole) injector efficiently tunnel into the active region within sub-picosecond timescales. Recombination of electrons with holes occurs through spontaneous emission, nonradiative Auger recombination, and stimulated emission, leading

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to population inversion. The recombined electrons then quickly exit the active region through the hole injector, transitioning into the electron injector of the subsequent stage within picosecond or sub-picosecond timeframes.

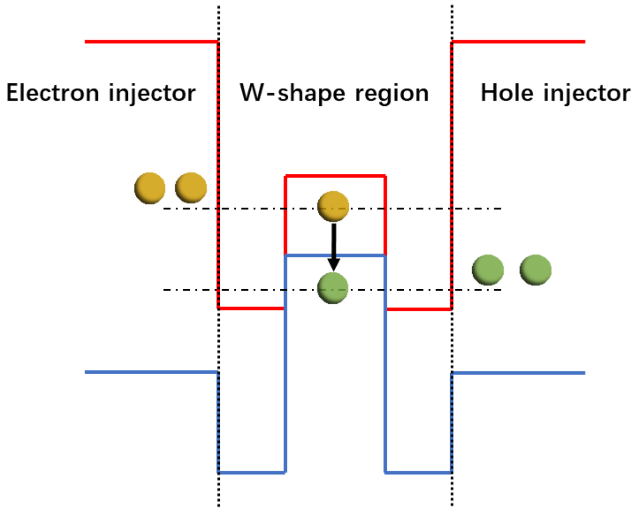

Figure 1: Schematic band structure of one stage in ICLs.

2.2. Semiclassical Langevin equations

In order to accurately consider the effects of noise, it is practical to integrate Langevin forces into the classical wave and rate equations. These supplementary terms, referred to as diffusion coefficients, depict the correlation functions of the noise sources. By determining these coefficients, the equations can be solved as if the light were a classical wave subject to fluctuations. Consequently, we have developed recent rate equations for ICLs that describe the evolution of the carrier number N per gain stage and the total photon number S across all gain stages [5,7]. These equations are presented below:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \eta\frac{I}{q} - \frac{N}{\tau_{tau}} - \frac{N}{\tau_{sp}} - \Gamma_p v_g g S + F_N(t) \qquad (1)$$

$$\frac{\mathrm{d}S}{\mathrm{d}t} = m\Gamma_p v_g g S - -\frac{S}{\tau_p} + m\beta\frac{N}{\tau_{sp}} + F_S(t) \qquad (2)$$

where I is the pump current, q is elementary charge, and η is the current injection efficiency. g is the material gain per stage, and v_g is the group velocity of light. Γ_p is the optical confinement factor per gain stage, τ_{aug} is the Auger recombination lifetime and τ_{sp} is the spontaneous emission lifetime. m is the number of cascading gain stages, τ_p is the cavity photon lifetime. β is the spontaneous emission factor, which accounts for the small fraction of total spontaneous emission that enters the lasing mode.

Applying a small-signal analysis to the rate equations (1) and (2), one can obtain the linearized equations through the

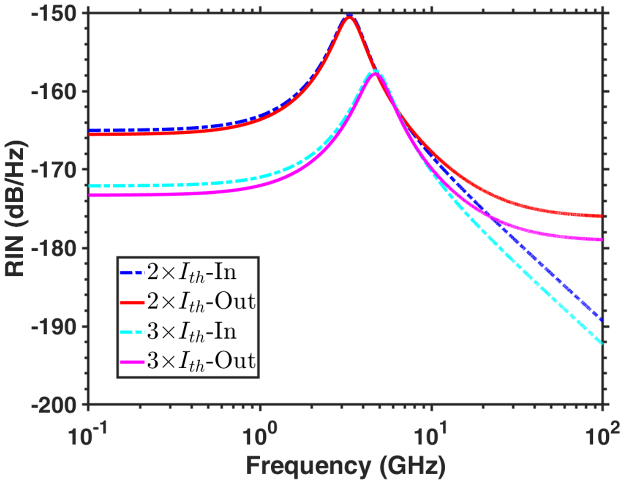

Figure 2: Spectrum comparison of intra-cavity photon noise and output photon noise for various pump currents. The emergence of the shot noise limit at higher frequencies is evident, highlighting the distinct characteristics between the two spectra.

Fourier transform:

$$\begin{bmatrix} \gamma_{NN} + j\omega & \gamma_{NS} \\ -\gamma_{SN} & \gamma_{SS} + j\omega \end{bmatrix} \begin{bmatrix} \delta N(\omega) \\ \delta S(\omega) \end{bmatrix} = \begin{bmatrix} F_N(\omega) \\ F_S(\omega) \end{bmatrix} \qquad (3)$$

where

$$\gamma_{NN} = \frac{1}{\tau_{sp}} + \frac{1}{\tau_{aug}} + \Gamma_p v_g g S, \ \gamma_{NS} = \Gamma_p v_g g$$

$$\gamma_{SN} = m\Gamma_p v_g g S + m\frac{\beta}{\tau_{sp}}, \ \gamma_{SS} = \frac{1}{\tau_p} - m\Gamma_p v_g g$$

Following the analysis of particle flows into/out of the different reservoirs [5], the diffusion coefficients can be derived as:

$$\langle F_N F_N \rangle = \eta\frac{I}{q} + \frac{N}{\tau_{aug}} + \frac{N}{\tau_{sp}} + \Gamma_p v_g g S$$

$$\langle F_S F_S \rangle = m\Gamma_p v_g g S + \frac{S}{\tau_p} + m\beta\frac{N}{\tau_{sp}}$$

$$\langle F_N F_S \rangle = -(m\beta\frac{N}{\tau_{sp}} + m\Gamma_p v_g g S)$$

Then the spectral density of the photon noise inside the laser cavity can be immediately derived by using Cramer's rule

$$S_{\delta S}(\omega) = \frac{|H(\omega)|^2}{\omega_R^4}[(\gamma_{NN}^2 + \omega^2)\langle F_S F_S \rangle + 2\gamma_{NN}\gamma_{SN}\langle F_S F_N \rangle + \gamma_{SN}^2\langle F_N F_N \rangle] \qquad (4)$$

To precisely account for the influence of vacuum fluctuations, which are essential in quantum noise analysis, it is necessary to include a new Langevin noise force $F_0(t)$ that

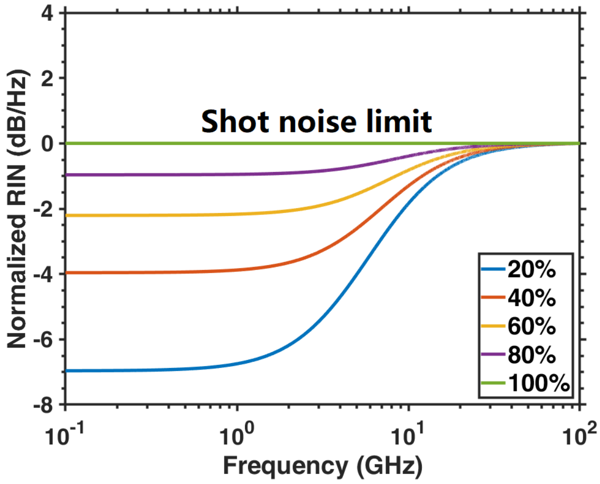

Figure 3: Variations in normalized output photon noise spectra as a function of pump current noise. The reduction of low-frequency noise below the shot noise limit (green line, 100%) can be achieved by decreasing the pump current noise.

represents the negatively correlated partition noise arising from the facet transmission mirror. By incorporating this noise term, the fluctuations in the output power can be expressed as follows:

$$\delta S_{out}(t) = (\eta_0 h\mu/\tau_p)\delta S(t) + F_0(t)$$

By utilizing the same method, we convert to the frequency domain by Fourier transform:

$$S_{\delta S_{out}}(\omega) = (\eta_0 h\upsilon/\tau_p)^2 S_{\delta S}(\omega) + 2\mathrm{Re}\left\{(\eta_0 h\upsilon/\tau_p)\langle\delta S F_0\rangle\right\} + \langle F_0 F_0\rangle \quad (5)$$

where

$$\langle\delta S F_0\rangle = \frac{H(\omega)}{\omega_R^2}[(\gamma_{NN} + j\omega)\langle F_S F_0\rangle + \gamma_{SN}\langle F_N F_0\rangle]$$
$$\langle F_0 F_0\rangle = \eta_0 (h\upsilon)^2 S/\tau_p$$
$$\langle F_S F_0\rangle = -\eta_0 h\upsilon S/\tau_p$$
$$\langle F_N F_0\rangle = 0$$

Figure. 2 highlights the distinct disparity between the output photon noise spectrum $S_{\delta S_{out}}(\omega)$ and the intra-cavity noise spectrum $S_{\delta S}(\omega)$, predominantly attributed to the prevailing influence of shot noise terms $\langle F_0 F_0\rangle$ at higher frequencies. Furthermore, Figure. 3 demonstrates that by diminishing the pump current noise manifested in the carrier diffusion coefficients, it is possible to reduce the output photon noise spectrum below the shot noise limit at low frequencies [3].

2.3. Stochastic simulation algorithms

The previous semiclassical formalism primarily focuses on evaluating intensity squeezing based on the relative intensity noise (RIN) spectrum. While this approach offers the advantage of providing a straightforward description of amplitude-squeezed states in semiconductor laser structures, compared to the more intricate quantum electrodynamics (QED), it falls short in capturing the granularity of photons and carriers. This limitation means that it cannot provide comprehensive information about photon statistics and intrinsic quantum fluctuations. To address these shortcomings, we extend a recent stochastic model [6] to encompass the generation of amplitude-squeezed light in the mid-infrared range, taking into account the specific band structure of ICLs. Notably, we differentiate between intracavity photons and external output photons, emphasizing the significance of the laser outcoupling process and the sub-Poissonian pumping process. These processes are crucial for interpreting the emission of light with sub-shot-noise characteristics.

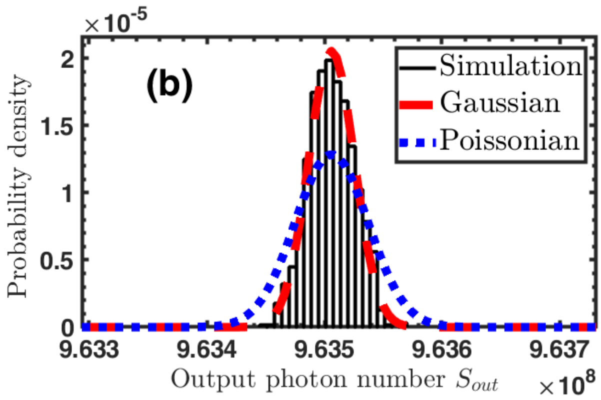

Figure 4: Output photon number S_{out} distribution for ICLs when operated under noise-suppressed pumping. Red dashed curves indicate Gaussian fitting and blue dot curves are Poissonian fittings with the same mean value.

In this method, we propose a stochastic framework that allows for an exact evaluation of the squeezing performance, hence eliminating the need for mathematical assumptions typically made in the derivation of differential descriptions. Instead, our approach leverages the Monte Carlo algorithm to accurately predict the statistical dynamics of the laser. By doing so, we explicitly account for the discrete nature of changes in photons and carriers, as well as the inherent noise stemming from fundamental physical processes such as pumping, spontaneous emission, stimulated emission, and transmission through the laser facet. These crucial aspects, often overlooked in conventional rate equation approaches, significantly impact the analysis. Within this context, the stochastic equations for the carrier quantity (N) and photon count (S) in ICLs can be expressed as follows:

$$N_{t+1} = N_t + R_{pump} - R_{st} - R_{sp} - R_{aug} \quad (6)$$
$$S_{t+1} = S_t + mR_{st} - R_p + m\beta R_{sp} \quad (7)$$

In the given equations, R_{pump} represents the pump rate into the active region, while R_{st} and R_{sp} correspond to the rates of stimulated emission and spontaneous emission, respectively. Additionally, R_{aug} denotes the rate of non-radiative Auger recombination. The laser photon decay rate, R_p, can be further decomposed into R_{int}, which represents the photon internal decay resulting from internal losses, and R_{out}, which signifies the out-coupling rate through the laser facets. The stochastic equations Eqs (6)-(7) provide a comprehensive representation of the operational characteristics of ICLs. Each term in these equations corresponds to a random event occurring within the laser cavity, as summarized in Table1.

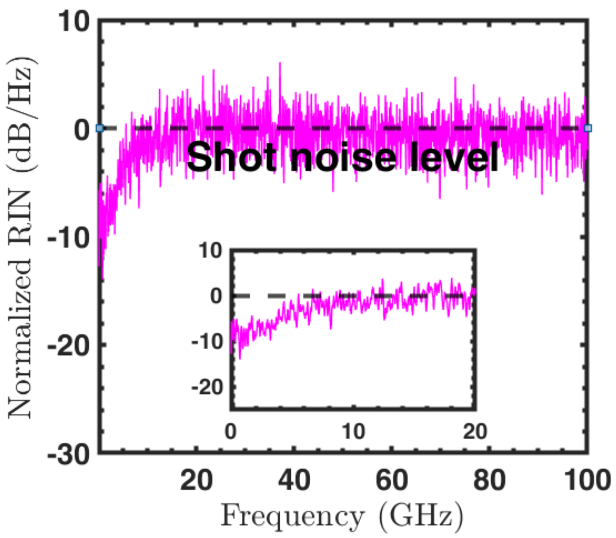

Figure 5: The output photon noise spectrum normalized by shot noise limit, with the black dashed line indicating the shot noise limit. The inset provides a zoomed-in view of the original figure.

Figure. 4 illustrates the promising potential for non-classical photon statistics in ICLs, where the conventional rate equation method fails to capture the phenomenon accurately. Particularly, under quiet pumping conditions at a high pump rate (a dozen times the threshold), the emergence of sub-Poissonian characteristics is evident, characterized by a narrower full-width at half-maximum (FWHM) compared to the Poissonian distribution (depicted by the blue dashed line). Furthermore, Figure. 5 depicts the corresponding output photon noise spectrum in the suppressed-pump noise configuration. This configuration yields a substantial squeezing factor of a few decibels (dB) and an extensive squeezing bandwidth of nearly 10 GHz.

3. Conclusions

Here, we address a novel class of quiet-light optoelectronic devices in which the photon-number fluctuations are well suppressed below the shot-noise limit. In particular, our numerical results demonstrate that ICLs can achieve significant intensity noise squeezing over a bandwidth of several GHz. This finding holds great promise for the development of mid-infrared light sources with ultralow noise levels which is important in this domain of wavelengths for which no quantum hardware yet exists.

Table 1: Average rates of stochastic events occurring in the ICLs stochastic equations.

Event type	Symbols	Average rate
Stimulated emission	R_{st}	$\Gamma_p v_g g S$
Spontaneous emission	R_{sp}	N/τ_{sp}
Photon internal decay	R_{int}	$v_g \alpha_{in} S$
Auger recombination	R_{aug}	N/τ_{aug}
Pumping	R_{pump}	$\eta I/q$
Out-coupling process	R_{out}	$v_g \alpha_m S$

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