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Invited Paper

Dynamic and nonlinear properties of mid infrared interband quantum cascade lasers

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ABSTRACT

Interband cascade lasers (ICLs) constitute a new class of semiconductor lasers allowing lasing emission in the 3– 7 μm wavelength region. Their structure presents similarities and differences with respect to both standard bipolar semiconductor lasers and quantum cascade lasers (QCLs). In contrast to QCLs, the stimulated emission of ICLs relies on the interband transition of type-II quantum wells while the carrier-to-photon lifetime ratio is similar to conventional bipolar lasers. ICLs can be classified into class-B laser systems like common quantum well lasers, and they exhibit a multi-GHz relaxation oscillation frequency that is related to the maximum modulation/chaos bandwidth achievable by these lasers. Moreover, ICLs take advantage of a cascading mechanism over repeated active regions, which allows us to boost the quantum efficiency and, thus, the emitted optical power. On top of that, the power consumption of ICLs is one or two orders of magnitude lower than their QCL counterparts whereas high-power of few hundreds of milliWatts can be achieved. Here, we report some recent results on the dynamic and nonlinear properties of ICLs. In particular, we demonstrate the generation of fully-developed chaos under external optical feedback. We show that ICLs exhibit some peculiar intensity noise features with a clear relaxation oscillation frequency. Together, these properties are of paramount importance for developing long-reach secure free-space communication, random bit generator, and remote chaotic LiDAR systems. Lastly, we also predict that ICLs are preferable devices for amplitude-noise squeezing because large amplitude noise reduction is attainable through inherent high quantum efficiency and short photon and electron lifetimes.

Keywords: interband cascade laser, mid-infrared photonics, quantum optics, amplitude-noise squeezing, nonlinear dynamics

1. INTRODUCTION

Most of the communication networks rely on optical components that were optimized for the so-called telecom wavelength in the near-infrared domain.[1] Optical fibers are the main medium for information propagation and key elements such as amplifiers and modulators are seamlessly integrated within fiber systems.[2] When fibers are not considered for light transmission, other schemes at lower wavelengths are considered for underwater communication[3] or satellite-to-ground quantum key distribution.[4] Despite many advantages in free-space communication, such as low attenuation and reduced scattering, mid-infrared (mid-IR) wavelength technology has known few main breakthroughs that could lead to a large adoption for real-field application. Only recent works with intersubband devices opened new opportunities for mid-infrared high-speed communication.[5,6] One of the current drawbacks of intersubband technology is that emitters require high voltage and bias current, thus leading to configurations that are far behind near-infrared state-of-the-art devices in terms of energy-to-data rate ratio. Interband cascade lasers (ICLs) constitute a new class of semiconductor lasers allowing lasing emission in the

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MIR typically between 3 and 7 micron optical wavelength region.[7] Their structure presents similarities and differences with respect to both standard bipolar semiconductor lasers and quantum cascade lasers (QCLs) which rely on intersubband optical transitions in the conduction band. Therefore, as opposed to QCLs, the stimulated emission of ICLs relies on the interband transition of type-II quantum wells.[8] With a carrier-to-photon lifetime ratio similar to conventional bipolar lasers, ICLs can be classified into class-B laser systems like common quantum well lasers. Consequently, they also exhibit a multi-GHz relaxation oscillation frequency that drives their modulation capabilities.[9] Moreover, ICLs take advantage of a cascading mechanism over repeated active regions, which allows boosting the quantum efficiency and, thus, the emitted optical power. In this work, we investigate the peculiar dynamic and nonlinear properties of ICLs emitting at 4.1 μm. In particular, we demonstrate the generation of fully-developed chaos under external optical feedback. We show that ICLs exhibit intensity noise features with relaxation oscillations which is of paramount importance for high-speed data transfer.[10] We also bring insights that make this kind of laser relevant for quantum applications such as squeezed states of light,[11] which have not been demonstrated using mid-infrared semiconductor sources so far. Together, these results provide new insights for the development of free-space laser communication, random bit generator, and remote chaotic LiDAR systems.

2. RELATIVE INTENSITY NOISE

The relative intensity noise (RIN) of semiconductor lasers degrades the signal-to-noise ratio (SNR) and increases the bit-error rate of optical signals hence setting a limit of a high-speed communication system.[12] System limitations due to poor SNR can be compensated by increasing the bias current of the laser source but at the price of larger energy consumption. In semiconductor lasers, the RIN mainly stems from intrinsic optical phase and frequency fluctuations caused by spontaneous emission as well as the carrier noise, describing the fluctuations in the optical power of a laser. Fig. 1 shows the evolution of the RIN of the ICL under study for different currents

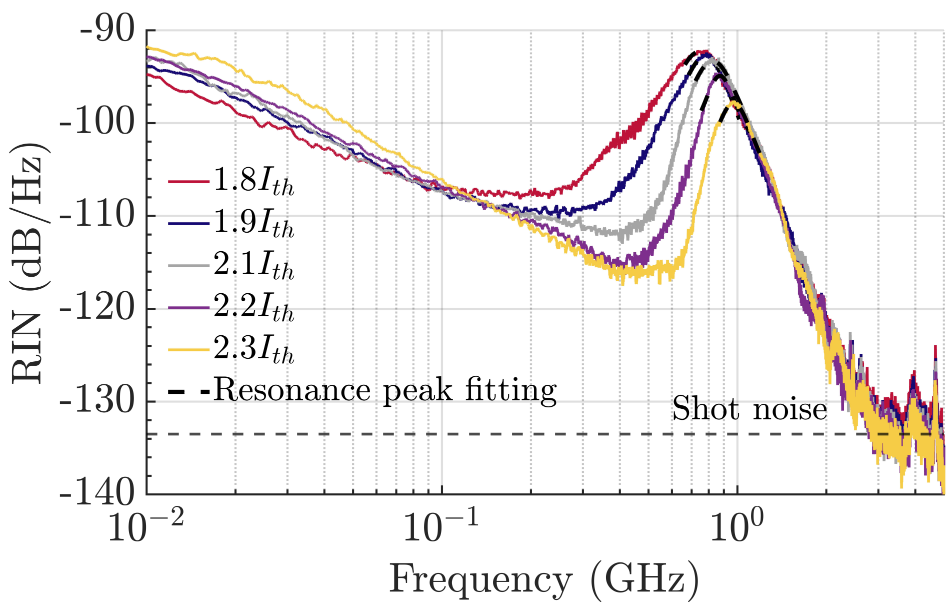

Figure 1. RIN spectrum measured over the 10 MHz-5 GHz interval at room temperature and for various pump currents. The horizontal dashed line represents the shot noise limit.

above the threshold current I_{th} at room temperature. The shot noise level is represented by the horizontal dashed line. At low frequency, around 10 MHz-100 MHz, the RIN level is significantly high, in the range of -95 dB/Hz, and drops when the frequency increases. In addition, a resonance peak is clearly identified in the RIN spectra at any bias current shown here. As opposed to QCLs which are overdamped oscillators due the fast intersubband transitions, the ICL displays a clear relaxation frequency in the order of 1 GHz that slightly increases with the bias current. Finally, let us stress that the noise is not influenced by bias current after the relaxation oscillation. We estimated the shot noise of the detector used in the experiments around -135 dB/Hz. This result constitutes an experimental evidence of relaxation oscillations in such ICLs, which is of first importance to better understand their high-speed capabilities and their chaos bandwidth when subjected to destabilization.

3. AMPLITUDE-NOISE SQUEEZING

The key property of a laser operating far above the threshold is its generation of coherent states of light[13] where the field fluctuations have an equal amplitude in the two quadrature components (e.g., laser amplitude and phase) and minimize the product given by Heisenberg's uncertainty principle. Measurement of Poissonian photon statistics and shot-noise-limited photocurrent fluctuations characterized by an balanced homodyne photodetector strongly supports this theory. However, previous studies from Y.Yamamoto *et al.*[14,15] revealed that amplitude-squeezed light in semiconductor lasers is achievable with a suppressed-pump-noise configuration, which displays reduced fluctuations in one quadrature component of the coherent state at the expense of enhanced fluctuations in the other. Here, We numerically demonstrate that ICLs are eligible sources for the generation of amplitude-squeezed light, hence operating below the shot noise level, as well as sub-Poissonian output photon statistics. In order to do so, we expand a recent stochastic model[16] to the case of amplitude-squeezed light generation in the mid-infrared range according to the ICLs' band structure.[17] In general, we provide a framework to permit an exact evaluation of the squeezing performance without the mathematical assumptions related to the derivation of a differential description, which predicts the laser statistical dynamics based on the Monte Carlo algorithm. More importantly, it intuitively accentuates the discreteness of the changes in photons and carriers and the inherent noise of all physical processes like pumping, spontaneous emission, stimulated emission, and transmission through the laser facet, which cannot be captured by the conventional rate equation approach. Fig. 2 (a) shows the balanced homodyne detection setup for the characterization of squeezed light at mid-infrared wavelength. Our numerical results are displayed in Fig. 2 (b)-(d). One can clearly observe a strong intensity-noise reduction in the case of the quiet pump in contrast to the normal pump in (b) and the nature of photon statistics becomes sub-Poissonian instead of Poissonian in (c). Moreover, a squeezing bandwidth of several GHz is attainable by using Fourier transform analysis in (d). This result will further accelerate the development of the original quantum hardware in the mid-infrared range which is not yet available and that can be implemented, for instance, in laser-based free-space secure communication systems.

4. OPTICAL FEEDBACK

Under external optical feedback, ICL can exhibit several types of non-linear dynamics, as also found in other interband semiconductor lasers.[18] Among all the non-linear patterns, hyperchaos[19] is of major interest as one can take advantage of chaos dynamics for a range of applications, from private communication based on chaos synchronization[20] to jamming-resistant LiDAR[21] and fast physical random bit generation.[22] In the mid-infrared domain, quantum cascade lasers (QCLs) also exhibit complex chaos under self-reinjection. Yet, they are intersubband lasers and so far, the typical chaos bandwidth is found to be less than 100 MHz, hindering the development of the aforementioned applications.[23] So far, experiments with ICLs under external optical feedback have shown chaos bandwidth of a few hundreds of MHz,[24] but recent findings about the relaxation oscillation frequency in ICLs are promising for chaos with multi-GHz bandwidth.[25] When performing experiments with a Mercury Cadmium Telluride (MCT) detector with a tabulated bandwidth of 800 MHz, we are able to generate flat chaos up to a frequency of 1 GHz, as illustrated in Fig. 3 (a). Furthermore, contrary to QCLs which require high bias currents and voltages, this wideband mid-infrared chaos was generated with a bias current of 160 mA and a voltage of 4 V. In addition, one can see in Fig. 3 (b) that the power of the chaotic signal is at least 10 dB above the noise between 0.03-1.23 GHz when smoothing the FFT signal on 1000 samples. This is another advantage as it means that almost no noise-filtering is required before processing this chaos for applications such as private communication or random number generation.

5. CONCLUSIONS

We have investigated high-speed properties of mid-infrared interband cascade lasers in recent experimental and numerical efforts. Relative intensity noise analysis showed clear relaxation oscillation at GHz frequency that was

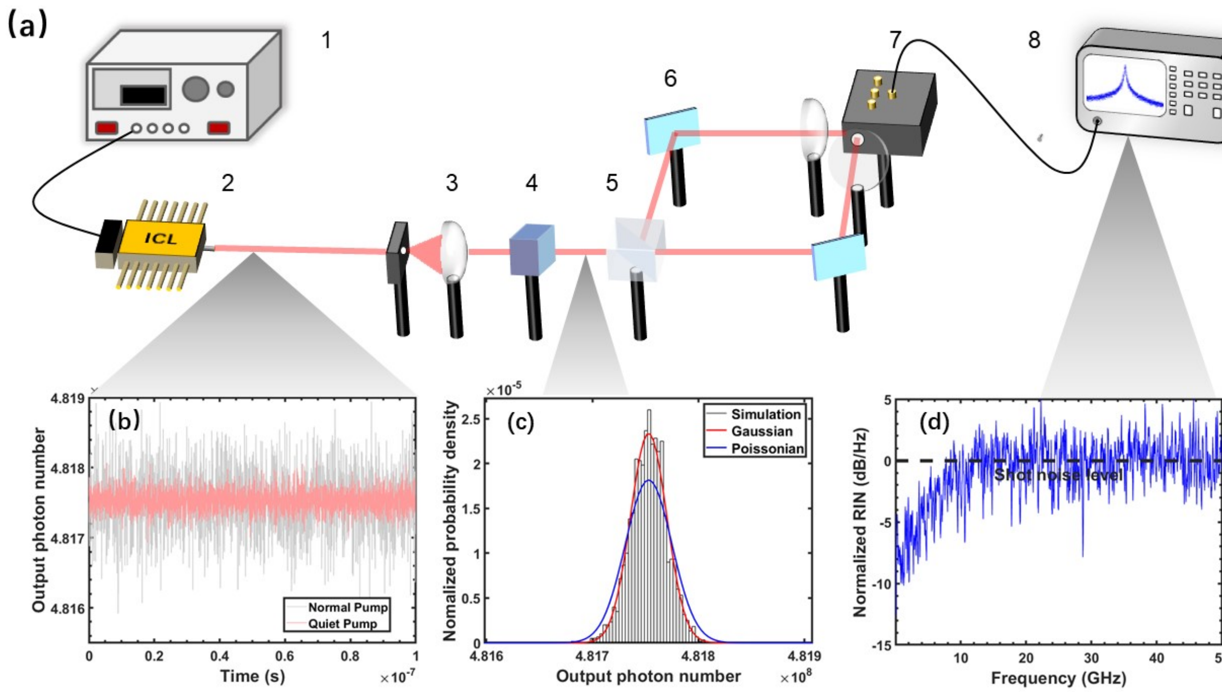

Figure 2. (a) Schematic of the balanced homodyne detection setup. 1) Quiet pump source, 2) Interband cascade laser, 3) Focusing lens, 4) Half-wave plate, 5) Polarizing beam splitter, 6) Mirror, 7) Balanced homodyne photodetector, 8) Electrical spectrum analyzer; (b) Simulated time series of amplitude-squeezed light (red) in ICLs under the suppressed-pump-noise configuration while the grey line represents the same situation under regular pump operation; (c) The simulated photon distribution of amplitude-squeezed light in ICLs. Red curve indicates Gaussian fitting and blue curve represents Poissonian fitting with the same mean value. The pump current is set as $25 \times I_{th}$. (d) The simulated frequency spectrum of amplitude-squeezed light in ICLs (blue). The black dashed line indicates the shot noise level.

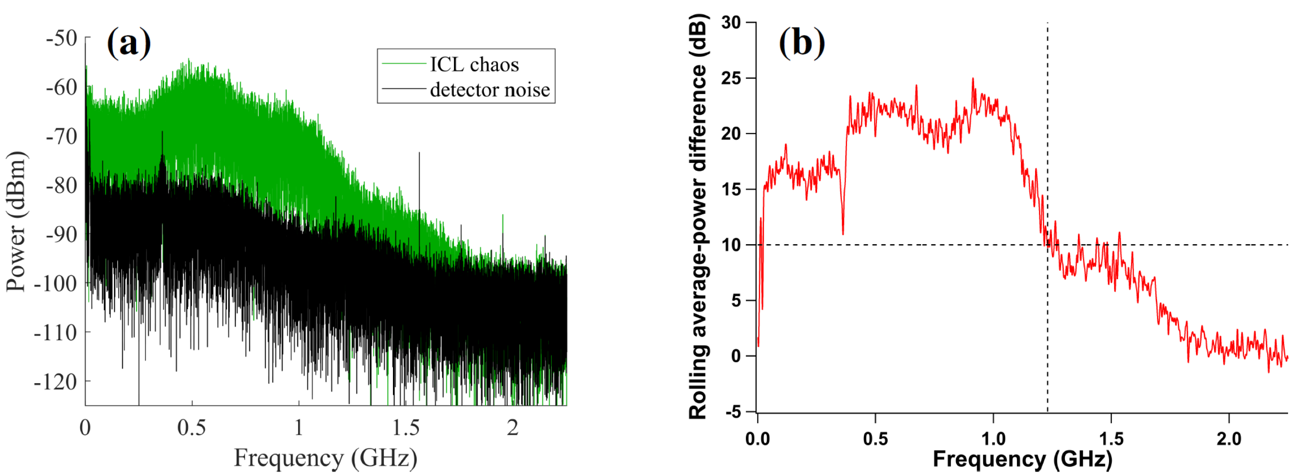

Figure 3. (a) Flat bandwidth chaos in a mid-infrared ICL subject to external optical feedback (green) and electrical noise of the MCT detector alone (black). It is relevant to note that the black curve gives access to the detector bandwidth, which is tabulated at 800 MHz; (b) Difference in power between the two previous curves, when performing a rolling average over 1000 samples (red). The dashed lines indicate the maximum frequency where the chaos signal is 10 dB above noise level. It is relevant to note that high above the system bandwidth, the red curve converges towards 0 dB, meaning that the oscilloscope noise becomes the main component (for f > 2 GHz).

later confirmed in external optical feedback experiments where the laser generated hyperchaos. The development of a stochastic model for an interband cascade laser with quiet pump operation paves the way towards squeezed light at mid-infrared wavelength. These results confirm the relevance of interband cascade lasers for applications ranging from quantum sensing to secure communication, especially when battery operation is required and prevents the use of more energy-consuming quantum cascade lasers.

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REFERENCES

[1] F. Chang, *Datacenter Connectivity Technologies: Principles and Practice*, Stylus Publishing, LLC, 2019.

[2] D. Thomson, A. Zilkie, J. E. Bowers, T. Komljenovic, G. T. Reed, L. Vivien, D. Marris-Morini, E. Cassan, L. Virot, J.-M. Fédéli, *et al.*, "Roadmap on silicon photonics," *Journal of Optics* **18**(7), p. 073003, 2016.

[3] J. Baghdady, K. Miller, K. Morgan, M. Byrd, S. Osler, R. Ragusa, W. Li, B. M. Cochenour, and E. G. Johnson, "Multi-gigabit/s underwater optical communication link using orbital angular momentum multiplexing," *Optics express* **24**(9), pp. 9794–9805, 2016.

[4] S.-K. Liao, H.-L. Yong, C. Liu, G.-L. Shentu, D.-D. Li, J. Lin, H. Dai, S.-Q. Zhao, B. Li, J.-Y. Guan, *et al.*, "Long-distance free-space quantum key distribution in daylight towards inter-satellite communication," *Nature Photonics* **11**(8), pp. 509–513, 2017.

[5] P. Didier, H. Dely, T. Bonazzi, O. Spitz, E. Awwad, E. Rodriguez, A. Vasanelli, C. Sirtori, and F. Grillot, "High-capacity free-space optical link in the midinfrared thermal atmospheric windows using unipolar quantum devices," *Advanced Photonics* **4**(5), p. 056004, 2022.

[6] M. Joharifar, H. Dely, X. Pang, R. Schatz, D. Gacemi, T. Salgals, A. Udalcovs, Y.-T. Sun, Y. Fan, L. Zhang, *et al.*, "High-Speed 9.6-μm Long-Wave Infrared Free-Space Transmission with a Directly-Modulated QCL and a Fully-Passive QCD," *Journal of Lightwave Technology* , 2022.

[7] J. R. Meyer, W. W. Bewley, C. L. Canedy, C. S. Kim, M. Kim, C. D. Merritt, and I. Vurgaftman, "The interband cascade laser," in *Photonics*, **7**(3), p. 75, MDPI, 2020.

[8] R. Q. Yang, "Infrared laser based on intersubband transitions in quantum wells," *Superlattices and Microstructures* **17**(1), pp. 77–83, 1995.

[9] P. Didier, O. Spitz, L. Cerutti, D. Diaz-Thomas, A. Baranov, M. Carras, and F. Grillot, "Relative intensity noise and intrinsic properties of RF mounted interband cascade laser," *Applied Physics Letters* **119**(17), p. 171107, 2021.

[10] O. Spitz, P. Didier, L. Durupt, D. A. Díaz-Thomas, A. N. Baranov, L. Cerutti, and F. Grillot, "Free-Space Communication with Directly Modulated Mid-Infrared Quantum Cascade Devices," *IEEE Journal of Selected Topics in Quantum Electronics* **28**(1), pp. 1–9, 2021.

[11] J.-L. Vey and P. Gallion, "Semiclassical model of semiconductor laser noise and amplitude noise squeezing. i. description and application to fabry-perot laser," *IEEE journal of quantum electronics* **33**(11), pp. 2097–2104, 1997.

[12] L. A. Coldren, S. W. Corzine, and M. L. Mashanovitch, *Diode lasers and photonic integrated circuits*, vol. 218, John Wiley & Sons, 2012.

[13] R. J. Glauber, "Coherent and incoherent states of the radiation field," *Physical Review* **131**(6), p. 2766, 1963.

[14] Y. Yamamoto, S. Machida, and O. Nilsson, "Amplitude squeezing in a pump-noise-suppressed laser oscillator," *Physical Review A* **34**(5), p. 4025, 1986.

[15] S. Machida, Y. Yamamoto, and Y. Itaya, "Observation of amplitude squeezing in a constant-current–driven semiconductor laser," *Physical review letters* **58**(10), p. 1000, 1987.

[16] J. Mork and K. Yvind, "Squeezing of intensity noise in nanolasers and nanoLEDs with extreme dielectric confinement," *Optica* **7**(11), pp. 1641–1644, 2020.

[17] S. Zhao and F. Grillot, "Stochastic model of sub-poissonian quantum light in an interband cascade laser," *Physical Review Applied* **18**(6), p. 064027, 2022.

[18] M. C. Soriano, J. García-Ojalvo, C. R. Mirasso, and I. Fischer, "Complex photonics: Dynamics and applications of delay-coupled semiconductors lasers," *Reviews of Modern Physics* **85**(1), p. 421, 2013.

[19] Y. K. Chembo, D. Brunner, M. Jacquot, and L. Larger, "Optoelectronic oscillators with time-delayed feedback," *Reviews of Modern Physics* **91**(3), p. 035006, 2019.

[20] O. Spitz, A. Herdt, J. Wu, G. Maisons, M. Carras, C.-W. Wong, W. Elsäßer, and F. Grillot, "Private communication with quantum cascade laser photonic chaos," *Nature communications* **12**(1), p. 3327, 2021.

[21] C.-H. Cheng, C.-Y. Chen, J.-D. Chen, D.-K. Pan, K.-T. Ting, and F.-Y. Lin, "3d pulsed chaos lidar system," *Optics express* **26**(9), pp. 12230–12241, 2018.

[22] Y. Guo, Q. Cai, P. Li, R. Zhang, B. Xu, K. A. Shore, and Y. Wang, "Ultrafast and real-time physical random bit extraction with all-optical quantization," *Advanced Photonics* **4**(3), p. 035001, 2022.

[23] O. Spitz and F. Grillot, "A review of recent results of mid-infrared quantum cascade photonic devices operating under external optical control," *Journal of Physics: Photonics* **4**(2), p. 022001, 2022.

[24] Y. Deng, Z.-F. Fan, B.-B. Zhao, X.-G. Wang, S. Zhao, J. Wu, F. Grillot, and C. Wang, "Mid-infrared hyperchaos of interband cascade lasers," *Light: Science & Applications* **11**(1), p. 7, 2022.

[25] H. Han, X. Cheng, Z. Jia, and K. A. Shore, "Nonlinear dynamics of interband cascade laser subjected to optical feedback," in *Photonics*, **8**(9), p. 366, MDPI, 2021.