Interband cascade technology for next-generation mid-IR communication and quantum applications

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***Abstract*—To achieve mid-infrared wavelength operation with semiconductor technology, efforts were mainly focused on intersubband devices requiring high voltage and current. In this work, we show our latest progress with energy-efficient interband emitters and receivers, paving the way towards application like free-space communication and squeezed light.**

***Index Terms*—interband cascade laser, interband cascade infrared photodetectors, free-space communication, mid-infrared photonics, squeezed light**

I. Introduction

Most of the communication networks rely on optical components that were optimized for the so-called telecom wavelength in the near-infrared domain. Optical fibers are the main medium for information propagation and key elements such as amplifiers and modulators are seamlessly integrated within fiber systems [1]. When fibers are not considered for light transmission, other schemes at lower wavelengths are considered for underwater communication [2] or satellite-to-ground quantum key distribution [3]. 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 [4]. One of the current drawbacks of intersubband technology is that emitters require high voltage and bias current, thus leading to configurations which are far behind near-infrared state-of-the-art devices in terms of energy-to-data rate ratio [5].

Interband cascade technology is promising to achieve emission in the 3-5 μm window while reducing the power consumption of optical sources by almost one order of magnitude compared to their intersubband counterparts. Here, we show that multi-GHz bandwidth can be achieved by combining an interband cascade infrared photodetector (ICIP) and a directly-modulated interband cascade laser (ICL) emitting around 4.1 μm. We also bring insights that make this kind of laser relevant for quantum applications such as squeezed states of light, which have not been demonstrated using mid-infrared semiconductor sources so far.

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II. High-bandwidth interband setup

The Fabry-Perot ICL under study is optimized for RF injection [6] and comes from Université de Montpellier. The ICIP (grown using molecular beam epitaxy (MBE) at nanoplus, and subsequently fabricated at TU Wien) is also optimized for RF operation with an SMA connector directly bonded on the structure. The detector shows a photoresponse between 2-4.5 μm, as shown in Fig. 1. In order to determine the bandwidth of the ICL-ICIP system, we use a Rohde&Schwarz ZVK Vector Network Analyzer (VNA) with maximum bandwidth of 40 GHz. The small signal output of the VNA is injected through the RF port of a bias-tee with 12 GHz bandwidth while the DC port of this bias-tee is connected to a custom-made battery current source that is set to 175 mA. The RF+DC signal is sent towards the ICL and the mid-IR light emitted by the laser is focused on the detector. The SMA port of the ICIP is connected to the input port of the VNA and this allows deriving the S12 response, as shown in Fig. 2.

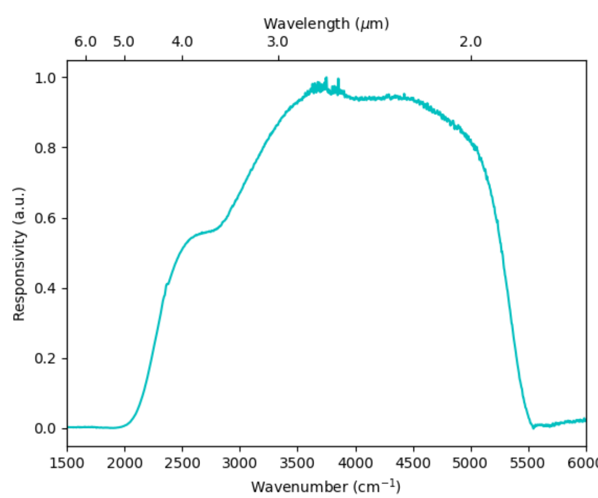

Fig. 1. Wavelength responsivity of the ICIP under study. This structure can work between 3-5 μm and is thus relevant for free-space applications.

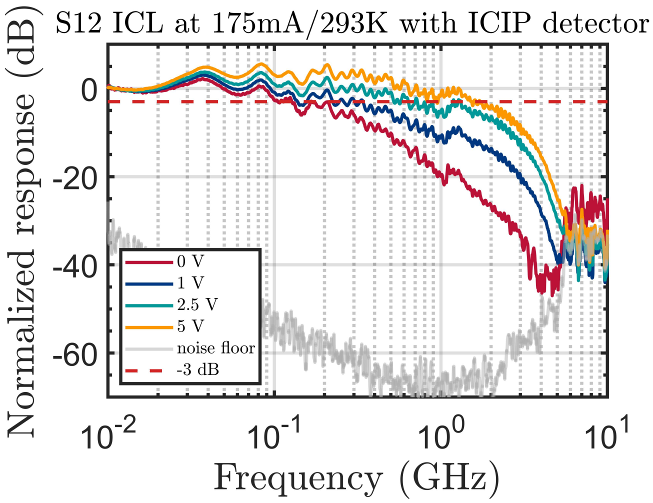

Fig. 2. Small signal response of the ICL-ICIP system for various detector bias levels.

When the ICIP is not biased, the 3-dB bandwidth of the system is limited to 100 MHz and this is not well adapted for communication schemes. Applying a constant voltage to the detector drastically improves the response, and a maximum bandwidth of 2 GHz can be achieved with a 5V bias.

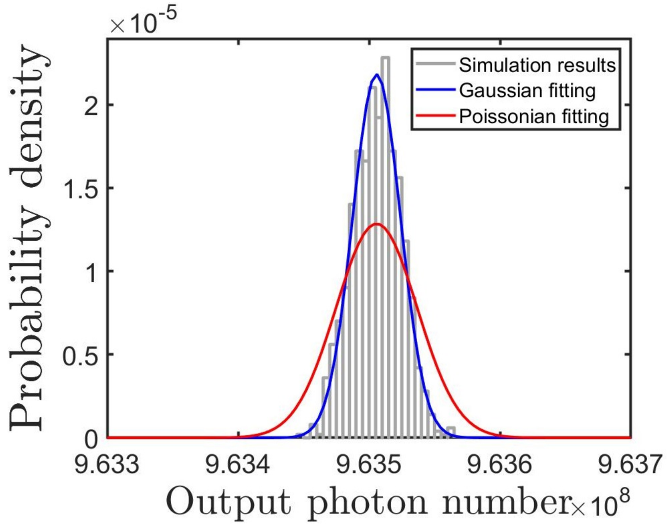

Fig. 3. Probability density distribution of output photon number with "quiet" pumping at high rate, the blue curve indicates Gaussian fitting and the red curve is Poissonian fitting with the same mean value.

III. Squeezed light with ICLs

Non-classical or "squeezed" states of light have been widely studied over the last few decades [7]. The so-called "squeezed" state has less fluctuations in one quadrature component than a coherent state but at the expense of enhanced fluctuations in the other quadrature component due to Heisenberg's uncertainty relation. Squeezed states of light offer intriguing potentials in different types of applications, such as quantum

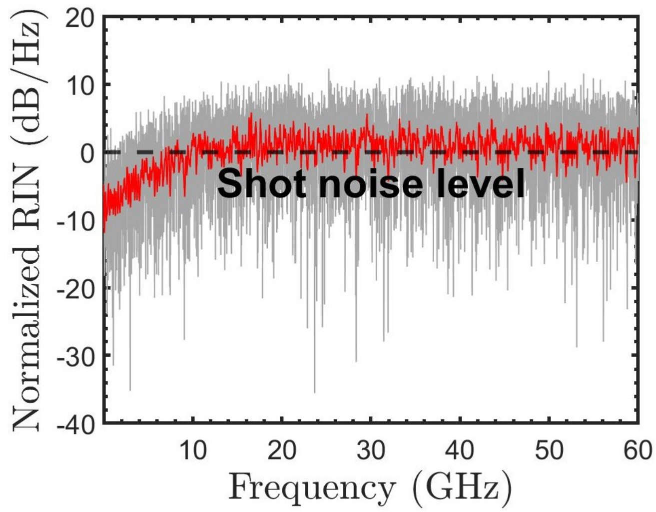

Fig. 4. The corresponding normalized RIN spectrum with "quiet" pumping for output photons. The red curve is smoothed from the gray curve and the dashed line signifies the shot noise level.

optical communications, precision measurements and quantum sensing. The generation of squeezed light from a semiconductor laser was initially realized with pump-noise-suppressed configuration [7]. Considering this method, we recently expanded a stochastic model [8] to the case of ICLs, which theoretically predicts that relatively strong amplitude noise squeezing within a bandwidth of several GHz can be attained. All the simulation parameters for the ICL can be found in Ref. [9]. One can clearly see in Fig. 3 that the output photon distribution shows sub-Poissonian characteristics at high pump rate, which reveals the anti-bunching of photons. In Fig. 4 the corresponding normalized output relative intensity noise (RIN) spectrum is reduced below the shot noise level in the low frequency region, which is another experimental indicator for the amplitude noise light squeezing.

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