Free-Space Gigabit Data Transmission with a Directly Modulated Interband Cascade Laser Epitaxially Grown on Silicon

S. Zaminga*, P. Didier *†, H. Kim*, D. A. Díaz-Thomas§, A. N. Baranov§, J. B. Rodriguez§, E. Tournié§
H. Knötig¶, O. Spitz‡ B. Schwarz¶, L. Cerutti § and F. Grillot*‖
*LTCI Télécom Paris, Institut Polytechnique de Paris, Palaiseau, France
†mirSense, Campus Eiffel, Bâtiment E-RDC, 1 rue Jean Rostand, Orsay, 91400, France
‡CREOL, University of Central Florida, Orlando, Florida 32816, USA
§IES, Université de Montpellier, CNRS UMR 5214, Montpellier, 34000, France
¶Institute for Solid State Electronics, TU Wien, Gußhausstraße 25-25a, 1040 Vienna, Austria
‖Center for High Technology Materials, University of New-Mexico, Albuquerque, NM 87106, USA
Email: sara.zaminga@telecom-paris.fr

2023 IEEE Photonics Conference (IPC) | 979-8-3503-4722-7/23/$31.00 ©2023 IEEE | DOI: 10.1109/IPC57732.2023.10360737

***Abstract*—This work demonstrates mid-infrared data transmission using an epitaxial interband cascade laser on silicon emitting at 3.5 µm. Direct modulation at 5 Gbit/s with on-off keying is achieved at room temperature while digital signal processing is used to further improve the system performance.**

***Index Terms*—Interband cascade laser, free-space optics, optical communications, silicon integration, mid-infrared photonics**

I. Introduction

The mid-infrared spectral range is exceptionally captivating for diversified applications, e.g. free-space communication [1] and precision spectroscopy [2]. Eye-safe operation, resistance to degraded atmospheric conditions [3] and very low atmospheric attenuation elect mid-infrared wavelengths as a cost-effective solution for the development of a wireless broadband network. Among the several mid-infrared optical sources, the cascading principle in quantum cascade lasers (QCLs) [4] and interband cascade lasers (ICLs) [5] has proven to be successful for the design of efficient, powerful, compact and stable devices. When the application requires low-power consumption, the latter is preferred to the former due to its low lasing threshold. This feature is in turn crucial for enabling the integration on silicon of the interband technology. In this paper, we employ a Fabry-Perot (FP) ICL epitaxially-grown on silicon emitting around 3.5 µm. The ICL is directly modulated with a pseudo random binary sequence (PRBS), representing the transmitted data. An interband cascade infrared photodetector (ICIP) based on a type-II InAs/GaSb superlattice detects the ICL signal, processed through digital techniques for the improvement and evaluation of the quality of transmission. This system allows us to achieve a data rate of 5 Gbit/s with a bit-error-rate (BER) lower than 2.18 $\times 10^{-6}$.

II. Laser description

In this work, we use a type-II ICL (see Figure 1a), fabricated by molecular beam epitaxy (MBE) on a 2-inch silicon substrate with a slight misorientation of 0.5° along the crystal axis [110] on which 1500 nm of GaSb buffer has been previously epitaxied [6]. The waveguide consists of 2 layers of n-doped GaSb, surrounding the 7 stages of the interband cascade active region. The type-II quantum wells with a ”W” geometry are composed of 2 electron wells of InAs, surrounding the hole quantum well in GaInSb. The thicknesses are chosen to obtain an emission at 3.5 µm. After epitaxy, the structure undergoes several technological steps to realize the laser component. The 8-µm wide laser mesas are created by UV photolithography and dry etching. The width of the laser is below the 10-µm thickness, where cracks appear in GaSb-based laser grown on Si [7]. The lasers are left as-cleaved to form a 2-mm cavity and epitaxial side-up soldered [8]. Figure 1b shows the Light-Intensity-Voltage (LIV) of the ICL with a maximum output power of about 11 mW and a threshold current around 59 mA at room temperature.

III. Experimental setup

The experimental configuration is illustrated in Figure 2. A low-noise current source (ILX Lightwave, LDX-3232) is used to provide continuous bias, while the ICL is maintained at 293 K through a temperature controller (ILX Lightwave, LDT-5412) and a thermistor. The response is flat up to nearly 1 GHz and it is assessed by using a 40 GHz Rohde & Schwarz ZVK vector network analyzer (VNA) (see Figure 1c). To achieve high-speed electrical modulation of the ICL, an arbitrary waveform generator (AWG, SHF 19120C) is utilized as pattern generator up to 12.5 Gbit/s. To explore various combinations of bit sequences and evaluate the system's response, a 2^{15}-long non-return to zero (NRZ) PRBS is generated using on-off keying (OOK) modulation format. The modulated electrical signal is amplified upstream using a 15-dB gain amplifier. After propagating through approximately 1 m of free space, the optical signal is focused on the back-side of an ICIP using a lens. The DC port of a Pasternack bias tee is employed to bias the detector using a Keithley source, while the AC contribution is captured by a 20-GHz oscilloscope with a sampling rate of

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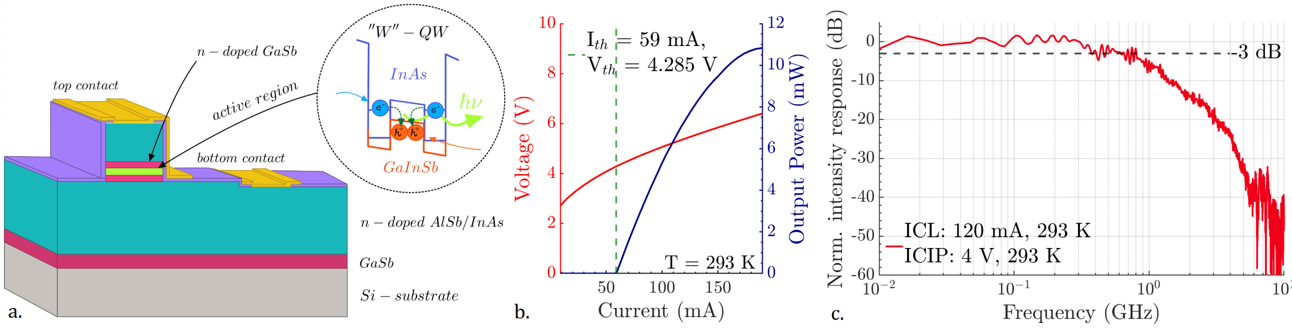

Fig. 1. (a) Schematic representation of the ICL grown on Si-substrate. (b) Light-Intensity-Voltage (LIV) curve of the 3.5-μm ICL. (c) Frequency response of the communication system at a pump current of 120 mA for the ICL and with the ICIP biased at 4 V. The response is flat up to nearly 1 GHz.

50 GS/s. Following detection by the oscilloscope, the signal undergoes offline processing using MATLAB. It is equalized using fractionally spaced feed-forward equalization (FFE) at a rate of four samples per symbol, to mitigate inter-symbol-interference (ISI).

IV. Experimental results

To measure the transmission efficiency, the eye diagram of the received message is visualized and the BER is measured. The latter is defined as the number of bit errors per number of bits sent. Considering the implementation of Forward-Error-Correction (FEC) coding and decoding to correct bit errors by introducing redundancy, in this work the transmission is considered error-free when reaching a maximum tolerated pre-FEC BER of 0.4 %, corresponding to a FEC code with 7 % overhead and hard-decision (HD) decoding [9]. The eye diagram is obtained as the superposition of a selected number of bits sent on the same time interval. When the eye is widely open, we easily distinguish the two different levels of modulation. In this work, by estimating a BER $< 2.18\times10^{-6}$ (see Figure 3), we demonstrate an error-free transmission of a 5 Gbit/s data rate PRBS-15, exploiting the OOK format for the direct modulation of the ICL.

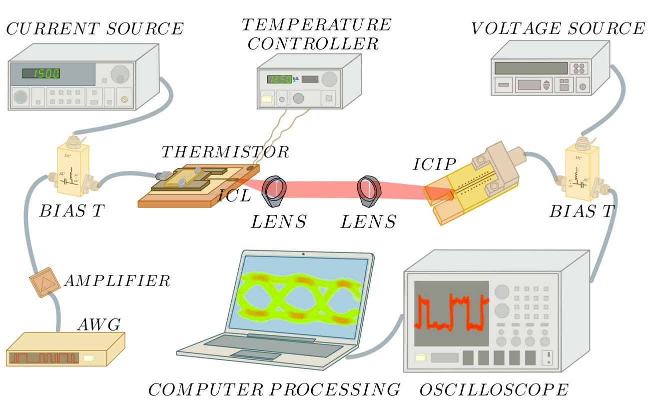

Fig. 2. Experimental setup for the high-speed free-space communication. The ICL is operating at 293 K, biased at 120 mA. The ICIP is biased at 4 V.

V. Conclusion

In this work, we achieved for the first time a 5-Gbit/s high-speed communication with a full interband cascade (IC) system, where the transmitter is an ICL directly grown on silicon. Future studies will focus on improving the transmitted message data rate and utilizing advanced modulation formats such as pulse amplitude modulation.

VI. Acknowledgements

The authors acknowledge professor Elie Awaad for its contribution to the development of the MATLAB code for the signal post-processing. The authors acknowledge the supports from the Agence Nationale de la Recherche (ANR-11-EQPX-0016) and Délégation Générale de l'Armement (DGA) as well from the European Office of Aerospace Research and Development (FA8655-22-1-7032).

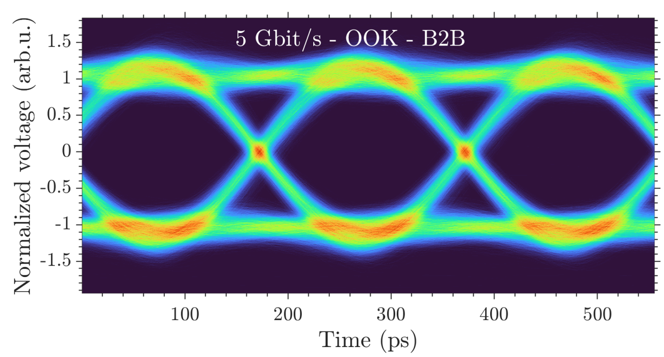

Fig. 3. Eye diagram of the 5-Gbits/s transmission after a free-space propagation of approximately 1 m and the application of channel equalization.

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