Free-space laser communications with quantum cascade devices in the thermal-infrared atmospheric window

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Abstract

The paper focuses on the recent advances in free-space laser communications using unipolar quantum technology. With quantum cascade lasers, modulators and high-sped detectors, we demonstrate multi-Gbits/s transmission in the thermal-infrared atmospheric window.

Index Terms

Quantum cascade devices, unipolar quantum optoelectronics, mid-infrared modulator, high-speed photonics, free-space communication

I. Introduction

Free-space laser communications offer an attractive alternative for transmitting high-bandwidth data when fiber optics is neither practical nor feasible. This technology has emerged as a strong candidate with a large potential of applications from everyday-life broadband internet to satellite links [1]. Recently, an international team demonstrated a record transmission speed in free-space of up to 1 Tbits/s on a single wavelength and over a distance of 53 km [2]. The availability of high-quality transmitters and detectors operating in the near-infrared window makes the 1.55 μm optical wavelength a natural choice for free-space optics systems. Nevertheless, two other wavelength domains can be considered. First the mid-wave infrared (MWIR) window between 3-5 μm, and second the long-wave infrared (LWIR) window between 8-12 μm, the latter being also called the thermal-infrared atmospheric window [1]. MWIR and LWIR wavelengths are renown for their superior transmission performances through inclement atmospheric phenomena, such as fog, clouds and dust [3]. On top of that, the LWIR domain provides stealth for the communication signal thanks to the random thermal blackbody radiation [1]. The outdoor environment indeed has a strong emissivity at these wavelengths, and this greatly reduces the probability of adversaries intercepting a LWIR laser signal. This work aims at investigating data transmission capabilities through unipolar quantum optoelectronics operating in the thermal-infrared atmospheric window.

To achieve this goal, the most important technological building block is the quantum cascade laser (QCL) which, unlike diode lasers, is a unipolar semiconductor laser whereby stimulated emission takes place via sub-picosecond electronic transitions between discrete energy states within the conduction band (Fig. 1 (a)). Owing to a proper quantum engineering of the band structure, QCLs can be made widely tunable from $3\,\mu\mathrm{m}$ [4] up to hundreds of $\mu\mathrm{m}$ [5] and can output power up to several watts [6], [7]. Using direct modulation, recent results showed a 11 Gbits/s data transfer with a QCL paired with an uncooled Quantum Cascade Detector (QCD) [8]. Our recent experimental efforts also demonstrated a free-space live video broadcasting with a room-temperature QCL emitting at about 8 μm [9]. In order to further improve the transmission capabilities and to overcome the intrinsic QCL's bandwidth limitation, the utilization of external unipolar modulators has become an important challenge. However, communication systems require modulators with a large signal-to-noise-ratio (SNR) on top of multi-GHz bandwidth, in order to accommodate bit-level separations. Here, we implement a novel Stark-effect modulator (Fig. 1 (a)) that combines large modulation depth and high linearity.

II. Experimental results and discussion

The transmission experimental setup is displayed in Fig. 1 (b). The optical source is a commercial $9\,\mu\mathrm{m}$-wavelength continuous wave (CW) QCL working at room-temperature and emitting up to $97\,\mathrm{mW}$ of output power. The beam is expanded with a first telescope and focused using another telescope on a $50\,\mu\mathrm{m} \times 50\,\mu\mathrm{m}$ external modulator that is driven at high frequency with an amplified DAC from Socionext. The modulated beam is either directly collected by a LWIR high-speed detector or deviated through a Herriott cell before impinging on the detector. The received signal is acquired with a 33 GHz bandwidth oscilloscope (Tektronix DPO70000SX). Two different receivers are considered for high-speed detection, namely an uncooled QCD already presented in one of our previous works [10] and a nitrogen-cooled quantum well infrared photodetector (QWIP), the latter exhibiting a bandwidth larger than 25 GHz [11]. The maximum data rate of the link is evaluated in the back-to-back configuration before adding a multi-pass Herriott cell so as to increase the transmission length of the light path up to 31 meters. Figure 1 (c) on top shows the eye diagram at 30 Gbits/s in the case of an on-off keying (OOK) modulation scheme while that on bottom shows a transmission at 24 Gbits/s for a PAM-4 modulation scheme. In both, after 31-meter transmission distance, the widely-opened eye diagrams confirm the quality of the transmission and allow determining a BER compatible with conventional error code correction, which means that the transmission can be considered error-free provided that correction is implemented. The aforementioned eye diagrams are obtained using conventional pre- and post-processing.

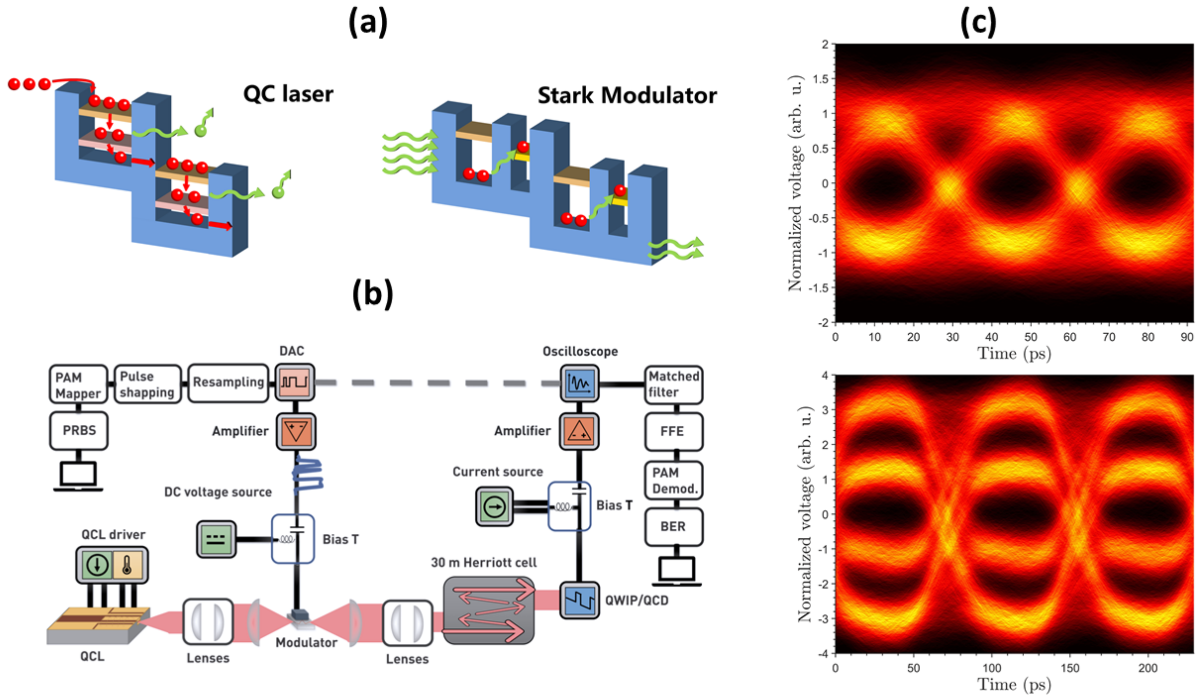

Fig. 1: (a) Building blocks of the unipolar quantum optoelectronics system; (b) Schematic of the full transmission setup including a QCL and the Stark modulator. The signal goes through the Herriott cell before being collected on a high-speed detector (QWIP/QCD) and recorded with a fast oscilloscope; (c) Recorded eye diagrams at 30 Gbits/s (OOK) and 24 Gbits/s (PAM-4) after 31-meter propagation distance when taking into account both pre- and post-processing.

This work demonstrates an unprecedented high-speed data transfer based on unipolar quantum opto-electronics operating in the thermal-infrared atmospheric window. These results pave the way towards the development of free-space laser communication systems that are inherently resistant to adverse weather conditions due to their wavelength of operation. As longer distance propagation is key to a wider adoption of this technology, future work will investigate free-space communications with an array of laterally-coupled QCLs in order to increase the output power and thus the propagation distance. A QCL array is also a candidate of choice for the generation of temporal dynamics that are more complex than chaos from a single QCL. Combining hyperchaos and high optical power would allow envisioning private free-space communications [12] without sacrificing the range and bit rate of the secure channel, even in a high-photon-flux environment. Last but not least, applications beyond the ozone absorption (9.0–10.2 μm) at high altitudes may also be considered.

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