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Bridging the 100 GHz - 10 THz domain with unipolar quantum optoelectronics

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ABSTRACT

The challenge of Unipolar Quantum Optoelectronics (UQO) is to bring reliable technology in the mid-infrared and terahertz domains with dozens of GHz bandwidth and room-temperature operation. The semiconductor devices based on this novel technology rely on two-dimensional electronic states localized in the conduction band, which implies that electrons are the only charge carriers involved. Though UQO technology has been proven useful for emission (quantum cascade lasers) and detection (quantum cascade detectors), it is still underdeveloped for other applications, like high-speed modulation. In this paper, we will review our recent results with a full transmission system UQO in the 8 to 14 µm atmospheric window, composed of a quantum cascade (QC) laser, an external modulator and a QC detector, all optimized for operation at 33 THz optical wavelength. Dynamics down to a few dozens of picoseconds are observed, which allow us demonstrating data rate transmission of 10 Gbps without any signal processing. In addition, the paper aims at discussing further applications of UQO in particular for radio over free-space. The basic principle for producing microwave carriers is based on an optical heterodyne beating technique taking advantage of the high-bandwidth potential of QC detectors. Then, the microwave signal is transmitted through a point-to-point wireless link by using radiofrequency antennas. With UQO, microwave signals of dozens of GHz can be achieved. To sum, this paper highlights the importance of using UQO devices operating at a few dozens of THz optical wavelength for both free-space optics and microwave photonics targeting 100 GHz radiofrequencies.

Keywords: quantum cascade laser, mid-infrared photonics, free-space communication, data transmission

1. INTRODUCTION

The terahertz (THz) domain, which is the frequency region between infrared and microwaves, spans from 0.1 to 10 THz and during the past two decades, intersubband technology strongly contributed to the development of THz emitters and receivers. Terahertz quantum cascade lasers (QCLs) were first demonstrated in 2001[1,2] under pulsed operation in a liquid-helium flow cryostat environment, then extended to continuous wave operation above liquid-nitrogen temperature[3] and the latest efforts are paving the way towards THz QCLs without the need of cryogenic cooling.[4,5] Alternatives were also proposed to increase the maximum temperature of operation of THz QCLs, such as the application of a strong magnetic field above 16 Tesla, in order to suppress the inter-Landau-level non-radiative scattering.[6] Another scheme, avoiding thermal relaxation mechanisms between upper and

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lower laser levels through optical phonons that is currently detrimental for room-temperature intersubband THz QCLs, is based on difference frequency generation in a mid-infrared QCL. This has led to THz room-temperature sources with output peak power up to a few mW.[7] The THz domain is of prime interest for spectroscopy of explosives and drugs,[8] for real-time imaging[9] and for capacity enhancement of free-space data communication.[10] For communication, the domain of interest is roughly 0.1 - 0.5 THz that holds several atmospheric transparency bands.[11] A common method to generate a frequency carrier in this 0.1 - 0.5 THz band is to achieve heterodyne frequency beating with two ultra-stable, narrow-linewidth distributed-feedback (DFB) lasers.[12] In this photonics-assisted THz transmission scheme, external modulation of one of the two lasers before the beating operation allows embedding the message to be transmitted.[13,14] Recent efforts have achieved data rates of hundreds of Gbits/s and propagation of the upconverted heterodyne wave over distances of more than ten meters.[15] So far this method has not been implemented with mid-infrared semiconductor lasers because high-speed external modulators with a large modulation depth are not yet widely available for these wavelengths. Conversely, heterodyne beating of mid-infrared DFB QCLs has long been studied and used for characterizing the bandwidth of mid-infrared detectors,[16] such as ultra-fast quantum cascade detectors (QCDs) and quantum well infrared photodetectors (QWIPs). Indeed, typical frequency values for direct modulation of QCLs[17,18] lags behind the state-of-the-art bandwidths of QWIPs,[19] despite theoretical works showing QCLs modulation bandwidth of hundreds of GHz[20–22] due to their intersubband nature.[23] The latest progress in unipolar quantum optoelectronics has enabled the development of Stark-effect modulators compatible with a wavelength of 9 μm (or in other words, a frequency of 33 THz).[24] The advantage of this detector is to combine a large modulation depth and a bandwidth of several GHz, that is outperforming existing technologies.[25–28] With this device, we realized a communication at a maximum data rate of 11 Gbits/s without pre- or post-processing. This results competes with schemes combining direct modulation and signal processing,[29] while being much faster than QCLs communication without processing.[30] Optimization and size reduction of this novel type of modulator is poised to allow external modulation of mid-infrared beam at frequencies up to 100 GHz and beyond. In this work, we describe some of our latest findings, that include the realization of a mid-infrared transmission link allowing the characterization of the rise time of the Stark-effect modulator. In addition, we show the potential of photonics-assisted microwave communication based on an heterodyne beating of QCLs by implementing a proof-of-concept experiment in the K_a band (between 26.5 - 40 GHz) that is of interest for 5G networks due to low atmospheric absorption.[31]

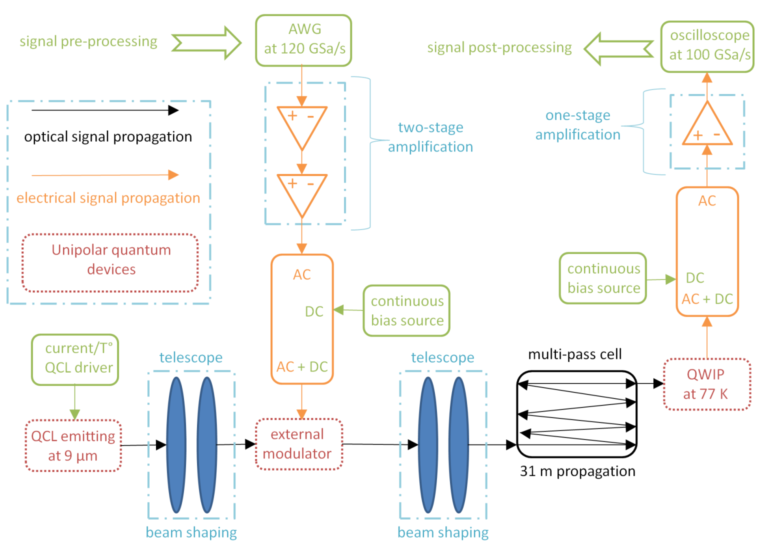

Figure 1. Experimental setup for the characterization of the Stark-effect modulator. The two-stage amplification between the AWG and the modulator allows generating a drive signal with a peak-to-peak amplitude of 15 Volts to take advantage of the full modulation depth of the modulator.

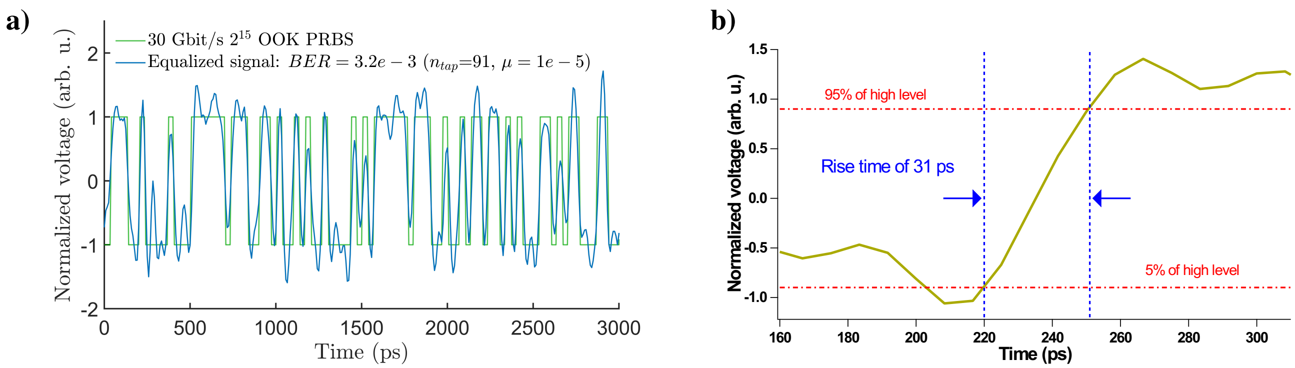

Figure 2. a) Extract of the 32768-bit long message transmission after a 31-meter free-space propagation. The green trace is the original binary message and the blue trace is the signal that is post-processed after being recorded with the fast oscilloscope. b) Focus on a transition between a low-level state and a high-level state showing a typical rise time of 31 ps.

2. PERFORMANCE OF THE MODULATOR: TOWARDS 10 PS RISE TIME

In order to characterize the maximum modulation speed that can be achieved with the Stark-effect modulator, we built a communication setup that is described in Fig. 1. The three unipolar quantum devices are the QCL emitting at 9 μm, the external modulator and the cryogenic QWIP with a bandwidth of more than 25 GHz.[18] The electrical modulation signal is generated by an arbitrary waveform generator (AWG) at 120 GSa/s before being amplified and injected into the external modulator. The 9 μm beam from the QCL is modulated and then propagated for a distance of 31 meters thanks to a multi-pass cell optimized for mid-infrared operation. Finally, the light exiting the multi-pass cell impinges the QWIP and the subsequent electrical signal is amplified before being recorded by an oscilloscope with a sampling rate of rate of 100 GSa/s. Using this setup and signal processing, it is possible to perform a transmission at 30 Gbits/s as shown in Fig. 2 a). The green trace is the initial binary message to be transmitted and the blue trace corresponds to the oscilloscope data after post-processing. In that case, the bit error rate is 3.2×10^{-3} and this is compatible with regular error correction codes that must be implemented in order to obtain an error-free message transmission. With this timetrace, it is possible to derive the modulator characteristic rise time, defined as the time required to go from 5 % to 95 %

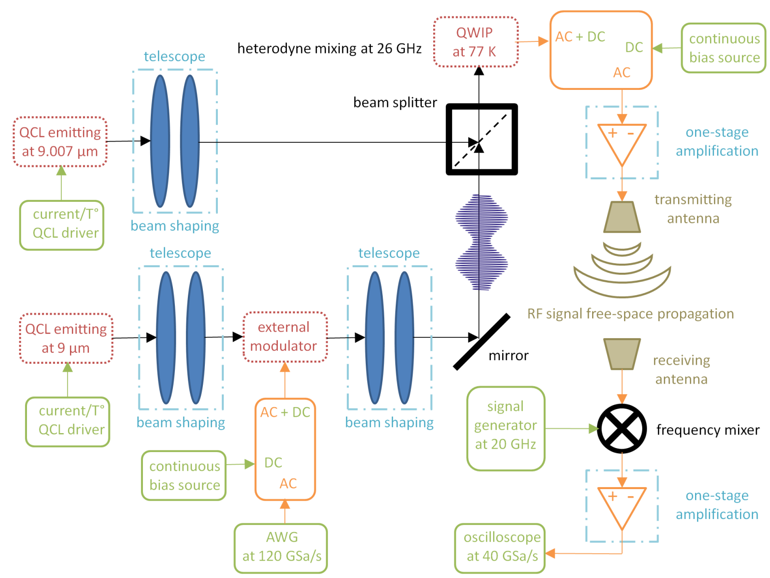

Figure 3. Experimental setup for the photonics-assisted microwave communication system based on the heterodyne beating of two QCLs. The two-stage amplifier between the AWG and the modulator is omitted in this sketch.

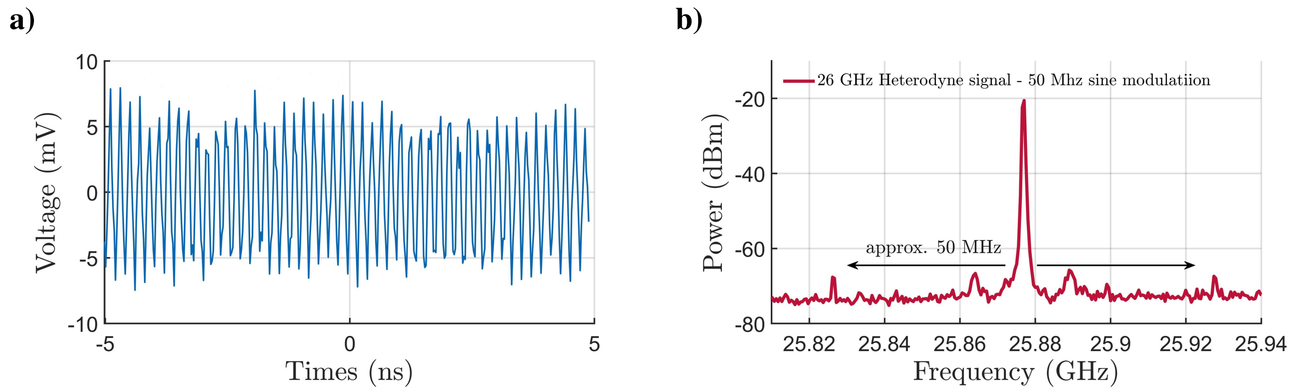

Figure 4. a) Timetrace recorded with the oscilloscope after the heterodyne signal around 26 GHz was downconverted with a frequency mixer. b) Electrical spectrum of the signal that is injected in the transmitting horn antenna and that exhibits the main carrier around 26 GHz and two satellite peaks stemming from the external modulation of one of the two QCLs.

of upper level as one can see in Fig. 2 b). We find a value of 31 ps for this 50 μm $\times$ 50 μm modulator and in the future, further reduction of the size of that unipolar quantum device will allow further decrease of the rise time, which is a trend already observed in QCDs.[32] The ultimate goal is to achieve modulation at mid-infrared wavelength with a rise time of less than 10 ps that could be paired with state-of-the-art QWIPs[33] for either high-speed free-space communication resistant to weather degradation[34] or for ultra-fast spectroscopy.[35]

3. MICROWAVE GENERATION WITH HETERODYNE BEATING

In this section, we describe our initial efforts about photonics-assisted microwave communication based on DFB QCLs heterodyne beating and on the aforementioned modulator. The setup can be found in Fig. 3 and shows two QCLs with slightly different optical frequencies, with δ_f the wavevelength spacing being 0.007 μm in that case in order to generate a microwave carrier at 26 GHz. This δ_f can be finely tuned by changing the temperature and/or the bias current of one of the two QCLs, and the conditions of operation of the two lasers must be extremely stable once the desired frequency beating is achieved. One of the two QCLs is also modulated as explained earlier, so that we do not only transmit a carrier at 26 GHz, but also a subcarrier (at 50 MHz in this proof-of-concept experiment). After the two beams impinge on the QWIP, the heterodyne signal is amplified prior to be sent to a transmitting horn antenna optimized for K_a band operation. After a few-meter free-space propagation, this radio-frequency signal is collected by a similar receiving horn antenna from Hemera, and the electrical signal is down-converted using a frequency mixer so that it can be observed with our 40 GSa/s oscilloscope. The subsequent signal containing the translated carrier and the small-amplitude subcarrier is amplified and can be visualized in Fig. 4 a). If instead of sending the heterodyne signal to an antenna, one observes it directly with an electrical spectrum analyzer with 26.5 GHz bandwidth, the spectrum shows the carrier at 26 GHz and two sideband peaks separated by 100 MHz, as depicted in Fig. 4 b). Two other symmetric frequency components are observed close to the 26 GHz carrier but further investigation is required to explain this phenomenon. Overall, this proof-of-concept experiment showed that it is possible to generate and propagate a radio-frequency signal with the heterodyne beating of two ultra-stable DFB QCLs and to use the Stark-effect modulator to perform an amplitude-modulation format transmission with a tone at 50 MHz. Future work will replace the 50 MHz sine wave by a realistic message like the one shown in green in Fig. 2 a) so that we can implement a demodulation process and recover the data. The next step is to extend this concept to the W band (75 - 110 GHz) and beyond in order to fully take advantage of the unipolar nature of these modulators and detectors ultimately limited by the scattering time of electrons, which is in the order of ps for intersubband devices.[36]

4. CONCLUSION

This work focused on our recent progress about high-speed modulation of mid-infrared light with external Stark modulators. These modulators are unipolar quantum devices optimized for a wavelength of 9 μm and they combine a large modulation depth with a rise time of a few dozens of ps that outperforms other existing technologies working at mid-infrared wavelength. We showed that these modulators were relevant for two communication applications, namely a direct transmission after 31-meter propagation and a proof-of-cocept experiment of a photonics-assisted microwave transmission in the K_a band. With our current unipolar quantum devices, the more relevant W band is a realistic target and will be investigated soon. Future work will also be dedicated to the improvement of the bandwidth of such modulators by reducing their active area. Knowing that QWIPs able to detect mid-infrared signal beyond 100 GHz already exist, we anticipate that similar performances can be achieved with Stark modulators, paving the way for a wide adoption of free-space communication systems based on intersubband technology. Finally, as the bandwidth of QWIPs is further extended to reach hundreds of GHz, the unipolar quantum optoelectronics heterodyne scheme that we presented in this work is poised to become a cost-effective method to generate waves in the 0.1 - 0.5 THz domain, and subsequently to carry out photonics-assisted terahertz high-speed transmission.

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