Preliminary results of bench implementation for the study of terahertz amplification in gallium nitride quantum wells

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Abstract. We present continuous-wave terahertz spectroscopic results obtained with a photomixing emitter and a bolometric detection. The tested elements are candidates for a further cryogenic THz experiment which will consist to demonstrate the effective amplification by optical phonon transit time resonance in gallium nitride quantum wells.

1. Introduction
In the actual goal of realization of sources and detectors in the terahertz (THz) frequency domain, we carry out a new gallium nitride (GaN) quantum walled (QW) device using the optical phonon transit time resonance (OPTTR) phenomenon\textsuperscript{[1]}. However, the experimental demonstration of effective wave generation needs the development of a spectroscopic bench working in the THz frequency range. Even if time-domain THz spectroscopy is currently rather common \textsuperscript{[2, 3]}, continuous-wave spectroscopy by photomixing remains marginal \textsuperscript{[4]}. The reason of this lack is related to the efficiency of available sources that is significantly reduced in continuous-wave operation with respect to pulsed operation. Frequency-domain spectroscopy has some advantages in regards of time-domain spectroscopy among which the frequency resolution or the phase extraction using homodyne detection \textsuperscript{[5]}. Alternatively it is possible to use a bolometric detection able to measure lower THz intensity for the verification of the effective amplification of our new QW GaN devices.

2. Terahertz amplification with optical phonon transit time resonance in GaN
The OPTTR is a well-known effect that takes its origins in sufficiently pure lattices at low temperatures when the mechanism of absorption of optical phonons with energy $\hbar \omega_0$ by free carriers is practically absent (this condition is achieved when $T \ll \hbar \omega_0/k_B$, where $k_B$ is the Boltzmann constant). The momentum space is by consequence divided into two parts, the so-called passive and active regions corresponding respectively to energies smaller or bigger than...
the optical phonon energy.
As illustrated in figure 1 (where the two cases of 2D and 3D transport are represented), the passive region is characterized by a very low optical-phonon emission rate whereas the active region by a great interaction rate. These two regions are separated by a threshold corresponding to the optical phonon energy value. The cyclic movement of electrons due to the combined action of electric field ballistic acceleration and energy loss by emission of optical phonons produces a negative differential mobility in the THz frequency domain [6]. As a consequence, the frequency of this cyclic movement linearly depends on the applied electric field. The limitations in term of frequencies can be summarized by two conditions on the free flight time $\tau_E$ of each electron (time for electrons to reach the energy of the optical phonon): $\tau_+ \ll \tau_E \ll \tau_-$, where $\tau_+$ and $\tau_-$ are respectively the scattering times in the active and passive regions.

An experimental verification of such a generation was obtained for the first time in InP samples by the group of Prof. L. E. Vorob’ev in St. Petersburg [7]. Nevertheless, recent publications [6] evidence that nitrides are promising materials for power generation in the THz frequency range because of the significant increase of the generation frequency band which extends from 200 GHz up to 7 THz at 77 K. However, from one hand, at the present time bulk nitride samples of sufficiently good quality are practically unavailable. Experimentally available samples are mostly heterostructures with 2D electron transport such as quantum-wells (QW) and heterolayers (HL). From another hand, it is worthwhile to emphasize that 2D transport has two evident advantages with respect to 3D case: (i) a possibility to increase the maximum generation frequency as shown in Fig. 2, that is the consequence of the sharper threshold of the optical phonon emission rate (see Fig. 2), and (ii) a possibility to obtain a greater amplification coefficient by the use of higher carrier densities and, at the same time, avoiding impurity scattering which tends to destroy the ballistic acceleration of electrons in the passive region.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Polar optical (PO) and deformation acoustic (DA) phonon scattering rates as functions of the electron energy normalized to the optical phonon energy in GaN at 10 K for both bulk and QW GaN.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Generation frequency bands as functions of applied external electric field in 2D and 3D InP and GaN at 77 K. Symbols refer to experimental results of ref. [7].

In the following sections we describe the preliminary development of an original THz spectrometer devoted to the measurement of THz emission by GaN QW.

3. Experimental setup
For the measurement of the GaN-transmission in the THz region, we have built a continuous wave (CW) THz-spectrometer represented schematically in figure 3. We used a low-temperature-grown GaAs photoconductive antenna illuminated by the beating of two tunable CW-DFB lasers emitting around 780 nm. The lasers wavelength emission is fixed by controlling the current and
temperature (using Peltier stages). As the nominal power required by our photomixing-device is around 60 mW [8], a tapered-semiconductor-amplifier was associated with the lasers in order to achieve this value. The THz generated field covers the range from 0.7 THz up to 1.7 THz. The developed experimental set-up uses two parabolic mirrors that collimate the THz field on the device under test (DUT). The detection is ensured by a 4 K cooled silicon bolometer associated with a lock-in amplifier synchronized with the electrical modulation of the photomixing device.

Figure 3. Experimental setup of THz spectroscopic bench (from 0.7 to 1.7 THz)

The procedure to obtain a spectrum in the frequency range of 0.7-1.7 THz with a 2 GHz step is the following. (i) A calibration spectrum is obtained without DUT then (ii) the measurement spectrum is obtained by placing the DUT in front of the THz beam. The resulting transmission spectrum is obtained by dividing the measurement spectrum by the calibration one.

4. Results
As shown on previous sections, the OPTTR phenomenon is effective when the GaN device is cooled down to low temperature. For this purpose, we measured several transmission spectra of candidate materials for the entrance windows of the cryostat. One example is given in figure 4 where the transmission spectrum was done through a 5 mm thick PTFE-slice (Polytetrafluoroethylene, also known as Teflon®). Several water-vapor-absorption peaks are clearly observed at approximately 0.98, 1.2, 1.22, 1.33 and 1.6 THz. To validate our bench, we have compared these results with a spectrum obtained by time-domain-spectroscopy at the RIKEN institute [9]. The overall shape of this spectrum as well as the absorption peaks reproduce well the spectrum obtained by Riken. Nevertheless, we obtain a transmission rate which is around ten times lower than these of RIKEN: this discrepancy can be explained by some loss between calibration and measurement spectra.

Finally, the performances of our THz frequency domain spectrometer are summarized in the table 1.
Figure 4. Transmission measurement of a 5 mm thick PTFE sample obtained with our frequency-domain spectrometer (continuous line) and compared with a 30 µm thick PTFE sample obtained with a time-domain spectrometer at the RIKEN’s tera-photonics group, Japan (dashed line)[9].

| Parameter                  | Value  | Unit |
|----------------------------|--------|------|
| Spectral range             | 0.7 – 1.7 | THz   |
| Frequency accuracy         | < 2    | GHz  |
| Power stability all over the band | > 75 | %    |
| Average power              | ≈ 10   | nW   |
| Signal to noise ratio      | > 20   | dB   |

Table 1. Typical performances of our THz spectrometric experimental bench

5. Conclusion
We realized a functional continuous-wave THz spectrometer in the 0.7 – 1.7 THz range. We implemented a calibration procedure and realized transmission spectra of several materials that are candidates for the windows of the 4 K-cooled cryostat that will be used for the demonstration of the THz radiations generation and amplification by bidimensional GaN structures through the OPTTR phenomenon.

Acknowledgments
We acknowledge the French National Research Agency (ANR) for funding the research under contract AITHER n°ANR-07-BLAN-0321.

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