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## 0.69 THz room temperature heterodyne detection using GaN nanodiodes

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**Abstract.** GaN-based asymmetric nanodiodes have been used as heterodyne detectors up to 0.69 THz in free-space configuration where Intermediate Frequency bandwidth has been measured up to 13 GHz. Monte Carlo simulations, used to estimate nano-device intrinsic conversion losses of 27 dB have confirmed these results.

### 1. Introduction

Heterodyne detection is a very convenient way to detect terahertz (THz) radiations. Indeed, heterodyne detection allows the use of conventional microwaves systems (such as spectrum analyzers) and simplifies the signal post-processing by down-converting the high-frequency radiation  $f_{RF}$  (usually named RF-signal) into a signal with an intermediate frequency (IF) falling into the microwave range [1]. State-of-the-art of electronic components for heterodyne detection of high frequency radiation are mainly achieved by Schottky diodes [2]. Since these components are based on vertical transport, they require advanced materials, challenging fabrication processes and critical technology aspects to operate at THz frequencies. Based on a different concept, the asymmetric nanodiodes have been proposed to obtain planar devices with non-linear, diode like, current voltage (I-V) characteristic [3]. Moreover, the use of high-mobility semiconductors make possible to achieve THz operations. Even if the use of unipolar GaN-nanochannels as THz mixers is fairly new, it presents a lot of room for improvements to make them competitive with Schottky technology. In a previous paper, through a systematic numerical study based on Monte Carlo (MC) simulations, we have presented the performances of such GaN nanodiodes as direct and heterodyne detectors in the 0.300 THz frequency range [4]. The aim of this paper is to present, over a wider frequency range, a systematic experimental study of the performances of GaN nanochannels as heterodyne detectors with a particular attention to their dependence on bias conditions and frequency of operation. In particular, we show for the first time that GaN nanochannels can be used as heterodyne detectors at high frequencies as 0.690 THz.

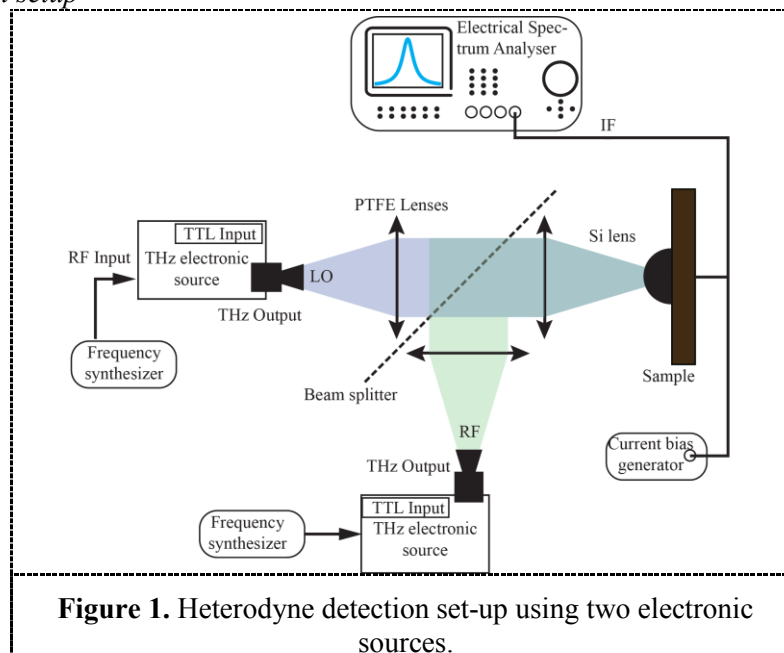


## 2. Experimental details

### 2.1. Sample description

The sample used is based on 2DEG unipolar nanochannels with a broken symmetry created by etching in the AlGaIn/GaN heterojunction two symmetrical L-shaped trenches (see [5] for technological details). In order to reduce the impedance of our nanodevice, 32 nanochannels were disposed in parallel without the need of any interconnection. In this way, the extrinsic parasitic elements can be limited: this is an important feature at these frequencies. We emphasize that the simplicity of the technological process used for the fabrication of these nanodiodes is remarkable, since it only involves the etching of insulating recess lines on a semiconductor surface. Another key aspect of these nanodevices is their planar geometry, which provides important advantages for the free-space radiation coupling over traditional diodes (Schottky barrier) used in current THz systems. Each nanochannel of our studied device has a length  $L$  and a width  $W$  such as  $L = W = 500$  nm. In order to use this device in free-space configuration, planar bow-tie THz antenna was monolithically integrated.

### 2.2. Experimental setup

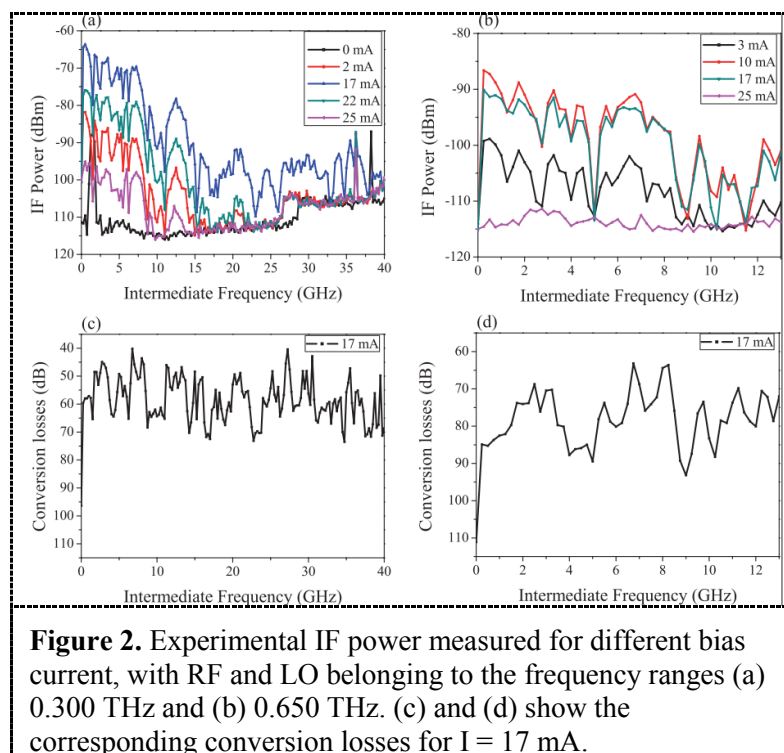


To highlight the ability of these devices to mix two THz radiations in the 0.300 THz frequency range and in the 0.650 THz frequency range – figure 1. We have used each time two electronic sources from Virginia Diodes Inc. (VDI®) which frequencies fall into the same range. As this kind of electronic sources are composed of a multiplication chain, the measurement frequency points have been verified to be spurious free (eg monochromatic signal). The RF input of the source is connected using a coaxial cable with subminiature version A (SMA) connectors to a frequency synthesizer, which delivers the microwave signal to be multiplied by the source. The latter will then radiate a THz frequency signal. For example, to reach 0.650 THz, we need a THz source with a multiplying factor of 48, and an input frequency of 13.54 GHz provided by the frequency synthesizer. In the 0.300 THz frequency range we fixed the RF frequency at 0.290 THz, and we varied the LO frequency from 0.290 to 0.330 THz, which means that the Intermediate Frequency varies between 0 and 40 GHz which is the bandwidth of our electrical spectrum analyser. In the 0.650 THz frequency range the RF frequency was fixed at 0.660 THz, and the LO frequency was varied from 0.660 to 0.673 THz, which means that the Intermediate Frequency varies between 0 and 13 GHz which represents the cut-off frequency of the FR4 sample holder. This frequency was simulated using CST® microwave studio program. This

holder was especially designed for  $50 \Omega$  impedance matching with the input impedance of our electrical spectrum analyzer. The antenna of the device was connected via gold-microbondings to printed HF-lines to SMA connector. The two THz radiations are collimated and focused using PTFE lenses, whereas a polyethylene terephthalate beam-splitter helps to spatially-superimpose the two radiations. Finally, a silicon hemispherical lens of 6 mm diameter, is placed at the rear side of our sample to improve the focalization on the device, to reduce the free-space coupling losses and to limit interferences inside the Si-bulk layer. A bias-tee is connected to the SMA connector of the sample in order to provide the DC-bias to the device, and to measure the IF with the help of a Rohde & Schwartz® FSU electrical spectrum analyser. In all cases the experiments were performed in free space and at room temperature configurations. In order to understand the physical mechanisms of mixing (in terms of output power), a semi-classical Monte Carlo (MC) simulation self-consistently coupled with a Poisson solver is used as previously explained in [6].

### 3. Results and discussion

The IF power measured with our device, as a function of frequency is presented in figure 2 for the RF and LO signals falling into the 0.300 THz range (a) and 0.650 THz range (b), for different bias current. In both cases, a strong attenuation around 13 GHz is observed: this effect cannot be attributed to the cut-off frequency of our device. Indeed, important figures of merit to be taken into account are the conversion losses (CL) of our mixer.



These have been determined as the ratio of the power at the IF to the power at the  $f_{RF}$  subtracting the losses induced by connecting elements and HF-lines, that were simulated using CST microwave studio and present a cutoff frequency around 13 GHz. Consequently, the CL can be plotted according to the IF – Figure 2 (c) and (d) – in the 0.300 and 0.650 THz frequencies ranges, respectively for the best bias conditions of  $I = 17$  mA. The CL of the whole integrated device are  $58 \pm 2$  dB in the 0.300 THz frequency range and increase by an additional 20 dB at higher frequencies to achieve  $78 \pm 3$  dB in the 0.650 THz frequency range. These values do not represent the intrinsic CL of the device since the losses due to radiation coupling with the antenna (especially in the 0.650 THz frequency range) and bondings-wires are difficult to measure. Since CL are mainly constant in each given frequency range,

one can conclude that the bandwidth of our mixer is at least of 40 GHz, i.e. the frequency limit of our electrical spectrum analyzer.

#### 4. Conclusion

We have investigated the potentialities of AlGaIn/GaN based nonlinear nanochannels for THz heterodyne detection. The room-temperature heterodyne detection up to 0.690 THz has been demonstrated for the first time with such a device. As a consequence their practical implementation as mixers of high-power sub-mm wave sources seems feasible. Moreover recent studies of similar GaN-based nanodiodes [6], have demonstrated the possibilities as Gunn oscillators to be employed as active elements of THz emitters. As a consequence, that opens the possibility to develop a fully integrated emitter/detector submillimeter-wave system working at room temperature.

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