

Light (Radiation)–Matter Coupling: The Sub-Terahertz Range – Our Path from Understanding to Applied Science

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The sub-terahertz spectral range bridges the traditional domains of microwave electronics and infrared photonics. For a long time, this region was comparatively difficult to access because efficient sources, detectors, and components were limited—the broader problem often referred to as the “terahertz gap.”

Today, advances in semiconductor materials (also seen in nitrides), nanostructures, high-frequency electronics, and spectroscopy are changing this situation. The sub-THz range is becoming an increasingly powerful environment for investigating how electromagnetic radiation interacts with matter.

However, beyond the fundamental limitations of high-frequency semiconductor electronics that constrain the efficiency of active devices, such as sub-terahertz emitters and detectors, significant challenges also arise from the integration of active and passive components. At sub-terahertz frequencies, parasitic effects, impedance mismatch, signal losses, and electromagnetic coupling between neighbouring components become increasingly important. As a result, the performance of an individual active device cannot be considered independently of its electromagnetic environment and the surrounding passive structures. This highlights the need for a comprehensive approach in which the design of semiconductor devices and the engineering of their electromagnetic environment are considered simultaneously.

We identify the central problem as the efficient coupling of sub-THz radiation to solid-state devices. At 100 GHz, the wavelength is about 3 mm, while the active semiconductor devices are much smaller than this wavelength. At the same time, conventional solutions such as wire bonding and rectangular waveguides begin to face limitations around these frequencies. This means that the problem cannot be solved by improving only the semiconductor device—the surrounding electromagnetic environment has to be considered as well. Our approach can be described as a system-level solution to the fundamental problem of sub-THz integration: instead of treating the active semiconductor device, transmission lines, antennas, resonators, and matching networks as separate components, we are designed and fabricated together on the same semiconductor platform. The proposed approach is therefore monolithic integration of active and passive sub-THz components using advanced nitride technology, particularly GaN.

The active parts are based on GaN heterostructures containing a two-dimensional electron gas (2DEG). We would like to emphasize that nitride 2DEG can provide high electron mobility together with high 2D electron concentration at room temperature, making it attractive for high-frequency devices. Our next step is to fabricate active components using this 2DEG, like High Electron Mobility Transistors (HEMTs) or others, such as switches based on lateral Schottky barrier diodes [1]. The design uses a 2DEG/Schottky-metal junction with an extremely small effective junction area—estimated at approximately 10–9 cm². Next, we move from individual semiconductor devices to antennas, transmission structures, and metastructures [2]—that is, from the active to the passive elements of our integrated circuit, respectively. Here it is worth to underline, that passive part occupies a dramatically different physical scale. We point out that the active

devices occupy only several square micrometers, whereas passive structures can occupy about 30 mm². This is unusual for any technological approaches in the field of semiconductors. The passive structures we are fabricating also on Ammono semi-insulating GaN substrates. Importantly, the substrate is not treated simply as mechanical support. Its electromagnetic properties matter: we specifically highlight low dielectric loss ($\tan\delta$) as necessary for good radiation efficiency.

Then, to integrate passive and active elements, rather than simply connecting the diode to an external antenna, our approach investigates the electromagnetic structure propagation around the integrated device itself. A particularly important element is the use of a metasurface to enhance the radiation efficiency of sub-THz antennas on relatively thick substrates. This solution demonstrates a significant increase in the gain of the planar antenna, even for a relatively thick A-GaN substrate of 200 μm (see Fig. 1). Then, we present first demonstrates this concept using a hybrid device with commercial GaAs diodes around 100 GHz. This hybrid structure is effectively an intermediate experimental step: it allows the antenna/metasurface concept and the radiation coupling to be investigated before achieving the final fully integrated GaN solution.

It is worth mentioning that our collaboration, both within IHPP PAS and with the group of Prof. Yashchyshyn at Warsaw University of Technology, reflects this interdisciplinary approach. IHPP PAS contributes its expertise in GaN technology, in particular low-loss Ammono SI-GaN substrates, 2DEG epitaxy, device design and processing, as well as substrate thinning. The antenna and sub-THz group at the Institute of Radioelectronics and Multimedia Technology (IR&MT), Warsaw University of Technology, contributes expertise in millimetre-wave design, rigorous electromagnetic simulations, and measurements in an anechoic chamber.

Ultimately, our goal is to develop a monolithic GaN platform in which the generation, detection, switching, and coupling of sub-terahertz radiation can be integrated within a single technological system.

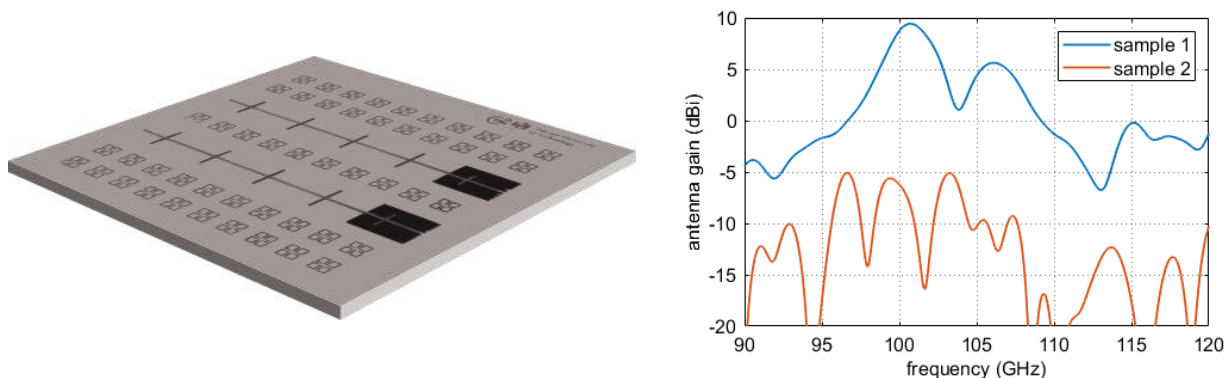


Fig. 1. (left) radiating planar antenna on A-GaN substrate designed and fabricated as the preliminary study; (right) measured antenna gain. Thickness of sample 1 and 2 equal 200 μm and 400 μm , respectively.

References

- [1] P. Bajurko, J. Sobolewski, Y. Yashchyshyn, P. Sai, S. L. Rumyantsev, T. Narytnyk, and G. Cywiński, "AlGaIn/GaN Distributed Schottky Barrier Single-Pole Single-Throw Millimeter-Wave Switches", *IEEE Access*, **11**, pp. 125909–125917, 2023.
- [2] Y. Yashchyshyn, P. Tokarsky, "Using a metasurface to enhance the radiation efficiency of subterahertz antennas printed on thick substrates", *Scientific Reports* **14**(1), 1–16, 2024.