THz Electronics: Transistors, TMICs, and High Power Amplifiers

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Abstract

THz transmitter and receiver demonstrations are the ongoing focus of a portfolio of programs within DARPA. Through the sponsorship of the Terahertz Electronics and related programs, a technology base is being established to effectively generate, detect, process, and radiate sub-MMW frequencies to exploit this practically inaccessible frequency domain with coherent signal control suitable for imaging, radar, spectroscopy, and communications applications. Transistors, integration technologies, power amplification, and their precision metrology are the key technical challenges under active investigation. THz InP-based transistors have been achieved that have enabled the world's fastest monolithic integrated circuits with demonstrated performance at 0.67 THz. Compact THz high power amplifiers using micro-machined vacuum electronic devices will enable radiation sources at sub-mm wave frequencies with the goal of 1.03 THz with 15 GHz of instantaneous bandwidth. Ultimately, low-loss interconnects and integration techniques will couple TMICs with HPAs to enable THz coherent heterodyne transceivers.

INTRODUCTION

Imaging, radar, spectroscopy, and communications systems operating in the sub-MMW frequency band (300 GHz to 3 THz) have been elusive owing to a lack of effective means to generate, detect, process, and radiate the necessary signals. In order to control and manipulate radiation in this especially challenging portion of the radio frequency (RF) spectrum, DARPA is presently sponsoring research into the important technical issues necessary to improve THz transmitters and receivers.

The practical transmission of sub-MMW radiation for defense applications will rely on the development of higher power sources and amplifiers with acceptable wall-plug efficiency, instantaneous bandwidth, and gain. The approaches described in this paper are a significant departure from historical methods of generating THz radiation using free-running and short-transient sources.

Compared with generation, the reception of sub-MMW signals is significantly less developed and has been largely restricted to cryogenic detection. We propose that dramatic improvements in system performance, including improved noise figure and phase noise characteristics is possible with an electronic solution. Applying RF and microwave receiver techniques, such as spectral filtering and phase coherent processing, it is reasonable to project huge improvements in signal-to-noise ratio (70dB or more) relative to bolometers, Schottky diodes, and other conventional "direct" (rectifying) detector approaches. The use of coherent heterodyne processing in which the relative phases of transmit and receive signals are exploited is one such method.

In order to realize sophisticated electronic approaches for sub-MMW systems in the THz Electronics project, the conceptual framework of a transceiver was adopted and is shown in Fig. 1 as a block diagram with corresponding performance goals listed in Table I. In the following sections, the research and development of transistor, integrated circuit, and amplifier technologies relevant to these blocks through ongoing and recent projects are described. Transistors with unity-current-gain cut-off (f_T) and maximum oscillation (f_{max}) frequencies are the focus of the device research that will significantly reduce charging and transit times in both InP-based bipolar heterojunction transistors (HBTs) and field-effect transistors (FETs). The development of integrated circuits at these frequencies focuses on creating high-speed, low-loss interconnects and on-chip waveguides suitable for monolithic integration. Finally, the development of compact, efficient HPAs in the sub-MMW frequency band is addressed by the complex and difficult scaling of vacuum electronic devices. This discussion expands on an overview of these projects

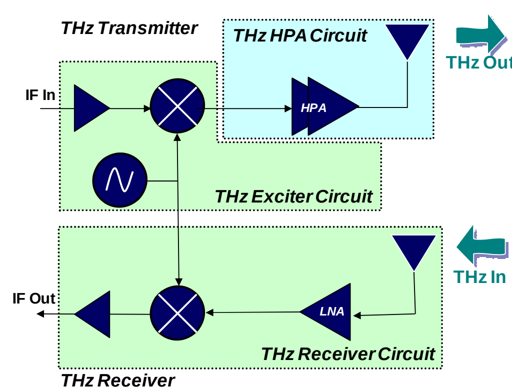

Fig. 1. Conceptual block diagram of the THz Electronics transceiver.

presented at the IEEE MTT 2010 International Microwave Symposium [1].

THz TRANSISTORS

The core of the THz Electronics program is the THz transistor. A large body of work has led to major achievements in the current pursuit of transistors with f_T and f_{max} above 1 THz. Increasing the maximum frequency of useful transistor and MMIC operation has been the objective of numerous defense projects for decades. Most relevant to this work are the improvements to InP HBTs and High Electron Mobility Transistors (HEMTs) achieved under the sponsorship of two previous DARPA projects, Sub-millimeter Wave Imaging Focal-plane-array Technology (SWIFT) and Technology for Frequency Agile Digitally Synthesized Transmitters (TFAST), both of which involved transistor advancements that will be discussed presently. At the inception of the THz Electronics program, HBTs with f_T ~ 0.8 THz [2] and HEMTs with f_{max} > 1.0 THz [3] were reported. While these reports are not completely understood, are nearly impossible to verify through direct measurement and have spurred debate in the community, the relevant point is that the underlying device technology was primed to advance toward meaningful THz operation. The proof would come in the form of sub-MMW MMIC functionality which depends directly on the device characteristics and model fidelity. These components are being fabricated and measured. The corresponding predicted and measured MMIC data has begun to be disseminated in the literature.

The SWIFT project advanced integrated amplifier and oscillator circuitry to operating frequencies above 300 GHz for the first time. This was directly the result of advances in both InP HEMT and HBT performances. Under SWIFT, 35 nm gate length InP HEMT technology demonstrated f_T ~ 0.5 THz and f_{max} ~ 1.2 THz with off-state breakdown voltage equal to 2.5 V with I_g = 0.25mA/mm [4]. These results correlated to both intrinsic device improvements and parasitic resistance and capacitance reductions based upon model extraction from S-parameters. Among the many achievements under the project that exploited these devices are InP HEMT multipliers, LNA, and power amplifier circuits all operating at over 330 GHz.

Going forward, THz Electronics has made great progress towards driving InP HEMT technology to 20 nm gate lengths and under this program, we will attempt to demonstrate f_T > 1.2 THz and f_{max} > 2.25 THz. These frequencies will be accessible through the reduction of C_{gs} to below 0.4 pF/mm and R_{source} < 0.1 Ω·mm. These HEMT devices are projected to have RF transconductance values of 3500 mS/mm compared with 2300 mS/mm for the 35 nm HEMTs measured under the SWIFT project.

A clear picture of the HEMT technology and scaling approaches being developed in the initial stages of the THz Electronics program has emerged in the literature and at major meetings over the last year, including published circuit demonstrations at 0.48 and 0.55 THz [5-6]. Within the project, working circuits at 0.67 THz and above have been measured and it is reasonable to expect that fully integrated assemblies involving multiple ICs will be fabricated and measured in the coming year using this HEMT technology. A recent example of progress toward THz circuitry is shown in Fig. 2 where S-parameter data from a recent 0.48 THz solid-state amplifier is plotted [6]. An early attempt to design a 3-stage cascade amplifier through the scaling of a 300GHz design with favorable noise figure to 0.67 THz has resulted in slightly detuned operation at 0.55 THz, but is a remarkable result from a measurement and operational frequency perspective [7]. The measured results of the packaged amplifier are shown in Fig. 3.

TABLE I
PROGRAM GOALS FOR THZ ELECTRONICS

	Center Operating Frequency	GHz	670	850	1030
Exciter/Receiver	Exciter P_{out}	dBm	4	2	0
	Exciter Phase Noise (1)	dBc/Hz	−33	−30	−27
	Exciter Modulation Bandwidth	GHz	15	15	15
	Receiver NF	dB	12	12	12
	Minimum Instantaneous Bandwidth	GHz	15	15	15
High Power Amplifier	P_{out} (2)	dBm	18	14	10
	Power Added Efficiency	%	0.75	0.5	0.2
	Minimum Instantaneous Bandwidth	GHz	15	15	15
	Gain	dB	20	18	16
(1) At 100Hz offset (2) At least 50% duty cycle					

In parallel with the HEMT advances, great successes in development of InP HBT technology occurred under SWIFT as well. There are no near term physical limits to extending InP HBT operation into the THz domain and extensive scaling laws have been derived to chart this course of research [8]. From these scaling laws, it is evident that the most critical technical challenge with HBT scaling is the drastic increase in current density resulting (and heating) as the corresponding device dimensions are reduced.

One approach being pursued under THz Electronics will vary the HBT junction widths with the inverse square of the device frequency bandwidth, which crudely translates into a constant device thermal resistance (tolerable junction temperature increases) scaling law under reasonable assumptions regarding device isolation and substrate thicknesses. Therefore, controlling the lateral dimension (emitter width) is of the utmost importance for obtaining the current density and thermal control required to extend the processes realized in TFAST. Using this approach, a 250 nm emitter HBT generation has been fabricated and characterized under the THz Electronics project and 128 nm emitter widths are in development [9]. There is a second approach to HBT scaling being pursued under the THz Electronics project. To surmount higher current density operation that leads to heating of the HBT, a substrate

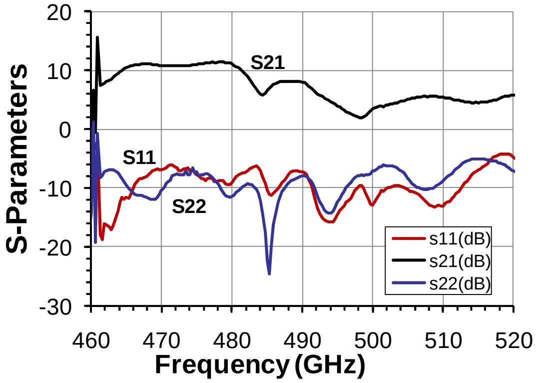

Fig. 2. Measured S-Parameters of 0.48 THz amplifier [6].

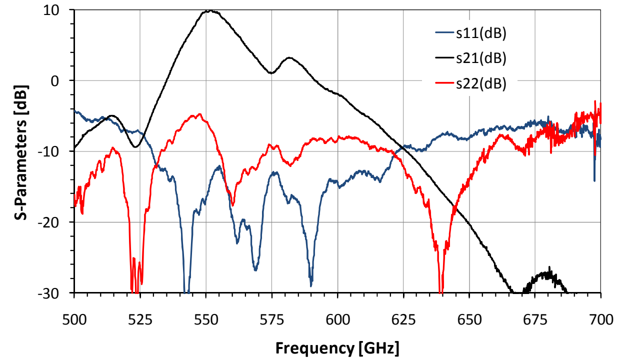

Fig. 3. Measured S-Parameters of cascode amplifier. A peak measured gain of 10 dB has been measured at 550 GHz was measured in package. A micrograph of the [7].

transfer process is being developed to transfer the transistor from the native InP substrate to a higher thermal conductivity AlN wafer [5].

THz Interconnects and Metrology

A key part of any sub-MMW integrated circuit approach is the realization of interconnect technology for wiring circuits with tolerable loss and sufficient signal bandwidth both on chip and within the system. Therefore, THz electronics requires the invention of high density integrated circuit technology appropriate for sub-MMW frequency scaling as well as inter-element connection technology. State-of-the-art cascaded frequency multiplier chains typically use discrete devices that are packaged into large, hand-machined blocks interconnected by waveguides using custom-fabricated transitions. Not only are these approaches not profiting from monolithic integration, but the size, weight, and cost of such structures are prohibitive. On-chip approaches to wiring THz transistors will include the development of low-loss via techniques for connecting thin-film micro-strip lines to HBTs as well as air-bridge and co-planar waveguide methods for efficiently connecting to HEMTs. Some of these methods were demonstrated to work above 300 GHz as part of the SWIFT and TFAST projects.

Traditional wirebond and E-plane probe millimeter wave interconnects have high losses and poor manufacturability at THz frequencies. There are severe technical challenges associated with improving the inter-element interconnections so that signals can propagate into and out of the TMIC and the THz Electronics program is supporting research that will assess a number of approaches. For example, THz micro-machined coaxial probe interconnects and integrated THz dipole probe interconnects are under investigation with goals of < 2 dB insertion loss and > 70 GHz of bandwidth at 1.03 THz by the end of the project. Other approaches make use of MEMS-like techniques capitalize on silicon deep reactive ion etching capabilities for batch fabrication, grayscale lithography, and wafer bonding.

Solving these interconnection issues to provide low-loss fixtures and well behaved couplings is going to be critical not only for connecting the total circuit but also for developing the metrology techniques required to measure at high sub-MMW frequencies with confidence. An example of a 0.67 THz circuit that illustrates these difficulties is shown in Fig. 4. S-parameter measurements with vector error correction are essential for evaluating transistor performance and extracting accurate transistor models. Direct measurements at higher frequencies are sought to reduce uncertainties associated with extrapolation to THz frequency.

THz High Power Amplifiers

Phase-sensitive transmit/receive systems typically require HPAs, not free-running sources to be practical. At THz frequencies, integration of an HPA with a first-stage exciter in a relatively compact assembly represents a formidable challenge. Therefore, to fully realize the potential of the TMICs in a system context, compact micro-machined vacuum electronic devices providing relatively high power sub-MMW sources with be developed under THz Electronics.

Vacuum technology offers a feasible solution for efficient THz transmitters, but will require a number of key inventions. The clear problem is that the complex and difficult size scaling required for this technology to achieve THz operation places an enormous burden on the fabrication methods and tolerances for interaction structures. Some of these issues have already been under investigation as part of the High Frequency Integrated Vacuum Electronics (HiFIVE) program. Under that effort, a high bandwidth (> 5 GHz) HPA at 220 GHz is the goal. Critical developments include the fabrication of the interaction circuit, a high current density integratable cathode structure, and achieving stable high-power electron beam transport.

As shown in Table I, THz Electronics is seeking to push the operating frequency of the HPA to the THz regime. Multiple approaches are being pursued to accomplish these goals. An Extended Interaction Klystron (EIK) approach that applies the concept of multiple interaction structures at offset frequencies to simultaneously achieve high gain from the superposition of multiple structures interacting with the signal and high bandwidth from the gradual off-set design of the same structures. Using this concept, it is reasonable to design an HPA that meets the goals of Table I and increases output power to > 20 dBm and gain to > 20 dB at 1.03 THz. The challenges of implementing an EIK design for the specifications of the THz Electronics project are severe and well documented [10]. When extending the design of a linear beam tube like an EIK to higher frequency, the most straightforward approach is to try to scale the parameters of an existing design.

The second vacuum electronic approach is based on the use of a folded waveguide structure that offers sufficient gain and bandwidth to satisfy the project objectives. In this approach, inventing a 3D magnet design that suppresses beam ripple is a major challenge. The planar periodic permanent magnet designs for THz Electronics would not only advance this project but would also revolutionize the approaches to minimizing the size and weight of vacuum HPA function.

The 670 GHz amplifier being developed will be a single FWG device. High PAE requires good beam transport, and hence low cathode edge emission and small magnetic field errors are important. Input and output transmission lines are as short as possible as the RF losses are significant at 670 GHz. Presently, a quasi-optical approach based on free space transmission is planned for the I/O networks.

CONCLUSIONS

DARPA has been supporting the development of THz technologies to effectively generate, detect, process, and radiate sub-millimeter wave (sub-MMW) frequencies between 0.3 to 3 THz in order to exploit this practically inaccessible frequency domain for imaging, radar, spectroscopy, and communications applications. In this paper, we have detailed the progress to date in the core areas of THz transistors, TMICS, on-chip and inter-element interconnects, and HPAs.

In addition to the direct exploitation of THz radiation and circuitry, there are significant potential opportunities for very fast electronics to improve precision analog microwave circuits and high-resolution data converters at substantially lower overall operating frequencies. For example, extreme reduction in the noise figure of low-noise amplifiers at more common lower application frequencies is predicted with devices that have very high cutoff frequencies. Also, the creation of extremely wide-bandwidth impedance converter circuits may be possible at low frequencies for antenna applications using extremely fast transistor and amplifier integrated circuit technology.

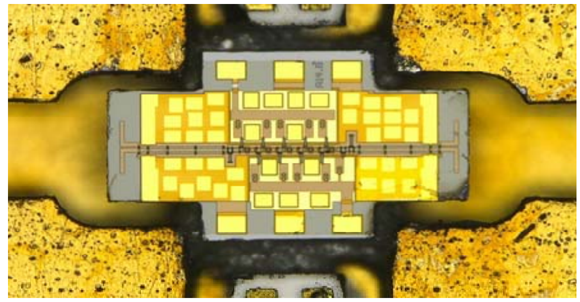

Fig. 4. Microphotograph of 670 GHz LNA in split block housing [11].

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