THz Vacuum Electronics

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Abstract: *The US Department of Defense Research and Engineering Enterprise funds leading-edge research that continually expands the boundaries of human capability. Over the past several years, a number of US DoD research programs have focused on creating vacuum electronic devices capable of operating in the THz region of the electromagnetic spectrum, typically defined as 300 GHz to 3,000 GHz. This paper will place these research programs in context, describe the program goals, and highlight selected breakthroughs.*

Keywords: cathodes; electron devices; magnetics; micromachining; submillimeter wave technology.

Introduction

Terahertz (THz) typically is defined as the range of frequencies between 300 GHz and 3,000 GHz, between the sub-millimeter and the infrared. [1] Other ways to quantify this spectral region include wavelengths from 1 mm to 100 μm , wavenumbers from 10 cm^{-1} to 100 cm^{-1} , and energies from 1.24 meV to 12.4 meV. The THz lies in the transition between classical and quantum mechanical behavior, where $h\nu \approx kT$ and critical dimensions approximate a wavelength at the device operating frequency. [2] As solid-state electronics approach this range from lower frequencies, device scaling, carrier mobility, and parasitics severely limit performance. From above, sources based on optical mixing and quantum-cascade lasers drop off dramatically in output power and efficiency. These issues create the well-known “THz gap” where signal generator and amplifier technology is lacking.

Vacuum Electronics To The Rescue

Fortunately, a third option exists for generating and amplifying power in this spectral region. Vacuum electronics is the technology that consistently has defined the outer boundaries of the frequency/power operating space [3]. However, because the dimensions of a vacuum device scale with operating frequency, the precision available from traditional machining techniques cannot keep up as operating wavelengths approach the micron scale. The boom in micro-electromechanical systems (MEMS) has fueled the development of fabrication technologies capable of up to three orders of magnitude finer precision compared to conventional machining, such as deep reactive ion etching (DRIE) and LIGA (a German acronym for lithography, electroplating, and molding). A quick back-of-the-envelope calculation would indicate that

application of these fabrication techniques to vacuum electronic devices should enable operation at frequencies up to three orders of magnitude higher. So why don't we have THz vacuum electronics already?

Limits On Device Scaling

Levush *et al.* [4] have defined convenient scaling laws for the peak RF power available from traveling-wave and standing-wave electron devices. The governing equation for traveling-wave devices is

$$P_{TW} = N \times 24 \left(\frac{1}{f}\right)^{8/3} (V_b)^{13/6} (J)^{4/3} \quad (1)$$

where N is the electron sheet beam aspect ratio or number of round beams, f is in GHz, V_b in kV, and J in A/cm^2 . From this equation it is clear that the beam power must rise much faster than the operating frequency just to maintain a constant output power level.

Of course, what does not appear in (1) is the increasing complexity of electron beam transport with increasing beam current density and operating frequency, with its corresponding decrease in beam diameter. For very small beams that generally operate in the emittance dominated regime, the minimum beam thickness scales as $T^{1/2} J_b / B J_c$, where T is the cathode temperature, J_b is the beam current density, B is the magnetic field strength in the beam tunnel, and J_c is the current density at the cathode. [4] Plugging the numbers required for THz operation into this equation points to the need for high magnetic fields and highlights the potential utility of cold cathodes.

These equations clearly define the engineering “pressure points” for reducing a THz vacuum device to practice. Other, more practical limitations have been exposed during the course of THz vacuum device research. As device dimensions decrease, the surface roughness of metals deposited by sputtering or evaporation remains approximately constant in the nanometer range. While this value is too small to be of concern at current operating frequencies, in the THz it approaches a significant fraction of a wavelength and can produce appreciable power loss.

Beam power density balloons as device dimensions shrink. Using the canonical values of 125 μm beam diameter, 100 mA beam current, and 20 kV anode voltage as might be used in a micromachined tube, the power in the electron beam calculates to 2 kW, a manageable value. The beam power density, on the other hand, is on the order of 160 GW/m^2 , or nearly 2,700 times the power density at the

surface of the sun. Clearly, any significant beam interception in this operating regime would be catastrophic.

US DoD Sub-mm and THz Programs

The Defense Advanced Research Projects Agency (DARPA) has instituted several programs to attack these problems. The Terahertz Imaging Focal-plane-array Technology (TIFT) program [5] began in FY04, focused on development of sources and detectors operating above 557 GHz. The end goals for the program were to produce sources with average power above 100 mW with DC power efficiency of 1%, direct detectors with $0.5 \text{ pW/Hz}^{1/2}$ noise equivalent power (NEP) in 50 GHz bandwidth, and heterodyne detectors requiring less than 0.1 mW local oscillator power per mixer to achieve $\text{NEAT}=1^\circ\text{K}$. The TIFT performers made great progress towards program goals and laid the groundwork for future DARPA sub-millimeter wave and terahertz programs.

The High Frequency Integrated Vacuum Electronics (HiFIVE) program [6] kicked off in FY07 with the goal of demonstrating an integrated, microfabricated vacuum electronic high power amplifier (HPA) circuit at 220 GHz for use in high-bandwidth, high-power transmitters. The Vacuum Electronic Circuit Elements technical track requested developments in solid-state driver amplifiers, high current density cathodes, high efficiency micromachined interaction structures, and innovative ideas for thermal management. The Vacuum Electronic Circuit Design, Integration, and Demonstration technical track supported design, integration, and demonstration of the target HPA. Based on the scaling arguments presented earlier, an aggressive goal was set in Phase I to demonstrate generation and efficient transport of a sheet electron beam with 25:1 aspect ratio and current density of 750 A/cm^2 . The ultimate performance goals for the HPA are a power-bandwidth product of $500 \text{ W}\times\text{GHz}$ with average output power of at least 50 W measured external to the device, and bandwidth of at least 5 GHz. The HPA wallplug efficiency is specified at 5%. HiFIVE produces a beamstick with 25:1 sheet beam aspect ratio, although this exceed what will be required to meet the amplifier specifications in the outphases. The HiFIVE program currently is in Phase II and exciting new results are expected in this calendar year.

The Terahertz Electronics (THz) program [7] started in FY08 with two technical areas of interest: Terahertz Transistor Electronics and Terahertz High Power Amplifier (HPA) Modules. The three-phase program targets center operating frequencies of 0.67 THz, 0.85 THz, and 1.03 THz respectively in each phase. The THz program currently is in Phase II with very exciting results so far. Status and results from the transistor technical area were presented by Albrecht *et al.* [8] at the 2010 IEEE International Microwave Symposium. The HPA technical area has demonstrated a TWT amplifier and promising early results for an EIK at 670 GHz. Current results will be presented at the conference.

The Way Forward

There is no question that significant breakthroughs have been demonstrated for THz vacuum electronics, and that more astonishing results are yet to come. Execution of the research programs that produced these breakthroughs also has uncovered some potentially fruitful areas for future research.

State-of-the-art thermionic cathodes for commercial and military vacuum electronics are the workhorses of the industry. Still, there is room to increase repeatability, reliability, uniformity, and current density. Fundamental questions about the chemical, mechanical, and electromagnetic processes governing emission remain unanswered. Cold cathode technologies including micromachined field emitter arrays, secondary emission cathodes, and carbon nanotube-based field emitters have shown promise but have yet to demonstrate sufficient total emission current, repeatability, and reliability to support their use in a fielded application.

Current manufacturing processes for magnetics have reached a high level of sophistication. However, problems still exist with field strength uniformity and isotropy that will only get worse as device dimensions decrease. For the next stage of device miniaturization, compact magnetics that are compatible with standard microfabrication processes must be developed.

Excellent modeling and simulation tools exist that have enabled first-pass design success for commercial vacuum electronics. As operating frequencies increase and microfabrication reaches widespread use, new M&S tools will be required that can simultaneously model fabrication process non-uniformity and electromagnetic performance.

Continued strategic investment by the US DoD will lead to new scientific breakthroughs enabling the next generation of THz vacuum electronics.

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