Sheet Electron Beam Millimeter-Wave Amplifiers at the Naval Research Laboratory

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Abstract — To meet the need to transmit increasingly massive volumes of data, both the defense and commercial sectors are turning to higher operational frequencies to take advantage of larger signal bandwidths while concurrently requiring increased amplifier power to achieve the necessary signal-to-noise ratios over large transmission distances. In response to these needs, the last decade has seen a leap in performance of a variety of millimeter-wave devices. The Naval Research Laboratory (NRL) is the principal U.S. Department of Defense R&D center focused on the development of the science and technology behind new millimeter-wave high power solid-state and vacuum electronic devices. Selected examples of NRLs research projects are described with an emphasis on high power millimeter-wave vacuum electronic devices.

Keywords: Vacuum electronics, sheet electron beam, traveling-wave tube, helix TWT, extended interaction klystron, coupled-cavity TWT.

I. INTRODUCTION

HIGH-power, compact millimeter-wave (MMW) and upper-MMW amplifiers are of increasing importance for a variety of applications. For some of these applications, substantial increases in power, specific power (power per unit volume and weight), bandwidth, and/or efficiency are required. An advantage of RF technology is that it has the potential to provide continuous operational coverage in even the most demanding environmental conditions. Although attenuation through the atmosphere generally increases with frequency, there are transmission windows – some quite broad – where RF transmitters can effectively operate. The challenge, of course, is to generate sufficient RF power to overcome attenuation effects while maintaining good efficiency and a compact form factor. Vacuum electronic (VE) amplifiers, which convert the kinetic energy of an electron beam into electromagnetic energy through the interaction with an electromagnetic structure, provide the highest single-device power up to the lower THz frequency regime. Until recently, the technological options for generating high RF power in the millimeter-wave spectrum have been limited to vacuum electronic devices based on fast-wave interactions (e.g., gyrotrons). These devices are capable of producing very high average powers into the low THz frequency range but are relatively bulky and require superconducting magnets.

The last decade has seen a leap in performance in a variety of slow-wave millimeter-wave devices driven by pencil electron beams such as helix TWTs [1], coupled-cavity TWTs (CCTWTs) [2] and extended interaction klystrons (EIK) [3]. While significant improvements in the performance of conventional pencil-beam vacuum electronics amplifiers have been made in this regime over the past decade or so, further improvements are restricted by fundamental physical limitations. For example, the diameter of a slow-wave device scales with the operating wavelength, λ (e.g., beam diameter ≤ λ/10), which limits the current that can be transported in available magnetic focusing channels and the RF field intensity that can be supported by interaction structures. To overcome these limitations, new approaches are required. Much of the work at the U.S. Naval Research Laboratory (NRL) has been focused on spatially-distributed electron beams, particularly sheet beams and multiple beams, which permit the current that can be transported through available magnetic focusing channels and the RF field intensity that can be supported by interaction structures. To overcome these limitations, new approaches are required. Much of the work at the U.S. Naval Research Laboratory (NRL) has been focused on spatially-distributed electron beams, particularly sheet beams and multiple beams, which permit significantly higher current to be transported through a circuit at a given voltage than is possible with pencil beams (assuming the current density can be maintained). Thus, distributed beam amplifiers offer the prospect of considerably higher power and specific power than can be achieved with pencil beam devices of comparable voltage.

This topological approach is shown in Fig. 1, where a quasi-sheet beam, consisting of many closely spaced pencil beams with a common interaction structure (a) is generalized to a sheet beam (b) and then to multiple sheet beams, either stacked as shown in (c) or in a co-planar array of the required number of units/modules, to achieve the desired total power. The concept of multiple stacked or co-planar sheet beams is motivated by the limitations on the total current that can be achieved at reasonable, sustainable current densities in the presence of beam instabilities and mode competition, both of which limit sheet beam width.

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II. SHEET BEAM AMPLIFIERS

Typically, an increase in device output power requires an increase in the electron beam power which entails increasing either the beam voltage or the beam current, or both. To achieve reasonably compact system sizes and weight, the beam voltage should be kept below ~20 kV. Above 20 kV, critical dimensions within the amplifier itself and in the associated power supply become large to avoid electric field breakdown. For a fixed voltage, the amplifier power is limited by the maximum beam current that can be transported through the interaction circuit without interception, electric field breakdown in the cathode-anode region, and thermal management considerations. The most productive approach to increasing beam power is to “unwrap” a cylindrical annular beam into a “sheet”, where the sheet thickness is approximately the same as the thickness of the annulus. Then, by increasing the sheet width, the total current can be increased without increasing current density, and beam power is increased without increasing beam voltage. A sheet beam with a transverse width-to-height aspect ratio of 10 can transport about 10 times the current as a round beam of the same voltage and current density.

We derived frequency-dependent scaling expressions for RF power generation and electronic interaction efficiencies based on the beam-wave interaction physics for two cases: standing waves and traveling waves. For the purposes of this analysis, comparison baselines were obtained from state-of-the-art pencil-beam EIKs [3] CCTWTs [4] at W-band and serpentine slow wave structure TWT at G-band [5]. The scaling for the peak RF power in watts for a traveling-wave device is as follows:

\[ P_{tw} = N \times 70 \left( \frac{1}{f} \right)^{8/3} (V_b)^{13/6} (J)^{4/3} \]  

where \( f \) is in GHz, \( V_b \) in kV, and \( J \) in A/cm², \( N \) is the sheet beam width-to-height aspect ratio or number of beams. The scaling for the peak RF power in watts for a standing wave device is as follows:

\[ P_{sw} = N \times 150 \left( \frac{1}{f} \right)^{13/4} (V_b)^{3/2} (J)^{3/2} \]  

The current density, \( J \), is measured inside of the beam tunnel of the slow-wave structure. High current density in the beam tunnel may be achieved through a combination of beam compression (convergence in the electron gun) and generation of high current density at the cathode surface. However, maximum current densities are limited by the inability of conventional permanent magnet (PM) fields to contain the high space-charge-bearing current (~1000 A/cm²). Magnetic fields required to contain the beam become larger as the current density increases, eventually approaching the limits for permanent magnet confinement (about 10 kG). Increasing the beam voltage to obtain higher beam power adds weight and volume to the device and introduces complications arising from breakdown issues. For stable sheet beam transport in a PM field, the focusing field must balance the natural expansion of the beam due to space charge and emittance (temperature). These conditions are expressed by the envelope equation, which can be written as [6]

\[ B^2 \left( \frac{e}{\beta m_0 c} \right)^2 Y_b = \frac{e I/X_b}{4 \epsilon_b m_0 (\beta \gamma c)^3} + \epsilon_y^2 = \frac{2}{\gamma^2 \beta^2 m c^2} \]  

where \( B \) is the solenoidal magnetic field; \( I \) is the beam current; \( 2Y_b \) is the beam height; \( 2X_b \) is the beam width; \( \epsilon_b \) is the permittivity of free space; \( c \) is the speed of light in vacuum; \( e \) and \( m_0 \) are the electron charge and mass, respectively; \( \beta \) is the beam velocity normalized to the speed of light; and \( \gamma \) is the relativistic mass factor. The beam emittance, \( \epsilon_y \), is related to cathode temperature and cathode height \( Y_{cath} \) as

\[ \epsilon_y = \frac{Y_{cath}}{2} \left( \frac{kT}{\gamma^2 \beta^2 m c^2} \right)^{1/2} \]  

where \( k \) is Boltzmann’s constant and \( T \) is the cathode temperature in Kelvin. For a single plane gun convergence, the magnetic field required for transport, \( B \), can be expressed as

\[ B[kG] = \left[ 0.034 \left( \frac{J[A/cm^2]}{(V_b[kV])^2} \right) + 2.0 \times 10^{-9} \left( \frac{T[K]}{(V_b[kV])^2} \right) \left( \frac{J}{J_{cath}} \right)^2 \right]^{1/2} \]
where \( J_{\text{cath}} \) is the current density at the cathode and \( Y_b \) is the beam height. For a sheet beam, only one-dimensional compression up to about 20 is practical, so to achieve the maximum current density supportable by a state-of-the-art PM magnetic field requires a high current density, \( \sim 50-100 \text{ A/cm}^2 \), at the cathode.

At present, thermionic cathodes are the primary electron sources used in vacuum electronic devices. The sustainable current density and the cathode longevity are interrelated. Although several cold cathode candidates offer specific advantages that may be realizable in the future, the thermionic cathodes are currently under development, such as reservoir cathodes [7] and scandia-doped dispenser cathodes [8] should be capable of producing between 50 A/cm\(^2\) and 100 A/cm\(^2\) with reasonable operational lifetimes. Existing thermionic cathodes routinely operate at 1-10 A/cm\(^2\). Assuming a cathode current density of 10 A/cm\(^2\) cathode, a 9 kG focusing magnetic field, and an operating frequency of 94 GHz, Eqns. (2) and (5) can be used to predict the peak RF power achievable by a sheet beam EIK. Curves of constant peak power as a function of beam voltage and aspect ratio are plotted in Fig. 2. The figure illustrates the effect of spreading the beam current into a sheet by increasing the aspect ratio. For example, for \( N=10 \) and a beam voltage of \( \sim 20 \text{ kV} \), a peak RF power of about 10 kW at 94 GHz should be possible.

The circuit consists of identical five-gap input, output, and buncher cavities together with a 5 mm \( \times \) 0.4 mm beam tunnel. The EIK operates in the \( 2\pi \text{TM}_{01} \)-like mode with the gaps spaced for synchronism with a 19.5 \text{ kV} beam. The individual gaps in each cavity are strongly coupled through coupling cavities on both sides of the beam tunnel, and power is injected into and extracted from the device via WR-10 waveguides and rectangular apertures. Each cavity also incorporates a mechanical diaphragm tuner to allow small adjustments of the resonant frequency. The circuit also incorporates \( \lambda/4 \) chokes to suppress coupling between the cavities due to misalignment or fabrication errors.

The interaction cavities and beam tunnel were formed in a single block of copper via electric discharge machining (EDM). Coupling iris plates and tuner assemblies were separately fabricated for the coupling cavities on opposite sides of the structure. Following fabrication and inspection, the circuit was welded to the gun, collector, and magnet pole pieces and inserted into the permanent magnet structure. Figure 3 shows photographs of the sealed-in gun/circuit/collector assembly inserted in the magnet and a detail of the final brazed circuit assembly (inset).

### III. W-BAND SHEET BEAM EIK

At NRL, a sheet-beam extended interaction klystron (EIK) at \( \sim 94 \text{ GHz} \) has been designed, fabricated, and tested. The EIK employs a Nd-Fe-B permanent magnet that produces a solenoidal field of 8.5 kG, allowing operation at a relatively low voltage of 19-21 kV. This magnet transports the 4 mm \( \times \) 0.32 mm, 3.5 - 4-A beam from the cathode to a depressed collector with \( \geq 99\% \) efficiency [6].

**Figure 2:** Predicted RF peak power at 94 GHz as a function of beam voltage and beam aspect ratio, \( N \), plane for standing wave devices, such as an EIK.

**Figure 3:** NRL W-band sheet-beam EIK assembled in the Nd-Fe-B permanent magnet; (inset) detail of the final brazed circuit assembly.
ICEPIC (icepic@kirtland.af.mil), a 3D particle-in-cell (PIC) code, was the primary computational tool used to design and optimize the amplifier circuit. As computed by ICEPIC, the output saturates at just under 10 kW.

Pulse testing of the amplifier has been performed using both a 1-W solid state driver and a 1-kW Extended Interaction Oscillator (EIO) driver. Measured beam transmission from cathode to collector exceeds 99% with no RF drive and decreases to 97% at saturation. Gain, linearity, and saturated power vary with small changes in drive frequency and buncher resonance, making detailed comparisons with simulations difficult, but the general behavior and maximum values observed are in excellent agreement with predictions. Figure 4 plots the measured pulsed output power and gain as function of input drive power at a frequency of 94 GHz, where the cavities were tuned to maximize linearity. When optimized for power, the SB-EIK generated a maximum power of 7.7 kW [9]. With the cathode at -21.3 kV and the collector at -11 kV, this corresponds to an electronic efficiency of 18%.

IV. KA-BAND SHEET BEAM COUPLED CAVITY TWT

To study high-power broadband device designs, the same sheet-beam gun design was slightly modified and used as the driver for a sheet-beam coupled-cavity traveling-wave tube (SB-CCTWT) with an operating frequency centered at ~35 GHz. The double staggered ladder coupled-cavity slow-wave interaction structure, with its all-metal construction, was chosen as a good balance between high power compatibility and bandwidth [10]. Based on 3D PIC finite-difference electromagnetic simulations using MAGIC 3D [11] and Neptune [12], the predicted peak RF output power is ~10 kW with a small-signal gain of 19-21 dB and a 1-dB bandwidth of >3 GHz (~5 GHz 3-dB bandwidth).

A unit cell of the structure consists of two rectangular half cavities separated by a septum with a beam tunnel and three coupling slots as shown in Fig. 5 (inset); the cavity is constructed without ferrules. The entire device consists of 22 cavities, including the input/output cavities. The input and output power is coupled through WR-28 rectangular waveguide. A photograph of the brazed circuit and input/output waveguides is shown in Fig. 5.

A broadband helix TWT [13] that can produce >200 W over the frequencies of interest has been used as the driver for the SB-CCTWT. Figure 6 compares the measured output power as a function of frequency to the predictions of Neptune PIC simulations (at a constant drive power of 150 W). The agreement is excellent, with slight differences at particular frequencies attributable to reflections at the output coupler and window. The amplifier gain at the 8.5-kW peak of the curve is about 17.5 dB. The output is not saturated at this level, as drive curve measurements show the output power to be still increasing with drive power at all frequencies in the band. Because of intrinsic losses in the input circuit, a higher power driver will be required to saturate the SB-CCTWT. A pencil-beam CCTWT having a maximum power of 800 W has completed testing and is being prepared for a series of experiments to explore saturation.

Simulations predict peak output power of ~10 kW, representing an electronic efficiency of ~14% without collector depression, and over 33% with the collector depressed to -11 kV (which remains to be demonstrated). The amplifier has a compact footprint (22 cm × 17 cm × 29 cm), resulting in a peak predicted volumetric power density of over 900 kW/m³. The measured SB-CCTWT output power represents more than a 10-fold increase in single-device output power relative to state-of-the-art pencil beam coupled-cavity TWTs with a comparable voltage.
Figure 6: Measured output power vs. frequency (points) compared to Neptune 3D PIC simulation. ($P_{in} = 150$ W).

V. SUMMARY

Spatially-distributed electron beam technology is a means to increase beam power while maintaining relatively low cathode voltages that are consistent with compact system volume and weights. Topologies such as rectangular cross-section sheet beams are inherently three-dimensional and their development has been facilitated by a new generation of 3D physics-based simulation codes that incorporate sophisticated models for the generation, focusing, transport, circuit interaction, and collection of electron beams. To demonstrate the utility of the sheet electron beam approach, we have developed two millimeter-wave prototype amplifiers: a W-band sheet-beam extended interaction klystron and a Ka-band sheet-beam coupled-cavity TWT. The W-band SB-EIK successfully generated 7.7 kW at a frequency of ~94 GHz in a compact, permanent-magnet-focused package. The Ka-band SB-CCTWT was designed for broadband operation and has generated 8.5 kW of peak output power with a 1-dB bandwidth in excess of 3 GHz centered around 35 GHz. At saturation, this amplifier is expected to generate ~10 kW.

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Paul Larsen is now with Ansys.

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