Ka-Band Coupled-Cavity TWT Amplifiers for Military Radar and Commercial Satellite Communication

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***Abstract* — Ka-Band Coupled-Cavity Traveling Wave Tube amplifiers have been developed for military radar applications requiring high power, moderate bandwidth and light weight. The design features and measured performance characteristics of these devices are presented. The technology advancements achieved in the radar programs are being leveraged to design Ka-band satellite communication amplifiers that surpass power limitations of existing solid state or helix TWT systems. The design features and expected performance of the communication amplifiers will be presented. Recent development of a 3-D nonlinear time-domain simulation code, GATOR, is aiding the communication device design effort. The application of the codes to high efficiency amplifier design will be illustrated.**

I. INTRODUCTION

CPI was contracted by the Army Research Laboratory in the mid 1990's to design high efficiency Ka-band coupled-cavity amplifiers for military radar systems. The initial success of the funded prototype TWT's led to the selection of CPI as the domestic TWT source for the seeker radar of the Patriot Advanced Capability (PAC-3) missile system and other Synthetic Aperture Radar (SAR) systems. The VTA-5703 SAR TWT is discussed here to illustrate the capabilities of CPI's Ka-band coupled-cavity technology.

Since the introduction of the radar TWT's, the interest shown by manufacturers of satellite communication amplifier systems in Ka-band coupled-cavity TWT's has quickly grown. CPI is responding to the demand by designing a 500 watt version of the radar tube which is operated up to 250 watts backed off from saturation. The typical amplifier system specification for the TWT includes high saturated power efficiency, >30%, and a conduction cooled package. Since the TWT's are operated in the linear drive region, backed-off from saturation, the overall efficiency and cooling is heavily dependant on multi-stage depressed collector design. Accurate simulation of the electron beam interaction with the travelling circuit wave and the prediction of the energy distribution and electron trajectories in the spent beam are critical computations for the electrode design of the depressed collector. During the past two years, CPI and other VED manufacturers have cooperated with the Naval Research Laboratory and SAIC [1] to develop a 3-D electron beam interaction code to parametric model coupled-cavity travelling wave circuits. This code, GATOR, has been validated against measured performance of the VTA-5703 radar TWT and the validation results are presented in this paper.

II. PULSED RADAR TWT SUMMARY

The VTA-5703 coupled-cavity TWT, shown in Fig. 1 in an SAR application, is a small, lightweight, high efficiency, conduction cooled TWT which produces approximately 1 kilowatt peak output power over 1 GHz bandwidth at 15% duty. The slow wave structure is a staggered double coupling slot cavity that supports a backward wave in the fundamental branch of its omega-beta characteristic. Consequently, the TWT is operated in the first space harmonic branch where the forward wave propagates in a passband where the phase shift between cavities varies from π to 2π over a cold bandwidth of approximately 13 GHz. The phase shift and cavity period define a circuit wave velocity that determines the beam voltage, 19 kV, required for synchronized interaction with the electron beam. The much wider cold bandwidth of the double staggered circuit moves the high interaction impedance ends of the passband, at π and 2π, away from synchronism with the beam, thereby avoiding amplifier oscillations. The reentrant cavities reduce the size of the circuits and enhance efficiency. The reduced cavity size allows a compact PPM focusing circuit and ultimately minimizes the overall size and weight. The TWT is packaged in a two-piece aluminum baseplate that is

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designed to withstand the stresses of shock and vibration. The final weight of the TWT is less than 5 pounds.

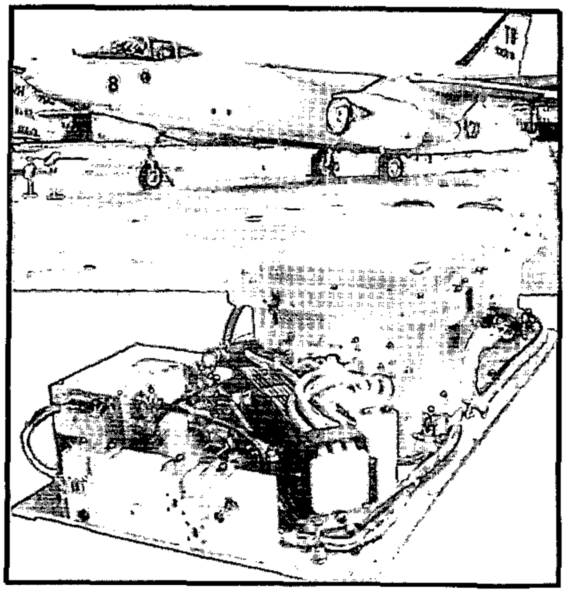

Fig. 1: VTA-5703 TWT in Airborne SAR Application.

Figure 2 illustrates the basic components of the TWT. The assembly of the TWT is based upon a sturdy integral polepiece PPM body into which the rf circuits are inserted. The rf circuits, gun, and collector are rf brazed onto the PPM body to complete the vacuum envelope. The resulting TWT is mechanically strong and the rf brazes may be reversed to remove and replace the gun or collector should repair be necessary. Conduction cooling blocks capture the body of the TWT between the upper and lower halves of the NC machined aluminum baseplate.

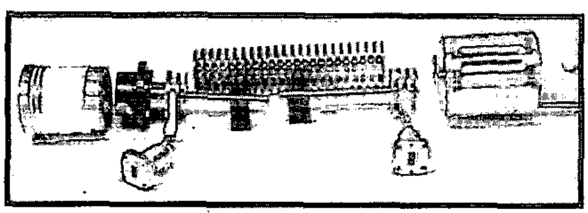

Fig. 2: Basic TWT Components.

The electron gun uses CPI's UniGrid technology for attaching the shadow grid to the cathode surface. An extensive thermal-mechanical modeling and experimental effort has been made to design thermally compensated cathode and grid supports. The single stage depressed collector yields overall efficiency greater than 20%.

The peak output power and body current are shown in Fig. 3 across 1 GHz instantaneous bandwidth. The saturated gain is approximately 42 dB.

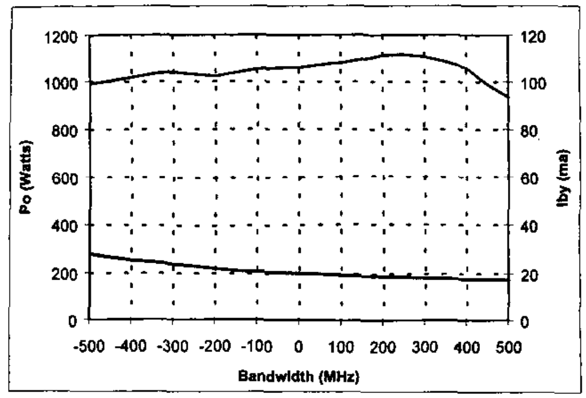

Fig. 3: Output Power and Body Current at 15% Duty.

III. GATOR MODELING

GATOR is a new a hybrid, nonlinear, time-domain simulation code wherein the dispersion of the structure is modeled by an equivalent circuit, but the electron beam is treated using analytic models for the RF and magnetostatic fields and a Poisson solver to simulate the space-charge fields [1]. The electron dynamics are adapted from a previously-described time-domain helix TWT simulation code [2]. The Lorentz force equations are fully 3-D but, at the present time, the fields are 2-D. However, the approach can be readily extended to 3-D. Both the circuit and Lorentz force equations are integrated in time self-consistently. GATOR can treat (1) multiple drive frequencies and the associated intermodulation products, (2) reflections between each of the cavities and at the input and output ports, (3) severs as well as the associated reflections, (4) dynamic velocity taper for efficiency enhancement, and (5) oscillations and backward waves and the associated circuit stability.

Thus far, GATOR has been applied to the modeling of this TWT in pulsed mode. The results of the transfer curve so obtained are shown in Fig. 4 where the dots represent measured power and the line is from GATOR. The agreement is good and the largest discrepancy between GATOR and the data is 0.12 dB at saturation.

An important capability of a 3-D code is the detailed treatment of the transverse evolution of the beam and the simulation of electron energy distribution for efficient depressed collector design. This capability is illustrated in the discussion of the communication version of the coupled-cavity TWT.

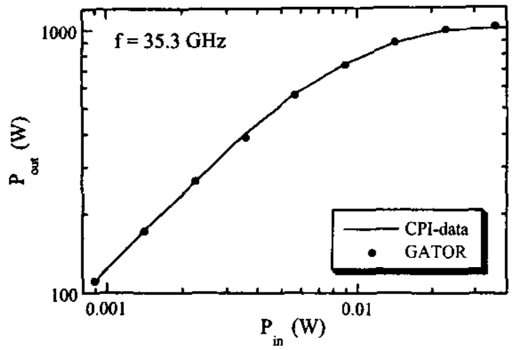

Fig. 4: Comparison Between GATOR and Measured Data.

IV. Proposed Communication TWT Design

The most common configuration for Ka-band satellite communication amplifier systems is an outdoor antenna or hub mounted transmitter enclosure without forced air or liquid cooling. The TWT's for these systems must be light-weight and conduction-cooled, attributes which are shared with existing radar tubes. Overall efficiency is important to meet limitations in prime system power and to minimize heat and baseplate temperature. However, since the amplifiers are operated in the linear drive region, high saturation efficiency is not required.

Table 1:Summary of Communication CCTWT

Parameter	Value	Units
Beam Voltage	16.0	kV
Beam Current	0.390	A
Focusing Method	PPM	
Circuit Sections	2	
Collector Stages	2	
Collector Depression	65% / 80%	
Small Signal Gain	43	dB
Frequency	30.5	GHz
Bandwidth	1	GHz
Saturated Power	500	watts
Operating Power	250	watts
Prime Power	1500	watts
Est. Size (L×W×H)	13.0 × 2.8 × 2.5	inches
Est. Weight	< 7.0	pounds

CPI's design will use a high efficiency two stage depressed collector to achieve overall efficiency requirements when the TWT is backed off from saturation. Furthermore, the small signal gain requirement is approximately 10 dB lower than for radar TWT's. By operating the TWT in a low-beam conversion efficiency, low gain mode, a simpler, thermally robust coupled-cavity circuit design can be implemented. The beam tunnel is opened up to reduce beam interception, an important thermal factor for a conduction cooled TWT. The lower gain of the output circuit eliminates the necessity of applying loss coatings to the circuit plates to stabilize the TWT against oscillations. Loss coatings increase manufacturing cost and are sources of cavity frequency non-uniformity that affect gain variation. Table I summarizes the current design parameters.

The design has progressed using CPI's 1-D small and large signal code which has baseline validation with measured operating performance of the radar TWT's. Figures 5 and 6 show the 1-D calculations of output power as functions of drive power and frequency.

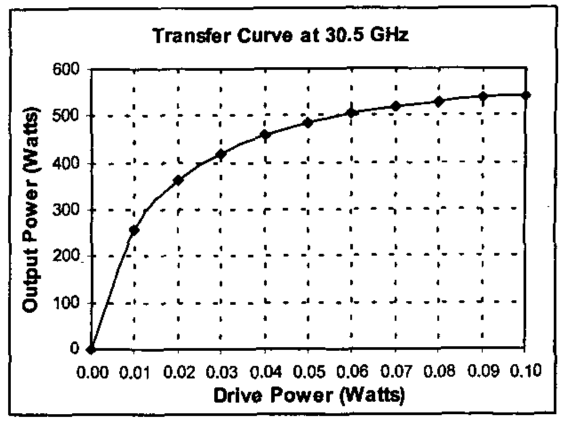

Fig. 5: Calculated Saturated Transfer Curve using the 1-D code

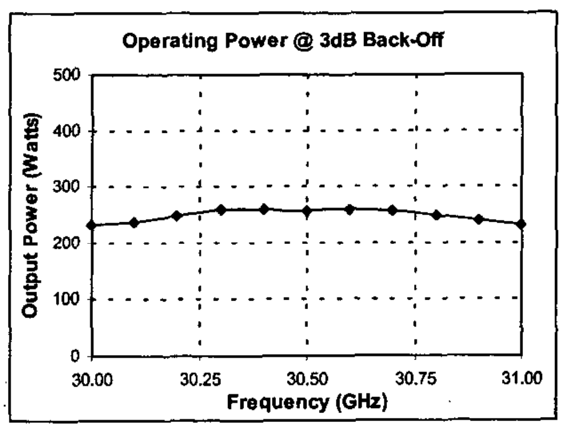

Fig. 6: Calculated Operating Power using the 1-D code

The GATOR simulations of the electron beam are presented in Figure 7 and show that the beam is laminar during the early stages of the interaction and expands as the interaction nears saturation. Note that the bunching of the beam near saturation is clearly shown.

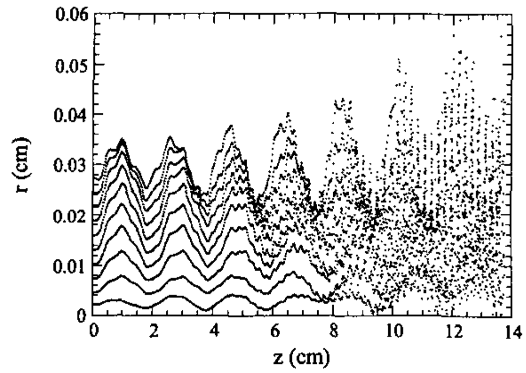

Fig. 7: Radial Evolution of the Beam.

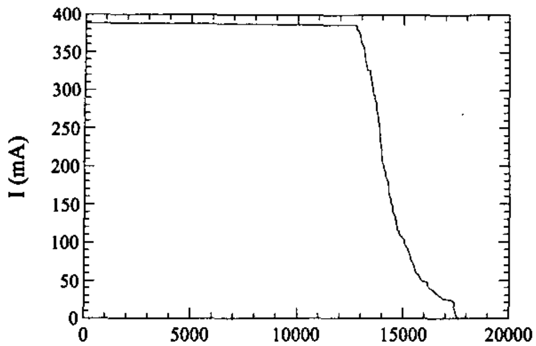

Fig. 8: Spent Beam Distribution.

The spent beam distribution is used to design a depressed collector for enhancing efficiency, and is defined as

$$I_{coll}(E) = \sum_{E_k = E}^{\infty} I_k ,$$

where I_k and E_k are the current and voltage of the k^{th} electron. This can be used to select bias voltages for a multi-stage depressed collector. If we consider an N-stage depressed collector with bias voltages V_1, ..., V_N, such that $V_{cathode} < V_N < .... < V_1 < 0$. The k^{th} electron will be collected by the j^{th} electrode when $-eV_j < E_k < -eV_{j+1}$.The powers recovered and dissipated is given by $P_{rec,j} = -I_k V_j$, $P_{dis,j} = I_k(V_j + E_k/e)$. We define the collector and devices efficiencies as $\eta_{coll} = e \sum_k P_{rec,k}$, and $\eta_{dev} = P_{rf}/(P_{beam} - \sum_k P_{rec,k})$, where P_{beam} in the injected electron beam power, and P_{rf} is the output RF power. It should also be noted that any electrons with energies such that $-eV_1 < E_k$ will be reflected back into the circuit. We plot the current of the spent beam integrated from zero voltage to the bias voltage in Fig. 8. This is the voltage that must be applied to an electrode to recover the energy in this portion of the electron beam.

The energy distribution is being used to design a high efficiency two stage depressed collector for the communication TWT. The collector design is being optimized for operating the TWT backed off from saturation where the linearity of the amplifier reduces intermodulation products.

A powerful feature of GATOR, being a time domain large signal code, is the ability to inject multiple signals and calculate the level of intermodulation (IM) products. A typical specification is that the 3[rd] IM product, C3IM, produced by two signals separated by 20 MHz, and injected at a total power level backed off 8 dB from saturation, be less than –25 dBc. GATOR predicts that the 3[rd] and 5[th] IM products for the communication TWT are less than -29 dBc.

V. CONCLUSION

Ka-band coupled-cavity TWT technology has demonstrated output power, bandwidth and weight advantages for high-resolution military radar applications. The extension of the technology into the satellite communication market is increasingly in demand and is expected to benefit from existing radar TWT designs. A prototype design for a 250 watt CW communication TWT is presented. A new 3-D electron beam interaction code, GATOR, has been developed to model large signal behavior of coupled-cavity circuits and to optimize the design of a highly efficient multi-stage depressed collector for the TWT. Preliminary results using GATOR are in excellent agreement with measured performance data.

ACKNOWLEDGEMENT

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