An Overmoded W-band Coupled-Cavity TWT

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An Overmoded W-Band Coupled-Cavity TWT

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Abstract—A 94 GHz overmoded TWT has been designed, fabricated, and successfully tested. The TWT operates in the rectangular TM_{31} mode of the cavity, while lower order modes are suppressed using selectively placed strips of a lossy dielectric. The 87-cavity TWT circuit was directly machined from Glidcop, a dispersion-hardened copper. The TWT was tested in a 0.25 T solenoidal magnetic field in 3 microsecond pulses. Operating at a voltage of 30.6 kV with 250 mA of collector current, the TWT was zero-drive stable and achieved 21 ± 2 dB linear device gain with 27 W peak output power. Taking into account 3 dB of loss in both the input and output coupling circuits at the windows, the gain of the TWT circuit itself is estimated to be 27 ± 2 dB linear circuit gain with 55 W of saturated circuit output power. Using the 3D PIC code CST Particle Studio, the linear circuit gain was estimated to be 28 dB and the saturated output power 100 W, in good agreement with the experimental results. The measured bandwidth of 30 MHz was significantly smaller than the predicted value of 250 MHz. The overmoded TWT is a promising approach to high power TWT operation at W-Band and to the extension of the TWT to terahertz frequencies.

Index Terms—TWT, overmoded, W-Band, vacuum electronics

I. INTRODUCTION

Coupled-cavity Traveling Wave Tube (TWT) amplifiers are reliable and compact vacuum devices at high frequencies with a variety of applications. At conventional microwave frequencies, TWTs have great operation parameters, with wide bandwidth, high average power, high efficiency and large gain. However, bandwidth, power, and efficiency of TWTs wane above 30 GHz. There is a need for TWTs in the W-band (75–110 GHz), and many research initiatives aim to expand the operation of TWTs to higher frequencies.

There have been some successful TWTs built in the W-band. Most notably, a coupled cavity TWT developed at Varian, Inc. achieved 8 kW of peak power at 10% duty factor near 95 GHz [1], [2]. However, advances in W-band TWT design have been limited since that achievement. More recently, a complex integral-pole-piece-ferruleless-coupled-cavity folded-waveguide circuit built by L-3 Communications, Inc. achieved 100 W average power, 250 W peak power, 30 dB of gain, and 1% bandwidth [3]. In addition, a larger bandwidth from a similar design at L-3 achieved 4 GHz of bandwidth and 75 W average output power for pulsed operation (150 W peak power) at 94 GHz [4].

There are many new ideas for high power W-band TWT designs. These investigated structures include a micro-fabricated helical structure with two electron beamlets [5], a suspended ladder structure [6], a wood-pile electromagnetic-bandgap waveguide [7], ridge-loaded folded waveguide [8] [9], or selectively metalized micro-fabricated folded waveguide [10]. These designs are promising, but have not yet been experimentally validated. Experimentally, a cylindrical dielectric Omniguide photonic bandgap TWT has demonstrated up to 4.5 dB of gain over a 10 GHz bandwidth in W-band[11]. In addition, a wideband W-band TWT with a serpentine waveguide has been designed and is under development [12].

An alternative approach to achieving high power TWT operation at high frequency is the use of sheet beam or multiple beam devices. A high power TWT in Ka-Band has been recently demonstrated using a sheet beam [13]. The sheet beam approach has also been successfully extended to W-Band in the form of a sheet-beam EIK klystron [14]. The sheet beam is a very promising approach but it differs from the present approach in that it is overmoded in only one dimension.

There are many efforts at higher frequencies using advanced fabrication techniques. Microfabricated TWT designs accept the limitations of the small wavelength devices and use advanced manufacturing techniques to achieve precision structures. A 220 GHz TWT amplifier with five electron beams has successfully demonstrated 28 dB of gain, 56 W of output power and a 5 GHz bandwidth at 214 GHz [15]. A 220 GHz sheet-beam folded-waveguide TWT made with nano-CNC fabrication techniques is in development which was simulated to have 35 dB of gain and up to 300 W peak power [16] [17]. Using UV-LIGA fabrication, a 60 W, 220 GHz folded waveguide TWT was successfully built at the Naval Research Lab [18]. The TWT has a beam tunnel of about 100 microns and a 50 GHz bandwidth. Though very successful, the small size of the beam tunnel in such devices is a difficult experimental constraint to overcome and requires a large magnetic field for electron beam confinement.

In this paper, we present the design and test of a novel, promising design for a TWT, namely an overmoded, or oversized design. Typically, coupled cavity TWTs are designed to operate in the fundamental mode, but the power handling capabilities of these devices drops rapidly with frequency primarily due to the decreased size of the device which is needed for small wavelengths. The small cavities at high frequencies lead to manufacturing difficulties and current limitations due to the size of the beam tunnel. By expanding TWT operation to a higher order mode of the cavity, thereby utilizing larger cavity sizes, the difficulties associated with higher frequencies can be minimized.

The overmoded, or oversized, cavity allows for a large beam tunnel in the TWT which provides the space for a high interaction current while operating with a relatively small magnetic field (2.5 kG). In addition, the oversized cavity can be direct machined with CNC milling instead of relying...
Fig. 1. A diagram of the overmoded TWT with dimensions labeled. A 19-cavity structure is shown, which was used in cold test. The final TWT had 87 cavities. Vacuum components are shown in purple, dielectric is shown in pink.

Fig. 2. The electric field magnitude for the (a) TM$_{11}$ (b) TM$_{21}$ and (c) TM$_{31}$ modes in the TWT cavity as calculated by HFSS.

Fig. 3. The transmission through one cavity vs. frequency. Each pass-band corresponds to a different mode in the cavity: TM$_{11}$, TM$_{21}$, TM$_{31}$, and TM$_{41}$ centered at 65, 75, 94, and 112 GHz, respectively.

II. Design

A. TM$_{31}$ Mode Cavity

The TWT was designed to operate in a higher order mode of a rectangular cavity. In doing so, the cavity is larger than an equivalent fundamental mode cavity for the same frequency. This leads to several advantages, such as easier machining, higher beam current, lower magnetic field, and lower heat loading. The specifics of the cavity are shown in Fig. 1. A two-cavity diagram of the TWT highlights the staggered slot design, where the vacuum components are shown in purple. Dielectric components are shown in pink, which load the cavities at certain locations.

For this design, the cavity was chosen to operate in the TM$_{31}$ mode. This mode allowed for a larger cavity structure and sufficiently high coupling coefficient for operation. Without dielectric loading, the lower order modes would be susceptible to oscillation in the TWT. A high loss dielectric (aluminum nitride – silicon carbide composite, STL-100, Sienna Technologies, Inc.) was selectively placed above and below each cavity to increase the losses in these modes, as is demonstrated in Fig. 2. Fig. 2(a) and (b) show that the electric fields of the TM$_{11}$ and TM$_{21}$ modes are peaked in the locations of the dielectric. Conversely, Fig. 2(c) shows that the TM$_{31}$ mode has little field or interaction with the dielectric loads.

This is shown quantitatively in Fig. 3, where the transmission, $S_{21}$ per cavity is shown as a function of frequency with and without the dielectric loading. These simulations were calculated in Ansoft HFSS. The simulations show large losses in the two lower frequency modes (TM$_{11}$ and TM$_{21}$) and the mode at 112 GHz (TM$_{41}$). The dielectric has very little effect on the TM$_{31}$ mode, centered at 94 GHz.

The dimensions of the cavity were selected through iteration in order to meet design goals of the TWT. It was desired to have a TWT with at least 30 dB of gain and above 100 W peak power. In this design, bandwidth was not optimized. Through simulations, the final parameters were determined as shown in Table I. The beam tunnel is 0.8 mm in diameter, one of the largest beam tunnels for a W-band TWT. For comparison, a recent design of a high power, serpentine waveguide TWT has a beam tunnel diameter of only 0.23 mm, which is less than 30% of the size of the present TWT beam tunnel [12]. These parameters for the overmoded TWT led to ideal operation at 93.9 GHz with 3.2 Ω coupling impedance and 0.3 dB/cavity loss. The loss is quite high in the TWT circuit, which allows for the circuit to be implemented without a sewer, since the round trip losses will be less than the gain of the TWT.

The design considered ideal machining conditions (marked “simulated” in the table), while the final machined parameters (marked “machined”) were adjusted to account for fillets due to the radius of CNC tools used.

B. Simulations

The TWT was initially designed using Pierce theory, and the design was later refined using computer simulations. The experiment operated with a 2.5 kG solenoid magnet, which provided an engineering restriction on the electron beam parameters. The specifics of simulation parameters are listed
TABLE I
SIMULATED AND MACHINED DIMENSIONS OF FINAL TWT STRUCTURE

<table>
<thead>
<tr>
<th>Property</th>
<th>Label</th>
<th>Simulated (mm)</th>
<th>Machined (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity Width</td>
<td>cw</td>
<td>5.60</td>
<td>5.79</td>
</tr>
<tr>
<td>Cavity Height</td>
<td>ch</td>
<td>2.54</td>
<td>2.54</td>
</tr>
<tr>
<td>Cavity Length</td>
<td>cl</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Slot Width</td>
<td>sw</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>Slot Height</td>
<td>sh</td>
<td>1.30</td>
<td>1.32</td>
</tr>
<tr>
<td>Beam Tunnel Radius</td>
<td>r</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Dielectric Height</td>
<td>dh</td>
<td>0.30</td>
<td>0.53</td>
</tr>
<tr>
<td>Dielectric Width</td>
<td>dw</td>
<td>0.70</td>
<td>0.58</td>
</tr>
<tr>
<td>Period</td>
<td>p</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Fillet Radius</td>
<td>r_f</td>
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<td></td>
</tr>
</tbody>
</table>

TABLE II
SIMULATED TWT OPERATION PARAMETERS

<table>
<thead>
<tr>
<th>Property</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>V_0</td>
<td>31.1 kV</td>
</tr>
<tr>
<td>Current</td>
<td>I</td>
<td>310 mA</td>
</tr>
<tr>
<td>Beam Radius</td>
<td>r_b</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>B_0</td>
<td>2.5 kG</td>
</tr>
<tr>
<td>Number of Cavities</td>
<td>n</td>
<td>87</td>
</tr>
<tr>
<td>Synchronous Operation Frequency</td>
<td>f</td>
<td>94 GHz</td>
</tr>
<tr>
<td>Coupling Impedance at 94 GHz</td>
<td>K</td>
<td>3.2 Ω</td>
</tr>
<tr>
<td>Loss per cavity</td>
<td>l</td>
<td>0.3 dB</td>
</tr>
</tbody>
</table>

in Table II. The final TWT had 87 cavities, taking advantage of the length of the magnetic field flat top available.

Analytical calculations for the gain in the TWT were performed following Pierce theory. In general, the gain follows the relationship

\[ G = -9.54 + BCN \text{[dB]} \]  

(1)

where \( B \) is a weighting factor dependent on frequency, space-charge, and loss, \( C \) is the Pierce parameter, and \( N \) is the number of wavelengths [19]. For the overmoded TWT parameters and operating conditions, \( B = 30.16, C = 0.0203 \) and \( N = 65.24 \) wavelengths. The analytical formula results in 30.4 dB of linear gain for the TWT at 94 GHz.

Latte simulations were performed by importing the dispersion relation, loss characteristics, and coupling impedance which were calculated via HFSS. LMSuite Latte is a 1-D code developed for studying helical TWTs [20]. In addition, the full 87 cavity structure was simulated in CST Particle Studio along with the expected magnetic field and expected electron beam parameters. These parameters were provided via the design of the 31 kV, 310 mA electron gun using Leidos Michelle software [21] to study the beam optics. Simulation results showing the bandwidth, gain, and saturation of the TWT are shown in Figure 4. Latte and CST results show good agreement for the linear gain and saturated power. For the operation parameters, the TWT is expected to have 32 dB of gain and 300 W peak power at 93.9 GHz. The calculated instantaneous bandwidth is 250 MHz, although optimizing bandwidth was not a design consideration for this experiment.

C. Cold Test

Low power measurements were performed in order to verify machining of the TWT cavities and material selection. The measurements were performed with a 2-port Agilent VNA with WR-08 (90-140 GHz) millimeter waveguide extensions.
Test structures were made with 9- and 19-cavity lengths out of OFHC copper and AL60 LOX glidcop. They were made such that they could be tested with or without dielectric loading in place. For the testing without dielectric loading in place, copper inserts filled the loading slots on the cavities. Details of the cold test and final structures are shown in Fig. 5. A breakout CAD drawing of the assembly is shown in Fig. 5(a). The cavities are machined in either side of a split block. Since the gap between the blocks is at a null in magnetic field, there are minimal losses due to RF leakage [22]. The dielectric loading is placed tangent to the cavities in four locations (two on the top, and two on the bottom of the cavities) and is held in place with copper inserts (shown in blue). WR-10 waveguides couple power into and out of the coupled-cavity circuit. The entire structure is clamped together. There is no need for a braze due to the demountable design of the TWT experiment, which will be discussed in the next section. Fig. 5(b) shows the 9-cavity cold test structure details, and Fig. 5(c) shows the final 87-cavity structure.

Test structures were made out of both OFHC copper and AL60 LOX glidcop in order to determine if there was a more suitable material for machining. Glidcop is an alloy of copper that has been impregnated with a small amount of alumina, leading to a harder material without much loss in conductivity. Low-Oxygen (LOX) glidcop also has a small quantity of boron. Glidcop has successfully been used in many vacuum electronics and accelerator applications. AL60 LOX glidcop has 0.6 wt. % alumina, 250 ppm boron, and a resistivity of 2.21 $\mu\Omega\cdot$cm.

The transmission, $S_{21}$, through 19-cavity cold test structures made from both glidcop and copper is shown in Fig. 6. The transmission through the glidcop structure was an improvement over the copper structure. In addition, the copper saw more reflection. This result is due to the fact that copper is more malleable and is more susceptible to machining errors, leading to difficulties when creating small, consistent, and precise cavities. The hardness of glidcop leads to more precise and consistent cavities. Following the success of the cold test, the final 87-cavity structure were made out of glidcop.

The effectiveness of the dielectric loading was also measured with the smaller cold test structures. The dielectric used was an aluminum nitride – silicon carbide (AlN–SiC) composite from Sienna Technologies. The dielectric was chosen because it has a high loss tangent, good thermal properties, and will perform well in vacuum conditions. Fig. 6 shows the 19-cell structures without (top) and with (bottom) dielectric loading in place. The TM$_{31}$ and TM$_{41}$ modes were observed during measurement centered around 95 GHz and 112 GHz, respectively. It can be seen that the dielectric loading reduced the transmission through the cavities for the TM$_{41}$ mode while having little effect on the transmission of the TM$_{31}$, in good agreement with the HFSS simulations. Fig. 6 also shows that the glidcop structures have lower loss than the copper structures. Consequently, the final 87-cavity structure for the TWT experiment was made with AL60 LOX glidcop.

Prior to installation, the transmission properties of the 87-cavity structure were also measured in cold test. With the dielectric loading in place, the TM$_{41}$ mode was not visible above the noise floor of the VNA (about -60 dB) for either structure. Fig. 7 shows the measured $S_{21}$ for the TM$_{31}$ mode of the structure along with the simulated transmission. The measured and simulated transmission of the TM$_{31}$ mode agree well in magnitude and bandwidth; there is a frequency shift in the measured transmission that is due to small machining errors.

### III. Experiment

#### A. Set-Up

The overmoded TWT was designed and built at MIT. The design is made to be modular for quick experimental turn-around times and has a wide range of operation conditions. The experiment is operated pulsed at 1 Hz with a pulse forming network that provides a 3 microsecond flat-top voltage pulse variable from 10-100 kV. Due to breakdown limitations, the TWT was limited to operation below 35 kV. The full experimental assembly and laboratory set-up are shown in Fig. 8. A 4-coil solenoid magnet, shown in outline in Fig. 9, provides a 2.5 kG field for the electron beam. Iron pole
Fig. 8. The TWT experimental set-up which was used for testing. The pulse forming network, power supplies, and controls are not shown.

Fig. 9. A cross-sectional CAD view of the TWT experiment. The 87-cavity TWT is highlighted in the cutout, showing the alignment surface to the anode and WR-10 coupling waveguide. The cavities are highlighted in blue and the simulated electron beam is shown in pink.

pieces on the front and back of the magnet were designed simultaneously with the electron gun to provide the nominal focusing field. In addition, a gun-coil provides up to 260 G to fine-tune the focusing field. The magnet is 26 cm in length with a 5 cm diameter bore and a 10 cm magnetic field flat-top.

The input power for the TWT was provided by two sources. A low power solid-state Amplifier Multiplier Chain (AMC) from Millitech provided up to 32 mW of power from 90-100 GHz. A high-power Extended Interaction Oscillator (EIO) from CPI, shown in Fig. 8, provided up to 300 W of power from 93.5–95.7 GHz. In combination, these sources provided the power necessary to characterize the linear gain, saturation, and bandwidth of the TWT under test.

Details of the vacuum components, including the electron gun and TWT circuit, are shown in Fig. 9. The 31 kV, 310 mA electron gun was designed in Michelle, a beam optics modeling software, to fit the parameters necessary for the experiment [21]. A 3.2 mm diameter cathode manufactured by Heatwave Labs provides up to 5 A/cm² on the surface, which is focused to a 0.6 mm diameter beam. The TWT circuit is about 7 cm in length, and is precision aligned to the anode surface. WR-10 waveguide couples power into and out of the TWT circuit with very low loss in the waveguide run from the window to the circuit. The windows are fused silica, with a thickness that transmits from 92–97 GHz with less than 0.1 dB losses, as measured with a VNA. To transmit through the window, the WR-10 waveguide is uptapered to WR-28 waveguide before the window and then downtapered back to WR-10 waveguide after transmission through the window. These tapers are used at both the input window and the output window. We measured that 3±0.5 dB of loss occurs at each window due to these tapers. This loss number is needed to analyze the measured gain to differentiate between device gain, measured from the input to the output port of the device, vs. gain on the circuit itself. A simple OFHC copper collector is used, and there are 2 L/s pumps on both the gun and collector sides of the experiment.

The tube is free-standing within the magnetic bore. It is held in place and aligned with 3-axis translation stages on either side of the magnet. The tube must be assembled and installed in the magnet simultaneously. Since the tube cannot be easily accessed after installation, the components underwent a bakeout at 150–200 °C prior to final assembly. This is sufficient processing for the pulsed experiment.

B. Beam Test

Prior to installation of the TWT circuit, a beam test was implemented to verify electron gun operation. For this test, the tube design shown in Fig. 9 was modified. The TWT circuit and waveguides were replaced by a 1.1 cm diameter, 30 cm long beam tunnel.

The beam tunnel was oversized so that it could be electrically isolated from the body without having to rely on the anode’s alignment surface for beam transmission. In addition, the anode reduces to a diameter of 0.8 mm for 0.25 inches prior to the beam tunnel. This test ensures that the beam is coupling through the anode which is the desired radius of the final beam and that the beam can be directed to the collector. The test involves the measurement of three currents in the tube: body, collector, and beam tunnel.

The results from the beam test are shown in Fig. 10. This figure shows the measured collector current vs. operation voltage as well as the total expected current. The total expected
current should follow the Child-Langmuir equation for a space-charge operated electron gun,
\[
I_0 = PV_0^{3/2}
\]
where P is the perveance of the gun. Michelle code simulations indicated the expected perveance to be 0.059 micropervs for ideal operation. At 31 kV, the measured collector current was 306±6 mA, in good agreement with the expected total current of 310 mA. The currents measured on the body and beam tunnel at 31 kV were 20 mA and 23 mA, respectively. Therefore, 88% transmission of the electron beam to the collector was measured. Although there is a relatively high beam interception, the overall total current was more than anticipated and more than 300 mA of current was transported to the collector.

C. TWT Results

After the beam test was completed, the overmoded TWT circuit was installed in the tube and tested at 30.6 kV. After a considerable effort at alignment, the highest current measured at the collector was 250 mA, significantly reduced from the 306 mA observed in the beam test. For these conditions, the TWT device linear gain was measured to be 21±2 dB. The magnetic field was about 2.0 kG for this operation. At these settings, the TWT was zero-drive stable. This result is shown in Fig. 11, which shows the measured output power vs. input power to the TWT device. Here, we define the TWT device gain as the gain measured between input and output ports of the TWT. The input port is the WR-10 waveguide just prior to the uptaper to WR-28 guide on the air side of the input fused silica window. The output port is defined as the WR-10 waveguide located after the downtaper on the air side of the output window. The low power data points used the solid-state AMC as the input driver, while the higher power points used the EIO. The low power points were fit to a linear curve which corresponds to 21±2 dB of gain. At high power, saturation is observed at 27 W of device output power.

To compare to theory, we must take into account coupling losses in the device. Previously, we noted that there was 3 dB of loss at both the input and output coupler. Taking into
account the 6 dB of cumulative coupling losses, there was 27±2 dB of circuit gain measured in the TWT. Fig. 13, shows the data from Fig. 11 where the device gain has been calculated and adjusted by 6 dB to represent circuit gain, and error bars have been added. Adjusting the saturated output power by 3 dB, there was 55 W of peak circuit output power at saturation.

A theoretical analysis was performed for the TWT using 250 mA interaction current (the observed current on the collector during linear gain operation), while keeping all other factors the same as previous analysis. With this current, the linear gain simulated in CST Particle Studio was 28 dB, and the saturated output power was 114 W. These results are shown next to the measured points in Fig. 13 and show the good agreement between simulation and theory.

A bandwidth measurement was done by maintaining constant operation parameters and varying the input frequency with the solid-state AMC drive input. The bandwidth of the TWT is shown in Fig. 14 for the high gain operation point. For the 94.26 GHz high gain point, the voltage was kept at 30.6 kV and the bandwidth was measured to be 30 MHz. This bandwidth is smaller than the predicted bandwidth of 250 MHz. We believe that this may arise from fabrication errors, beam quality, and voltage ripple during the flat top of the pulse.

IV. DISCUSSION AND CONCLUSIONS

An overmoded W-band TWT has been built and tested, showing successful operation in the TM_{311} cavity mode. The TWT is zero-drive stable, and no evidence of oscillations in the lower-order TM_{11} or TM_{21} modes was observed. The overmoded TWT has one of the largest beam tunnels for a W-band TWT and is able to operate with a 2.5 kG solenoid magnet and an electron gun that was designed to produce 310 mA at 31 kV. Simulations in both 1-D Latte and 3-D CST Particle Studio for ideal operation conditions predicted 32 dB of linear gain and 300 W peak output power.

Testing of the electron gun showed transmission of 306±6 mA to the collector, corresponding to 88 % transmission of the beam. During operation of the TWT, under the best alignment conditions, 250 mA was transmitted to the collector. The large beam interception limited the gain and power output of the device. The origin of the large beam interception is not understood at this time. However, in device operation with 3 microsecond pulse lengths at a repetition rate of 1 Hz, no visibly damage to the structure or other deterioration was observed. Adjusting simulations to correspond to operating conditions of 250 mA, CST Particle Studio predicted 28 dB of linear gain and 100 W of peak output power.

The overmoded TWT was measured to have 21±2 dB linear device gain at 94.26 GHz, and a peak output power of 27 W. Adjusting for ±1 dB of input and output coupling losses, there was 27±2 dB of linear gain in the TWT circuit and 55 W of peak output circuit power. This is in good agreement with theory.

This overmoded TWT has shown successful operation in the TM_{311} cavity mode, and the research can be used to expand TWTs to operate at high powers in oversized cavities at higher frequencies.

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