Design of a Multi-kW Ka-Band Elliptical Beam Amplifier with PPM Focusing*

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Abstract: *To achieve higher output power while maintaining the compact size and weight of typical PPM-focused TWTs, we have explored options for incorporating a sheet or elliptical cross section electron beam in a coupled cavity or folded waveguide circuit. This approach allows significantly higher beam current to be propagated at a given voltage and magnetic field amplitude than is possible in a round beam. However, there are fundamental design constraints that limit the aspect ratio of the beam and the corresponding circuit designs that can be utilized. Here, some of these constraints will be discussed and designs presented for elliptical beam Ka-band TWTs that are capable of >2 kW output power with a 20 kV, 1A electron beam.*

Keywords: Elliptical beam; folded waveguide; TWT; millimeter wave; vacuum electronic; amplifier; Neptune.

Introduction

We have previously designed, fabricated, and tested two multi-kW millimeter-wave amplifiers, a broadband coupled cavity (CC) TWT in Ka band [1] and a narrowband extended interaction klystron (EIK) in W band [2]. Both devices are driven by a 20 kV, 3.5-A sheet electron beam in a uniform magnetic field produced by a permanent magnet structure [3]. However, these devices are quite large and heavy, on the order of 0.5 ft^3 (.014 m^3) and 45 kg, because of the permanent magnet structure that produces the 6-8 kG uniform field needed to transport the beam in these devices.

For many applications, a more compact amplifier is required while still maintaining the maximum power and bandwidth possible. Because the permanent magnet solenoid dominates the size and weight of the previous amplifiers, it is highly desirable to replace this magnet with a periodic permanent magnet (PPM) structure. Here, we describe some of the challenges that impact the implementation of PPM focusing and present simulation results for a folded waveguide version of an elliptical beam Ka-band TWT at a power level of ~2 kW.

Beam Generation and Transport

Our previous sheet beam devices employed a novel electron gun designed around a curved cathode (section of a cylinder) that produced focusing in only a single plane. This design was easily scalable in aspect ratio and current simply by changing the width of the cathode and the corresponding straight portion of the racetrack-shaped focus electrode. The drawback to this approach is the thermal beam emittance that results from the large convergence in the thin beam direction (y). To illustrate, the rms magnetic field required to match the space charge and emittance in the narrow dimension of a sheet beam is found from the envelope equation [4]. Assuming no current loss and a uniform beam, with the emittance due solely to cathode temperature, the field in kG is

$$B_{rms}^2 = 0.034\frac{J}{\sqrt{V_k}} + 7.8 \times 10^{-9}\frac{x_b^2}{x_c^2}\frac{J^2}{J_c^2}\frac{T}{y_b^2},$$

where current density J is in A/cm^2, x and y are along the broad and narrow beam directions, respectively, V_k is the beam voltage in kV, and T is the cathode temperature in kelvin. Subscripts b and c refer to the beam and cathode, respectively. Typically in a high-power TWT, the focusing field must be 1.6 – 2 times the matched or Brillouin value to account for beam bunching and energy loss.

For our previous sheet beam (0.35 x 4 mm beam cross section, 10 x 4 mm cathode) and a cathode temperature of 1300 K, we have $B_{rms} = (1.9 + 6.8)^{0.5} = 2.95$ kG. With the same beam parameters and cathode loading but with uniform convergence in x and y, we obtain $B_{rms} = (1.9 + 0.24)^{0.5} = 1.46$ kG. Given the limited PPM field amplitude that can be achieved, a more uniform gun convergence is preferred.

The beam aspect ratio is further limited by the potential excitation of the fundamental TE_{10} mode in the beam tunnel. The TE beam tunnel mode disrupts the beam and can cause oscillation, because it provides another RF path through the circuit. Our previous CC-TWT has a 0.7 x 5 mm beam tunnel and a uniform focusing field of 6 kG. Even though the TE_{10} mode is not cut off in the operating band, beam transmission is excellent in the large uniform field, and simulations show no sign of beam instability. However, if the solenoidal field is replaced with a PPM field (chosen to match the beam in a smooth beam tunnel), the transverse mode is strongly excited and the beam is driven into the circuit wall. These results are illustrated in Fig. 1, with results from NRL's particle-in-cell code, Neptune [5]. Beam transmission is >99.9% for cases (a) and (b) but drops to 26% for case (c), where transverse beam motion is evident.

For this design study we have selected a smaller aspect ratio beam with correspondingly lower beam current. A preliminary gun design for this 20 kV, 1 A, 0.5 x 1.5-mm elliptical beam has been devised using the MICHELLE beam optics code [6] and the Galaxy Simulation Builder optimization tool [7]. The MICHELLE particle distribution from this gun [8] is injected into Neptune for TWT simulations.

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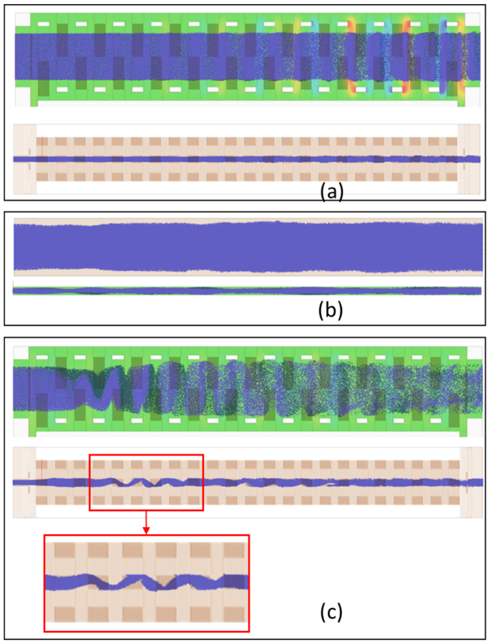

Figure 1. Broad and narrow beam views of 20-kV, 3.5 A, 0.4 x 4 mm beam as modeled by Neptune. (a) CC-TWT with 6 kG solenoidal field. (b) smooth 0.7 x 5 mm beam tunnel with matched PPM field (2.3 kG amplitude, 8 mm period). (c) CC-TWT with same PPM field.

Circuit Design and Predicted Performance

We have performed designs and simulations of both FWG and CC circuits. The achievable power and bandwidth in each will be reported here.

The CC TWT uses the same circuit profile of our previous device [1] but with a smaller 0.8 x 3 mm beam tunnel and more periods to account for the lower gain per period. However, the number of interaction gaps is limited to about the 30 used here by stability considerations. Neptune simulation results are shown in Fig. 2, using an analytic PPM field (2 kG peak, 8 mm period, and additional side focusing for the wide dimension). We have not yet adjusted the cavity parameters to improve stability or increase bandwidth, although some improvement in both areas should be possible.

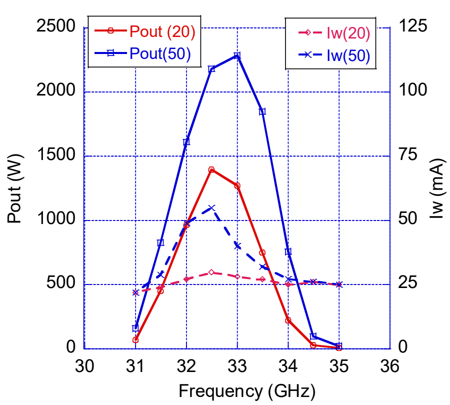

Figure 2. CC-TWT simulated output power and beam interception, with input power of 20 W and 50 W.

The 41-gap FWG circuit has a 0.8 x 2.8 mm beam tunnel. A compatible PPM structure that produces a 2.3 kG peak field with a 7 mm period has also been designed and is used in these simulations, along with the same electron beam as before. Neptune simulation results are shown in Fig. 3.

Both amplifiers are DC stable and very compact for a 2 kW amplifier: ~ 6 x 6 x 30 cm. The FWG version is simpler to fabricate and is slightly smaller in the vertical direction, as oriented in Fig. 3. Because the PPM field amplitude decreases rapidly as the pole gap increases, this circuit dimension must be minimized. Thus, the FWG circuit is our preferred option for fabrication.

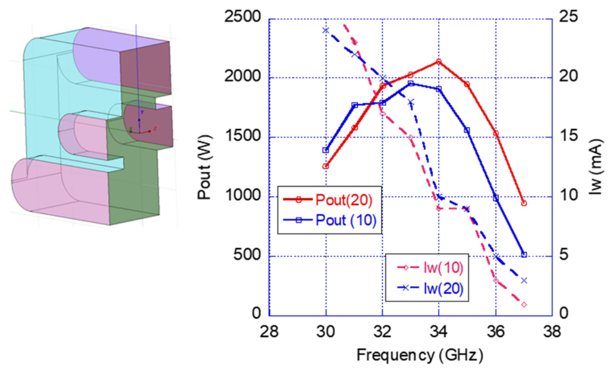

Figure 3. FWG geometry and simulated output power and beam interception, with input power of 10 W and 20 W.

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