PULSE POWER DRIVEN HIGH POWER TRAVELING WAVE TUBE AMPLIFIERS

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Abstract.

Results are presented on the development of a two stage, high efficiency, high power 8.76 GHz severed traveling wave tube amplifier. Peak powers of more than 400 MW have been obtained over the complete electron beam duration, with a conversion efficiency from the electron beam to microwave energy of 45%. The maximum, *single frequency*, average output power was 210 MW corresponding to an amplifier efficiency of 24%. The severed amplifier showed an asymmetric "sideband" like structure in the frequency spectrum of the microwave radiation. Theoretical analysis and simulation are used to examine the device performace. A substantial number of electrons are found to be accelerated in the slow wave structure.

I. INTRODUCTION

Recent experiments have demonstrated the generation large microwave powers at frequencies of up to 35 GHz[1-4]. This article presents similar data obtained with a severed, two stage traveling wave tube amplifier operated at 8.76 GHz. The experiment extends work reported earlier on a single stage amplifier operating at the same frequency[2,5]. In this work we reported narrow band, high gain operation of single stage periodic structure TWT. The amplifier was powered by an 850 kV, 0.8 - 1.6 kA electron beam. A maximum gain of 33 dB, with an output power of 110 MW in the TM_{01} mode was achieved at a beam current of 1.6 kA. Attempts to operate with higher gain lead to oscillation at the input frequency. The severed amplifier was developed to substantially reduce positive feedback to the input and to allow higher gain and output power operation. The maximum gain and total power achieved with the two stage amplifier was 37 dB at an output power of 410 MW, with a beam current of 975 A and diode voltage of 850 keV. The amplified power at the magnetron frequency was 210 MW, corresponding to a 24% conversion efficiency. The remaining power appeared in 'sidebands' separated from the center frequency by about 100 MHz.

In the following sections we review the main characteristics of the two stage TWT. The results are compared with simulation data and with analytic theory. Two comprehensive papers describing the results have been accepted for publication in the Journal of Applied Physics[6,7].

II. EXPERIMENTAL DATA

A. *Experimental Configuration.*

The high power TWT's and the electron beam driver have been described previously[5,6]. An 850 kV, 0.8-1.6kA, 100 nsec., 6mm diameter electron beam is injected into a rippled wall slow wave structure with an average radius of 1.32 cm, a ripple depth of 8 mm, and a periodic length of 7 mm. The rippled wall entrance and exit sections are tapered to minimize impedance mismatch to the uniform guide. An input microwave signal of about 100kW is fed to the amplifier and the amplified signal is extracted to free space through a large conical horn. We measure the gain of the device using substitution techniques. At high gains (~35dB) the single stage amplifier tends to oscillate due to feedback from the mismatch at the amplifier output. To eliminate the oscillation we used a severed amplifier consisting of two identical rippled wall amplifier sections separated from each other by a section of carbon absorber. The electron beam is bunched and the wave amplified in the initial interaction region. The microwave signal is attenuated by about 30 dB in propagation through the graphite section while the beam and the space charge wave on the beam propagate virtually unchanged through the sever. In the second interaction region the electromagnetic wave is reconstructed from the bunched beam and further amplification occurs. Note that feedback cannot occur through the sever which does not support any mode, including the slow or fast space charge waves, propagating against the electron beam.

B. *Single Stage Amplifier.*

The single stage amplifiers have a narrow passband with a 3 dB bandwidth of order 20 MHz. The gain increases monotonically with beam current up to the peak current used of 1.6 kA. Maximum gains of 33 dB at output powers of 110 MW and at an energy conversion efficiency of 11% have been achieved. Pulse durations are equal to the pulse power duration and are independent of the applied magnetic field strength. There is no evidence of saturation of the growing wave.

At power levels of less than about 70 MW we find that the radiation is essentially monochromatic whereas at higher powers there are always sidebands. Under conditions where we obtain a single frequency output we have measured the phase to be stable to be within the $\pm 8^0$ accuracy for the diagnostic.

C. *Severed Amplifier Characteristics.*

We have used severed amplifiers to obtain average radiated powers of over 400 MW at about 45% efficiency. The power levels quoted are averaged over the beam pulse duration; peak power levels exceed 500 MW. Pulse

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duration; peak power levels exceed 500 MW. Pulse shortening has not been observed at these microwave power levels. Unlike the single stage amplifier the two stage device has a bandwidth comparable to that calculated using conventional TWT theory. In Fig. 1 we compare the peak gain of the 22 period single stage structure with that of the severed amplifier as a function of the beam current. The peak gain of 37 dB occurs in

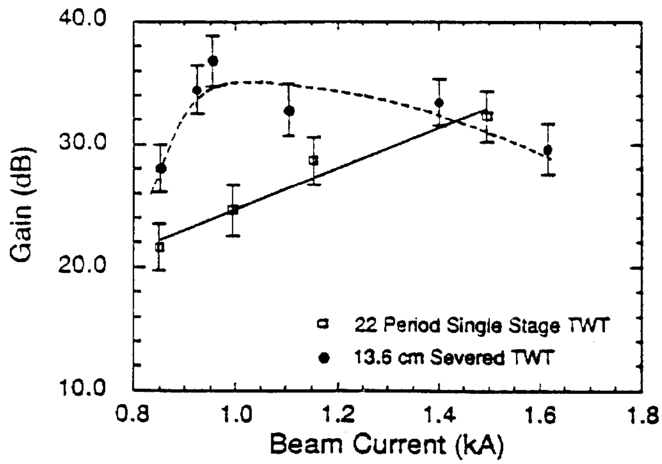

Fig.1 Comparison of gains from single and two stage traveling wave tube amplifiers.

the severed amplifier at a beam current of about 975 A compared to the single stage device in which the gain increased monotonically with beam current. The radiated spectrum shows sidebands which are asymmetrically located with respect to the 'carrier' frequency with the upper sideband displaced from the center frequency by a greater amount than that for the lower sideband. Frequency shifts vary between 30 and 130 MHz and depend on the beam current and the radiated power level. The fraction of the total radiated power going into the sidebands increases with increasing beam current.

D. Simulation Results.

Data has been obtained using the MAGIC code on the performance of single stage amplifiers. The microwave characteristics of ripple wall structures are very sensitive to details in the boundary conditions. As a result of this the interaction with an 850 keV electron beam was found to develop at 8.1 GHz instead of the 8.76 GHz measured experimentally. The injected microwave power was approximately 175 kW. Output powers of about 175 MW are recorded from a thirty period structure corresponding to a tube gain of about 30 dB.

Fig 2 shows the output from the code for the radial electric field at the output section of the amplifier. The field is measured just outside the beam radius. The offset in the radial electric field signal is due to the electric field of the unneutralized electron beam. Initially the modulation produced by the injected wave leads to a 10 % electric field modulation which increases to 100 % at the output of the amplifier. In fig 3 we show the momentum spectrum of the electrons measured

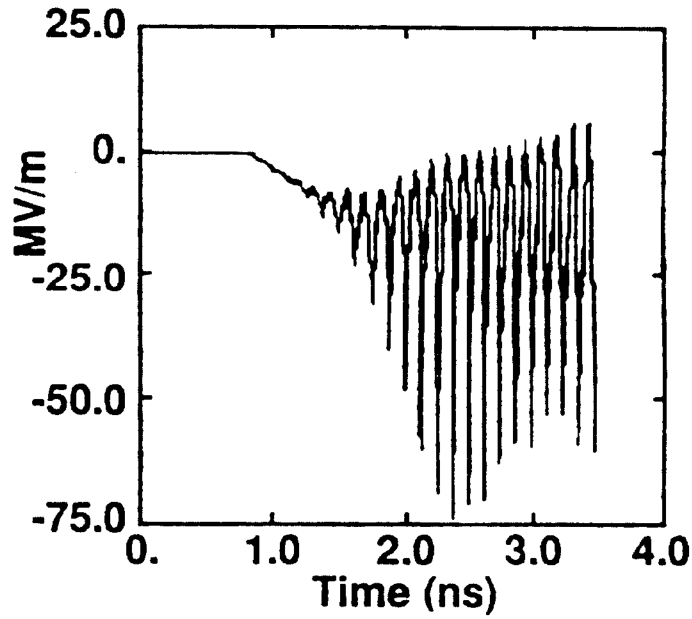

Fig.2. Radial electric field at the output of the amplifier.

as a function of position at the end of a 3.5 nsec simulation run. There is a substantial spread in the electron momentum (measured as γv) corresponding to particles with energies ranging from 125 keV to 1.85 MeV with many of the particles clustered at the extremes in the electron energy. The

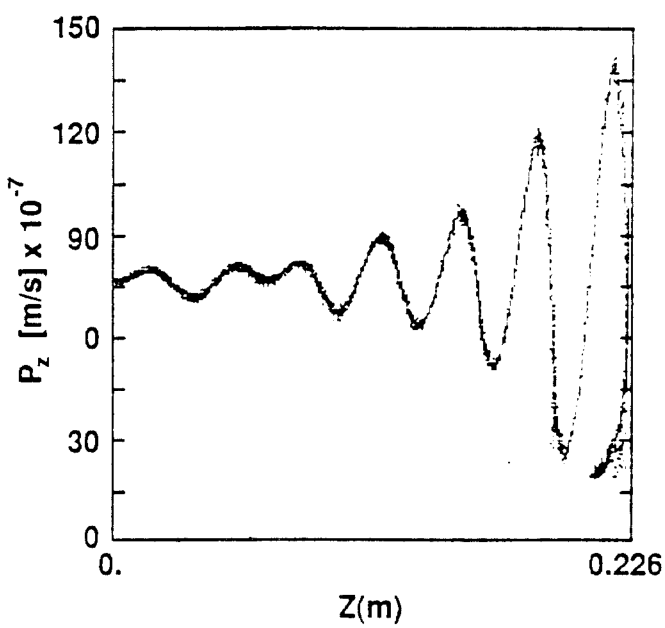

Fig. 3. Momentum spectrum of the electrons as a function of position along the amplifier.

average electron energy, of course, decreases. A second feature is the perturbation in the momentum spectrum found close to the input of the tube. This is due to the reflected power from the output end of the amplifier and results, in longer simulation runs, in the growth of sidebands similar to those recorded experimentally.

III. DISCUSSION OF RESULTS

A. Bandwidth Characteristics.

We attribute the very narrow bandwidth observed in the single stage device to the transmission characteristics of the structure. There is a slight mismatch between the rippled wall amplifier impedance and that of the uniform guide sections. In addition the structure is short so that transmission peaks are widely spread. The number of peaks in the transmission coefficient between $k = 0$ and $k = \pi/l$, where l is the periodic length, is equal to the number of ripple periods in the amplifier. As shown in reference 7 the bandwidth is set by the structure characteristics and is narrowed during the amplificiation process retaining a constant gain-bandwidth product. For the severed amplifier the transmission coefficient is dominated by the sever and the gain-bandwidth curve reverts to that expected based on conventional amplifier analysis.

B. Gain.

An analysis of the particle dynamics in the microwave field and simulation data show that it takes a significant fraction of the amplifier length to accomplish the beam bunching needed before amplification commences. Following beam bunching the gain is found to approximate that calculated using the Pierce formalism, modified to allow for relativistic beam energies. The bunching process typically takes 30 % of the amplifier length to develop. We cannot make a direct comparison between experimental data and theory because the tapers in the amplifier have not been included in the analysis or simulation. The simulation data for the gain as a function of position after bunching is complete, is consistent with the experimentally obtained data .

C. Sidebands.

"Sidebands" have been observed experimentally in both the severed amplifier and, at sufficiently high output microwave powers, in the single stage device. Simulation shows a similar phenomenon in long (20 nsec) runs. The fact that the sidebands are not symmetrically located with respect to the center frequency, and the fact that the gain is still increasing linearly with structure length implies that the sidebands are not due to particle trapping. Particles with energies greater than the injected energy can cause wave growth at lower frequencies than the 8.76 GHz center frequency, whereas the lower energy particles may interact with higher frequency transmission peaks in the TM_{01} passband of the structure. We expect to find greater structure on the high frequency side of the center frequency, since the electron velocity is bounded by the speed of light. The preferred frequencies will match the peaks in the transmission peaks described earlier for the beam loaded structure. The sidebands are especially pronounced in the severed amplifier due to the high gain and to the fact that the electromagnetic wave must be reconstructed from the broad electron momentum spectrum, which is preserved in transit through the sever. The reflection of the amplified signal back to the input of the amplifier causes large amplitude waves to be present at the start of the amplifier or, in the case of the severed tube, to the input of the second amplifier stage. The reflected waves cause the electron momentum spectrum to be strongly modified at the entrance to the amplifier. The spread in electron energy then allows radiation to grow from noise at the preferred wavenumbers for the amplifier. The wavenumbers are set by the finite length of the system and are a direct consequence of the impedance mismatch at both ends of the amplifier. For these reasons we expect the sideband phenomenon to be much more important in high current, high power TWTs than in conventional low power, long amplifiers.

IV. ACKNOWLEDGEMENTS

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