Review of High Power Traveling Wave Tube Amplifiers

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Abstract- In this paper, we review work performed on high power traveling wave tube ampifiers. The tubes operated in the X-band at 8.76 GHz with both a single stage and severed amplifier configuration. The peak total powers achieved were on the order of 400 MW, corresponding to gains of 37 dB.

INTRODUCTION

Recent experiments in high power coherent radiation devices have shown a trend to higher power and frequency.[1-5] This research is driven by the need, for example, for the next generation of rf accelerators. One experimental device which has yielded attractive high powers it the rippled wall Cerenkov traveling wave tube amplifier. This paper reviews results of experiments conducted at Cornell University with a Cerenkov TWT operating in the X-band at 8.76 GHz. This research documented the operation of the tube in a single stage and a severed stage mode of operation, with the peak powers achieved of 410 MW and single frequency powers of 210 MW.

In the following sections, we give a brief description of TWT physics, followed by a description of the experimental configuration. We then give the results of the single stage amplifier experiments and the limitations of this device. We conclude with a discussion of the severed amplifier and an outline of its operation.

EXPERIMENTAL CONFIGURATION

The TWT interaction may be described as follows. To allow electrons and electromagnetic radiation to interact so that the electrons loose energy, the radiation must have a low enough phase velocity that the electrons and the wave crests are in synchronism. To reduce the wave phase velocity below the speed of light c, a cylindrical slow wave structure is formed by introducing a periodic ripple to the wall of a cylindrical waveguide. A beam of high energy electrons is then propagated along the axis of the waveguide so that the electrons can interact with the transverse magnetic (TM) modes. The electrons loose energy to the co-propagating mode, causing the amplitude of the wave to increase.

In our experiments, the electron beam was generated by a water-filled Blumlein transmission line. The electrons were produced from a field-emission diode with a carbon cathode. The diode voltage is 850 keV, and has a 100 nsec pulse duration. The electron beam is a pencil beam, with a 6 mm diameter and current in the range from 800 to 1700 Amperes. The electrons are confined by a solenoidal magnetic field, variable in the range from 0 to 14 kG. The slow wave structure is a rippled wall waveguide with an average radius of 1.32 cm, a ripple depth of 8mm, and a periodic length of 7 mm. The single stage devices have a tapered entrance and exit transition region which extend over 15 cm length. The severed tube has two uniform sections separated by a carbon absorber. The experimental schematic for a single stage amplifier is shown in Figure 1. The microwave power is coupled into the amplifier through side arms. The power is provided by a 250 kW magnetron. This device has been described in detail elsewhere.[6]

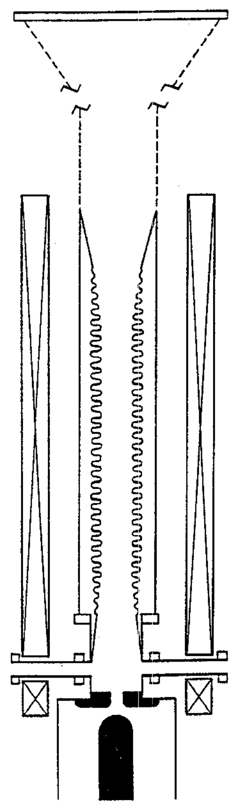

FIG. 1. Schematic showing the TWT. The rf input is through the radial side arms. The coupling is to the TM_{01} mode. The pencil beam is injected through the foilless anode.

The amplified signal is coupled into the far field using a large conical horn. All microwave measurements are performed in the far field using standard gain antennas. Gain is determined using a substitution method in which the amplified power is compared to the power of the magnetron alone. This method was also verified by calorimetry.

SINGLE STAGE AMPLFIER

The initial experiments were performed on a single stage amplifier. Two amplifiers, with 11 and 22 periods were used. Each operated in the TM_{01} mode and had a narrow passband with a 3-dB bandwidth of order 20 MHz. The gain increased monotonically until a beam current of 1.6 kA, at which point the tubes typically began to oscillate due to positive feedback from small mismatches at the entrance and exit of the slow wave structure. Maximum gains were 33 dB, corresponding to output powers of 110 MW and an energy conversion efficiency of 11%. Pulse durations were equal to the pulse power duration and independent of the applied magnetic field strength. Figures 2 and 3 summarize the frequency response curves and the peak gain versus beam current for both amplifiers. Clearly, the tubes had a very narrow bandwidth of order 20-30 MHz. In the absence of a beam, the bandwidth of a single transmission peak is on order 200 MHz (The amplifier passband is about 1.7 GHz.) , much larger than that with beam loading. In each case, however, the monotonic variation of gain with beam current is apparent for both amplifiers. In neither case was there any evidence of saturation; the gain remained linear with the input power.

In addition, we performed frequency and phase measurements of the amplified signal, using heterodyning and phase comparator techniques. At output amplifiers powers of less than 70 MW, we found that the microwave signal was monochromatic. At high output powers, strong sidebands were present in the signal, as was the case for the severed amplifier. Under conditions where single frequency operation was possible, we performed phase measurements. Figure 4 shows the measured phase angle between the amplified signal and a low power, phase stable reflex klystron. The amplified signal under these conditions was phase stable to the accuracy of the detector, $\pm 8^0$. The time interval of interest, where the output power is large, is indicated by the arrows. The initial values of the sine and cosine of the phase have been set to zero to avoid numerical instabilities, while immediately after the end of the pulse, the numerical instability is readily observable.

SEVERED AMPLFIER

Above 1.6 kA beam current, corresponding to about 110 MW output power in X-band, the single stage amplifiers began to oscillate due to positive feedback from small mismatches at the entrance and exit of the TWT. To reduce the positive feedback and hence increase the possible power from

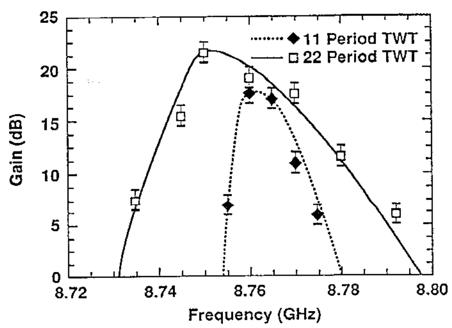

FIG. 2 The frequency response for the 11 and 22 period amplfiers. The response was measured with a 950 A beam current in the 11 period structure and a 900 A current in the 22 period structure.

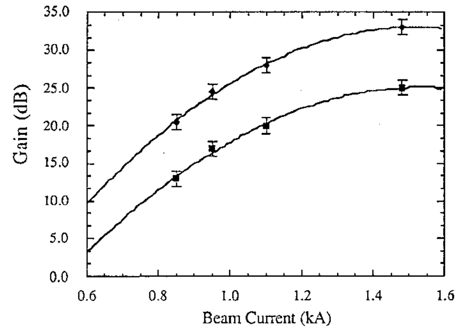

FIG. 3 Peak gain in the single stage amplifiers as a function of beam current. In the region shown here the amplifiers had no positive feedback oscillations.

the amplifier, we severed the amplifier. The configuration and design for the severed amplifier has been discussed elsewhere.[6] The overall length of the sever section was 13.6 cm. With these amplifiers we obtained total output powers, averaged over the rf pulse duration, of 400 MW. Peak powers, on the order of tens of nanoseconds, corresponded to greater than 500 MW. Figure 5 shows the pulse response of the amplifier and, for comparison, the frequency response of the unsevered 22 period structure. The bandwidth of the severed amplifier is much closer to that of the unsevered, un-beam loaded structure. The peak gain of the severed amplifier was 37 dB, at a beam current of 975 Amperes, corresponding to a total output of 400 MW. Figure 6 shows a comparison between the gain versus beam current for the severed amplifier and the 22 period unsevered amplifier. Unlike the unsevered tube, the severed tube saturates with respect to the beam current.

The severed tube also showed "sidebands" in the frequency spectrum. The "sidebands" were spaced from 30 to 130 MHz from the magnetron driver frequency, with the spacing becoming greater as the beam current was increased.

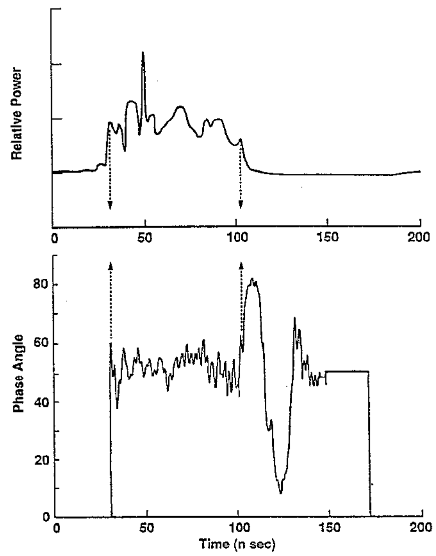

FIG. 4 Measured phase angle between a local oscillator and the TWT output. The zero phase is arbitrary.

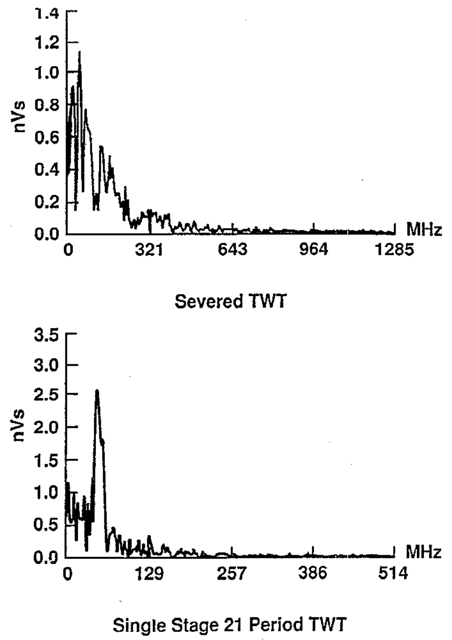

FIG 5 Fast Fourier transforms of the outputs from the severed and unsevered amplfiers. Note the richer frequency content of the pulse from the severed amplifier.

Also, the "sidebands" were spaced asymmetrically with respect to the carrier frequency. The upper "sideband" was displaced by a greater amount from the carrier frequency than the lower "sideband". The frequency spacing is shown in Figure 7. The "sideband" structure was apparent at all power levels investigated in the severed amplfier. Furthermore, a significant amount of power was located in the "sidebands. This power spectrum was measured by calibrating the heterodyning system using known power inputs. The maximum average power at the carrier frequency was 210 MW, corresponding to an energy conversion efficiency of 24 %.

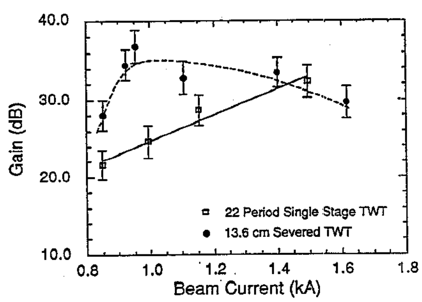

FIG 6 Gain as a function of beam current for the severed amplifier and the unsevered 22 period TWT. The severed amplfier has a peak gain at 900 A and then begins to saturate.

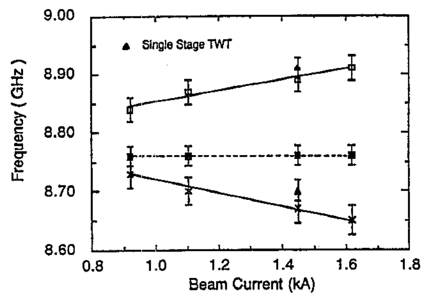

FIG 7 Frequency spacing for the "sidebands" as a function of beam current. Note that the "sidebands" are asymmetrically about the center frequency and that the spacing increases with current.

CONCLUSIONS

We now summarize the results of the amplifier experiments. The single stage amplifiers provide useful gain (i.e., no oscillation) in the current range from 800 to 1700 Amperes. The output is monochromatic until the output power reaches 70 MW, at which point a "sideband" structure develops in the frequency spectrum.
Above 1.7 kA, the tube goes into oscillation from positive feedback. to eliminate the oscillations, we severed the amplifier. The severed amplifier achieved a total overall power output of about 400 MW, as verified by calorimetry. The power at the carrier frequency was 210 MW, giving an amplifier efficiency of 24 %. Theoretical work has been performed to investigate the amplifier performance, including the "sidebands". Most of the effects seen here can be attributed to finite length effects. This work is described elsewhere.

ACKNOWLEDGEMENT

This work was supported in part by the Department of Energy and the AFOSR and in part by the SDIO-IST and managed by Harry Diamond Laboratories.

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