HIGH POWER TRAVELING WAVE AMPLIFIER EXPERIMENTS

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ABSTRACT

Several high power X band traveling wave amplifiers (TWA) have been fabricated and tested. The tubes have gains ranging from 13dB to 32dB at 8.76 GHz. and output powers ranging from 3 to 100 MW. The amplifiers are driven by the interaction of a slow space charge wave on an electron beam with an electromagnetic wave supported by the structure. The electron beam energy is 850 keV with currents in the 1 kA range. The amplifiers all operate in a single mode over a narrow frequency range. The amplifier gain increases rapidly with the beam current and with increases in the structure length. We summarize in this paper the amplifiers' main features.

1. INTRODUCTION

Several experiments have been reported recently in which very high microwave powers have been achieved[1-4]. The majority report experiments in oscillator configurations [5]. For some high power applications, such as drivers for high energy electron accelerators, the radiation must be emitted in a narrow bandwidth and have a fixed and controllable phase relationship between each source. One approach to achieving this goal is to drive a series of amplifiers from a single oscillator. In this paper we report on the design and implementation of several high power amplifiers. The experiments' purpose is to determine the characteristics of an amplifier, driven from an intense relativistic electron beam with a field emission cathode, at interesting power levels.

The amplifier is an axisymetric rippled wall slow-wave structure. Such configurations support two basic wave types : i.) a backward wave, and ii.) a forward wave. When an intense relativistic electron beam is propagated through the structure, the beam space-charge waves may interact, under the proper conditions, with either wave type. The backward wave interaction gives the backward wave oscillator (BWO), and the forward wave interaction gives the traveling wave amplifier (TWA). Since the beam space-charge waves can in principle interact with several structure modes, we attempt to drive the lowest mode so hard that it will dominate the interaction.

EXPERIMENTAL CONFIGURATION

These experiments use a Blumlein to produce 850 keV, 1 kiloampere, 100nsec, electron beams. A field emission diode produces electrons which are injected along a strong axial magnetic field through a 6mm. diameter channel in the anode plate. Figure 1 shows the experimental schematic.

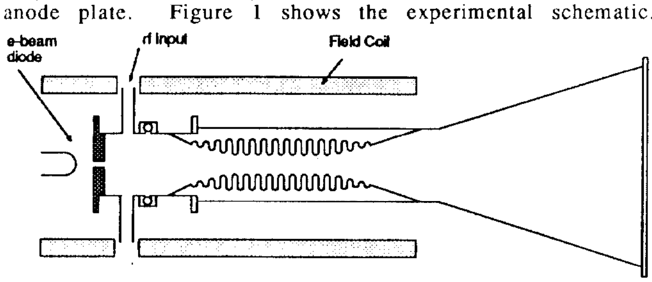

Figure 1. Amplifier Experiment

As shown, the rf input signal is coupled to the amplifier through port(s) located a half guide wavelength from the anode plane. The sidearm waveguide is operated in the rectangular guide TE10 mode and coupled to the cylindrical guide TM01 mode through the wave's H-field. The cylindrical waveguide radius is 1.75 cm.. A tuneable magnetron supplies microwave power at the amplifier input. The amplifier has three sections: a tapered input, a tapered output, and a central uniform region. The three central structures reported have 11, 15, and 22 periods, with input powers of 130 kW, 100 kW, and 40 kW respectively. Each has an axisymmetric periodic ripple with a periodic length of 0.7 cm., an average diameter of 2.64 cm, and a ripple depth of 0.8 mm. The ripple amplitude in all tapered sections decreases linearly over 10 periods at a constant average diameter. The decreasing ripple amplitude reduces the reflected power by about 20 dB over that found with a smooth taper only[6]. Following the exit taper the tube diameter increases adiabatically to 5 cm and terminates in a long horn antenna with a 25 cm diameter output window. Dispersion relation calculations[7] show that the TM01 passband has a forward wave extending from 8.10 GHz. at k=0 to 9.77 GHz. at k= 4.5 cm^{-1}. At the highest frequency the wave phase is only 0.46 c. Since the electron velocity is greater than 0.8c, the lowest order mode interaction is with a forward wave. Finally, the TM11 mode cut-off frequency is higher than the upper limit, 9.77 GHz., of the TM01 mode passband. The only competing mode at the experimental frequencies is the TE11 interaction, which is not found experimentally.

EXPERIMENTAL MEASUREMENTS

All microwave measurements are made using antennas in the output horn's far field . Power levels are referenced to the transmitted magnetron power and gains are determined by a substitution technique. The receiving horn is located, with the appropriate polarization to detect axisymmetric TM guide modes, at the location of the peak (3 degrees) in the radiation pattern. Far field measurements show the expected radiation pattern with a dip on the axis. Rotating the detector's plane of polarization results in a drop of 40 dB in the rf. The detected signal is coupled to the screen room through a long length of X-band waveguide and terminated in a precision attenuator followed by a crystal detector. The crystal detector output goes to a Tektronix 7912 digitizer. Gains were determined by finding the attenuation needed to bring the detected signal to 50 mV. Occasional checks, using a dispersive line, were made to determine that the radiation matched the magnetron frequency. No significant signal was monitored at other frequencies below 26 GHz. From this observation and the passband characteristics outlined earlier we conclude that the observed interaction, centered at 8.76 GHz. as determined by heterodyning measurements, is in the expected TM01 mode. Figure 2 shows crystal detector data obtained under peak output power conditions for the eleven period structure operated at a beam current of 950 Amperes. The precision attenuator is set at 48 dB compared to the 30 dB setting required to give an equal (50 mV.) crystal detected output from the magnetron alone. An 18 dB attenuator setting gives a beam only radiation level from the crystal detector of 50 mV, well below that from the magnetron only and 30 dB down on the amplified signal. However, as the beam current or the structure length increased, the beam only radiation level increased to within 7 dB of the magnetron only signal. The crystal detector output shows that the rf pulse lasts for the complete 90 nsec duration of

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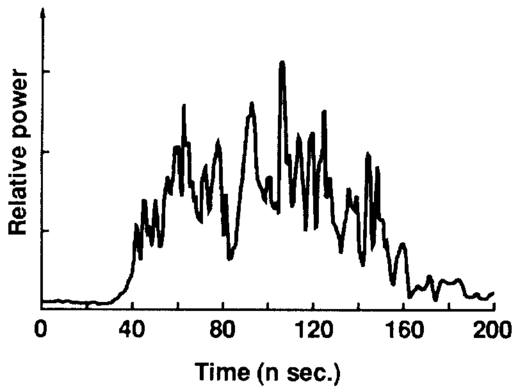

Figure 2. Typical crystal detector response.

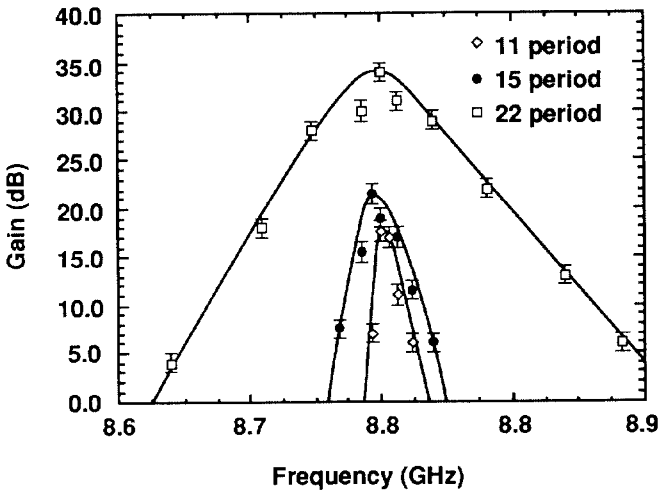

Figure 3. Amplifiers' Bandpass

the beam-high voltage pulse. The fluctuations in the amplified signal level are typically of order of or less than less than 3 dB. and are probably associated with beam fluctuations. From microwave data of this type we have constructed curves showing the gain versus frequency for the 11, 15, and 22 period amplifiers. The results are shown in figure 3 for a 950 A. beam with the 11 period structure and a 900 A beam for the 15 and 22 period structures. Note especially the narrow bandwidth of the gain curve for all structures. If we define the bandwidth as the points where the power has dropped to half its maximum value (minus 3 dB), we find the bandwidth increasing only slightly with beam current or structure length. Nevertheless, there are substantial regions outside of this bandwidth where gain is seen. These outside regions increase with current and structure length. The linear dispersion relation indicates that the slow space charge wave interaction with the structure is expected at 8.85 GHz. whereas the experimental data show maximum gains at around 8.765 GHz.. For the 11 period structure the magnetron drive frequency was varied over a wide range outside of the region showing gain. In addition cold tests revealed the existence of no cavity modes in the input rf circuit. Figure 4 shows another feature of interest. The amplifier gain and the microwave pulse duration are essentially independent of the applied magnetic field strength over the range 5-13 kG. Both results are shown for the eleven period structure at the lowest current and lowest gain. This behavior is in marked contrast to that found with high power BWO's, where the high power microwave pulse duration is much less than that of the pulse power and the output power shows a marked decrease when the relativistic cyclotron frequency approximately matches the radiation frequency[4]. The pulse duration decrease shown at the guide fields extremes

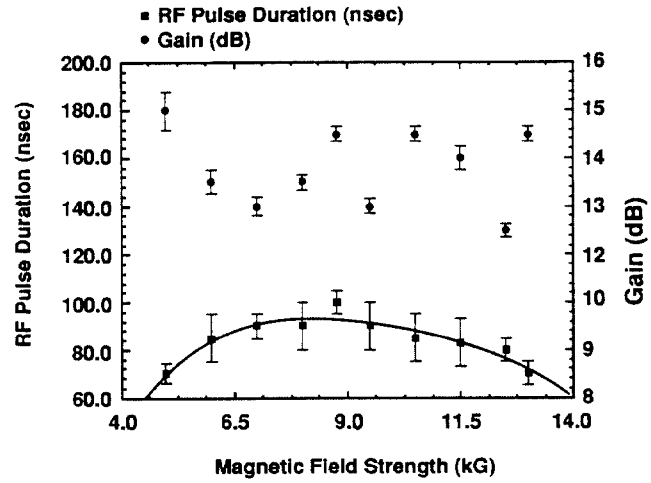

Figure 4. Amplifier Gain and Pulse Duration Variation with Magnetic Field Strength

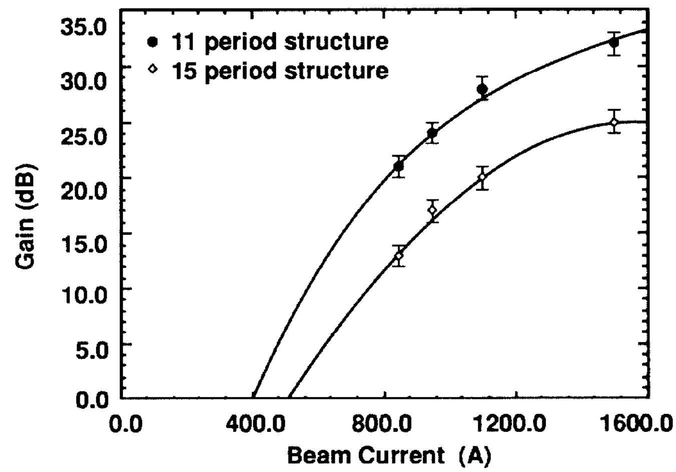

Figure 5. Gain of the 11 and 15 period structures as a function of beam current

corresponds to changes in the beam diode characteristics. Figure 5 shows gain versus current for the 11 and 15 period structures.

Heterodyne measurements have been performed to downshift the signal into the digitizer system pass band. Typical results of these measurements appear in figure 6. As expected these measurements show that the amplified wave frequency matches the magnetron input frequency and that the fast Fourier transform of the output wave has a bandwidth at half peak of 11.5 MHz, which is comparable to that expected based on the natural bandwidth set by the pulse duration. The heterodyned waveform is remarkably clean and noise free in a number of shots. Finally we note that the amplifier output power tracks the magnetron input power over the range available.

Table 1 shows a comparison of all three structures' gains under various current conditions.

DISCUSSION OF RESULTS

Three amplifiers have been fabricated and tested in our current investigations. Two worked well under all conditions, while the third acted as a driven oscillator under one condition but as an amplifier when driven by a lower current. At the higher current at a frequency about 50 MHz off the peak gain condition, the third device showed a 29 dB gain , while at the lower current the gain was 35dB, corresponding to an output power level of over 100 MW. All amplifiers have been tested to ensure that operation is in the TM01 mode and that they are operating as designed. The

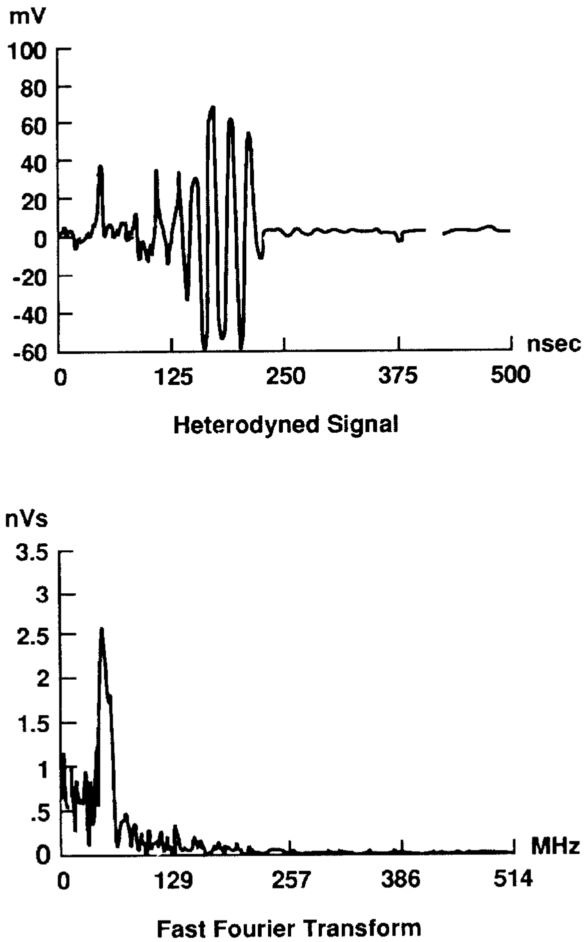

Figure 6. Heterodyned Signal and fast Fourier transform

bandwidth of the devices is less than originally expected and is probably due to the large difference between the group velocities of the TM structure wave and the beam space charge wave.[8] This is in comparison with lower power conventional amplifiers where the phase and group velocities are approximately equal over a broad range of frequencies, i.e. the design is for broadband operation.

Heterodyne measurements confirmed that the operating frequency matched the input magnetron frequency and showed that the bandwidth was very narrow and approximately equal to the signal's natural bandwidth. To date we have not measured the phase stability of the amplifier.

The absence of any dependence of the gain or rf pulsewidth on the applied magnetic field for the 11 period structure is perhaps the most interesting result . This is markedly different to the results reported for BWO's. Although the data only concerns the shortest structure at the lowest gain and current, this conspicuous absence provides some expectation that the existing systems can be scaled to longer pulse durations.

CONCLUSIONS

The experimental results described above confirm that it is possible to design and operate an high power traveling wave amplifier driven by a field emission generated intense electron beam. The system design enforced operation in the axisymmetric TM01 mode of the amplifier which showed no evidence of oscillation at the gains reported. In almost all respects the amplifiers behaved as expected which is a refreshing change for ultra high power devices and provides hope for a scalable system. Efficiencies of at least 10% are achievable as shown from the 22 period structure gain.

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