HIGH POWER TRAVELLING WAVE TUBE AMPLIFIERS FOR RF ACCELERATORS

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Abstract

Results will be presented from recent research carried out on the development of high efficiency, high power travelling wave tube amplifiers. The work presented includes a description of the characteristics of single stage and severed two stage amplifiers operating in X band at 8.76 GHz. Peak average output powers of 400 MW have been achieved and phase stability demonstrated in single stage devices at powers of up to 70 MW.

Introduction

A considerable effort has been mounted in recent years towards the development of ultra high power microwave sources. Several experimental groups have reported that very high microwave powers (in some cases in excess of 1 GW) have been achieved[1-9] at frequencies ranging from about 1 to 35 GHz. For some high power applications the radiation must be emitted at a single frequency and have a fixed and controllable phase relationship between each source[5,10,11]. 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, implementation and operational characteristics of high power amplifiers. Each amplifier employs an axisymmetric rippled wall slow-wave structure which allows interactions between slow space charge waves carried on the relativistic electron beam, and forward waves on the structure. This regime is well suited to applications requiring a number of phase locked outputs since multiple amplifiers may be driven by a master oscillator and the relative phases of the inputs controlled at modest (< 1MW) power levels.

Experimental Configuration

A Blumlein is used to produce an 850 kV, 1 kiloampere, 100nsec, pencil electron beam from a field emission diode. The beam is injected through a uniform guide transition section into a rippled wall TWT structure, which has been described previously. The transition consists of a ten period tapered rippled wall section and provides a smooth transition to the central amplifier structures which have either 11, 21 or 30 periods. Each of the TWT's 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 cm. The output section of the amplifier is also tapered and is similar to that used in the input. Following the exit taper the tube feeds a long conical horn antenna with a 25 cm diameter output window.

The design of the amplifier is based on having a forward wave interaction in the TM_{01} mode of the rippled guide. Measurements and calculation show that the TM_{01} passband supports a forward wave from 8.10 GHz. at k= 0 to 9.77 GHz. at k= 4.5 cm^{-1}, the π point for the structure. At the highest frequency (the π point) the wave phase is 0.46 c, well below the electron velocity of about 0.9 c, thus ensuring that any interaction in the TM_{01} mode is with a forward wave. In high gain operation a two stage amplifier is used in which two 21 period amplifiers are operated in series and driven by the same electron beam. The amplifiers are isolated by a graphite sever which absorbs the electromagnetic wave grown in the first amplifier but allows the space charge wave to propagate. No wave propagation is possible through the sever in the sense opposed to the electron flow.The electron beam, supported space charge wave enters the second amplifier, after propagation through the sever, where further wave amplification occurs. The gain of the two systems in series exceeds, under some circumstances, that of either one individually although some loss will occur in the severed section.

AMPLIFIER MEASUREMENTS

Measurements are made by sampling the microwave signal transmitted through the output horn. The receiving antenna is located in the far field at the peak (3 degrees) in the radiation pattern. The detected signal is coupled to the screen room through a 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. Power levels are determined by a substitution method measurement of the gain and from a knowledge of the output power of the magnetron. Calorimeters have been used to confirm the power level measurements. No significant signal was monitored at other frequencies below 26 GHz.

We summarize some results from the single stage device since they have been reported previously. The single stage amplifiers show a narrow passband with 3 dB bandwidths of order 20 MHz. The gain increases monotonically with beam current up to the peak current used of 1.6 kA. Maximum gains of 35 dB at output powers of 100 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.

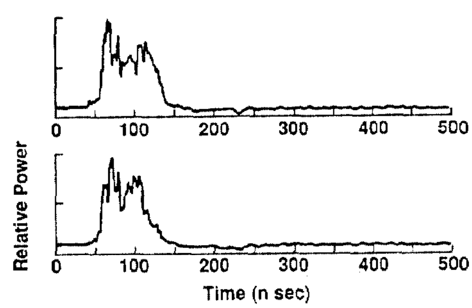

Fig. 1. Repesentative crystal detector traces showing power output from the severed amplifier at peak power of about 400 MW.

In more recent work we have used severed amplifiers to obtain average radiated powers of 380 MW at 40 % efficiency. The power levels quoted are averaged over the rf pulse duration; peak power levels exceed 500 MW. Pulse shortening has not been observed at these microwave power levels. Fig. 1 shows crystal detected outputs from the severed amplifier at a beam current of 950 A. In Fig. 2 we compare the peak gains of the single stage and the severed amplifiers as a function of the beam current. The peak gain occurs at a lower beam current than was found in the single stage amplifiers.

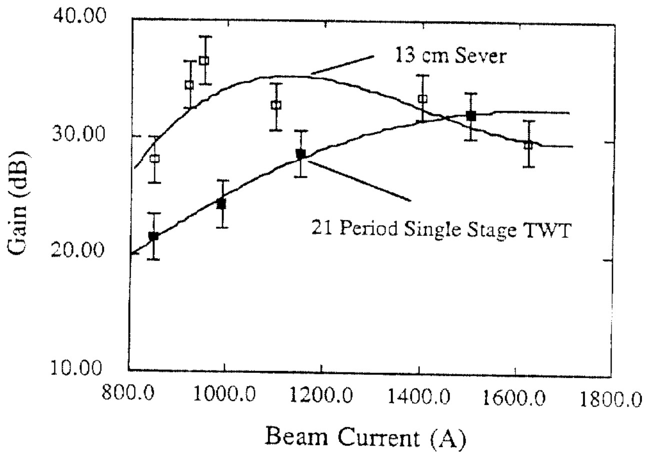

Fig. 2. Comparison of gains of single stage and severed amplifiers as a function of the beam current.

We have also carried out measurements of the frequency and phase stability of the amplifiers using heterodyning techniques and phase comparators respectively. Fig. 3 shows a comparison between the frequency downshifted outputs of a single stage and a severed amplifier at 900 A beam currents. The appearance of 'sidebands' is evident. In Fig. 4 we show the measured phase stability of the single stage amplifier during the output pulse. The amplified signal is phase stable during the beam pulse to within the 8^0 accuracy for the diagnostic. As the beam current is increased the sidebands develop and carry an increasing fraction of the radiated power. The sideband signals 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. In very recent observations with a 30 period amplifier output radiation has been monitored at powers of about 70 MW with no evidence of the sideband radiation.

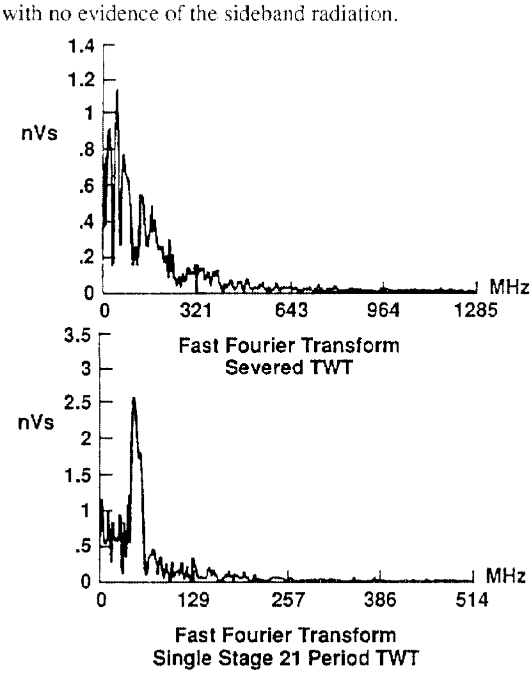

Fig. 3. FFT's of output from the severed and single stage amplifiers.

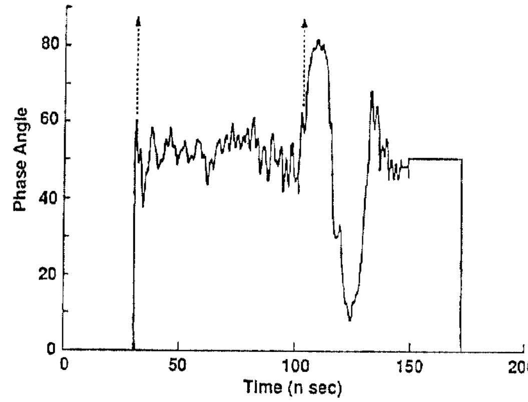

Fig. 4. Phase stability measurement of single stage amplifier. The arrows indicate the beginning and end of the microwave power pulse.

Discussion of Results

Three single stage and one two stage severed amplifiers have been fabricated and tested in our current investigations.The bandwidth of the single stage devices is less than 30 MHz and is comparable to the natural bandwidth based on the rf pulse duration. The finite length of the structures plays an important role in determining the bandwidth. Finite length effects have been modelled using a dielectric loaded cavity inserted in an otherwise uniform guide. In this geometry there are a series of cavity transmission maxima as a function of the wave frequency which become modified by the presence of a beam propagating through the system. Similar structure is shown by the TWT amplifiers. A detailed analysis of this interaction shows that the bandwidth in a single transmission peak is narrowed by an amount equal to the structure gain. i.e.

$$(\Delta f)_{beam} = (\Delta f)_{structure}\, 10^{-(gain[dB])/20}.$$

The response of the loaded system acts, as is common in many systems, to maintain the product of the gain and the bandwidth constant. Although the slow wave structure used is different to the cavity configuration modelled we expect that the results obtained for the cavity case have more general validity. In the structures used the unloaded, measured bandwidth of an individual peak varies between 120-240 MHz and from the above relation drops to a beam loaded value in the range 10-20 MHz depending on details of the beam current and structure length. This range of values matches the experimental observations.

In related studies the growth of the wave has been modelled in a finite length section of dielectric loaded guide. In this case we find that gain only develops after a significant fraction of the structure has been traversed. The physics of this process is similar to that found in FEL systems where the gain on resonance is zero until bunching has developed. Fig 5 shows the calculated gain and rf conversion efficiency for a 20 cm long interaction region with an initial rf field strength of 1 MV/m and a beam current of 450 A. Almost 50 % of the structure length is taken up with achieving bunching. In the calculations the beam current is only one half that used experimentally, and the experimental interaction lengths ranges between 40 and 100 % of that used in the calculations It seems reasonable to expect that comparable bunching lengths are obtained in practice. Hence structure gains are perhaps closer to 2 dB per period rather than the average value of about 1 dB per period obtained by assuming that the gain is uniform along the 21 period structure length. The gain as estimated above is in closer agreement with expected values using standard TWT theory and, in particular, better represents the observed scaling with structure length. Pierce 'C' parameters range from 0.18 to 0.25 as the beam current is increased from 850 -1600 A.

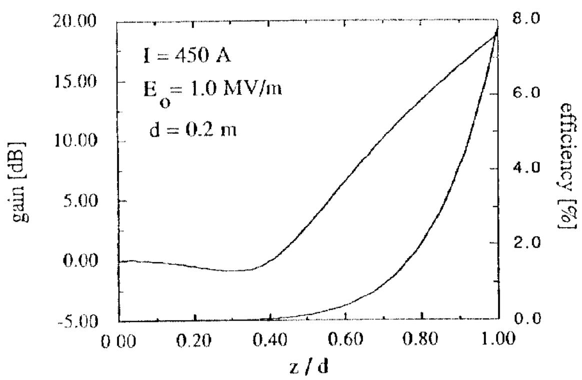

Fig. 5. Calculated gain curve for a 20 cm long single stage Cerenkov amplifier. Note the delay in onset of the gain while bunching occurs.

To date we have only obtained limited data on the severed amplifier operation, however certain features are clear. Most importantly we can obtain gains greater than those found in the single stage device and the microwave output continues throughout the useful pulse power duration. Time average powers of order 400 MWatts have been obtained and peak powers of up to 500 MWatts. The rf energy conversion efficiency is about 40%. Among the interesting features is the fact that the bandwidth is about a factor of five greater than that obtained for the single stage amplifiers. A possible cause for this increase is space charge debunching of the beam in propagation through the sever.

CONCLUSIONS

The experimental results described above confirm that it is possible to design and operate single and two stage high power traveling wave amplifiers driven by a field emission generated intense electron beam. In almost all respects the amplifiers behaved as expected which is a refreshing change for very high power microwave devices and offers hope for the design of a long pulse high energy system. Efficiencies of at least 11% and peak power of 100 MW in X band are achievable in single stage amplifiers and average powers of at least 400 MWatts at greater than 40 % efficiency in two stage devices, Measurements indicate phase stable outputs at power levels up to 70 MW in a 30 period long structure driven by a 500 A beam.

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