Axial extraction of high-power microwaves from relativistic traveling wave amplifiers

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(Received 10 June 1996; accepted for publication 3 July 1996)

We report theoretical and experimental results from research into coaxial extraction of high-power microwaves from X-band traveling wave tube amplifiers. Power levels exceeding 60 MW have been measured at 9.1 GHz. The output level is relatively constant for the full 70 ns duration of the 700 kV, 500 A electron beam pulse. Results indicate that this coaxial geometry is broadband when compared to traditional, highly tuned radial extraction and may thus have applications in a range of high-power microwave devices. © 1996 American Institute of Physics. [S0003-6951(96)04637-2]

A number of high-power microwave sources are based on the interaction between a relativistic electron beam and axial electric fields. Within this category the klystron and the traveling wave tube amplifier (TWT) are perhaps the most common devices when control of phase and frequency are essential requirements. In both devices a beam is bunched as a result beam-wave interactions in either discrete cavities or in a periodic traveling wave structure. The rf output is typically extracted via a rectangular waveguide side arm mounted in the last cell of the output structure. In klystrons the output structure is used for both rf conversion and extraction and the rf efficiency is very sensitive to the cavity dimensions, whereas in the TWT the output is only used to extract the rf power developed in the amplifier.

We present results from theoretical and experimental studies describing the coupling from a high-power traveling wave tube amplifier, operating in the TM$_{01}$ circular mode, to a transmission electron microscope (TEM) mode in a coaxial waveguide while the beam is dumped in a hollow inner conductor. It is found that this low reflection configuration exhibits advantages over that used in existing devices, namely: (i) The mode conversion efficiency of the extractor is insensitive to the dimensions of the inner conductor and is relatively broadband. (ii) The inner and outer conductors are parallel to the confining magnetic field and hence the output section is magnetically insulated. Although the work described used a TWT amplifier the results may be applicable to a klystron with a traveling wave output section.

The coaxial extraction section of the TWT used in this work is shown in Fig. 1. The amplifier consists of a two-stage TWT with a phase advance of $\pi/2$ per cell designed to work with an 800 kV, 500 A pencil electron beam. The periodic structure has an inner (iris) radius of 0.9 cm, an outer radius of 1.56 cm, a periodic length of 0.77 cm, and has a 12-period taper to the outer tube radius at each end. The output of the amplifier is fed to a coaxial section in which the radius of the inner conductor has been varied between 0.7 and 1.1 cm, and power extracted with various penetration lengths of the inner conductor into the tapered section. The taper is sufficiently gradual that the output microwave signal level is constant to within a few percent whether an inner conductor is present or not. This is shown in Fig. 2 for the case with the inner conductor present. Previous experimental measurements and simulation data have shown that reflections from the ends of the amplifier lead to the development of side bands and result in severe fluctuations in the power envelope of the output rf. The relatively flat output signal is therefore a sensitive indicator of a low reflection coefficient at the output of the amplifier. The narrow bandwidth of traditional side-arm output couplers places a stringent requirement on the beam quality and pulse width in order to prevent excitation of unwanted frequencies. These requirements can be relaxed if reflections from each end of the amplifier are made small enough, not only at the input frequency, but also for the range of frequencies for which the amplifier gain is substantial. This may be accomplished using the coaxial extractor concept described in this letter.

The axial converter design arose from noting that the TM$_{01}$ circular mode can be very effectively coupled into a TEM coaxial waveguide mode in a guide with the same outer radius if the inner radius is selected correctly. Analytic calculations, supported by simulation data indicate that for a tube radius of 1.56 cm a range of inner conductor radii from 1.0 to 1.1 cm have power reflection coefficients below 0.5%. Simulation data indicate that similar results may be obtained within the tapered section of the TWT provided that the end of the inner coaxial tube is located midway between two rises. In Fig. 2 we show simulation data for the energy reflected when an incident 300-MHz-wide Gaussian pulse enters the coaxial mode converter. Data are presented with the mode converter at three axial locations, and is given as a function of the radius of the inner conductor. The data points (d) are obtained from a modal analysis of the junction between a uniform circular waveguide and a coaxial waveguide at 9 GHz. Note that the reflected energy is less than 0.5% approximately 1.5 periods from the end of the uniform amplifier for an inner conductor radius of 0.7 cm.

An important feature of the axial converter is the shielding of the electron beam from the periodic structure by the inner conductor. Figure 3 shows the total Poynting flux, including both rf and beam component as a function of distance, for both a uniform cylindrical output [trace
and for the coaxial output case [trace (a)]. It can be seen that the microwave signal grows in amplitude throughout the amplifier and decays as the wave enters the tapered section. This reduction in power level occurs as energy is extracted by bunches rapidly slipping out of the decelerating phase and entering the accelerating phase of the wave (in the absence of the inner conductor the wave phase-velocity gradually increases from $0.9c$ at the start of the tapers to $1.7c$ at the end). The reduction can be as much as 80% of the peak power level developed in the amplifier. In the case with the inner conductor the rf power level is maintained at the value set by the location of the mode converter. The dc level shifts at $z=0$, 19, and 33 cm correspond to changes in the Poynting flux associated with the beam as the return conductor geometry is changed. The rf power output in the two cases shown is 25 MW in the absence of the inner conductor and 90 MW with the inner conductor. In this figure the mode converter is located at $z=19$ cm and the beam is dumped in the collector at 33 cm. The inner conductor decouples the wave and the beam when the beam enters the inner conductor.

The optimal design for coaxial extraction is a compromise between (a) maximizing power extracted relative to saturation level, (b) minimizing reflections from the extractor and, (c) minimizing surface fields. The power extracted will be maximized when the inner conductor is close to the start of the tapers, but this would also reduce the radial gap between the coaxial conductors and thus increases the probability of rf breakdown. A smaller inner conductor radius may slightly increase the reflections (Fig. 2) but will increase the gap and hence reduce the breakdown probability. For example, the radial excursion of a nonrelativistic electron emitted close to the coaxial extractor is about 5% of the radial gap. The excursion scales as the square root of the radiated power for fixed magnetic field strength so breakdown thresholds may be increased by an increase in the guide magnetic field.

We have tested the axial extraction system experimentally with a 100 ns, 700 kV, 500 A beam generated using a field emission diode. It should be noted that the beam energy is 100 kV less than the design figure, but based on earlier results we expect good amplifier gain even if the beam and slow wave structure parameters do not satisfy the classical resonance condition exactly. The beam is 0.6 cm in diameter.
and is guided by a 10 kG magnetic field. After passing through the amplifier the beam is dumped into the hollow center conductor. Preliminary data are shown in Fig. 4 which presents results for a 7.1 mm radius inner conductor located 3.5 periods into the taper from the end of the uniform section of the amplifier. The microwave envelope, as detected by a calibrated radial electric field probe mounted in the coaxial section, and a mixer output signal are shown. The microwave output is relatively constant for approximately 70 ns matching the stable portion of the beam profile, and the signal has the correct frequency as indicated from a FFT of the mixed signal. Peak output signal levels exceed 60 MW, and are 2.5 times that measured when the signal is detected in the uniform pipe at the end of the taper. The smoothness of the output pulse indicates that the reflection from the mode converter is small. The fluctuations observed are believed to be largely due to the relatively poor beam quality associated with the field emission diode used.

We have presented preliminary data, backed by simulation that demonstrate the efficient electromagnetic conversion from a TM_{01} mode in a circular cross section traveling wave periodic structure to a TEM mode in a coaxial guide. The performance of the mode converter is broadband when compared to radial extraction geometries and is relatively insensitive to the dimensions of the inner conductor. For small enough inner conductors the conversion may occur close to the end of the uniform section of the amplifier enabling the saturated power of the amplifier to be extracted. Except for the location of the inner conductor relative to the saturation point, the extractor has no effect on the efficiency of the beam wave interaction. The overall efficiency of the TWT is limited by the degree of beam bunching and the design of cells in the output section prior to the extraction point. This has not been optimized in the experiments reported here.

This work was supported by the Department of Energy and also, in part, by the AFOSR under the MURI program. The MAGIC code was provided by MRC.