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TRAVELING-WAVE TUBE AMPLIFIER CHARACTERISTICS STUDY FOR STOCHASTIC BEAM COOLING EXPERIMENTS

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Summary

The characteristics of continuous-wave wideband traveling-wave tube amplifiers have been experimentally investigated over a frequency range of 1.5 to 4.5 GHz. We present measurements of characteristics important for stochastic beam cooling systems that are generally not available from manufacturers' data sheets. The amplifiers measured include models 1177 H01 and 1277 H01 having output power capabilities of 10 to 20 W, respectively, at frequencies of 2 to 4 GHz. The power transfer characteristics, the phase-shift characteristics as functions of frequency and the input power level, the voltage standing-wave ratio, harmonics and intermodulation products content were accurately measured and are discussed. Also several approaches are discussed for the reduction of harmonics and intermodulation products.

Introduction

An effort is underway at the Fermi National Accelerator Laboratory and Lawrence Berkeley Laboratory to design the Antiproton Source which will make it possible to produce proton-antiproton collisions at energies near 2 TeV in the center of mass.[1] The Antiproton source will be capable of accumulating 4×10^{11} antiprotons in four hours when a wideband feedback system for stochastic beam cooling is used. This method has been effectively used for the gradual reduction of betatron oscillations and longitudinal momentum spread of a coasting particle beam.[2]

The Antiproton Source program requires the development of two types of wideband amplifier systems, one type capable of operating at power levels of several hundred watts and the other at power levels of several thousand watts in the frequency bandwidths covering 1-2 GHz and 2-4 GHz. Since the pickup electrodes generate very small signal power levels from the antiproton beam amplifier systems should have a gain in excess of 90 dB and 150 dB, and noise figures as low as possible.

Our previous experiments[3,4] and considerations[5] indicate that new amplifier systems should be designed which meet the above requirements for fast cooling of betatron oscillations and longitudinal momentum spread. Initially Power Gallium-Arsenide Field-Effect Transistors and Helix Traveling-Wave Tubes (TWT) were considered as potential devices for the amplifier driver and output stages. Detailed device characteristics studies have shown that at the present time only helix-type TWT's are capable of meeting the technical objectives of output power level, bandwidth, phase-shift variations, and reliability.[6,7] Because of the TWT's excellent gain bandwidth and output power capabilities, the device can significantly contribute to the development of stochastic cooling systems. However, device characteristics must be carefully studied, particularly with respect to generation of harmonics and intermodulation products during amplification process. Harmonics and intermodulation products are generated as a result of the inherent nonlinearity of the beam-helix wave interaction process in TWT's when multiple input signals (or noise) are applied. The generation of such harmonics and intermodulation products in the amplifier system may cause the stochastic heating rather than cooling of antiproton beam.

Dynamic Range and Power Transfer Characteristics Measurement

The dynamic range measurement of the TWT amplifier show performance characteristics such as linearity and gain. Approximately 100 mW of signal power was required to drive the TWT amlifier under test to provide full power output and operate beyond the saturation.

Figure 1 shows the output power of the TWT amplifier as a function of the input power level with the input signal frequency as a parameter. Results of the measurements show that the amplifier has its 1 dB compression point at output power level of 40, 42 and 45 dBm for frequencies of 3, 2 and 4 GHz, respectively. Saturation points were 45, 42 and 45 dBm for input signal frequencies of 3, 2 and 4 GHz. The output power variation across the specified bandwidth was approximately 12 dB. As the input power approached 0 dBm, the output power curve showed a marked saturation. The linear operating range of the TWT amplifier was definitely below 0 dBm of input power over the 1.5 to 4.5 GHz range. The output noise power level of the TWT was -55 dBm. For this measurement the spectrum analyzer bandwidth was 300 KHz.

Phase-Shift Characteristics Measurement

Figure 2 is a set of curves showing the phase-shift of the TWT amplifier output signal as a function of frequency at various input power levels. The measuring system phase-shift had been subtracted and this figure presents the true phase-shift of the TWT amplifier output with zero phase set at 2.5 GHz and -10 dBm input power level. The amount of phase-shift over a bandwidth of 2-4 GHz at 0 dBm input power level was $\pm 30^\circ$. At input power level of -10 dBm, the phase-shift was $\pm 21^\circ$.

Figure 3 is the phase-shift of the TWT amplifier as a function of input power level with input signal frequency as parameter. The 2, 3 and 4 GHz curves are all normalized with respect to each other through a zero-phase set point fixed at 2.5 GHz and -10 dBm input power level. For the input power dynamic range from 0 to -20 dBm, the phase-shift as a function of the input power level varies 2, 7 and 45° for the input signal frequencies of 4, 2 and 3 GHz, respectively.

Dynamic Range and Intermodulation Products Measurement

The dynamic range and intermodulation product measurement of the TWT amplifier shows such performance characteristics as the linearity, gain, harmonic interference, and the intermodulation performance which can be expected from the amplifier at certain specified frequencies. As a result of the inherent nonlinearity of the electron beam-helix wave interaction process, harmonics and intermodulation products are formed when multiple input signals (or noise) are applied which reduce the available power levels of the fundamental signals. Distortion and nonlinear effects are caused by electron bunching, velocity modulation, and electrons overtaking in the beam.[8,9] Generally, when two input signals with frequencies f_1 and f_0 are applied to the TWT amplifier the frequency of the intermodulation signal is $mf_1 \pm nf_0$, where m and n are positive integers. One of the integers may take the value

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zero so that harmonics are included. The order of the general intermodulation products is given by the sum of the integers m + n. A pair of sample frequencies were used in the measurement: 1.8 and 2 GHz. An in-phase power combiner added the two separate signals together to produce the two carrier signal.

Before the two carrier signal was used to drive the TWT amplifier it was observed on the spectrum analyzer to determine its own harmonics and intermodulation product content. With power level set at 5 dBm for both signals which was the maximum input power level used for the measurement, the harmonics, intermodulation products as well as the mixing sum and difference of the signals were all 35 dB or more below the main signal levels. The dynamic range of the TWT amplifier operating with a two carrier signal was lower than that of single signal operation.

In Fig. 4, the output power of the two main carriers and some of their harmonics and intermodulation products are plotted as a function of the main carrier's input power. The two signal frequencies 1.8 and 2 GHz were chosen because the second harmonics, the sum and difference of the signals and third order intermodulation products are mostly in the pass band of the amplifier. The two carriers were designated as f_1 (2 GHz) and f_0 (1.8 GHz). At 0 dBm input power level, the sum of f_1 and f_0 was less than 5 dB below the carriers and the second harmonics were less than 10 dB below the carriers. At +5 dBm input power level, the $f_1 + f_0$ component actually had a higher output than the 1.8 GHz carrier. Even at -10 dBm input power level, the second harmonics and the $f_1 + f_0$ component were less than 20 dB below the carrier's output power levels which were, at this point, 1 W and 0.5 W, respectively, for f_1 and f_0. In Fig. 4 all presented data were corrected for the measuring system errors.

Voltage Standing-Wave Ratio Measurements

The input and output Voltage Standing-Wave Ratio, VSWR, were measured across the 1.5 - 4.5 GHz frequency range. A network analyzer was used for this measurement. The maximum VSWR of the input was less than 2.0, while the maximum output VSWR was less than 2.2.

Conclusions

Wideband TWT amplifiers with low and medium output power levels are becoming a key component for future stochastic beam cooling systems. Our measurements show that in addition to second harmonics, third order intermodulation products ($2f_1-f_0$, $2f_0-f_1$), and fifth order intermodulation products ($3f_1-2f_0$, $3f_0-2f_1$), strong sum-and-difference components ($f_1 \pm f_0$) are present in the output signal. Generally, in the quasi-linear or small input region the rate of increase of the second harmonic and sum-and-difference components is approximately twice that of the fundamental signal. The rate of increase of the third order intermodulation products is approximately three times larger than the fundamental signal increase rate. Linearity requirements of the stochastic beam cooling systems, with respect to harmonics, sum-and-difference components and intermodulation products generation during amplification process, can be met by an output power backoff from the saturation point and applications of amplitude and phase pre-distorting networks together with feed-forward techniques. Optimization of the TWT operating conditions could reduce the device distortion. Furthermore, the possibility should be explored of developing a special TWT having improved amplitude linearity with respect to those commonly available. The design of standard TWT's by manufacturing industry has, in most cases, emphasized power efficiency, output power levels, bandwidth, gain, size, reliability rather than amplitude linearity. For stochastic beam cooling systems, the emphasis should be on amplitude linearity, bandwidth and reliability, sacrificing to some extent power efficiency and gain. The amplitude linearization of the TWT would also result in an improvement in phase linearity.

The required output power level of the octave-bandwidth amplifier for the stochastic cooling systems can be obtained by either a large number of low power CW Traveling-Wave Tubes (200 W saturated power level) or a relatively small number of medium power TWT's (1.5 kW saturated power). The use of low power TWT's rather than medium power tubes has the following advantages: higher reliability, availability of the tubes from at least three major manufacturers, willingness of one manufacturer to redesign the TWT to reduce harmonic and intermodulation product output, and a better output power-to price ratio ($100/W for 200 W tube versus $220/W for 1.5 kW tube). The octave bandwidth CW medium power TWT's are available only from one major manufacturer which presently is not willing to make any tube modification for reduced harmonic and intermodulation products output. Mean-Time-Between-Failure (MTBF) of 200 W TWT's is, approximately, between 15,000 and 20,000 hours. The 1.5 kW TWT's has MTBF of approximately 3,000-5,000 hours. With a high redundancy design, the reliability of a 200 W TWT system can be significantly higher than that of a 1.5 kW TWT system.

Concerning the configuration of high power TWT's in the output stage, the TWT's can be reliably used only as single units in the octave bandwidth. Although, the operation of several TWT's in parallel configuration is possible for obtaining higher power levels, it requires a complex protection circuitry, careful phase and amplitude matching and precise maintenance of the matching conditions over the operational lifetime of the output stage. So far, parallel configuration of TWT's has been used exlusively in military electronic counter measure systems, in the octave bandwidth, purely to increase the output power level. It cannot be used to reduce the harmonics and intermodulation product content due to a complex interaction of beam-helix wave in TWT's.

In satellite communication applications where requirements are more stringent in terms of amplitude, phase linearity and gain stability (to some extent similar to stochastic cooling system requirements), the parallel combination of two TWT's has been used only for relatively narrow (8%) bandwidths. Specifically, a satellite earth terminal was developed which is capable of delivering 1 kW CW in a bandwidth extending from 5.9 GHz to 6.4 GHz (C-Band) by combining two 600 W TWT's and using precision type input and output components.[10] At X-Band frequencies the satellite communication systems successfully use only 5% bandwidths. The relatively narrow operational bandwidths in both cases was essentially determined by the accuracy of phase tracking in all precision components used in the system, such as the input in-phase power splitters, attenuators, phase shifters, the TWT's and the output in-phase power combiners.

Single TWT configuration in the output stage would eliminate the precise amplitude and phase matching requirements over the required large bandwidth and output signal dynamic range. Furthermore, such a configuration will allow freedom in optimizing the operating conditions of each tube in the system, as well as the application of amplitude and phase predistorting networks and feedforward techniques.

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Reference to a company or product name does not imply approval or recommendation of the product by the University of California or D.O.E. to the exclusion of others that may be suitable.

References

1. The Fermi Laboratory Antiproton Source Design Report, Fermi National Accelerator Laboratory, Batavia, IL, February 1982.

2. D. Möhl, G. Petrucci, L. Thorndahl, S. Van der Meer, Physics and Technique of Stochastic Cooling, Phys. Rep. 58, 73 (1980).

3. G. Lambertson, et al, Stochastic Cooling of 200 MeV Protons, Proc. of the 11th Int. Conf. on High-Energy Accelerators, Geneva, Switzerland, 794-799, July 1980. Experientia Supplementum, Vol. 40, Birkanser Verlag, Basel, Switzerland.

4. G. Lambertson, et al, Experiments on Stochastic Cooling of 200 MeV Protons, IEEE Trans. Nucl. Sci. NS-28, No. 3, 2471-2473, (1981).

5. B. Leskovar, C.C. Lo, Low-Noise Wide-Band Amplifier System for Stochastic Beam Cooling Experiments, IEEE Trans. Nucl. Sci. NS-27, No. 1, 292-301, (1980).

6. B. Leskovar, Reliability Considerations of Traveling Wave Tube and Power Gallium Arsenide Field-Effect Transistor Amplifiers, Lawrence Berkeley Laboratory Report No. LBL-13861, (1981).

7. B. Leskovar and C.C. Lo, Traveling-Wave Tube Amplifier Characteristics Study for Stochastic Beam Cooling Experiments, Lawrence Berkeley Laboratory Report No. LBL-14142, (March 4, 1982).

8. J.L. Putz, Predicting Nonlinear Effects in TWT's, Microwaves 4, 32-39, (June 1965).

9. M.K. Scherba, J.E. Rowe, Characteristics of Multi-signal and Noise-Modulated High-Power Microwave Amplifiers, IEEE Trans. Elec. Devices, ED-18, No. 1, 11-34, (1971).

10. R.E. Shuken, Paralled TWT's Boost Uplink Power, Microwave Systems News, 7, 55-60, (1977).

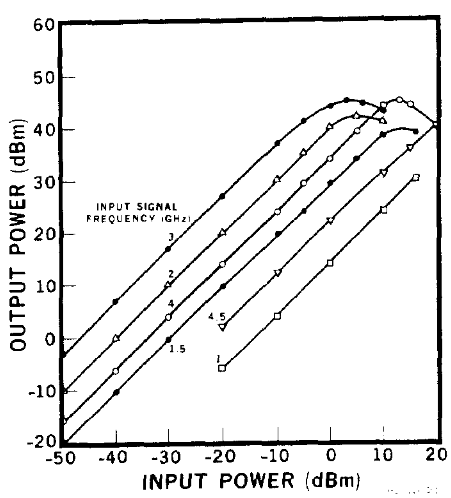

Fig. 1 Output power as a function of the input power level with the input signal frequency as parameter.

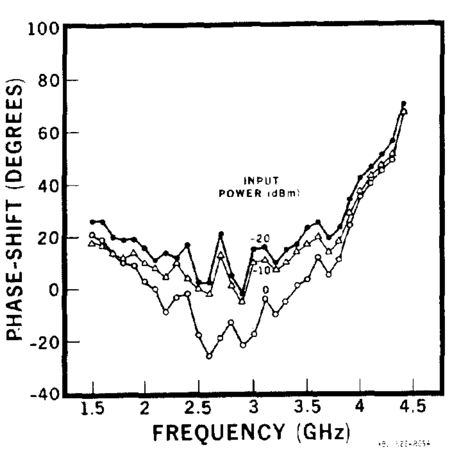

Fig. 2 Amplifier phase-shift as a function of frequency with the input power level as parameter.

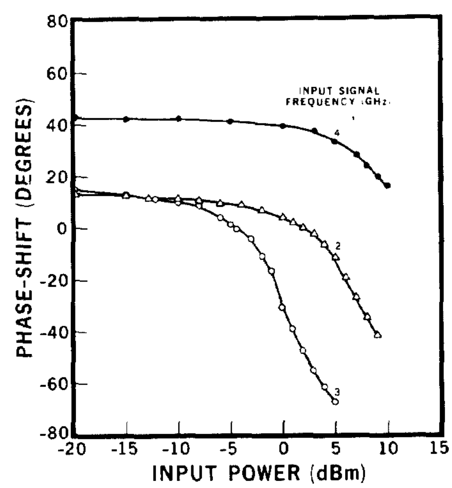

Fig. 3 Amplifier phase-shift characteristics as a function of the input power level with input signal frequency as parameter.

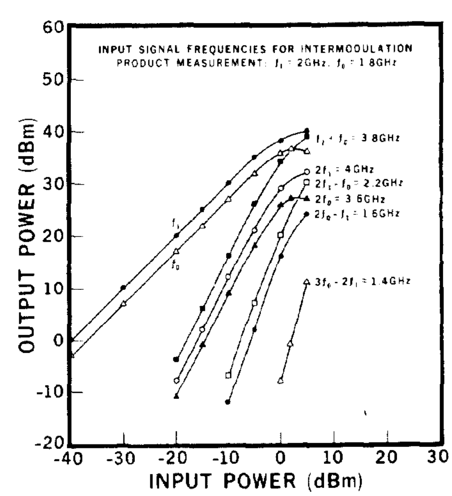

Fig. 4 Typical performance characteristics of the 2-4 GHz traveling-wave tube amplifier.