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High-Power Travelling Wave Tubes for Direct TV Broadcast Satellites

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The paper describes the design and status of a 12 GHz/200 W helix and a 450 W coupled cavity tube. Both tubes operate with a self-radiating multistage-depressed collector for achieving high efficiency. The tube weights realized are 2.6 kg for the 200 W tube and 6.7 kg for the 450 W tube.

Introduction

DEVELOPMENT of high-power X-band tubes for satellite applications started in 1971 when a 70 W travelling wave tube (TWT) was developed. Since at that time no immediate use in a satellite could be seen, the tube was modified for terrestrial use. This tube has now been in use for six years, and is an off-the-shelf item. The tube design was basically derived from Symphonie technology. With this design 1.2 million life hours have been accumulated up to date. The longest sample run is 44,000 hours. The technology itself proved their space compatibility on two Symphonie satellites. So far, 85,000 operating hours have been accumulated in space with four tubes.

Different tube designs were studied in the power range of 50-1600 W at X-band. Almost in parallel a television-broadcast-satellite (TVBS) study was being conducted. The outcome of this study was that TWT's in the power range of 200-700 W will be required for this application. The development of a 700-800 W tube was started. It ended with a breadboard model with 40% efficiency achieved with a single-stage depressed collector. More detailed TVBS studies finally led to two specific power requirements, 200 W and 450 W. The development work was started for TWT's with this power level aiming for electrical and identification models.

In the following paragraphs, the concept and rf measurements achieved to date on those tubes are presented.

Tube Design and Results

450 W TWT TL 12450

Figure 1 shows the breadboard model of the tube TL 12450. The overall length is 50 cm, and the tube weight is 6.7 kg (7.1 kg with fully potted gun).

Concept

The tube itself basically consists of three main subassemblies: 1) electron gun, 2) delay line system, and 3) collector.

Electron Gun

The electron gun uses a modified "Pierce" optic for beam-forming. The cathode used is of a tungsten matrix type. Extended life tests show that with this type of cathode more than 100,000 h can be achieved operating with a cathode loading of 0.75 A/cm^2. In this life test program 1 million hours has been accumulated with tubes and diodes, and six tubes have operated successfully to date for 47,000 h. The longest sample run with diodes is more than 100,000 h. Twelve samples have presently reached 70,000 h, and 10 other have passed the 45,000 h point. Furthermore, another life test program with 25 tubes was started. Twenty tubes have operated between 5,000 and 30,000 h so far.

Designing the gun for 450 W led to a cathode loading of 1.1 A/cm^2 because of the beam area compression ratio of 50, which is regarded as the upper limit for long-life space tubes. Due to this, life programs were performed with different cathode loadings in order to find the relation between cathode loading and life.

Figure 2 shows the result. It is seen that with a cathode loading of 1.1 A/cm^2, a cathode life of 90,000 h is achievable which exceeds the required 7-year life (62,000 h).

Because of the high operating voltage of the approximately 9 kV, the gun design has to take into account the special insulating requirements. This could be solved by using the so-called sandwich technique, where the gun envelope is formed by the insulating ceramic itself. This concept is proven up to 25 kV and vibration levels up to 100 g.

Delay Line System

The tube uses a coupled cavity circuit as a delay line because of thermal requirements. The delay line is formed by copper resonators and iron pole pieces. The pole pieces are part of the vacuum envelope, and extend right down to the electron beam. This integrated technique has two main advantages. 1) best use of the magnetic material $SmCo_5$, which means lowest possible magnet weight, and 2) complete compensation of transverse magnetic fields and, therefore, excellent beam transmission.

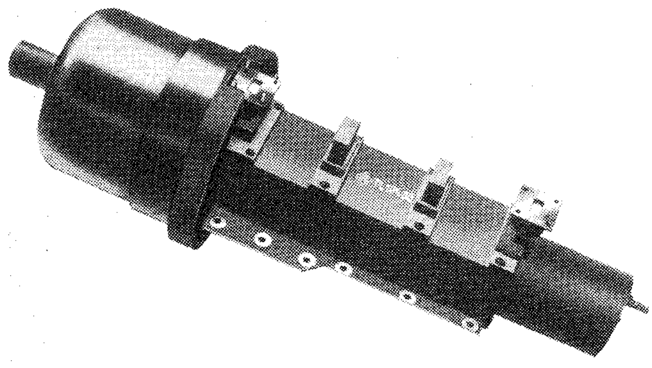

Fig. 1 450 W satellite TWT TL 12 450.

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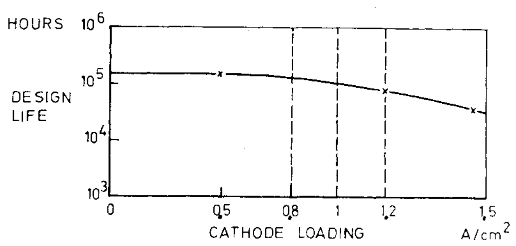

Fig. 2 Design life capability vs cathode loading.

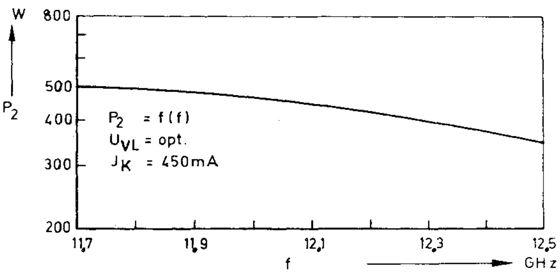

Fig. 3 Saturated output power vs frequency for the 450 W TWT TL 12 450.

The delay line itself consists of three sections which are separated by an internal sever. This gives high insulation between input and output beyond 100 dB. The sections are terminated by absorbers which are designed to withstand very high-reflected power, for instance 100 W continuously, or total output power for a few seconds.

The system has excellent thermal properties, because each copper resonator is directly screwed to the baseplate which is part of the tube housing. The thermal gradient is such that the maximum temperature drop between the baseplate and the hottest point of the output resonator is only on the order of 30°C. For the baseplate to which the tube is mounted, the permissible temperature is −30 to +85°C, which means that the resonator temperature maximum is 115°C. This is well below the maximum allowed copper temperature for long-life tubes.

Collector

Because of the high overall efficiency required the collector is of 5-stage design. A special feature is that the collector is completely decoupled from the baseplate, and radiates its dissipated power directly into space without any additional radiators. The radiator temperature will be at 300-350°C. The mechanical design leads to very low collector weight, approximately 2.0 kg at a total tube weight of 6.7 kg, because direct heat conduction, rather than radiation, is used inside the collector from the electrodes to the outer envelope which is entirely on ground potential. The collector design itself was successfully tested mechanically and electrically in a prequalification program.

RF Measurements

The tube is designed to operate between 11.7 GHz and 12.5 GHz. In order to cover the band, three sets of voltages have to be used. Each set of voltage gives a 1 dB instantaneous bandwidth of 300 MHz.

Figure 3 shows the saturated output power of the breadboard model. From this figure it can be seen that the 1 dB bandwidth is approximately 600 MHz.

Figure 4 shows the measured instantaneous bandwidth of the breadboard model for a typical set of voltages. Optimizing the tube for the required 30 MHz channel leads to less than a 10 W output power variation in a channel.

A typical transfer curve is shown in Fig. 5. The tube gets saturated with an input power of 2 mW which corresponds to

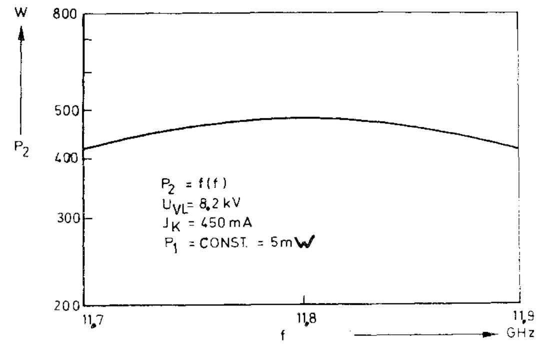

Fig. 4 Instantaneous bandwidth of satellite TWT TL 12 450.

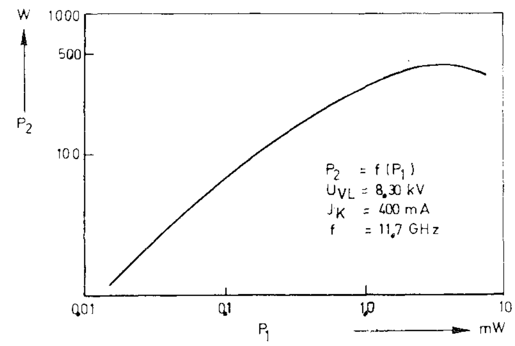

Fig. 5 Output power P_2 vs input power P_I for the 450 W TWT TL 12 450.

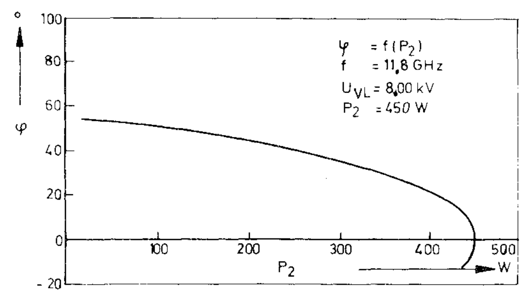

Fig. 6 Nonlinear phase shift vs output power P_2 for the satellite TWT TL 12 450.

53 dB saturation gain. Overdrive levels of up to 10 dB are no problem.

The nonlinear phase-shift is shown in Fig. 6 for a typical voltage setting. In this case the total nonlinear phase-shift is approximately 55 deg, and the a.m.-p.m. conversion factor was measured to be 4.5 deg/dB.

The overall efficiency for different collector designs is shown in Fig. 7.

Fifty percent efficiency is achievable with the chosen 5-stage design. The confidence to meet this figure is obtained by comparing the design goal with the already measured results on other tubes with multi-collector design. In Fig. 7 the curve is given for the 20 W tube TL 12024. So far, a collector efficiency of 85% was achieved with the 5-stage collector design which would lead to an overall efficiency of 48%.

The results obtained indicate, however, that the 50% goal is achievable by improving both the focusing quality from 97% to 98%, and the collector efficiency from 85% to 87%.

Due to an assembly error in the collector, unfortunately only a collector efficiency of 74% could be measured. In spite of the high dissipated power in the collector, no thermal problems were found, even when loading some electrodes up to 500 W.

With a model where the above changes were realized, 50.4% efficiency could be measured.

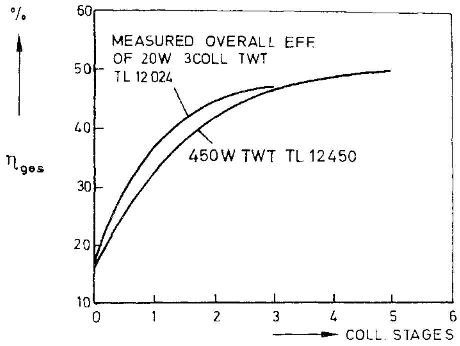

Fig. 7 Overall efficiency η vs number of collector stages.

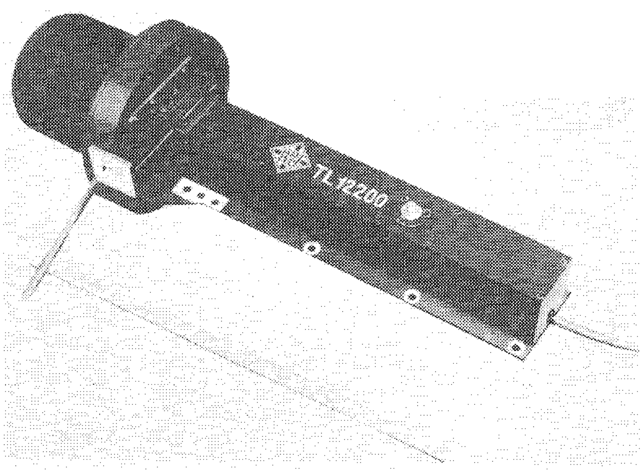

Fig. 8 200 W satellite TWT TL 12 200.

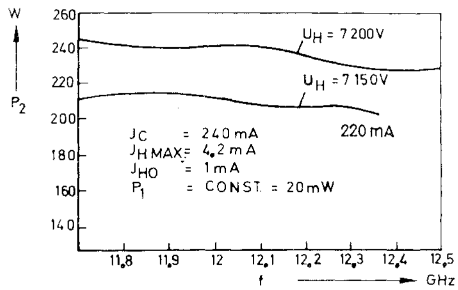

Fig. 9 Output power P_2 vs frequency for the satellite TWT TL 12 200 (all voltages and input power P_2 constant).

200 W TWT TL 12200

Figure 8 shows the breadboard model of the tube. The overall length is 40 cm, and the weight is 2.6 kg.

Concept

The basic design is in some respects quite different from the 450 W tube, and more or less similar to the well-known 20 W OTS tube.

Electron Gun

The electron gun is again of a modified "Pierce" type. A tungsten matrix cathode with a 0.7 A/cm^2 current loading is used which operates near 1020°C. This will result in an expected life of more than 100,000 h minimum. The mechanical design is similar to the orbital test satellite (OTS) tube where radial HV-feed-throughs are used. These feed-throughs are potted with polyurethane which allows operation of the tube under any pressure from normal ambient down to good vacuum.

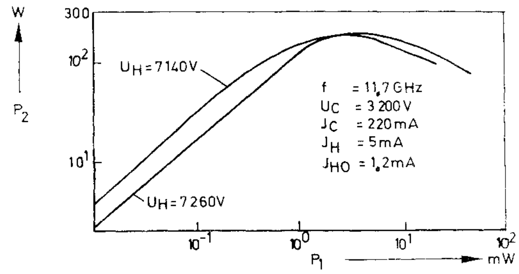

Fig. 10 Output power P_2 vs input power P_I for the satellite TWT TL 12 200.

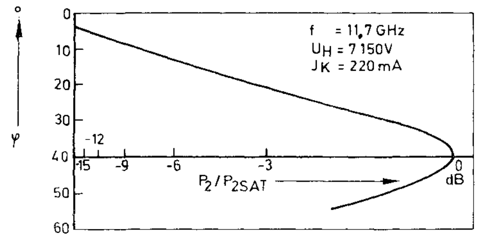

Fig. 11 Nonlinear phase shift ϕ vs output power P_2 for the satellite TWT TL 12 200.

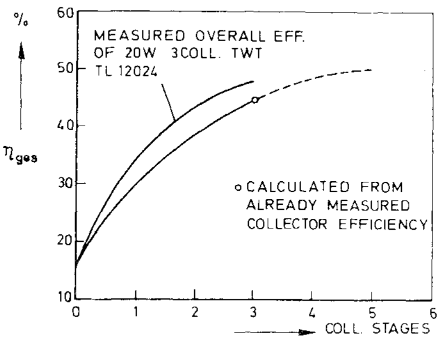

Fig. 12 Overall efficiency η vs collector stages for the satellite TWT TL 12 200.

Delay Line System

The delay line used for this tube is a tape helix. By means of special heat removal design, the helix can be kept within a safe operating temperature for satellite operation, which corresponds to a temperature of about 200°C. The tube is severed and internally terminated by carbon layers on the BeO-helix supporting rods.

In order to have minimum temperature drop from the helix to the baseplate, the pole pieces are of special design, and are braced directly to the vacuum envelope in the output section. The integrated ppm-focusing system uses temperature compensated $SmCo_5$-magnets which give the lowest possible weight for the required axial magnetic force. It should be mentioned that using a helix for this power level is a well-proven design with field experience on a 9 GHz 200 W TWT.

Collector

The collector is of the same basic design as for the 450 W tube. Presently, the tube is equipped with a 3-stage, self-radiating collector that will finally result in 45% overall efficiency. The weight of the collector is approximately 1000 g at a total tube weight of 2600 g which results in a radiator temperature of about 350°C.

RF Measurements

The tube is designed for an instantaneous bandwidth of 800 MHz.

In Fig. 9 the output power vs frequency for constant conditions is shown. The tube has an excellent broadband performance and there is less than 0.5 dB power variation across the whole band.

Figure 10 shows a typical transfer curve. The tube saturates with an input power of 20 mW, which corresponds to 40 dB minimum saturation gain.

Figure 11 shows the nonlinear phase-shift of the tube. The total phase-shift is approximately 40 deg. This is a typical figure across the whole 800 MHz band. Measured intermods give values which are typical for helix tubes (11 dB at saturation, and 36 dB at 13 dB below 2 carrier saturation). The measured noise figure is below 35 dB. The second harmonic was measured 30 dB below the fundamental. This is due to the waveguide output which suppresses the coupling efficiency at these frequencies. The a.m.-p.m. conversion factor was measured to be 4 deg/dB.

The achievable overall efficiency vs collector stages is shown in Fig. 12. From this figure it is evident that 45% should be easily achievable by comparing it with the already measured values of our 20 W tube TL 12024. The same is foreseen for SBS and Anik C.

So far, however, an efficiency of only 42% could be demonstrated with the breadboard, which is 3% below the expected value. It was found that the third collector stage and the refocusing region were not fully optimized. Due to this, backstreaming of electrons occurred resulting in an increased helix current. Separate collector testing was performed, and resulted in a maximum collector efficiency of 84%. With this figure an overall efficiency of 45% will be achieved which exceeds the design goal of 44%.

Conclusions

Two high-power 12 GHz tubes were developed which are presently in the engineering model phase. The 200 W and the 450 W tubes are designed to operate with a self-radiating multistage collector. The self-radiating collector design itself was successfully pre-qualification tested.

The rf test results which are available to date state that the tubes will meet their main specified parameters for use as power amplifiers for broadcasting satellites. The key parameters for the 200 W tube are 44% efficiency and 2.6 kg weight, and for the 450 W tube, 49% efficiency and 6.7 kg weight.