Traveling-Wave Tube for the Communication Satellite "Symphonie"

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A traveling-wave tube of European origin for application in spacecraft power amplifiers is described. For the frequency range from 3.7 to 4.2 GHz, the tube delivers an optimum saturated output power of about 12 w at an over-all efficiency of about 38%. Utilizing the special Alnico-alloy VS 55 developed by Krupp and special design techniques, a relative weight of less than 40 gm/w is obtained. It is shown that nonlinear distortions (am-pm-conversion and compression) are strongly dependent on such parameters as rf input (output) power and helix voltage. At an efficiency of 35% the am-pm-conversion is less than 4°/db. Further, it is shown that optimum operation conditions exist for minimum intermodulation. The relevant parameters are different from those for optimum over-all efficiency. Nickel A and 0.1%-Zr nickel is used for cathode material. Results on life tests indicate that a life of more than 50,000 hr can be obtained.

Introduction

IN 1964 the microwave tube department of AEG-TELEFUNKEN began developing traveling-wave tubes (TWT's) for communication satellite applications under a contract of the German "Ministerium für wissenschaftliche Forschung." The development work is based on our extended experience with microwave tubes and especially TWT's for civil and military application. The main features of the TWT's which were developed until then within AEG-TELEFUNKEN were their good transfer characteristics, especially for application in broadband radio link systems, long tube life, and resistance to severe environmental conditions. Based on this experience a TWT for space application had to be developed. Additional requirements for the TWT for satellite application are the following: 1) lowest possible weight (this means lowest weight/watt rfpower at sufficient low electrode dissipation consistent with long life), 2) highest possible efficiency, 3) low pressure- and vacuum-environment, 4) highest possible reliability, and 5) low nonlinear distortion for multi-carrier operation.

At the end of the development program a TWT was obtained which, in different respects, simultaneously comes up to the advanced state of the art. In some respects we gained knowledge that has not been published before. When in 1967 the project "Symphonie" was set up, a TWT, type TL 4002, could be offered as a broadband amplifier for the satellite transponder. For this project an extended qualification test program including life test on about 100 tubes has been started. The TWT TL 4002 is shown in Fig. 1.

Design

The design of this type was chosen according to the foregoing requirements. To reduce weight, periodic permanent magnet (PPM) focusing and miniature coaxial rf connectors are used. The weight of a PPM-system depends strongly on two parameters, the inner pole piece diameter and the quality of the magnetic material to be used. The inner pole piece diameter has to be as low as possible. For the TWT TL 4002 it has been reduced to 6 mm. The magnetic material used is an Alnico alloy recently developed by Krupp. The alloy is called VS 55 and has a higher energy product ($5.5 \cdot 10^6$ Oe-Gauss) and a higher coercive force (1800 Oe) than do conventional Alnico alloys like Alnico 8. A further reduction in weight can be obtained by choosing a proper value of the helix parameter (in cm-GHz/$v^{1/2}$)

$$\gamma a = 2\pi \cdot fa/Vp = 10^2 f \cdot a/U_h^{1/2} \quad (1)$$

where a is the helix radius, f is the rf frequency, and U_h is the helix voltage. The highest gain/cm and the flattest gain response vs frequency for an electron beam of fixed parameter are obtained at $\gamma a \approx 1$. Combining all this in the TWT TL 4002 resulted in a weight of less than 40 gm/w.

Since it must withstand severe environmental conditions, the TWT TL 4002 is of all metal-ceramic construction. Special care had to be taken to obtain a rugged electron gun assembly at sufficient low heater power consumption. The tube, including its magnets, is embedded by epoxy resins on a gold-plated magnesium mounting plate.

Although there are other possibilities for tube failures (e.g., reduction of insulating resistance, evaporation of helix material and reduction of the loss of the attenuator on the helix supporting rods or microleaks), tube life ultimately is limited by cathode wearout. To get a good life and reliability a cathode loading of only 90 ma/cm² is used. By extensive resistor network calculations an electrode configuration was obtained which resulted in a low change of cathode loading across the cathode surface of only ±5% at a beam compression of 40. The power dissipation of any electrode including collector and helix is reduced to a quarter compared to conventional TWT's.

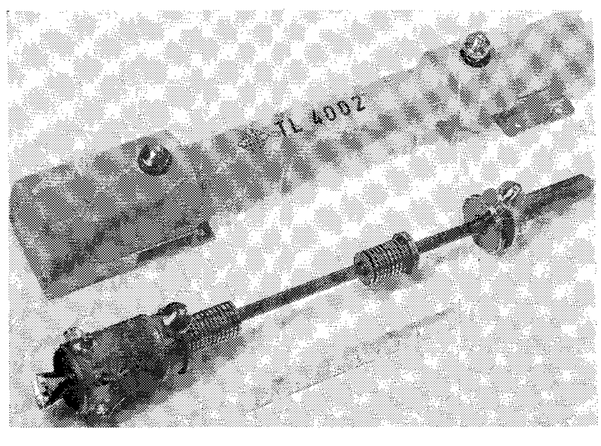

Fig. 1 TWT TL 4002.

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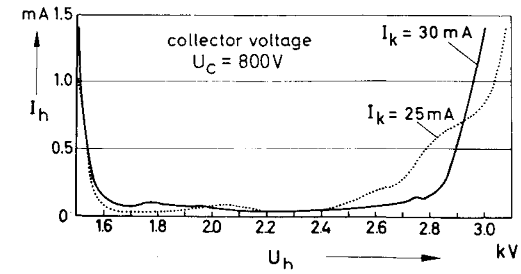

Fig. 2 Helix interception current vs helix voltage for different values of cathode current.

The best compromise among the need for high over-all efficiency, the expense for the power supply, and the over-all reliability seems to be a TWT with a single-stage collector, operated at reduced potential. Therefore, a single-stage collector is used in the TL 4002.

At the beginning of the development very little published material was available on TWT nonlinear distortions, especially for multi-carrier operation. Therefore, a lot of experimental investigations on this topic had to be carried out.

It is well known that beam focusing has an essential influence on different features such as life and efficiency. The beam transmission T (%)

$$T = 100(J_k - J_h)/J_k \tag{2}$$

has to be as close to 100% as possible (I_h = helix current, I_k = cathode current).

An analog computer program had been run to evaluate optimum entrance conditions of the electron beam from the electron gun into the PPM system. These computations showed that the first peak of the magnetic field should be about 70% of the main system, and the beam should be converging slightly when entering the magnet system.

When assembling the magnet stack, the peaks of the magnetic field are adjusted to $\pm 2\%$ from the average; positive and negative peaks have to be equal to within 1%, and transverse magnetic field components have to be less than 1% of the axial component. When we tried to obtain low helix interception with rf-drive of the TWT and high-efficiency simultaneously, we found that the transmission without rf-drive should not only be excellent for the specified helix and collector voltage but also for a wide range of the helix voltage around the specified value and at a much higher collector potential reduction than specified. Further, a good beam transmission should be obtained at elevated cathode current. Figure 2 shows the helix current vs helix voltage for a cathode current of 25 and 30 ma. This corresponds to a transmission of more than 99.5% within the helix voltage range from 1600 to 2500 v.

Figure 3 shows the helix current for different cathode currents vs collector voltage at fixed helix voltage. Down to $U_c \approx 0.15\ U_h$ the helix current is nearly constant, corresponding to a transmission of more than 99.5%.

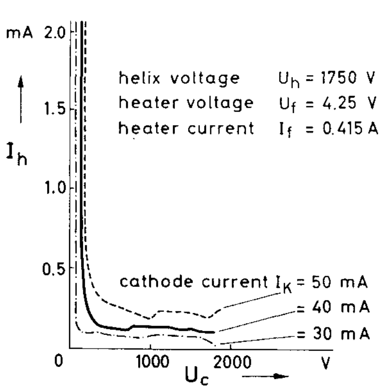

Fig. 3 Helix interception current vs collector voltage without rf drive.

Characteristic Data of the TL 4002

The specific TWT developed according to the preceding considerations has the following rf characteristics:

Frequency range	3.7–4.2 GHz
Optimum saturation power P_2SATopt	12 w
Small signal gain G_{ss}	55 db
Optimum over-all efficiency η_{opt}	38%

The tube is broadband matched. The cold VSWR for the entire frequency range without any need for tuning is less than 1.25. The cathode current can be changed over a wide range at excellent beam transmission. If the cathode current is changed, there is no need for the readjusting the magnetic system. Consequently, the output power can be changed from about 1 w to about 15 w. For the output power range from 7 to 15 w, nearly constant efficiency is obtained. For a single carrier saturation output power of 10 w at optimum efficiency as it is necessary for the communication satellite Symphonie, the d.c. data have to be adjusted as follows:

Cathode current I_k 27 ma	Helix voltage U_h 1900 v
Collector voltage U_c 1000 v	Heater power P_f 1,7 w

As in the communication satellite Symphonie, either single-carrier or multi-carrier operation shall be used; a good part of the developmental work was devoted to TWT-nonlinearities. In the following, mainly these investigations are described.

Single-Carrier Transfer Characteristics

For the TWT TL 4002 operating at constant cathode current as well as for all TWT's of similar design, three parameters must still be adjusted to obtain optimum performance. These are helix voltage U_h, collector voltage U_c, rf input power P_1 or rf output power P_2 alternatively. As the rf output power is of greater importance for system performance, in the following essential tube characteristics are mainly related to rf output power.

Once the parameters for optimum performance have been chosen, it is necessary to know what input power has to be provided. For this reason the relation between input and output power is of interest. This depends strongly on the helix voltage, but not on the collector voltage. Figure 4 shows input-output relations for the TWT TL 4002. From Fig. 4 it can be concluded that the helix voltage for optimum small signal gain is U_h = 1750 v and for optimum saturated rf output power U_h = 2075 v. The small signal gain is about 55 db. Despite this high gain the tube is short-circuit stable. To obtain this external and internal feedback had to be avoided. By proper construction of the rf couplers, external rf feedback via rf leakage is eliminated. Internal feedback is reduced using attenuators with extremely low reflection ($r < 0.3\%$), by manufacturing helices with pitch tolerances of less than 2% and by using severed helices, which increases decoupling between rf input and output to more than 120 db.

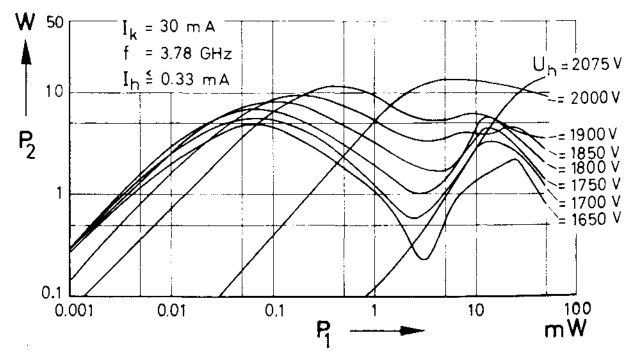

Fig. 4 Input power vs output power for different values of helix voltage.

In spite of all this, feedback may occur by means of reflected electrons from the collector. These have been eliminated by proper construction of the collector and by introducing transverse magnetic components in the collector.

One of the most important features for all devices in satellites is efficiency. A fairly high efficiency is still now one of the decisive advantages of the TWT over semiconductor devices. TWT over-all efficiency is

$$\eta = \frac{P_2(P_1, U_h)}{P_f + J_h U_h + J_c U_c(P_1, U_h)} \tag{3}$$

P_2 depends on rf input power and helix voltage as it is shown in Fig. 4. Because of rf drive an electron velocity spectrum is produced in the electron beam. Most of the electrons are slowed down, transferring kinetic energy to the rf wave. The energy loss of these electrons corresponds to a voltage change of $e \cdot \Delta U$. As electrons can only give up energy to the collector they can only be collected by the collector if $U_c \geq \Delta U$. Otherwise they are repelled and collected by the helix resulting in increased helix interception current. Collector potential, therefore, can only be reduced to such an extent that helix power dissipation is within safe limits. As the velocity spectrum of the electron beam for a TWT of given design depends on output power and helix voltage, efficiency itself can be plotted vs output power with helix voltage as parameter. In Fig. 5 this is done for the TWT TL 4002. The optimum over-all efficiency is $\eta = 38\%$ at about 90% of optimum saturation power. For fixed helix voltage best efficiency is obtained at saturation power. Similar curves will be obtained for TWT's of similar design.

In contrast to the published observations made by Schindler[1] an over-all efficiency of 38% was obtained even at a value of the helix parameter γ_a of only 1.1.

Nonlinearities produce distortions of the signal modulated on a rf carrier. These distortions depend on the rf power level of the carrier. Two different types of level-dependent nonlinearities, amplitude and phase nonlinearities, have to be distinguished.

Amplitude nonlinearities can be measured by the compression factor

$$c = 1 - \frac{(\Delta P_2/P_2)}{(\Delta P_1/P_1)} \tag{4}$$

ΔP_1 is a change of rf input power P_1. The associated change in rf output power P_2 is ΔP_2. This compression factor is of minor importance for fm signals, which are used in satellite systems.

A measure for level-dependent phase nonlinearities is the am-pm-conversion factor

$$k_p = \frac{\Delta\phi}{\Delta P_1/P_1} \text{ expressed in deg/db} \tag{5}$$

$\Delta\phi$ is the phase change of the output rf-wave caused by a change ΔP_1 of rf input power P_1. Am-pm-conversion as well

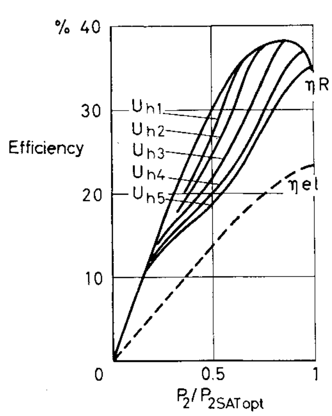

Fig. 5 Over-all efficiency of the TWT TL 4002 vs output power at different values of helix voltage.

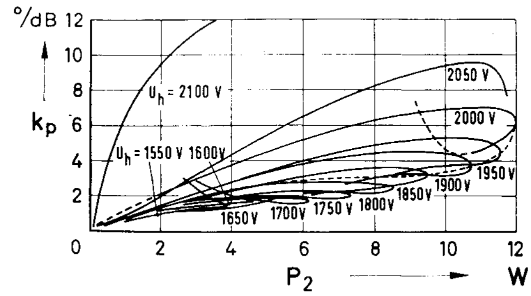

Fig. 6 Am-pm-conversion of the TWT TL 4002 vs output power for different values of helix voltage.

as efficiency depends on rf output power and helix voltage. Figure 6 shows a diagram of am-pm-conversion vs rf output power with helix voltage as a parameter. For a fixed helix voltage the am-pm-conversion factor is proportional to rf output power. It comes to a maximum at about 50–80% of saturation power and decreases near to saturation. Am-pm-conversion increases with increasing helix voltage. Figure 6 shows that am-pm-conversion varies in such a wide range that it is impossible to state am-pm-conversion as a tube characteristic. It makes more sense to take the maximum efficiency at a given value of am-pm-conversion as a tube characteristic. For the TWT TL 4002, one can determine from Fig. 5 and Fig. 6 that the maximum over-all efficiency at $k_p = 4°$/db is about 38%. Unfortunately there are not sufficient data so far available for other TWT's to compare this figure.

Nonlinear Distortions at Multi-Carrier Operation

At multi-carrier fm operation the amount of distortion is mainly determined by intermodulation products. Intermodulation transfers part of the modulation from one carrier to the other. It has been investigated elsewhere[2] that the amount of distortions for multi-carrier fm transmission depends on the number of carriers and the order of intermodulation product falling on an fm carrier. The highest level occurs for the third-order intermodulation products at the frequencies $f_m + f_n - f_r$ (f_m, f_n, f_r are frequencies of different carrier). Wescott[2] evaluated the maximum tolerable level of these intermodulation products for fm multi-carrier transmission taking into account the limits for intermodulation noise for radio link systems recommended by the CCIF.

To determine the set of parameters U_h, P_1, U_c which would yield the highest efficiency at a fixed rf input level for third-order intermodulation products, two-carrier measurements

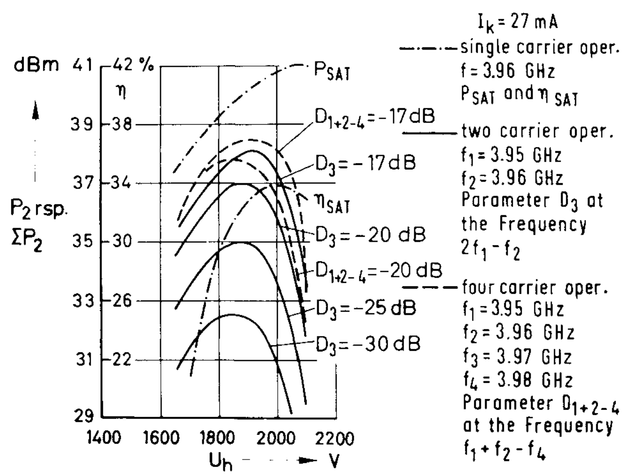

Fig. 7 Total output power of the TWT TL 4002 at multi-carrier operation with intermodulation products as a parameter.

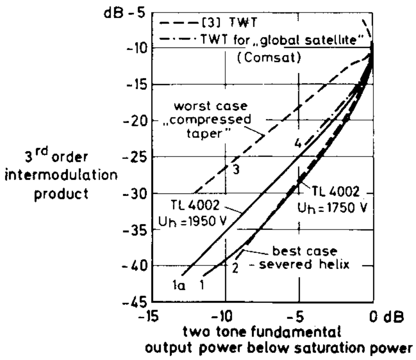

Fig. 8 Third-order intermodulation products below saturation power.

were performed. The third-order intermodulation product D_3 at the frequencies $2f_{1,2} \pm f_{2,1}$ was observed. The two-carrier output power was measured as a function of helix voltage for fixed values of D_3. Corresponding measurements were performed with four instead of two carriers. In this case the third-order intermodulation products with the frequency $f_1 + f_2 - f_4$ were measured. The results of these measurements are shown in Fig. 7, where three different types of curves are plotted vs helix voltage: 1) single-carrier saturation power, 2) maximum over-all fundamental output power for two-carrier operation for different values of D_3, and 3) maximum over-all fundamental output power for four-carrier operation for different values of D_{1+2-4}.

The result is that there is a maximum of multi-carrier fundamental output power at a helix voltage below the value for optimum saturation power. The helix voltage increases somewhat with increasing level of third-order intermodulation products. The maximum of multi-carrier fundamental output power for different numbers of carriers but the same level of third-order intermodulation products appears to be at about the same helix voltage. To obtain the highest efficiency, the results of Fig. 7 can be combined with those of Fig. 5 for the special case of two carriers and $D_3 = -17$ db. Any power level is transferred from Fig. 7 to Fig. 5 on to the curve for efficiency vs output power with constant helix voltage. All these points are connected by a dotted line. The result is that maximum multi-carrier efficiency is obtained at a helix voltage somewhat lower than that for highest single-carrier efficiency. After evaluation of the optimum operating parameters for multi-carrier operation, the question remains how the amount of intermodulation products of the TWT TL 4002 compared with those of other TWTs.

In Fig. 8, D_3 of the TWT TL 4002 is plotted vs the "backoff" of the two-carrier fundamental rf output power with respect to the two-carrier fundamental saturation rf output power for two conditions: 1) for helix voltage adjusted for optimum single carrier efficiency (curve 1a) and 2) for helix voltage

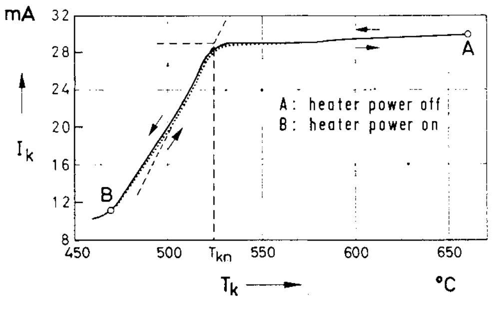

Fig. 9 Cathode current vs cathode temperature.

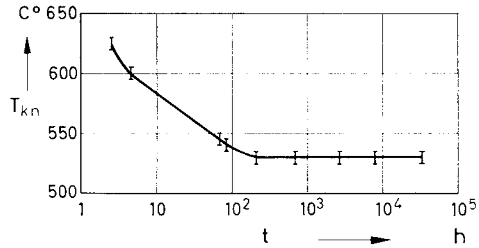

Fig. 10 Transition temperature vs time of operation.

adjusted for nearly optimum multi-carrier efficiency for $D_3 = -17$ db (curve 1).

For a comparison two corresponding curves measured by Foster and Kunz[3] are shown in Fig. 8. One is the best curve obtained for a severed helix tube (curve 2) and the other is the worst curve (curve 3) obtained for a TWT with compressed helix taper. In addition, a curve is shown for a TWT which in Ref. 2 is said to be the TWT for the COMSAT global satellite. It can be seen that the curve for the TWT TL 4002 adjusted for optimum multi-carrier performance is nearly the same as for the best tube. The curve for the TWT TL 4002 adjusted for optimum single-carrier efficiency is slightly better than for the tube from Ref. 2 (curve 4).

Tube Life

As was pointed out earlier, tube life is a matter of cathode life. For the design of the cathode of the TWT TL 4002 we referred to the investigations of Bell Labs.[4] Ni-A and 0.1% Zr doted Ni with 1 mm thickness is used as cathode base material. The base material has a triple carbonate rather than a double carbonate coating. By means of this a somewhat lower work function of the cathode was obtained. An excellent measure for cathode quality is the transition temperature from space-charge-limited emission to saturation current. The definition of this temperature is shown in Fig. 9 (T_{kn}). Transition temperature depends sensitively on many parameters as residual vacuum processing of the tube and cathode activation. For the TWT TL 4002 a transition temperature of $530 \pm 20°C$ was measured for more than 20 tubes. It is known that transition temperature changes long before any change in emission can be observed. Therefore, the transition temperature is measured during life tests by dip testing. The result of these measurements is shown in Fig. 10. Cathode activation is completed 100–200 hr after processing of the tube. The transition temperature is constant up to 20,000 hr indicating a good probability for obtaining more than 50,000-hr life. This conclusion is supported by the results we obtained on the life of the TWT type TL 6 for radio link communication. For this tube we obtained an average life of 35,000 hr and best figures around 65,000 hr.

References

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