The inductive output tube
The latest generation of amplifier for digital terrestrial television transmission

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The inductive output tube (IOT) is the latest generation of amplifying device for use in high-power transmitters. It entered service in 1991 and is now used world-wide as a more efficient replacement for the klystron at UHF.

The performance of the IOT in analogue television transmitters is outlined here. The article also presents and discusses the results of its performance as the final amplifier in the new generation of digital terrestrial television transmitters.

1. Introduction

The transmission of a terrestrial television service at UHF frequencies commenced several decades ago. Since its inception there has been continuous improvement in the technology employed – both in the electron tubes available as the final high-power amplifiers and in the transmitters themselves. The principal objective throughout this period has been to reduce the cost of ownership of a transmitter whilst in no way compromising the reliability which is the hallmark of the television broadcast transmitter.

Three different types of tubes are in general use as the final amplifiers in UHF television transmitters:

– tetrodes;

– klystrons;

– inductive output tubes.

When the UHF television service began, tetrodes were a natural choice. They were available and considerable experience of their use as VHF amplifiers had already been obtained. With some development they were soon capable of providing output powers of up to 20 kW at frequencies of up to 860 MHz. However, their gain is low and their average lifetime is only up to 15,000 hours.

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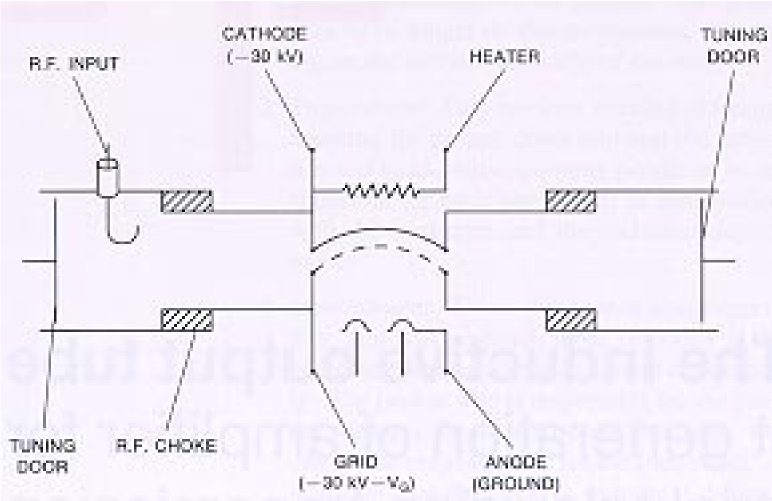


Figure 1
Schematic of the IOT electron gun region.

Klystrons have been used as the final amplifier tube for many years. They have high gain, high stability, excellent reliability and long lifetimes. The main disadvantage of these rugged tubes is their lack of efficiency. By the early 1980s, the RF conversion efficiency had been improved to 40% but, nevertheless, energy awareness still emphasized the demand for even greater energy savings. Consequently two modifications to the klystron were introduced:

1. A low-voltage beam control electrode was incorporated in the gun region. Using this electrode, the beam current can be pulsed between two values – a high value during the high power, relatively short, sync pulse period of the TV waveform and a low value during the picture period. Thus the average beam power consumption has been reduced considerably.
2. A multi-stage depressed collector has been incorporated, so that an appreciable proportion of the energy remaining in the electron beam, downstream of the RF interaction region, can be recovered.

Despite these advances, the search for even more efficient amplifier tubes continued. This included an examination of old ideas and resulted in the development of a new family of UHF television amplifiers – the inductive output tube (IOT). This tube entered service in 1991 and is now used world-wide. It is established as the technology of choice for the final amplifier in new higher power UHF TV transmitters.

This article describes the IOT, outlines its performance in analogue TV transmitters, and presents and discusses the results of its performance as the final amplifier in the new generation of digital terrestrial television transmitters.

2. Principle of operation

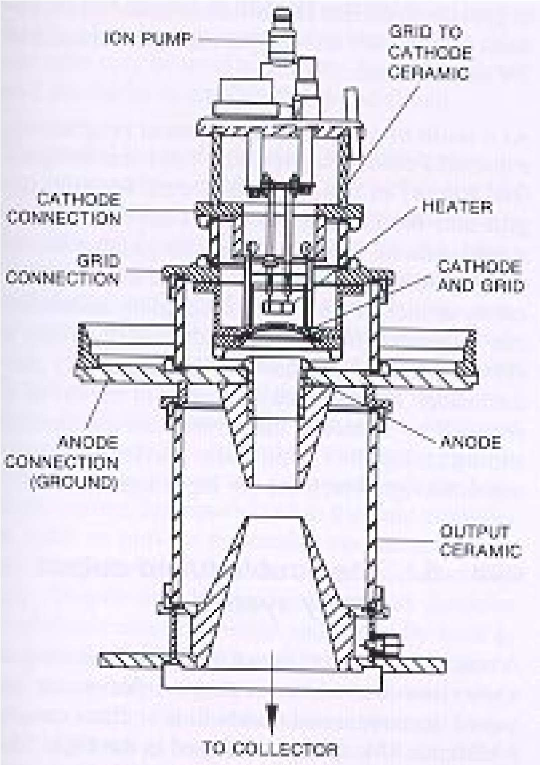
The principle of operation of an IOT is not new. Indeed it was originally described by Andrew Haeff as long ago as 1939 [1]. Essentially, the IOT combines various aspects of tetrode and klystron technology to produce a compact highly-efficient amplifier.

The major difference between the operation of a klystron and an IOT is the method used to form the bunches in the electron beam. In a klystron, velocity modulation is imposed on the beam electrons at an RF input gap. This is followed by a long drift space in which electrons which are speeded up at the input gap catch up with electrons which passed the input gap earlier but which have subsequently been slowed down. Thus bunches of electrons are formed.

In an IOT, on the other hand, the RF input signal is applied between the cathode and a grid which is positioned close to and in front of the cathode (see *Fig. 1*). The electron beam is thus density modulated within the gun region itself. A DC bias voltage (V_G) of about minus 80 volts relative to the cathode potential is applied to the grid so that with no RF drive a quiescent current of about 500 mA flows. The cathode is held at the negative beam potential of about –30 kV and the density-modulated beam is thus accelerated through an aperture in the grounded anode to the output section. Here, power is extracted via a conventional klystron output system, except that a double-tuned cavity system is used in order to provide the 8 MHz channel bandwidth required for UHF TV transmissions in Europe and many other parts of the world. Finally the electron beam is dissipated in a copper collector of traditional design – either air-cooled or liquid-cooled depending upon the power level involved.

Abbreviations

8-VSB	Eight-vestigial sideband
BER	Bit error rate
COFDM	Coded orthogonal frequency division multiplex
DVB	Digital Video Broadcasting
FOM	Figure of merit
ICPM	Incidental phase modulation
IOT	Inductive output tube
OFDM	Orthogonal frequency division multiplex
PEP	Peak envelope power



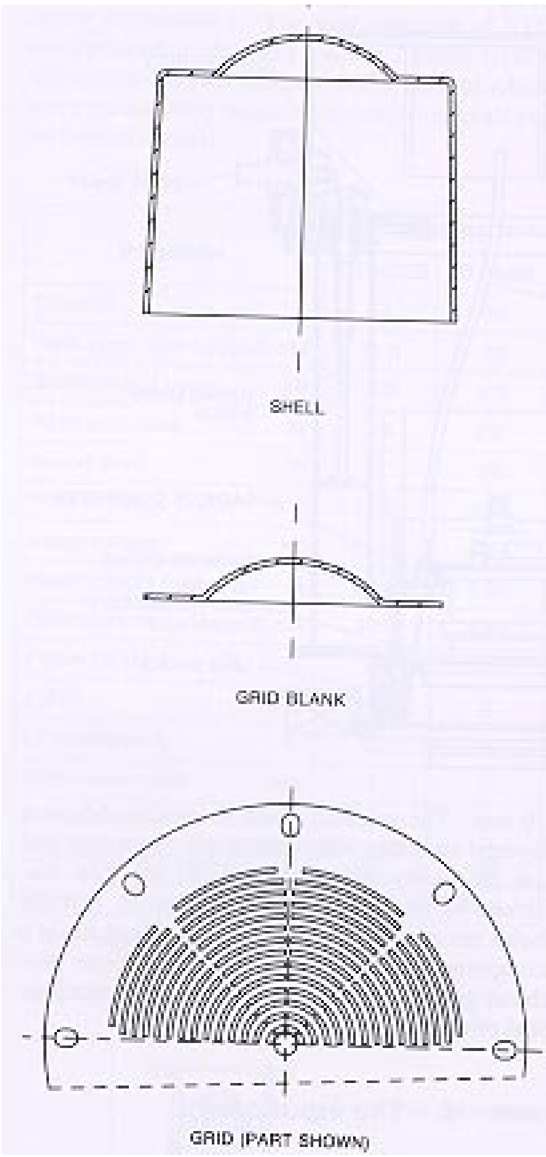


Figure 2
IOT construction.

Figure 3
Drawings showing a graphite grid shell, a grid blank and a finished grid.

3. *The electron gun design*

A typical arrangement of an IOT gun structure is shown in *Fig. 2*. With the exception of the grid, all elements of the gun are taken from or use the same technology as the well-proven designs used in conventional klystrons. The grid itself is clamped in place in front of the cathode, supported on a metal cylinder and isolated from the cathode by a ceramic insulator which also forms part of the vacuum envelope. This is the grid-to-cathode ceramic insulator through which the RF energy from the input cavity enters the tube to apply the RF voltage to the grid. A second ceramic insulator supports the electron gun at the correct distance from the grounded anode. This second insulator is also part of the vacuum envelope and holds off the beam voltage of up to 35 kV.

Computer-aided design (CAD) techniques have been used to determine the values of various gun parameters – such as the cathode and grid radii of curvature. Other parameters such as grid wire size and the number and shapes of the apertures can also be established. One vital dimension is the cathode-to-grid separation; this gap is at the end of a complex transmission line, the other end of which is the input cavity RF input connector. Indeed this distance is crucial to the operation of an IOT because parameters such as tube gain and linearity are particularly sensitive to it. It is essential that not only is this distance set accurately but also that it is maintained over the design life of the tube (which was set at a minimum of 20,000 hours).

The choice of material is therefore of fundamental importance, especially since it must maintain its physical shape when placed in close proximity to a cathode operating at a temperature of about 1,000°C. Pyrolytic graphite has a particular advantage for this application in that its strength increases with temperature up to about 2,500°C. The grids are produced by feeding methane into a low-pressure chamber containing a graphite rod of the correct form to produce the required graphite "shell"– a cylinder with a closed-shaped end (*Fig. 3*). The cold gas is passed into a hot zone in the reactor which is heated by an RF eddy current system from outside the vessel. The temperature is set to about 2,000°C and the pressure to around

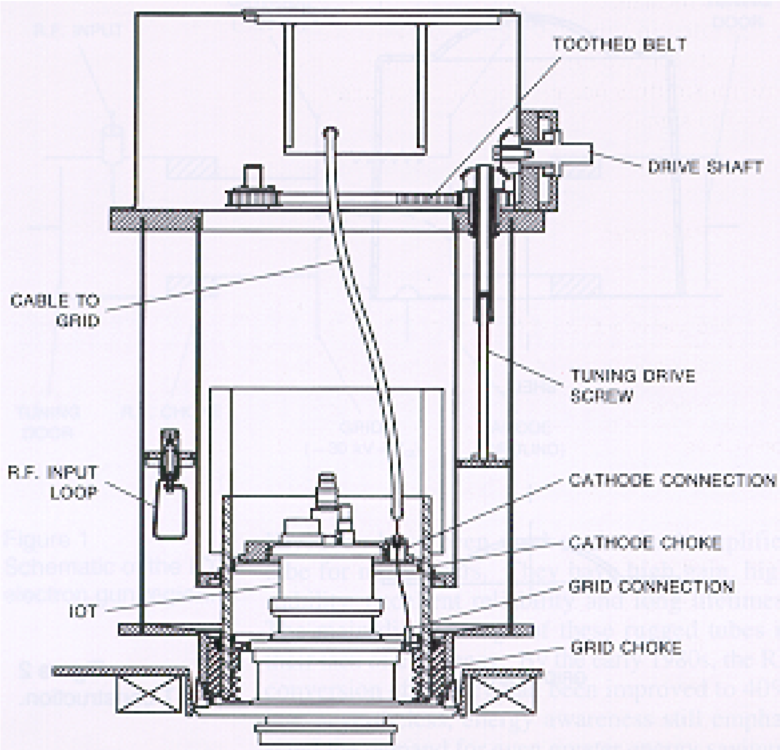


Figure 4
IOT input cavity.

10 torr. The graphite shells so produced have a layered structure with anisotropic properties and are physically strong. The shells are then machined to the shape and size required, and the holes are cut into the resultant grid blank using a computer-controlled laser. This technique produces grids having excellent thermal and mechanical properties.

4. The input cavity

External resonant cavities (that is, cavities external to the vacuum envelope) have been used on klystrons for many years. Generally they consist of a split box, the two halves of which can be placed around the klystron and bolted together. There are two doors within the cavities – one in each half – whose positions can be adjusted so that the tuned frequency can be changed.

In principle, a similar structure can be adapted for an IOT input cavity. However in this case the inner wall of the cavity has to be connected between the cathode and grid – two electrodes which are both at a large negative potential. Further, it is necessary to maintain the outer wall of the cavity and its tuning mechanism at ground potential. The cavity therefore incorporates RF chokes between the two parts which are designed to prevent the leakage of RF energy whilst holding off the full beam potential. Care has to be taken with the choice of insulating material for the chokes; it has to provide excellent DC isolation under all conditions of humidity and temperature encountered in TV transmitters.

As a result of a specific development programme, a patented coaxial input cavity has been designed (see *Fig. 4*) in which the dielectric for both the grid and the cathode chokes is derived from a single ceramic cylinder. This design also allows the grid lead to be fed through the centre of the cavity so that RF and video decoupling assemblies can be placed close to the tube itself, giving a system which possesses very good linearity performance. The resonant frequency of the cavity is changed by adjusting the position of the annular sliding tuning door, which also carries a loop antenna through which the RF input signal is fed.

5. The double-tuned output cavity system

A major requirement for an amplifier operating in a television transmitter is that it achieves the required instantaneous bandwidth – for example 8 MHz for PAL system I (as used in the UK). The conventional klystron has intermediate cavities which are stagger-tuned to slightly different frequencies in order to do this. However the IOT has no such intermediate cavities and so it is necessary to employ a double-tuned output cavity system. The design adopted (see *Fig. 5*) consists basically of a pair of orthogonal conventional cavities.

The primary cavity is clamped around the IOT. It contains a rotatable RF coupling loop which can adjust the amount of coupling (via a short length of transmission line and a door-knob type antenna) to the secondary cavity. The secondary cavity contains a dome structure whose size is such that the cavity covers the required frequency band. A standard “klystron-type” output coupler connects the cavity to the output feeder system. The cavities are cooled with filtered forced air.

There are four adjustable controls – a tuning control for each cavity and two coupling loops. These are fitted with digital indicators or scales so that the IOT can be tuned rapidly to any required channel of operation.

6. Analogue TV performance

Tubes installed in negative modulation analogue TV transmitters can be operated in either of two distinct modes. In the first mode, the tube amplifies either the vision signal alone or the sound signal alone. A number of tubes are employed and their outputs are combined so that the overall transmitter output consists of the combined vision and sound signals at the correct relative power levels. For high-power transmitters, more than one tube may be used to amplify the vision signal and, similarly, to amplify the sound signal.

The second mode of operation, which is termed the *common amplifier mode*, is one in which individual tubes amplify both the vision and the sound signals. For this application, the linearity of the tube's transfer characteristic is of vital importance. When amplifying two signals simultaneously, any non-linear amplifier will produce intermodulation products. These products can generate unacceptable disturbances on the television picture, depending upon their amplitudes: the maximum permitted values are therefore defined by transmitter specifications. Transmitters are equipped with facilities to pre-correct the input signal to the final amplifier in order to provide reasonable compensation for the non-linearity of the tube's transfer characteristics. Despite this, klystrons operated as common amplifiers cannot be pulsed and generally have to be derated by about 4 dB with respect to their nominal vision-only output power. Consequently they become inefficient. It is therefore customary to operate klystrons as vision- or sound-only amplifiers and to adopt a common amplifier mode of operation only in an emergency.

In contrast, the IOT has an excellent linearity characteristic and can be operated at high power levels in the common amplifier mode with a level of intermodulation products which can readily be pre-corrected to give an acceptable overall transmitter performance. The vast majority of IOTs are operated in this way. *Table 1* gives typical test results for two different IOTs, both of which were transmitting negative-modulation analogue television signals.

Parameter		Tube type	
		IOT9202R	IOT8505
Channel		43	35
Peak sync, vision output	kW	12.8	55
Sound output power	kW	1.28	5.5
Peak sync drive	W	70	231
Sound drive	W	5	20
Peak envelope power	kW	22.2	95.1
Beam voltage	kV	21.9	35
Beam current (mid-grey)	A	0.82	1.56
Beam current (quiescent)	mA	490	520
Figure Of Merit	%	78	111
ICPM	deg	2	2
LF non-linearity	%	10	15
Differential phase	deg	1	5
Differential gain	%	9	4
Intermodulation products*	dB	–55	–52
Gain	dB	22.6	23.8

* with respect to peak sync.

Table 1
Common amplifier performance.

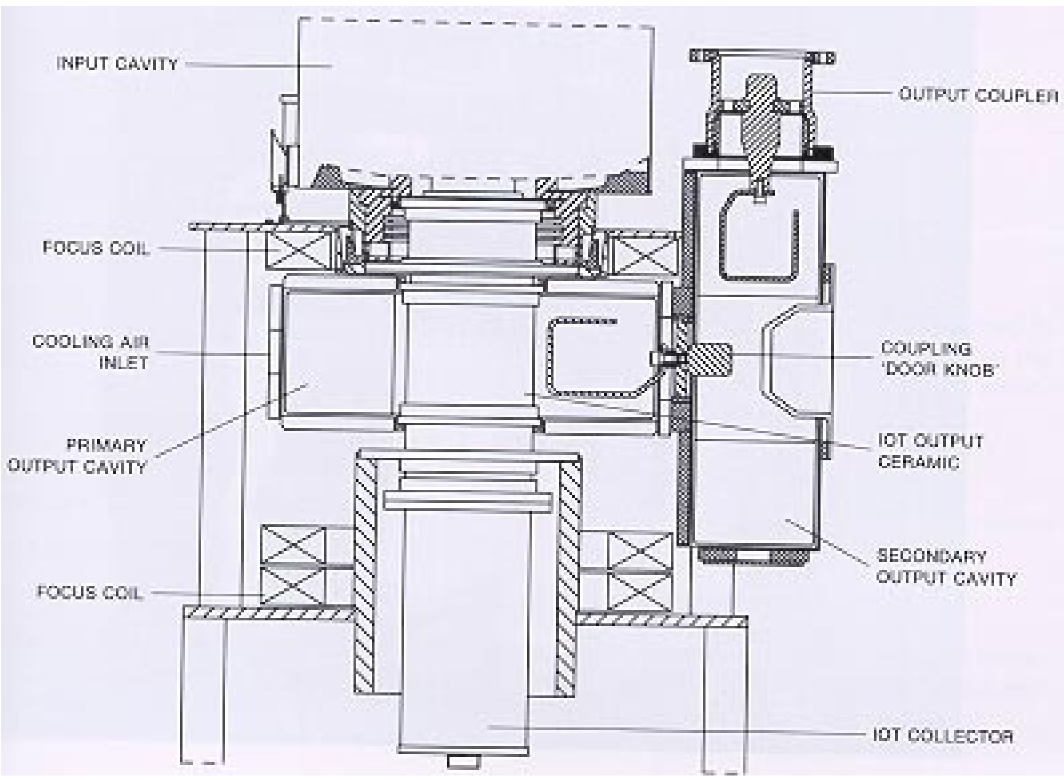


Figure 5
IOT output system.

Figure 6
The IOT9202R inductive output tube.

The IOT9202R (*Fig. 6*) is an air-cooled tube, designed for lower power operation whereas the IOT8505 has a liquid-cooled collector and is designed for high-power transmitters. The Figure of Merit (FOM) is high. The values of the TV parameters – ICPM, LF non-linearity, differential gain and phase, and intermodulation products – were all measured with no pre-correction applied to the IOT input signal, apart from the sync stretch necessary to obtain the correct sync-to-black ratio at the output.

The values of these parameters do vary over the UHF TV frequency range: e.g., non-linearity rises to about 22% at channel 69. Nevertheless the results show that the IOT can readily be corrected using existing technology to give good overall transmitter performance. The gain of the tube (20 to 23 dB) is considerably lower than that of a klystron (30 to 40 dB) but appreciably higher than that of a tetrode (about 15dB). Drive powers of several hundred watts are required for the high-power IOTs but this is well within the capability of present-day solid-state amplifiers.

IOTs have also been tested when amplifying a positive modulation analogue TV signal – in which white luminance is at a high power level and peak sync is at a low power level. Since the

Figure of Merit (FOM)

A major driving force in the development of new amplifying tubes for UHF television transmitters has been the quest to reduce operating costs. Comparison of the operating efficiency of different tubes is therefore an important factor when judging their relative merits. The TV broadcasting industry has adopted the Figure of Merit (FOM) as the comparative standard. It is customary to refer to the power of a TV transmitter as that power transmitted during the peak sync pulse of the TV waveform. However the TV signal is an amplitude-modulated waveform and the power level for a very high proportion of the time is far less than the peak sync level. The beam current of an IOT varies in accordance with the instantaneous RF power required and therefore the average beam power consumed is much less than the peak beam power required during the peak sync period.

The Figure of Merit is defined as:

$$FOM = \frac{RF\ Peak\ Sync\ Output\ Power\ (P_V)}{Average\ Beam\ Power\ (P_B)} \times 100\%$$

where the average beam power is the power consumed when a mid-grey luminance signal is being transmitted. Values of FOM greater than 100% can therefore be obtained.

For a tube operating in common amplifier mode, the FOM is defined as:

$$FOM = \frac{P_V + P_A}{P_B} \times 100\%$$

where P_A is the audio (sound) power.

Peak Envelope Power (PEP)

When a single tube is used to transmit both the vision and sound services, it is referred to as the *common amplifier mode*. The peak instantaneous RF output (*P*) occurs at the moment when the voltage vectors for the vision and the sound services sum. For a monophonic system this is given by:

$$P = V(1 + \sqrt{A})^2$$

where *V* is the peak sync vision output and *A* is the ratio of sound power to peak sync vision power. For a 10:1 vision-to-sound ratio this gives:

$$P = 1.73V$$

When operated in the common amplifier mode, an IOT can be specified by its peak envelope power (PEP) rating. This is defined as the instantaneous RF output power which can be obtained when the grid is at the same potential as the cathode.

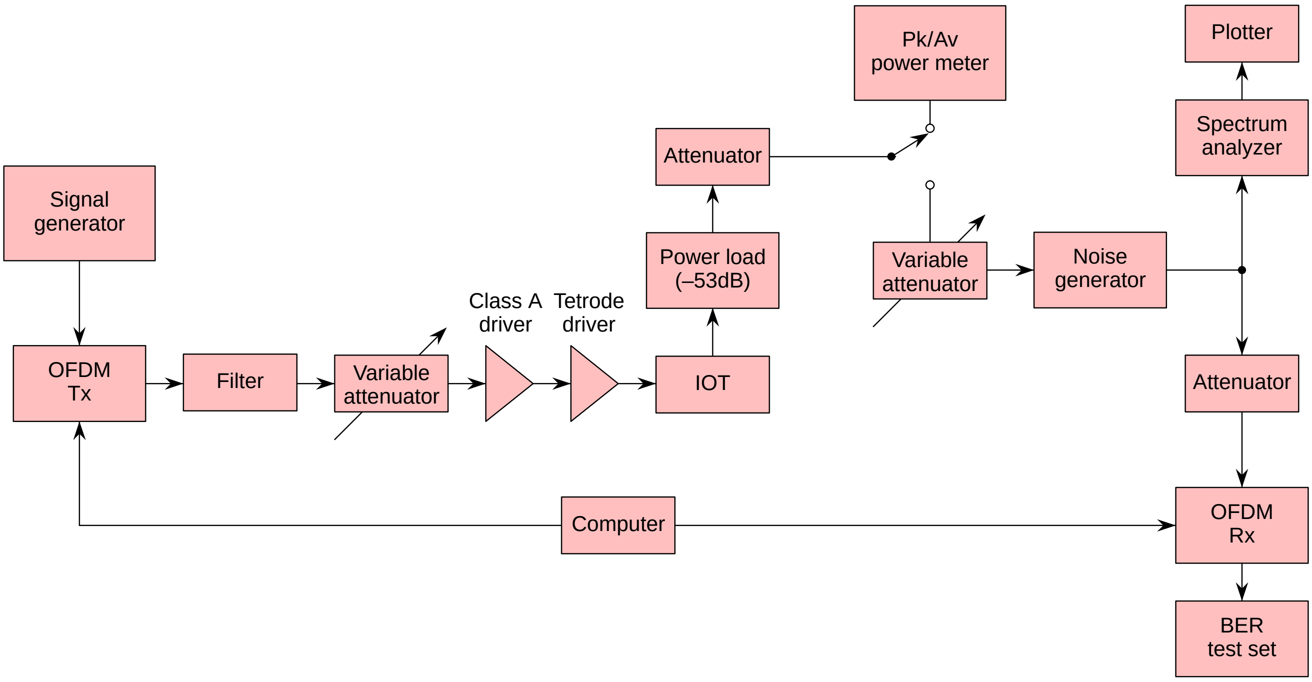
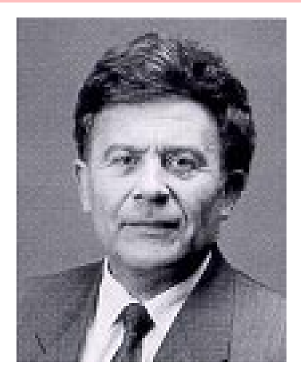


Figure 7
Experimental arrangement for investigating the digital performance of low- and high-power IOTs.

SECAM system has an amplitude-modulated rather than a frequency-modulated sound carrier, tests were conducted in vision-only conditions. An IOT8404 gave a peak white output power of 27.5 kW in European channel 35 at a beam voltage of 30 kV and an average beam current of 1.35 A, corresponding to a FOM of 68%. The gain was 22 dB and the LF non-linearity, differential gain and differential phase of the tube were 6%, 4% and 1 degree, respectively, demonstrating the suitability of the tube for this application.

7. Digital TV performance

The future of terrestrial television broadcasting is not analogue but digital and a major concern for the broadcaster is to establish the power levels of the proposed digital transmitters. Two of the (pos-



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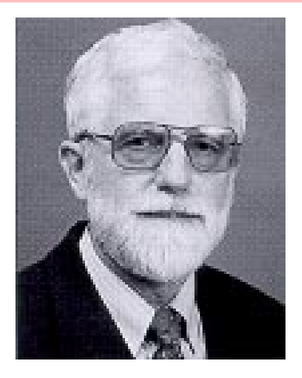
Roy Heppinstall then joined EEV at Chelmsford where he has worked on the development and application of high-power tubes – travelling wave tubes, klystrons and inductive output tubes. He has held a number of engineering and technical management posts with the company and is currently Head of Applications in the Television Broadcasting Strategic Business Unit of the EEV Power Tube Division.

Dr Heppinstall is author or co-author of many papers on television transmitter amplifiers and is the inventor or co-inventor of numerous patents.



***Mr Geoffrey Clayworth** graduated with a B.Sc. in Physics from Birmingham University in 1961 and joined EEV in Chelmsford where he held a series of development and production engineering posts, working on microwave beam tubes. In 1974, he became Section Manager with responsibility for manufacturing efficiency, cost control and technical customer relations in matters relating to high-power klystrons.*

In 1980, Geoffrey Clayworth was appointed Manager of the High Power Klystron Department at EEV and, in May 1991, became Head of Klystron and IOT Projects with responsibility for new beam tube amplifiers for use in high-power UHF television transmitters. Since 1992, he has managed the Television Broadcasting Strategic Business Unit of the EEV Power Tube Division.

Mr Clayworth is author or co-author of many British patents and technical papers. He has also presented papers on television transmission at conferences throughout Europe and the USA.

sibly conflicting) factors involved are to obtain an appropriate coverage area and at the same time avoid interference with other transmitters – either other digital transmitters or, during the period of simultaneous transmission of both systems, analogue transmitters which may even be operating on adjacent channels.

Two quite different digital transmitting standards have been proposed – the European DVB (COFDM) system and the USA 8-VSB system. In both cases the signals are characterized by having a large dynamic range – in particular they have a high peak-to-mean power ratio. Any amplifying system used in a digital television transmitter must therefore have the following characteristics:

1. Its average power level capability must be higher than the specified average digital power of the transmitter.
2. It must be able to handle short-duration high-power transients. Significant clipping of these transients results in an increased level of intermodulation products and bit error rates (BERs).
3. The non-linearity of its transfer characteristic must be sufficiently low that the resultant effects on the digital signal can be compensated by the transmitter pre-correction circuits. Degradation due to non-linearity becomes evident through an increase in BER and in the level of the sidebands outside the channel frequency range.

The digital performance of both a low-power and a high-power IOT have been investigated using the experimental arrangement shown in *Fig. 7*. The adjustable attenuator after the OFDM transmitter was used to vary the drive level into the intermediate power amplifiers (IPAs) – a class A solid-state amplifier and a 1 kW tetrode operating in tandem. Thus the output power level of the IOT could be varied. The noise generator allowed the introduction of a defined Gaussian signal-to-noise level so that BER versus S/N ratio characteristics could be determined. An attenuator was used to ensure that a constant input level to the receiver was maintained independent of the IOT output level. A 2^{23}–1 Pseudo Random Binary Sequence was chosen as the test signal. Measurements on the low-power IOT were taken using a 432-carrier OFDM signal generated by a prototype modulator whereas measurements on the high-power tube were taken with a 2k carrier system.

BER versus S/N ratio characteristics were determined in each case, with and without the IOT in circuit. Hence the S/N degradation or loss of noise margin due to the IOT alone could be established. *Figs. 8*, *9* and *10* show a selection of the characteristics, and *Tables 2* and *3* summarize various aspects of the performance when the tubes are operated at different average power levels. As expected, as the average power level is increased, both the signal-to-noise degradation and the side band levels increase. At the same time the peak-

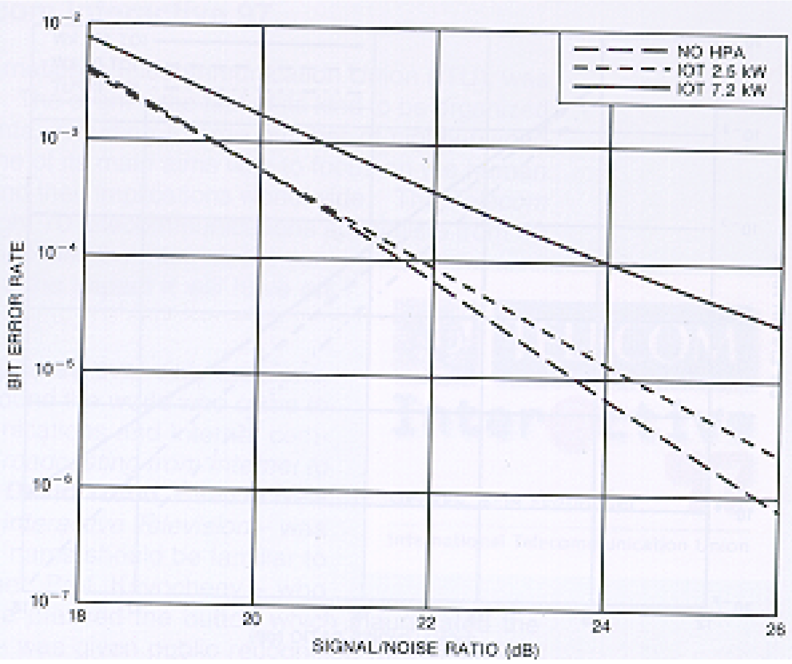


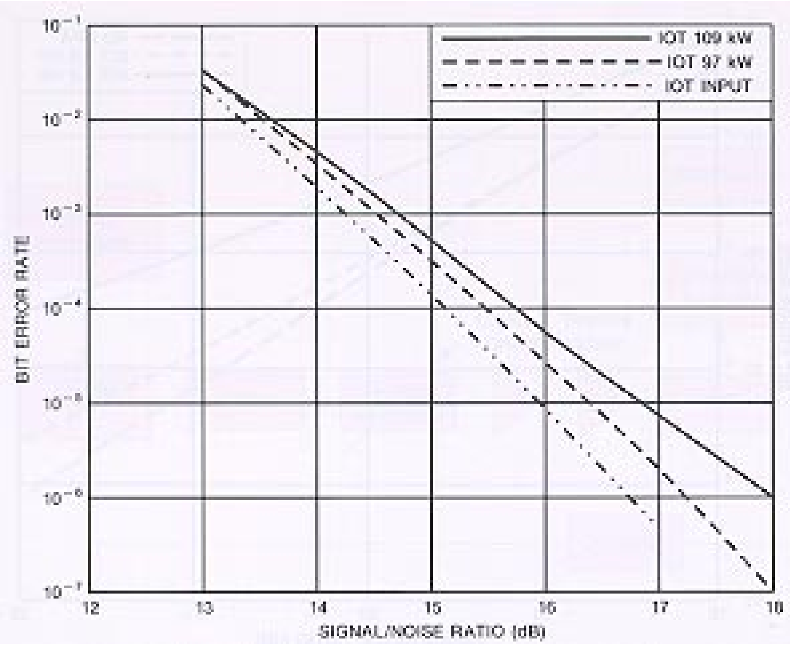
Figure 8
IOT D140R: BER versus S/N ratio at 22 kV beam voltage, 16-QAM signal.

Parameter		IOT peak output power (kW)		
		18	25	28
Peak-to-average ratio	dB	8.6	6.9	5.9
Average power	kW	2.5	5.1	7.2
Sideband level	dB	–28	–27	–26
S/N degradation at BER = 10^{-4}	dB	0.3	0.7	2.3
PEP rating	kW	25	25	25

Table 2
Digital performance of IOT D140R at 22 kV beam voltage.

Parameter		Type of QAM				
		16	16	64	64	64
IOT peak output power	kW	109	97	114	99	77
Peak-to-average ratio	dB	7.1	7.8	8.0	10.4	11.5
Average power	kW	21	16	18	9	5.5
Sideband level	dB	–20	–25	–20	–23	–25
S/N degradation at BER = 10^{-4}	dB	0.3	0.1	5.0	1.3	0.6
PEP rating	kW	85	85	85	85	85

Table 3
Digital performance of IOT D2100 at 35 kV beam voltage.



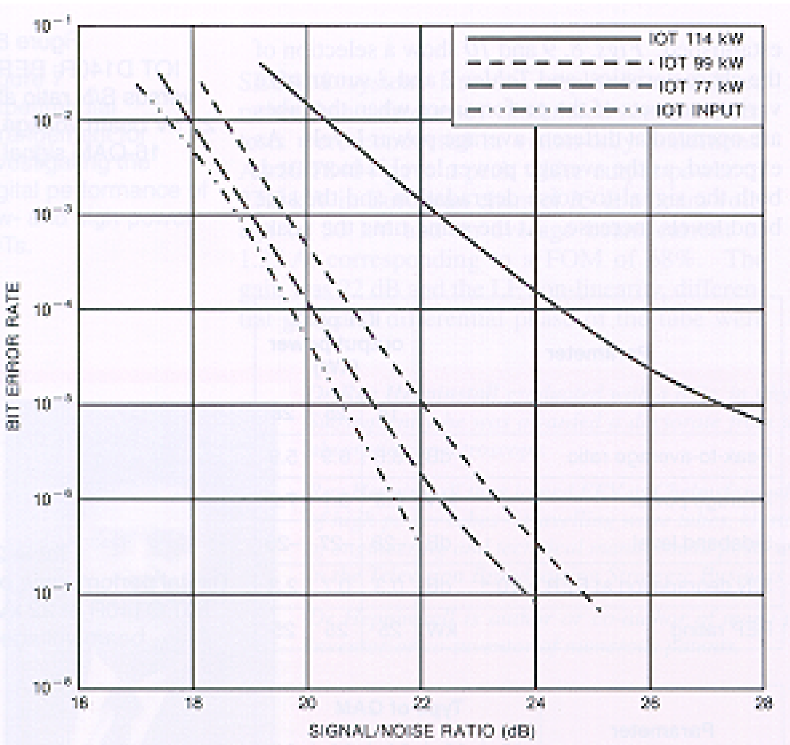


Figure 9 *(upper)*
IOT D2100: BER versus S/N ratio at 35 kV beam voltage, 16-QAM signal.

Figure 10 *(lower)*
IOT D2100: BER versus S/N ratio at 35 kV beam voltage, 64-QAM signal.

to-average ratio decreases due to saturation effects within the tube.

The peak power rating of an IOT for digital service is obviously a question of considerable importance. In order to be able to amplify the transient high-power digital peaks, the cathode of the tube has to be able to provide the high peak beam current required. Experience in analogue service has shown that tubes can achieve long lives when operated in common amplifier mode at power levels corresponding to their PEP rating. The results obtained show that tubes can be operated at peak digital power levels which are the same as the PEP rating – with low signal-to-noise degradation. Further, the peak-to-average ratios are such that the average powers are well within the tube ratings. The sidebands however are higher than the limit which might be required to avoid interference to other transmitters, and linearity pre-correction and filtering techniques will be needed to reduce them.

8. Final Remarks

During the last six years, IOTs have been installed in hundreds of analogue UHF TV transmitters throughout the world. A range of tubes has been developed to meet the range of performances required by those transmitters. Operating experience has shown that they are an excellent choice for this application. An IOT was used for the successful digital TV field trials in the USA and they are now installed in a number of digital transmitters. The experience gained, together with the results of experimental work of the type described here, show that IOTs are an excellent choice for digital UHF television transmitters.

Acknowledgements

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The views expressed here are those of the Authors and are not necessarily those of the General Electric Company in the UK (the parent company of EEV Ltd).

Intellectual Property Rights

The IOT is the subject of numerous granted patents in the United Kingdom, and corresponding patents in other countries.

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