THE HELIX TWT: OVER 70 YEARS OLD BUT NOT READY TO RETIRE

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Abstract - *There has been a longstanding opinion in the field of Microwave signal amplification that vacuum electronic devices, in particular helix traveling wave tubes (TWTs), are an obsolete and will be replaced by solid state imminently but yet the technology lives on!*

This paper hopes to provide the reader with a better insight into how helix TWTs work, the performance enhancements achieved as the technology has matured and the obtainable benefits when utilising the competing solid state technology.

INTRODUCTION

The helix traveling wave tubes (TWTs) has been employed as the final power amplifier for a range of microwave applications since its invention over 70 years ago [1], [2]. For many decades the helix TWT was the product of choice for many airborne electronic warfare (EW) applications; offering a broad instantaneous bandwidth, high RF output power, pulsed and/or continuous wave capability and high conversion efficiencies all in a relatively compact and rugged device.

The 1990s saw a decade of change for the helix TWT with many system designers succumbing to the hype of the solid state propaganda train rejecting the helix TWT as a viable option for many systems; considering it as an obsolete technology thereby potentially initiating the demise of the helix TWT and relegating it to a bygone era. However, instead the helix TWT has continued to flourish and for many applications still offers the most viable solution in terms of both performance and cost.

Advances in the design approach, manufacturing techniques and material technology have enabled the helix TWT to evolve into a far superior product range over the last two decades, offering multi-octave performance at efficiencies of greater than 25% over the full operating bandwidth with high manufacturing yields. One of the key advantages with the helix TWT is its capability to offer high levels of microwave power at frequencies up to 40GHz over an extended temperature range with minimal degradation in RF performance.

HELIX TWT FUNDAMENTALS

The helix TWT relies on the interaction between an electron beam and a travelling microwave signal to impart energy on to the signal significantly amplifying it. In order to achieve this interaction a high quality vacuum is required to maximise the mean free path of the electrons enabling them to propagate through the device without collision with gas molecules.

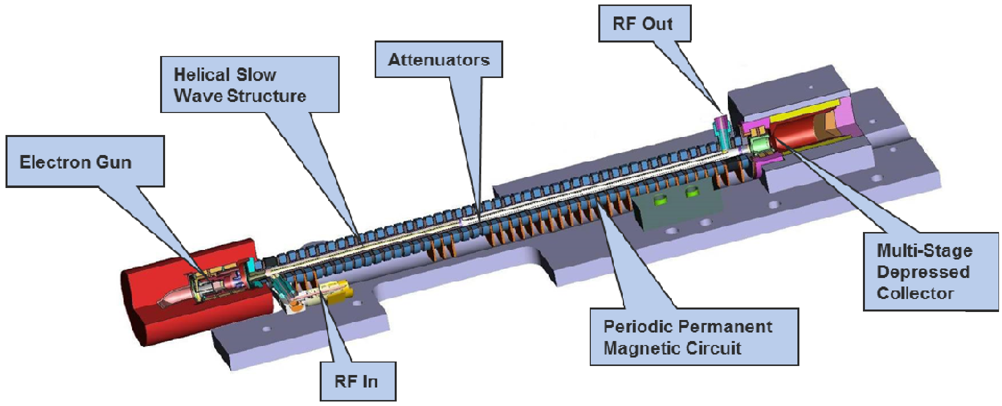

Figure 1: Elements of the helix TWT

Within the TWT the first key element is the electron gun comprising primarily of a heated cathode with a series of accelerating electrodes; the cathode is heated to approximately 1000˚C enabling electrons to be pulled from the front surface to form an electron cloud these are then accelerated by an electrostatic field. By shaping the electric field the electron trajectories can be focused towards a common point to form a narrow beam, the size of which is ultimately determined by the internal space charge forces within the beam. By injecting this narrow beam into a suitably profiled magnetic field it is possible to prevent space charge expansion and the beam can propagate through the magnetic field at a fixed size (see Figure 2). The magnetic field is typically provided by a periodic permanent magnetic (PPM) circuit that forms a series of magnetic lenses repeatedly focusing the electron trajectories back towards the device axis overcoming the natural expansion of the beam due to internal space charge forces.

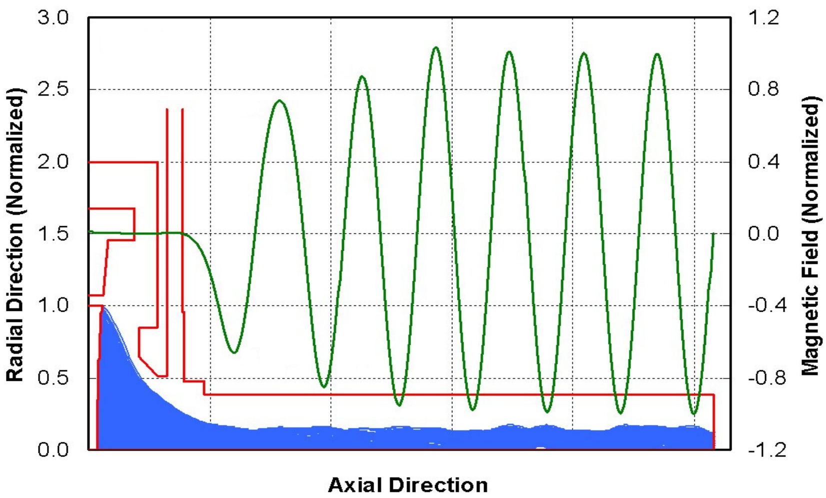

Figure 2: Forming and focusing the electron beam

A helical slow wave structure is an essential part of the traveling wave tube. It acts as a delay line, in which the RF signal travels at nearly the same speed along the device as the electron beam. The injected electromagnetic waveform on the helix interacts with the electron beam, causing bunching of the electrons in an effect known as velocity modulation. This bunching of the electron beam induces current movement on the helix and an associated voltage waveform is produced further enhancing the electron beam bunch. This induced waveform rapidly grows as more and more electrons are forced into the bunch, becoming significantly larger than the initial injected signal and as a result RF signal amplification takes place. The amplifying RF signal gains its energy directly from the electron beam, so as the RF power increases the beam energy drops.

The RF signal is injected on to the helix via the RF input, which obviously must be transparent to the RF signal whilst maintaining the internal vacuum of the traveling wave tube. The RF input to the TWT can be either a waveguide or coaxial transmission line and typically incorporating a ceramic window within the line to form the required vacuum seal, the transmission line and window designs are suitably profiled to minimise RF reflections and maximise signal transmission over the operating bandwidth of the TWT. Beyond the ceramic window, within the vacuum envelope of the TWT, the transmission line is typically transformed to a coaxial line that incorporates a series of impedance steps to match the input transmission line to the frequency dependent helix impedance.

The RF output shares the same design requirements as per the RF input with the additional requirement of being able to handle the significantly amplified RF signal level, which ultimately determines the choice of output transmission line from the TWT and the ceramic window design.

The RF gain of a TWT is directly related to the physical length of the helical slow wave structure, the beam voltage (by virtue of the associated phase velocity of the slow wave structure) and the beam current to a lesser extent. Under small signal conditions the gain of a TWT remains constant with input drive but as the level of energy extraction from the electron beam increases the gain of the TWT drops to the extent that at RF power saturation the gain has dropped by between 6dB and 10dB depending on the design of the helical slow wave structure. In addition to this gain compression with RF input drive the helical slow wave structure exhibits a frequency dependent gain characteristics, which is most apparent in multi-octave TWTs where the gain at the centre of the operating band is significantly higher than at the frequency extremes.

To maintain operational stability the small signal gain provided by a helical slow wave structure is typically limited to about 25dB, in order to increase the overall gain of the TWT multiple sections are used with each section being terminated by an attenuator region. The attenuator fully absorbs the RF signal at the end of each of the helical slow wave structure sections and the bunch within the electron beam induces a new RF signal on the next section thereby achieving an increased overall gain level from the TWT. When estimating the overall gain of the TWT it is necessary to consider the initial loss associated with launching the RF signal on to the helix (about 9dB), the loss associated with inducing the RF signal onto the helix after an attenuator region (about 5dB) and general circuit losses (normally relatively low, ≈1dB). The attenuators, that are essential for stable operation of the TWT, are formed by depositing a graduated layer of carbon on to the surface of the dielectric rods that support the helix within the vacuum envelope of the TWT to form the helical slow wave structure. The carbon depositing process has changed very little since its initial conception over 70 years ago and is still viewed as “black art” to those within the TWT industry.

Although the RF/electron beam interaction process can be made relatively broadband, by altering the dimensions of the helical slow wave structure to minimise dispersion over the operating bandwidth of the TWT, the interaction process is relatively inefficient and after the amplified RF signal has been extracted from the helical slow wave structure the electron beam still contains a significant level of energy. The energy remaining in the electron beam is absorbed by the collector, which converts it to heat, by utilising a multi-stage depressed collector it is possible to recover a high proportion of the beam energy electrically reducing the thermal burden of the TWT and maximising the overall electrical efficiency of the device. By optimising the collector electrode number, operating potential and shape it is possible to maximise beam energy recovery for any given operating frequency of the TWT, however, as the bandwidth of the TWT increases this optimisation process becomes more challenging and a compromised collector design is often adopted ultimately limiting the electrical efficiency improvements that can realised.

DESIGN ENHANCEMENTS

The original helix TWT designs operated at fixed frequencies offering relative low amplification factors but it quickly became apparent that the helix slow wave structure offered the potential for broadband operation with significant levels of amplification possible. These early tubes provided the system designers the opportunity to consider more challenging applications for the helix TWT and with the advent of multi-octave broadband requirements the study of dispersion shaping in the helical slow wave structure became important [3]. In the case of a helix within a metal tube the dispersion can be reduced by placing the tube very close to the helix, thereby offering increased bandwidth but this will reduce the interaction impedance adversely affecting the efficiency of the interaction process. The approach more commonly employed is to use a tube with metal vanes projecting radially inwards toward the helix; by optimising the dimensions of these vanes one can achieve the desired flat dispersion characteristics whilst maintaining an acceptable level of interaction impedance over the required operating bandwidth of the device.

For many years radially profiled vane structures were commonly employed to achieve operational bandwidths of up to about 1.5 octaves, but with the adoption of electrical discharge machining (EDM) in the late 1980's more complex vane shapes could be considered enabling dispersion to be controlled over greater bandwidth to the extent that more than 3 octaves has now been achieved [4]. To achieve improved output power performance and reduce the harmonic output level from the lower end of the TWT operating band negative dispersion is now employed, so rather than have a flat phase velocity characteristic over the full operating band the phase velocity of the slow wave structure increases linearly by about 3% over the first octave and then remains constant over the remainder of the operating band. These improvements in the helical slow wave structure design have been made possible by the advances in 3D electromagnetic (EM) simulation packages such as CST Studio Suite® providing the TWT designer with essential propagation and impedance information for any design concept (see Figure 3), thereby enabling configuration optimisation prior to committing to manufacture.

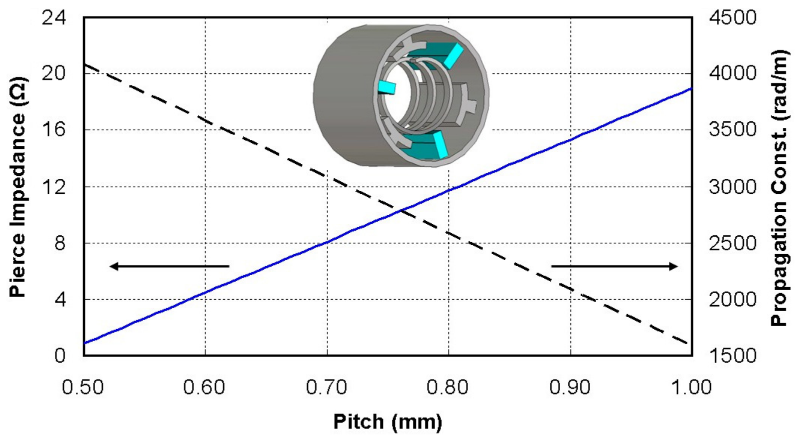

Figure 3: Variation of Pierce impedance and propagation constant with helix pitch at 18GHz

Within a helix TWT the RF amplification process relies on the exchange of energy from the electron beam to the RF signal on the helical slow wave structure, so generally if there is a requirement for higher output power one needs to increase the electron beam energy by increasing its current and/or voltage. Although some increase in performance is possible by profiling the pitch of the helix within the slow wave structure [5], this technique is commonly used on narrow band devices to achieve an increase in output power of up to 3dB with no change to the electron beam parameters. Fundamentally profiling the helix pitch ensures that the RF signal remains aligned with the slowing electron beam bunch as energy is extracted from it, although one can utilise pitch profiling to deliberately extract energy from the RF signal in order to reform the electron beam bunch and thus maximise the interaction process. This technique of profiling the helix pitch has successfully been adapted for broadband helix TWTs [6] and is now commonly employed in new TWT developments to maximise device electronic efficiency. The level of broadband performance enhancement achievable is illustrated in Figure 4, both TWTs operate at the same voltage and beam power but the original design doesn't incorporate helix pitch profiling.

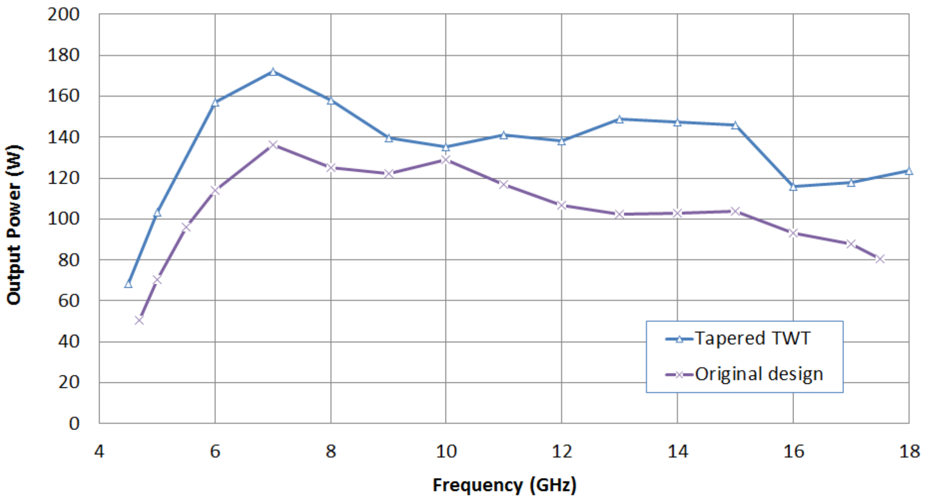

Figure 4: Broadband performance enhancement via helix pitch profiling

As the operational bandwidth of a helix TWT is extended to multiple octaves it is quite common for the performance at the lower extreme of the frequency band to be significantly lower than the mid-band performance, as illustrated in Figure 4, and as the device bandwidth is extended towards 3 octaves this degradation in performance becomes more marked.

An alternative to helix pitch profiling as a means of performance enhancement is to precondition the input drive signal to the TWT; one such approach is harmonic injection, a technique that can be used to improve three areas of TWT performance

i) Suppression of intermodulation products enabling the TWT to be driven closer to saturation for communication applications.

ii) Harmonic suppression, reducing the harmonic level at the fundamental saturation point.

iii) Fundamental output power enhancement, more than just the power associated with the harmonic content of the signal.

Unlike harmonic and intermodulation suppression where the injected harmonic signal is only attempting to cancel the harmonic signal generated within the TWT, with harmonic enhancement one is relying on the constructive interference of the driven fundamental mode and a second order non-linear mode formed by the injected harmonic signal and the naturally occurring harmonic signal within the device. This constructive interference yields a more efficient bunching of the electron beam enabling a greater level of energy extraction resulting in a significant increase in the output power within the fundamental signal. Using harmonic enhancement it is possible to achieve an output power increase from between 3dB and 6dB over the first octave of an ultra-broadband TWT (>3 octaves bandwidth).

As stated in the previous section after the RF amplification process has been completed the electron beam still contains a significant level of energy that can potentially be recovered via a multi-stage depressed collector (MDC), this concept is not new and has been successfully employed on various linear beam vacuum devices [7]. The design approach generally employed involves an electron beam magnetic reconditioning zone just prior to the collector then, using a series of electrodes, selectively collects electrons of different velocity profiles within the beam. Each collector electrode is appropriately shaped and operates at a reduced potential relative to its predecessor thereby forming a series of retarding lenses that act on the electron beam, the idea is that each electrode captures electrons at almost zero velocity thereby minimising the heat generation due to kinetic energy loss. By electrically recovering the electron energy using multiple collector electrodes one increases the overall efficiency of the TWT, for optimum efficiency six or seven collector stages maybe used achieving collection efficiencies in excess of 90%, this is the approach commonly employed on narrow band communication devices destined for space where efficiency is paramount.

For narrow band TWTs the variation in electron beam velocity distribution with frequency post the RF amplification process is relatively small thereby enabling the MDC to be designed with a high number of electrodes without adversely affecting the efficiency of the device over its operating frequency band. However, as the bandwidth of the TWT increases one introduces a greater variation in the spent beam velocity distribution with frequency and thus the resulting lensing effect of a given MDC design changes reducing its collection efficiency. Once the operating bandwidth of a TWT exceeds 1.5 octaves it is common place to only use two or three stages in a MDC as the efficiency benefits associated with adding further stages becomes minimal.

The materials employed within the helical slow wave structure of a helix TWT have to be compatible with the very high braze temperatures used in the manufacture of the device and as a consequence their RF properties exhibit minimal temperature dependency over the normal operating temperature of the device. Hence the RF performance offered by a helix TWT remains relative constant over a broad operating temperature range (-55˚C to +85˚C) without the need for any temperature related compensation. Generally the operating temperature range of a helix TWT is not limited by the RF performance of the device but instead the operating temperature limit of the helix structure.

There are three factors affecting the operating temperature of the helix these are:

i) RF losses – minimal change with temperature due to material choice

ii) Electron beam interception – resulting from changes to the magnetic focusing field

iii) The extended thermal conduction path from the helix to the external heatsink – minimal change with temperature due to material choice

As the operating temperature of the of the device increases or decreases the properties of the magnets used within the PPM structure also change and as a consequence the electron beam is subjected to a different level of confining field and different magnetic field profiles within the launch regions of the electron gun and collector. Although various design techniques are employed to minimise the electron beam de-focusing associated with these magnetic field changes they are not 100% effective.

Because the magnets within the PPM structure are in direct contact with the external vacuum envelope of the TWT they form part of the thermal conduction path and thus operate at a temperature in excess of the external environment temperature. This elevation in magnet material temperature can ultimately introduce permanent de-magnetisation effects within the magnet material if taken to the extreme. Advances in magnet material has enabled the temperature limit for this irreversible effect to be significantly increased and as a consequence helix TWTs are often expected to operate at environmental temperatures up to 105˚C, rather greater than any equivalent solid state technology.

Realising many of these design enhancements has only been possible through the adoption of sophisticated 3D simulation packages in the design process. Being able to accurately predict the performance characteristics of a particular design parameter significantly reduces the need for design optimisation by multiple manufacturing iterations; the approach historically applied for helix TWT product development. The accuracy of many of these simulation tools is sufficient to allow one to analyse the effect component dimensions have on device performance (see Figure 5) and thereby enabling manufacturing tolerances to be defined. Currently the simulation packages are isolated products requiring TWT designer interpretation to transfer and combine results, but as the packages mature it is anticipated that it will soon be possible to construct virtual helix TWTs especially with the advances being made in particle-in-cell (PIC) and multi-physics simulators.

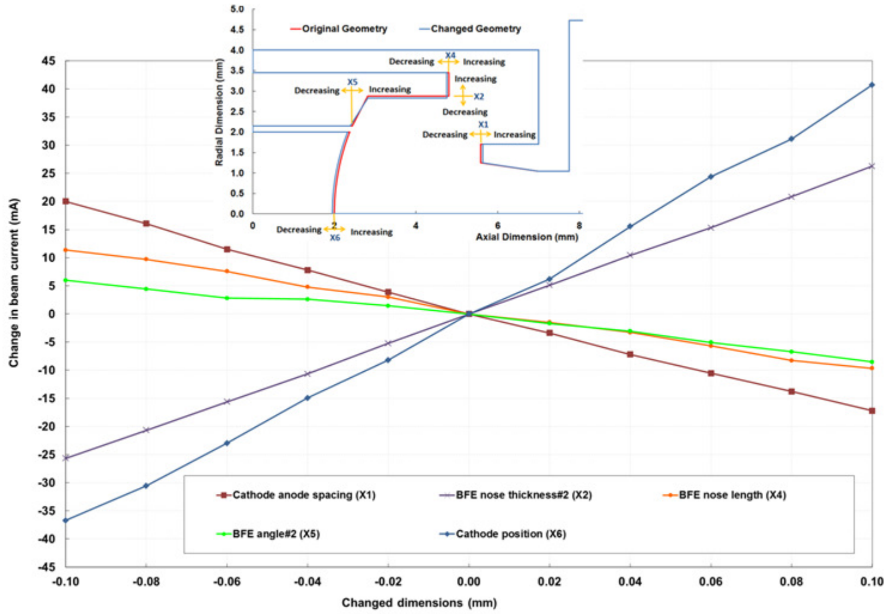

Figure 5: Electron gun tolerance analysis

COMBINING TECHNOLOGIES

Back at the beginning of the 1990's, when the system designers started to consider solid state amplifiers (SSA) as the only solution to their entire broadband high power application needs, a fundamental change in helix TWT technology took place in an attempt to address this trend with the inception of the Mini MPM. Up until that point the helix TWT had been designed to operate at a relative high operating voltage and had a relatively low watt per unit volume ratio making it impractical for many applications especially phased array combing. The Mini MPM offered a low voltage compact amplifier solution combining a miniature helix TWT, a compact high voltage power supply and the latest high power solid state driver all in one unit less than a wavelength high for use in a linear element phased array. Although never used for its original intent the Mini MPM did yield a new breed of Mini TWTs based around an operating voltage of approximately 4.5kV and designed to give up to 100W over the 6-18GHz operating band, which has subsequently be further extended to both 4.5-18GHz and 2-18GHz.

The low operating voltage of the Mini TWT makes the design more challenging but the benefits are increased electronic efficiency and increased linear gain factor. In order to make the size of the Mini TWT as compact as possible gain is deliberately removed from the TWT and transferred to the solid state driver amplifier, which was only made possible through the performance enhancements being made in that technology. So rather than feel challenged by the advances in solid state technology it is being utilised to address some of the short comings of the helix TWT technology.

The four areas in which solid state technology can enhance the performance of a helix TWT by conditioning the RF input signal to the TWT are pre-amplification, equalisation, linearization and power enhancement, as illustrated in Figure 6.

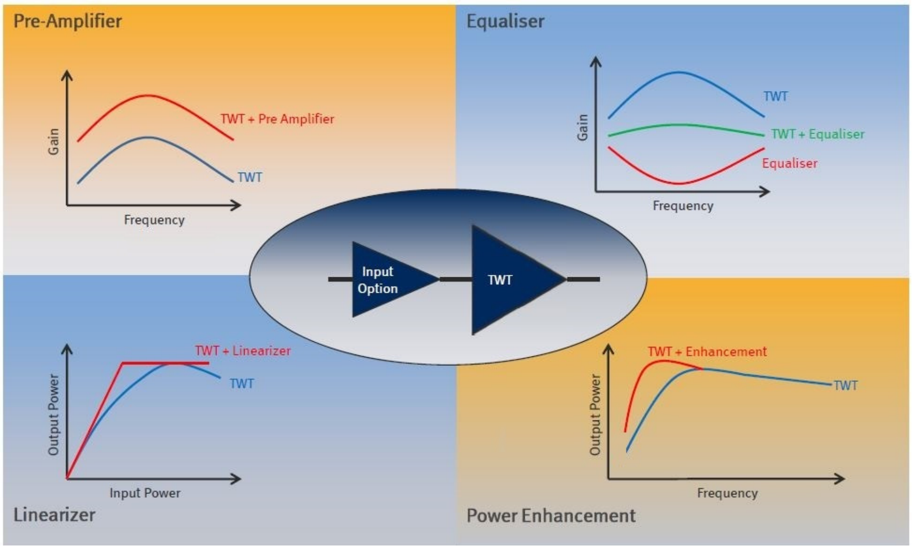

Figure 6: Combining technologies to achieve improved performance

Pre-Amplifier: Gain is removed from the TWT and added back in via the SSA, the main advantage being the reduction in the noise figure for the system. With a realistic level of gain transfer to the SSA it is possible to achieve a system noise figure approximately equivalent to that of the SSA rather than the significantly larger value associated with the TWT.

Equaliser: As mentioned previously the typical gain characteristics of a helix TWT has significant frequency dependence especially if it's providing gain over more than an octave bandwidth. For certain system applications this variation in gain characteristics can be problematic, so by adding the appropriate frequency dependent loss in the form of an equaliser into the RF input line to the TWT the system exhibits a flat gain characteristic although its noise figure degrades in line with the RF loss added by the equaliser. By combining a pre-amplifier and equaliser it is possible to achieve a flat gain response over the frequency band of the system and recoup some of the degradation in the noise figure of the system.

Linearizer: As the RF input drive to the TWT is increased so is the energy extraction from the electron beam causing it to slow, introducing a phase change in the RF signal and reducing the TWT gain. This non-linear behaviour of the TWT means that the 1dB gain compression occurs up to 3dB below the RF output power saturation point and gives rise to unfavourable multi-carrier performance characteristics, limiting the maximum output power that the TWT can deliver in certain applications. Using a linearizer to introduce gain and phase expansion to the input drive signal that mirrors the TWT's non-linear characteristic it is possible to move the 1dB gain compression point much closer to the TWT saturation point significantly improving its multi-carrier performance characteristics.

Power enhancement: Traditionally fundamental output power enhancement by harmonic injection has been achieved using a driver TWT and power TWT chain; the driver TWT is configured to produce an output with significant harmonic content that is then injected into the power TWT to produce the desired constructive interference effect to yield fundamental signal enhancement. The use of a driver TWT for harmonic power enhancement has always had limitations both in bandwidth and the need for a second high voltage power supply. By replacing the driver TWT with a multi-channel SSA, which generates the appropriate fundamental and associated harmonic signals, it is possible to increase the power enhancement bandwidth to over an octave utilising a low voltage power supply.

THE FUTURE

One of the fundamental justifications for adopting to use high power SSAs as a replacement for TWTs is that they offer graceful degradation and thus offer a more reliable solution. However, studies by Boeing [8] suggest that SSA graceful degradation is a myth since generally it is the final stage of the amplifier that fails rendering the device useless. The more recent approach of combining multiple SSA is not necessarily more resilient to the effects of single device failure as many of the combining techniques rely on all feed elements being active. So, unless the design process has considered the effect of missing drive elements there will be a domino effect if one element fails potentially resulting in the failure of all the feed elements. Nevertheless the addressable market for the helix TWT is evolving and although there are still currently requirements for broadband helix TWTs offering about 100W up to 18GHz it is anticipated these could ultimately be satisfied by solid state technology. As a consequence the future for helix TWTs will be in offering compact solutions at higher power levels and higher frequencies.

It is anticipated that there will always be requirements for helix TWTs provided their designs continue to evolve with market trends, ultimately what will determine the demise of the helix TWT is not competing technologies but the diminishing population of designers!

REFERENCES

[1] N.E. Lindenbald, US Patent 2,300,052, filed May 4, 1940, issued October 27, 1942

[2] R. Kompfner, "The traveling wave tube as an amplifier at microwaves", Proc. IRE, 35, February 1947, pp. 124-127

[3] S.F. Paik, "Design formulas for helix dispersion shaping", IEEE Trans. Electron Devices, vol. 16, pp. 1010-1014, 1969

[4] T.K. Ghosh et al. "Development of ultra wide band helix mini-TWTs", in Proc. IVEC, Monterey, 2010, pp. 303-304

[5] V. Srivastava, R.G. Carter, B. Ravinder, A.K. Sinha and S.N. Joghsi, "Design of helix slow-wave structures for high efficiency TWTs", IEEE Trans. Electron Devices, vol. 47, pp. 2438-2443, December 2000

[6] T.K. Ghosh, A.J. Challis, A. Jacob and D. Bowler, "Design of helix pitch profile for broadband traveling wave tubes", IEEE Trans. Electron Devices, vol. 56, pp.1135-1140, May 2009

[7] H.G. Kosmahl, "Modern multistage depressed collectors – A Review", IEEE Trans. Electron Devices, vol. 70, pp. 1325-1334, November 1982

[8] E.F. Nicol, B.J. Mangus and M.K. De Pano," TWTA versus SSPA: A new look at Boeing fleet on-orbit reliability data and comparison factors", in Proc. IVEC, Monterey, 2006, pp. 61-62