WATKINS-JOHNSON CO.
PALO ALTO, CALIFORNIA

FIRST CLASS
Permit No. 204
Palo Alto,
Calif. 94304

WATKINS-JOHNSON

Manufacturing and Office Locations

UNITED STATES

CALIFORNIA

Watkins-Johnson
3333 Hillview Avenue
Palo Alto 94304
Telephone: (415) 493-4141

Watkins-Johnson
440 Mount Hermon Road
Scotts Valley 95066
Telephone: (408) 438-2100

Watkins-Johnson
11222 La Cienega Blvd.
Inglewood 90304
Telephone: (213) 670-4850

FLORIDA

Watkins-Johnson
7001 Lake Ellenor Drive
Orlando 32809
Telephone: (305) 851-2391

MARYLAND

Watkins-Johnson
700 Quince Orchard Road
Gaithersburg, 20760
Telephone: (301) 948-7550

MASSACHUSETTS

Watkins-Johnson
279 Cambridge St., Ste. 113
Burlington 01803
Telephone: (617) 272-7235

NEW YORK

Watkins-Johnson
808 Shrewsbury Avenue
New Shrewsbury, N.J. 07724
Telephone: (201) 842-2422

OHIO

Watkins-Johnson
2500 National Rd., Ste. 200
Fairborn, Ohio 45324
Telephone: (513) 426-8303

TEXAS

Watkins-Johnson
4230 LBJ Freeway
Dallas 75234
Telephone: (214) 289-9131

INTERNATIONAL

ITALY

Watkins-Johnson Italiana
S. p. A.
Piazza G. Marconi, 25
00144 Roma-EUR
Telephone: 59 45 54
Telex: 60117
Cable: WJROM-ROMA

UNITED KINGDOM

Watkins-Johnson
Shirley Avenue
Windsor, Berkshire SL4 5JU
Telephone: Windsor 69241
Telex: 847578
Cable: WJUKW-WINDSOR

WEST GERMANY

Watkins-Johnson
8033 Planegg
Münchenerstr. 17
Telephone: (089) 859-9441
Telex: 529401
Cable: WJDBM-MUENCHEN

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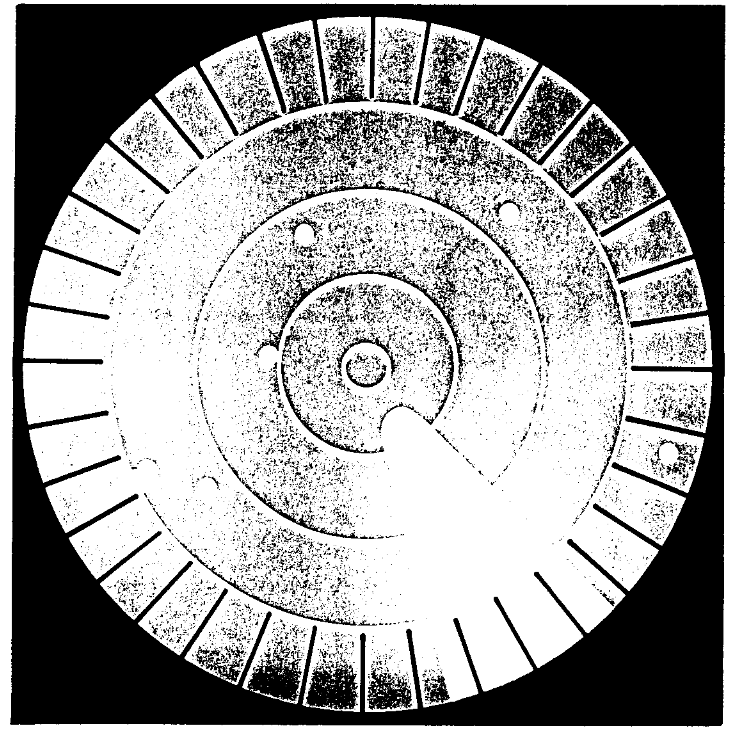
Developments in FML and Miniature Millimeter LNTWA Devices



This issue of Tech-notes describes two devices vital to electronic countermeasures and receiver systems: the frequency memory loop (FML) and the miniature millimeter low-power, low-noise TWT amplifier (LNTWA).

Part One

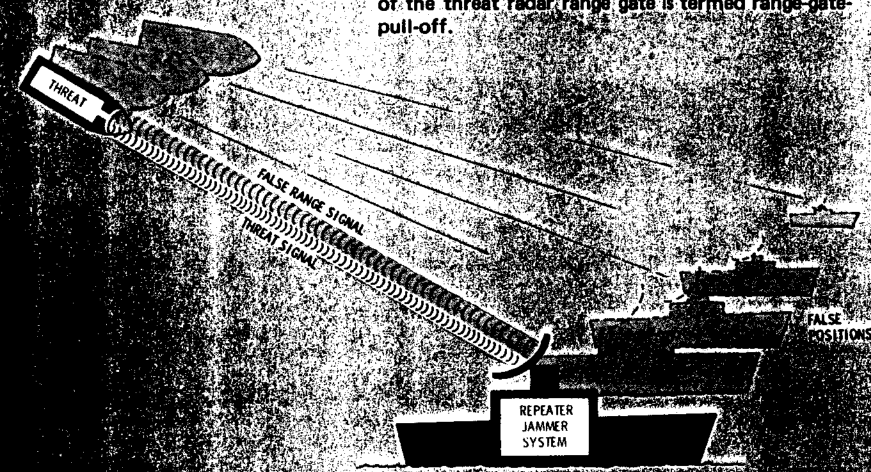
The FML device combines with a chain of traveling-wave-tubes to produce a very effective repeater jammer system. In this FML system, the TWT is the key element, since it combines wide bandwidth and high gain with low noise figure.

Part Two

Today's surveillance receiver systems are being extended to look to higher frequencies. Along with the more stringent demand for performance is the demand for smaller TWT size without loss of quality. State-of-the-art technology is satisfying these wide bandwidth applications with the miniaturized LNTWA.

tech-notes

Fig. 1.
A range deception repeater jammer. Range tracking is broken by retransmitting a sufficiently strong RF signal to activate the threat radar, and then progressively delay the transmission of the False Range Signal relative to the Threat Signal. This deception of the threat radar range gate is termed range-gate-pull-off.



Part One

The FML Device: An Effective ECM System

An ECM repeater jammer is basically a system used to obscure the range, azimuth and elevation information that another radar is trying to obtain. Some radar systems interpret range as the time between a transmitted and returned signal. Range-gate-pull-off is one mode of active jamming, Fig. 1. The FML system is used to receive, process and "store" the frequency transmitted from a threat radar, then transmit a false signal after a predetermined delay. The key to the transmission of a signal that will cause the threat radar to lose tracking, lies within the ability of the FML device to store that frequency for a specified length of time while maintaining good spectral purity.

A FML Loop Transistion Description

Signal flow for a four-level FML system is shown in Fig. 2. The received signal is amplified by the input and loop TWTs, where it is then divided into two paths. One path goes directly to the intermediate and high power TWTs, while the other is coupled to the time-delay section of the recirculatory memory loop.

After a predetermined delay, the input RF switch opens the input path, and the loop RF switch closes the coupled loop path just as the RF signal appears at the delay line output. At this time, the recirculation loop is "filled" and the RF signal continues to recirculate through the loop TWT, reproducing the input frequency. The high power pulse TWT can then be turned-on at the time (or a number of times) required to transmit the signal. After the signal is transmitted, RF switch action opens the coupled loop path and closes the input path. This terminates the stored RF signal while preparing the loop to memorize another input signal.

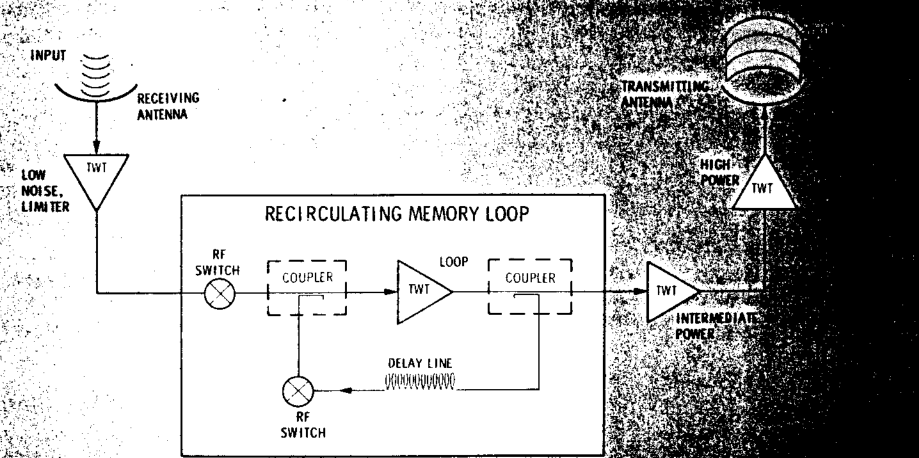


Fig. 2. A simplified repeater jammer system using the recirculating memory loop device. Four levels of signal amplification are performed from receiver to transmitter: each level requiring a TWT designed for specific input, output and overdrive parameters.

Advantages of the FML device over the other ECM devices, such as the frequency synthesizer techniques are:

- nearly instantaneous response capability by utilizing the first pulse of the received signal.
- ability to handle a new input frequency immediately after storage of the first input signal at a different frequency.
- wide bandwidth, fast performance and field reliability at low cost.
- high degree of spectral purity.

Signal Processing from Receiver to Transmitter

An input signal to the FML system (Fig. 2) undergoes four levels of signal processing: each level requiring an amplifier suited to a special task. Because radar input power levels cover such a wide range of values, the low-level input TWT must be flexible. Since the system signal-to-noise ratio is determined by the input TWT amplifier, the input TWT noise figure

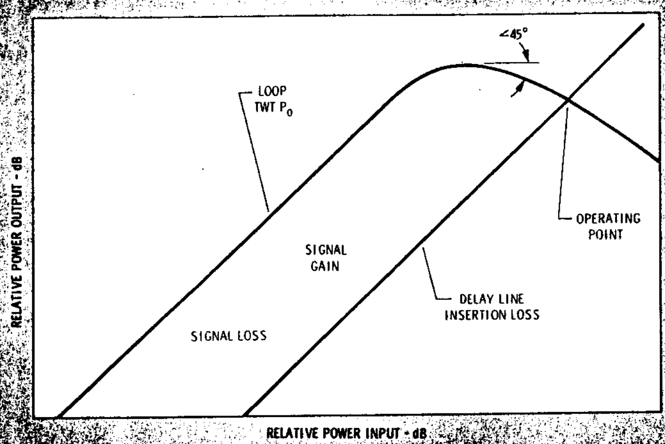


Fig. 3 Sequence of signal build-up in the memory loop device. The stable operating point is at the intersection of the loop Po curve and the delay line loss curve.

becomes a critical parameter. Simultaneously, should the input signal go beyond saturation of the input TWT, the TWT must also perform as a good limiter.

In order that the input frequency be "memorized" in the recirculatory loop, the loop TWT must meet critical parameters such as, high gain, precise gain shaping, low-fine grain structure, good overdrive, low-noise power, and high-small signal suppression. Less than optimum performance in just one of these areas can lead to storage failure modes of RF pulses with undersirable pulse widths and delay.

To insure that the high power TWT output is effective in transmitting the signal to the threat radar, the intermediate level TWT must boost the loop TWT output to a sufficiently high level. Also, each TWT in the chain must be matched to those interfacing with it to insure that the system power output meets minimum requirements for all input levels.

Loop Tube Dynamic Overdrive

Aside from the loop TWT function in overcoming the delay line insertion loss, the tube properties such as, small signal gain and noise suppression in the overdrive mode are critical to long time storage. The loop tube is designed with a small signal gain greater than the tubeless loop insertion loss. This allows an input signal to be amplified on successive circulations through the loop until power saturation occurs in the loop TWT. This sequence of signal build-up is shown in Fig. 3. Final operation takes place at the output power point where the TWT gain equals the tubeless loop loss (TWT plus delay line gain is unity). As long as the slope of the overdrive curve does not exceed 45°, the signal will build-up and lock-on to the final operating point after a finite number of circulations.

DELAY LINE TYPE	SIZE AND WEIGHT	APPLICATION	TYPICAL MEMORY TIME CAPABILITY	SPECTRAL PURITY (TYPICAL PREFERRED MODE SEPARATION)	LOOP TWT SMALL SIGNAL GAIN REQUIREMENTS	AMPLIFIERS REQUIRED	BANDWIDTH CAPABILITY (PER DELAY LINE & TUBE)	SYSTEM COST (PER OCTAVE)
WAVEGUIDE	MEDIUM	SHIPBOARD	25 µs	GOOD (5 MHz)	40 dB	1	1/2 OCTAVE	LOW
COAXIAL	SMALL	AIRBORNE	5 µs	FAIR (10 MHz)	50 - 70 dB	1	1 OCTAVE +	LOWEST
ACOUSTIC	SMALLEST	AIRBORNE	5 µs	FAIR-GOOD (5-10 MHz)	70 dB +	2	1/2 OCTAVE	MEDIUM

Table 1. Characteristics of memory loop devices using waveguide, coaxial and solid state delay lines.

Moding Interference

Since the FML is a recirculatory device, an interference phenomenon known as "Moding" occurs if a RF signal from one circulation interferes with that of a preceding circulation. Whether this interference is constructive (or destructive) is determined by whether the RF distance around the loop is an even (or odd) multiple number of half wavelengths. Natural loop frequencies, or "modes", are those satisfying the condition that an integral number of wavelengths precisely fill the loop. Separation between these preferred modes is equal to the reciprocal of the transit time around the loop. As moding occurs, the frequency components of a stored signal will gradually shift to the nearest adjacent natural frequency.

Delay Line, How Long and Which Type?

The frequency separation between the preferred modes (resulting from the loop transit time) determines the limits of the system spectral purity. The longer the delay line, the better the spectral purity. However, there are several considerations that restrict the delay line length. For example, the incoming signal must completely fill the loop or unwanted noise will build-up and eventually "capture" the stored signal. Also, the delay line insertion loss increases with time delay. Too long a delay line places unreasonable gain requirements on the loop TWT.

FML device characteristics using three types of delay line structures typically found in FML systems are shown in Table 1.

Waveguide delay lines are typically employed where a long memory time is required. They are slightly dispersive, that is, the delay time is a function of frequency. However, the delay line insertion loss is relatively low and is generally independent of frequency and temperature. For example, a 200 nanosecond delay line has an insertion loss of approximately 16 dB at X-band frequency.

Critically important size and weight requirements (with memory times generally less than 5 microseconds) are typically met with a coaxial delay line, and to a less extent, with an acoustic delay line. The delay time of the coaxial delay line is not a function of frequency, but, the insertion loss is proportional to frequency. Also, the coaxial delay line insertion loss does exhibit a linear relationship with temperature.

This insertion loss temperature dependence is an important characteristic to keep in mind during the design of an airborne FML system with extreme temperature variations. Insertion loss and delay time of a coaxial delay line are approximately twice the order of magnitude of its waveguide counterpart at the S- and K_u-band frequencies.

The acoustic delay line is also important due to its small size and light weight. A piezoelectric transducer converts the transverse RF wave to a longitudinal acoustic wave. During the conversion, the RF wave velocity changes from the speed of light to the speed of sound. The acoustic waves propagate through a crystal delay line media before being reconverted to RF. However, the drawbacks of this type of delay line are its inefficient transducer conversion and its narrow bandwidth capability. Two loop TWTs are required to compensate for the higher insertion loss of the acoustic delay line, thereby, increasing the complexity and cost of the device, and decreasing the reliability.

Several technological firsts in the waveguide delay line and the loop TWT which greatly improve the performance of the 25 microsecond memory time system have been realized at the Watkins-Johnson Company. Spectral purities exceeding 75% of the energy within 5 MHz of the input frequency are currently being achieved. Another major achievement is the successful demonstration of loop TWT interchangeability in long memory-time FML devices. This interchangeability results in a simplified procedure for replacing units in the field, along with improved system utilization and efficiency.

Watkins-Johnson Company has also developed a 1 watt single tube loop TWT with a 65 dB small signal gain. This small size TWT meets full storage specifications of 7.5 to 18.0 GHz within a temperature range of $-54^{\circ}C$ to $+120^{\circ}C$.

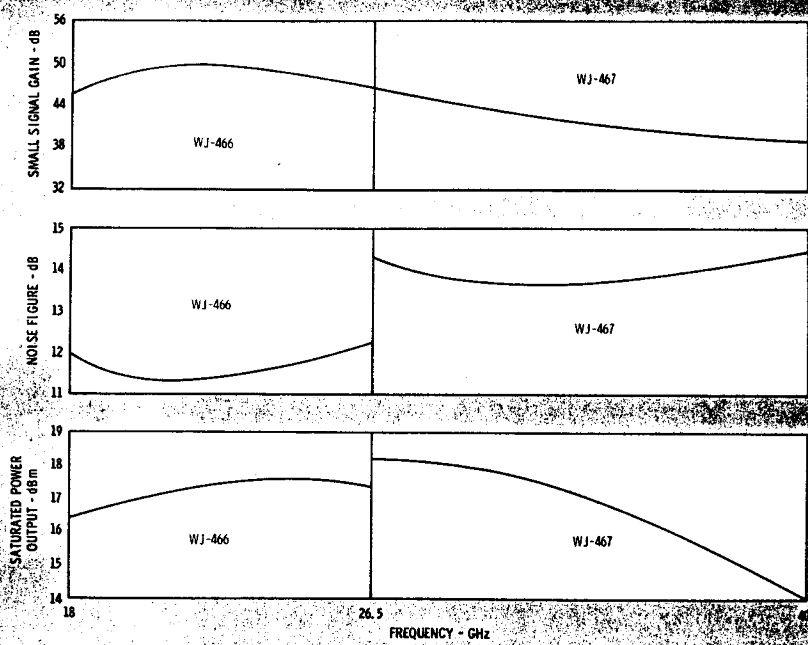


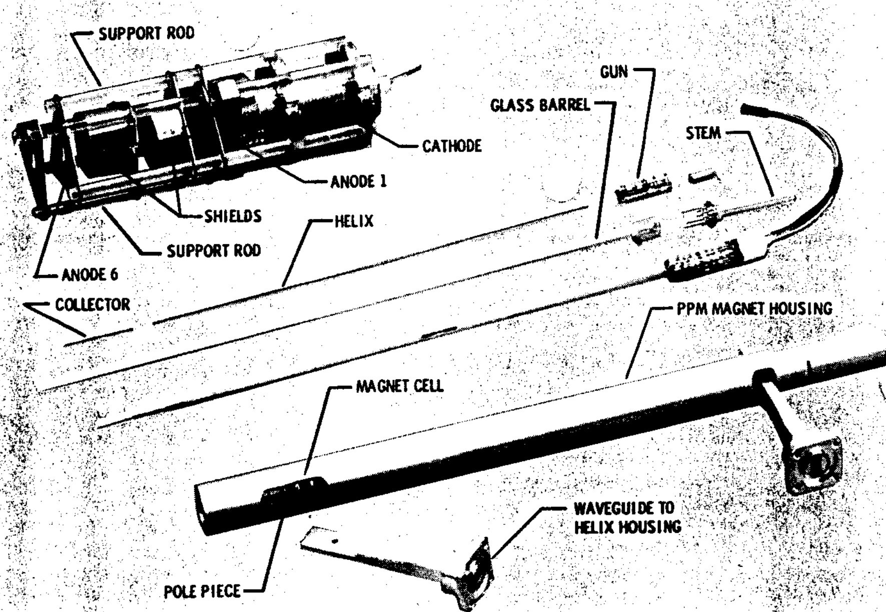
Fig. 4. Performance characteristics of miniature LNTWAs over the 18 to 40 GHz frequency range. Frequency range of the example amplifiers used are 18 to 26.5 GHz for the WJ-466, and 26.5 to 40 GHz for the WJ-467.

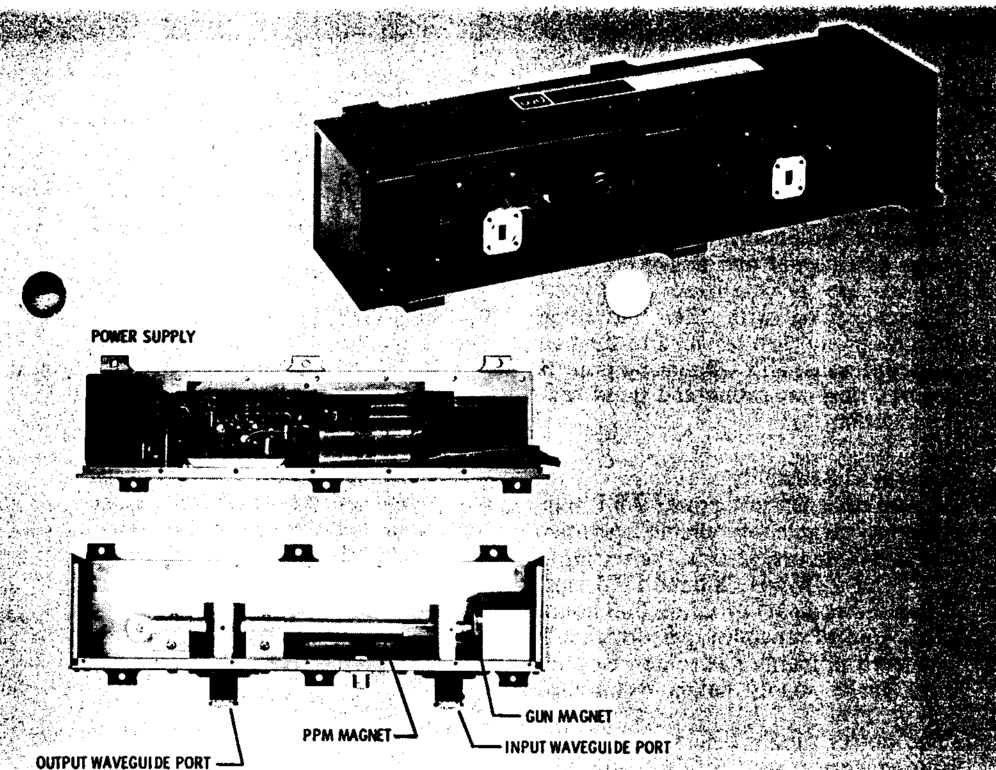
The Miniature Millimeter LNTWA

Because of spectrum crowding in the J/K-band frequencies there has always been an interest in higher frequency to provide more bandwidth. In "secure" communication systems, the advantage is the narrow antenna beam width. By going to higher frequencies it is possible to reduce beam width, thereby making it harder to intercept a transmitted signal. Also, todays surveillance receiver systems are being extended to look to frequencies above 18 GHz. Both of these applications require that the TWT amplifier functions of pre-amp, local oscillator, or driver for power tubes extend into the millimeter frequency range (40 GHz). Figure 4 illustrates the performance characteristics of two miniaturized LNTWAs up to the millimeter range.

The function of the miniaturized tube, in wide bandwidth shipboard and airborne applications, is to monitor the emissions of other radars. Their small size plays a key role, since maximum amplifier usefulness can be obtained by placing the TWT as close as possible to the receiving antenna. This portion discusses the technology responsible for producing the small size and low

Fig. 5. Miniature LNTWA showing components of PPM magnet, helix, barium emission shields, anode and cathode. This construction technique is an example of the WJ-466 and WJ-467 TWTs. Actual size of the TWT and power supply package is 2-1/2x3x12-1/2 inches.





cost miniaturized LNTWA.

State-Of-The-Art Technology

Reduced size and weight, as well as projected RF performance, design goals are approached by combining existing millimeter wavelength TWT design techniques with recent power supply developments. The fabrication is similar to the periodic permanent magnet (PPM) focusing technique of amplifiers below 18 GHz, however, unique designs are required for high cathode current, RF coupling, high voltage regulation and packaging.

Problems Created in Scaling to Higher Frequencies

Reducing the amplifier size creates major changes in the electron gun cathode-to-anode focusing scheme. By using PPM magnetics, and by increasing the length of the helix circuit, higher gain can be produced. However, high gain per unit length and close beam-to-helix spacing makes it necessary to decrease the electron beam diameter in order to minimize helix current interception, or the generation of backward-wave oscillations. This reduction in beam diameter results in a cathode current density above 0.5 amps per cm^2, which exceeds the operating limit of oxide cathodes. Tungsten impregnated cathodes solve this load limitation with the additional capability of operating at four times that of the oxide cathode current density. However, operating at higher tungsten cathode temperatures (1100°C versus 790°C) creates an associated problem of barium emission. The problem of barium deposit on the anode of the electron gun is accentuated by the close space between elements and high frequency of operation.

Solving the Close Space Problem

Solution to these problems start by making use of an impregnated tungsten matrix cathode whose material is selected for minimum barium emission, Fig. 5. The emitted Barium is trapped by placing shields along the sides of the cathode. The number of anode insulating support rods are doubled and alternated in use to increase the effective anode spacing. This technique minimizes any current between the elements should small amounts of barium be deposited on the anode support rods due to extended periods of operation.

Getting It Together – Packaging

Special mounting of the glass vacuum envelope and largemass gun magnet assembly (12 ounces) is required to withstand the temperature extremes of -62°C to +85°C, aircraft vibration specified by MIL-E-5400, and survive the hammer blow shock of MIL-STD-901.

Electron beam to helix separation is typically 4 mils for the example TWT amplifiers shown in Figure 5. Should the helix move axially by more than 4 mils during vibration, beam and helix interception could damage the tube. Environmental damage is prevented by using a two-stage support technique. First, the helix is supported by fluted tubing which is shrunk locked over each turn of the helix. Then the fluted glass is supported within the PPM magnet structure by a process that uses 50 precisely aligned pole pieces holding the glass outside diameter at intervals of approximately 0.2 inches.

Switching Regulator Reduces Power Supply Size

High operating voltages and long term reliability requirements force the abandonment of voltage regulation by pass elements at the converter high voltage output. Instead, reliable voltage regulation is best achieved by employing a switching regulator on the input line with high voltage photodiode sense feedback. Reliability is greatly improved by removing the semiconductors from the high voltage end (output) and maintaining all active regulation at low voltage end (input).

Finally, the power supply, and the tube with its magnet structure, are mounted separately to the adjacent walls of two L-shaped aluminum extrusions. The large gun-magnet and converter transformer are encapsulated in stycast material along with their mounting hardware and then fastened to the two adjacent walls. This fabrication process insures rigid mounting and good heat conduction.

Improved Reliability

A well designed low power TWT amplifier is capable of reliable operation of 50,000 hours. In fact, life testing at 25°C on a JW-464, X-band PPM amplifier shows an MTBF of 60,000 hours. This kind of reliability performance is achieved primarily due to new cathode and power supply design techniques.

The power supply commonly used in the modern low-noise TWT amplifier is the switched mode type operating at about 20 KHz. It provides small size and optimum efficiency due to:

- Availability of reliable high speed, high current, and high voltage transistors and rectifiers.
- Use of lower stressed components with better margins of safety.
- Use of higher quality screened components when necessary.
- Attention to design details in order to minimize the number of power supply components.
- The use of fixed resistors in lieu of potentiometers.

The cathode preferred in most state-of-the-art traveling-wave tubes is the impregnated tungsten matrix cathode. It consists of porous tungsten, the pores of which are impregnated with barium calcium aluminates. The major advantages of this cathode are:

- High cathode current density.
- Life times of 70,000 hours when operated at 1000°C at current densities less than 2 amps per cm^2.
- Superior resistance to gas poisoning and positive ion cathode bombardment.

Reducing TWT Amplifier Cost

The generally accepted procurement practice is to solicit two or more qualified TWT manufacturers for bids. Competition between manufacturers is keen and the award usually goes to the lowest bidder, even with the current emphasis on reliability. Today there is a trend to write "universal" tube specifications, which allow the purchase of one thousand or more amplifiers at a time.

This practice has forced the TWT manufacturer to improve production techniques and tube yields, hence reducing costs. An example indicative of the above was the recent award of a contract for over one thousand low-power amplifiers at a price of less than $1,000 each, including both the tube and integral power supply. If the TWT user continues to specify universal tubes, TWT manufacturers will continue to invest in equipment and resources that will allow larger production lines to be established. This would then make it possible for further significant cost reductions.

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