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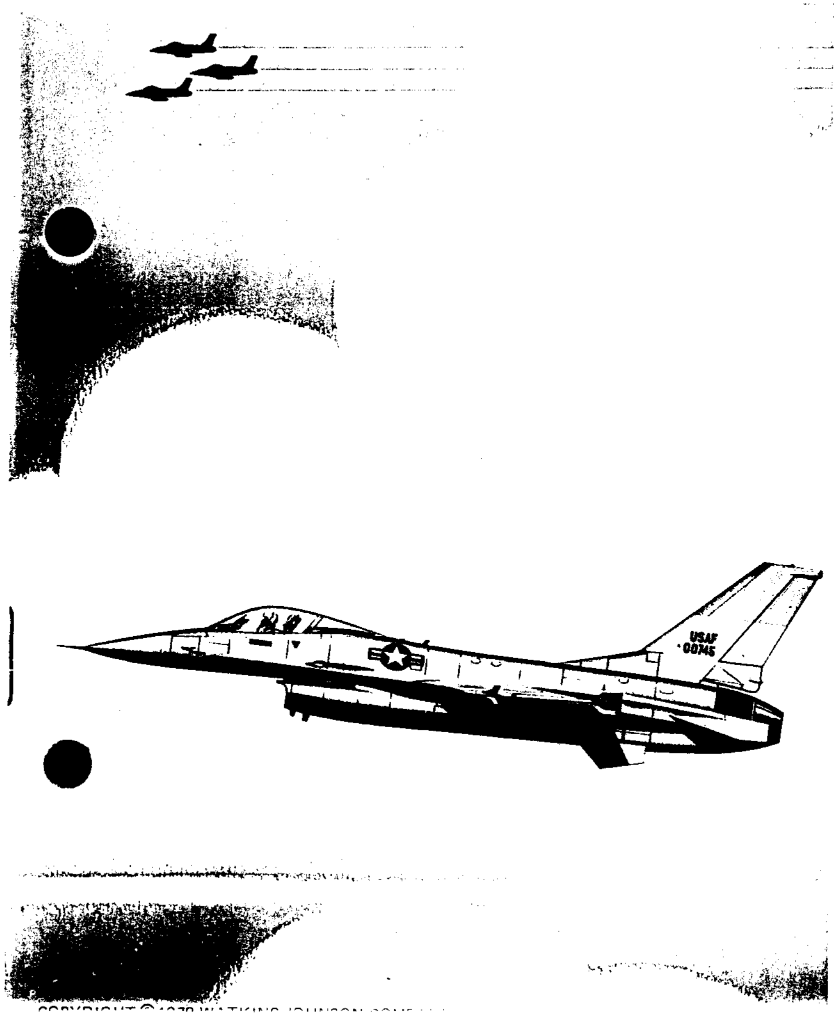
Hyperabrupt Varactor-Tuned Oscillators



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Manufacturing and Office Locations

United States

SALES OFFICES

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

Watkins-Johnson
2525 North First Street
San Jose 95131
(408) 262-1411

Watkins-Johnson
831 South Douglas Street
Suite 131
El Segundo 90245
Telephone: (213) 640-1980

DISTRICT OF COLUMBIA
Watkins-Johnson
700 Quince Orchard Road
Gaithersburg, Md. 20760
Telephone: (301) 948-7550

FLORIDA
Watkins-Johnson
325 Whooping Loop
Altamonte Springs 32701
Telephone: (305) 834-8840

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

MASSACHUSETTS
Watkins-Johnson
5 Militia Drive
Suite 11
Lexington 02173
Telephone: (617) 861-1580

NEW JERSEY
Watkins-Johnson
90 Monmouth Street
Suite 207
Red Bank 07701
Telephone: (201) 842-2422

OHIO
Watkins-Johnson
2500 National Road
Suite 200
Fairborn 45324
Telephone: (513) 426-8303

TEXAS
Watkins-Johnson
9216 Markville Drive
Dallas 75243
Telephone: (214) 234-5396

International

ITALY
Watkins-Johnson Italiana
S.p.A.
Piazza G. Marconi 25
00144 Roma-EUR
Telephone: (6) 59 45 54
Telex: 63278
Cable: WJROM-ROMA

GERMANY, FEDERAL REPUBLIC OF
Watkins-Johnson
Manzingerweg 7
8000 Muenchen 60
Telephone: (089) 836011
Telex: 529401
Cable: WJDBM-MUENCHEN

UNITED KINGDOM
Watkins-Johnson
Shirley Avenue
Windsor, Berkshire SL4 5JU
Telephone: (7535) 69241
Telex: 847578
Cable: WJUKW-WINDSOR

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The characteristics of the oscillators used within an ECM receiver or transmitter system are critical with regard to being able to set onto a particular frequency. The varactor-tuned oscillator has proven to be ideal for such systems, since it exhibits very fast settling time; however, it's nonlinear, high-voltage tuning characteristic has proven to limit its applicability. A new type of varactor-tuned oscillator utilizing a hyperabrupt varactor provides both a linear tuning characteristic and fast settling time performance. These devices also exhibit low post-tuning drift (PTD) characteristics and, consequently, are ideal for frequency-agile ECM equipment applications.

Varactor-tuned oscillators (VTO's) using abrupt junction varactors have been used for several years in frequency-agile receiver and jammer applications. Although characterized by low PTD and fast settling times, the resulting nonlinear tuning curves of VTO's require that a separate linearizer be used to reduce the tuning slope ratio across the frequency band and to decrease the maximum tuning voltage required. The linearizer slows the tuning response, increases cost, and reduces the MTBF. The hyperabrupt varactor tuned oscillator (HVTO) provides one solution to this problem by combining the speed of the unlinearized VTO with a linear tuning characteristic.

The oscillators described in this article have settling times of less than 50 ns, PTD less than 1 MHz, and tuning slope ratios less than 1.5:1 over tunable bandwidths

$$\left(\frac{F_{High}-F_{Low}}{F_{Center}}\right)$$

of up to 45%.

Applications

The two most common uses of microwave tunable oscillators in modern ECM systems are as frequency-agile local oscillators in receiver systems and fast-modulation noise sources in active jamming systems. Figure 1 illustrates the use of a hyperabrupt varactor-tuned oscillator as a local oscillator in a receiver system, while Figure 2 illustrates a block diagram of an active jamming system using the HVTO as the microwave power source. In both system applications the HVTO must exhibit the following performance characteristics:

1) Linear voltage-versus-frequency characteristic
2) Minimum fine-grain tuning slope variation
3) Low post-tuning drift
4) Fast settling time
5) Tuning voltage range less than 10 volts to allow direct integration with high-speed digital-to-analog conversion circuitry.

In reality, the HVTO to be used in an ECM application is an oscillator subsystem which may contain integral voltage regulators, temperature controlling circuitry, digital-to-analog conversion circuitry, and load isolation and power amplification circuits.

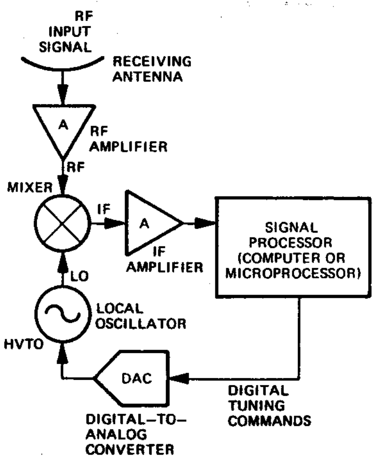

Figure 1. A receiver system using the HVTO as the local oscillator.

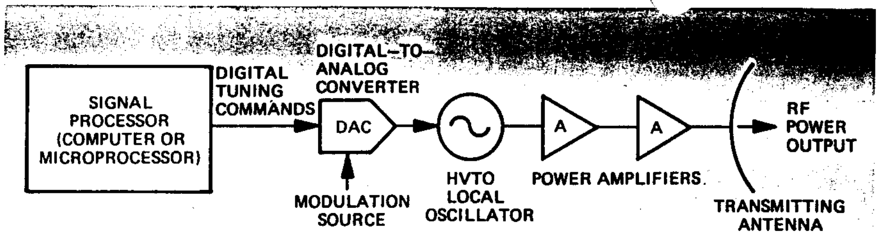

Figure 2. An active jamming system using the HVTO as the microwave power source.

Figure 3 shows an example of an HVTO subsystem.

In EW receiver applications, the linear tuning characteristic and high-speed tuning capability of the HVTO result in a high intercept probability for the receiver as well as high frequency resolution. If the HVTO's frequency of operation as a local oscillator is not accurately known because of tuning errors caused by frequency drift, the receiver may improperly identify, or fail to detect an incoming signal due to gaps in the frequency coverage.

In the active jamming application, the HVTO's linear tuning characteristic, low post-tuning drift and high-speed tuning capability are essential

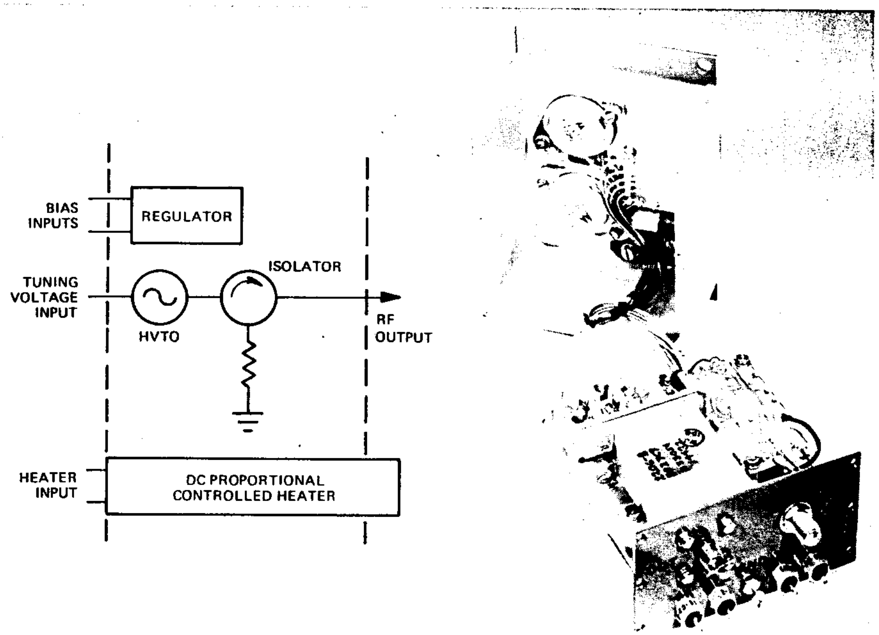

Figure 3. Example of an HVTO subsystem.

for frequency-agile operation. The oscillator can be stepped across a wide range of frequencies in a short period of time (e.g., less than 100 nanosecond time intervals). Once the jammer is tuned to the desired frequency, it must not deviate from that frequency within the limits of the threat receiver's IF bandwidth. If the jammer does not tune to the correct frequency, or if it drifts from that frequency after being tuned, there is a possibility that the threat may not even detect the jamming signal.

Performance of the HVTO Subsystem

To date, HVTO subsystems have been built in the frequency range from 0.5 to 12.0 GHz in tunable bandwidths up to 45%. Their general characteristics can be summarized as follows:

1) Settling times less than 50 ns to within 2 to 5 MHz of final frequency.
2) With digital-to-analog conversion circuitry integral to the oscillator subsystem, the settling time is less than 1 microsecond to within 2 to 5 MHz of final frequency.
3) Tuning linearity relative to a best-fit straight line is less than ±0.5%.
4) Tuning slope ratios are less than 1.5:1 for tunable bandwidths of 45%.
5) Post-tuning drift from 500 ns to 10 milliseconds of less than 1 MHz.
6) Power output from 0 dBm to 20 dBm, depending on the addition of amplifier modules.
7) Tuning voltage range of less than 10 volts.

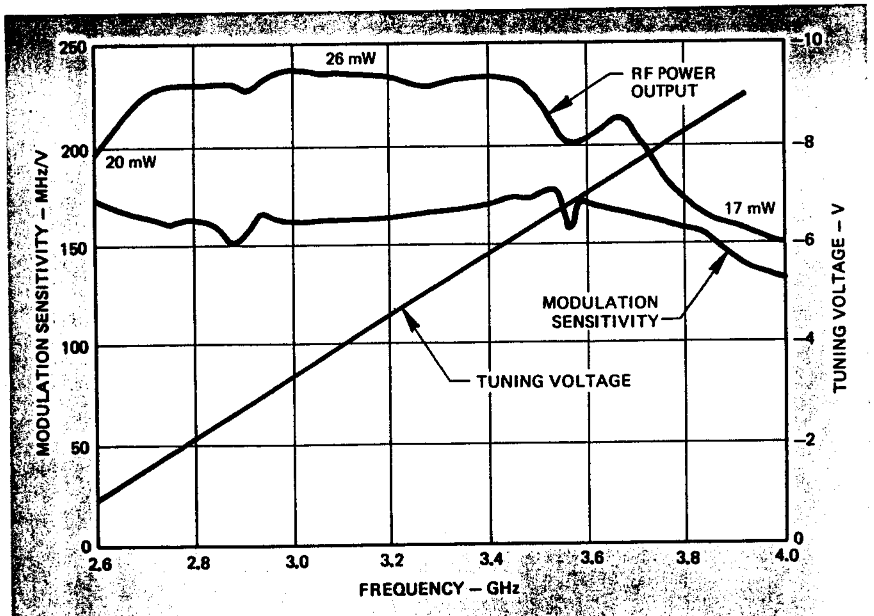

Figure 4. Power output, tuning voltage and modulation sensitivity characteristics of a 2.6-to 3.9-GHz HVTO subsystem.

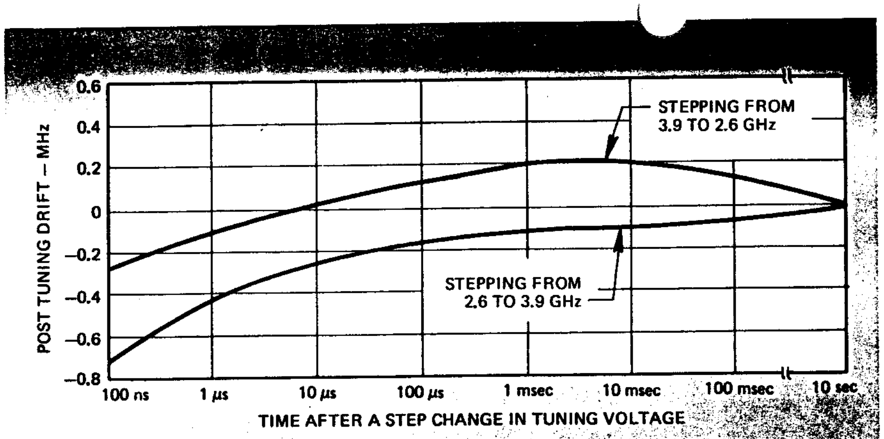

Figure 5. Post tuning drift characteristics of 2.6-to 3.9-GHz HVTO subsystem.

The power output, tuning voltage and modulation sensitivity characteristics of a 2.6- to 3.9-GHz HVTO subsystem are illustrated in Figure 4; its post-tuning drift characteristics are shown in Figure 5. This HVTO subsystem contains the oscillator, active load isolation and amplification, integral regulators, and temperature control circuitry. The tuning voltage required to tune from 2.6 to 3.9 GHz is -0.9V to -8.8V, and the modulation sensitivity variation ratio is less than 1.25:1 across the frequency range. The maximum post-tuning drift is less than 650 kHz from 100 ns to 10 seconds for any step change in tuning voltage in the band.

Performance characteristics are illustrated in Figures 6 and 7 for a fundamental 3.0 to 5.0 GHz subsystem. The

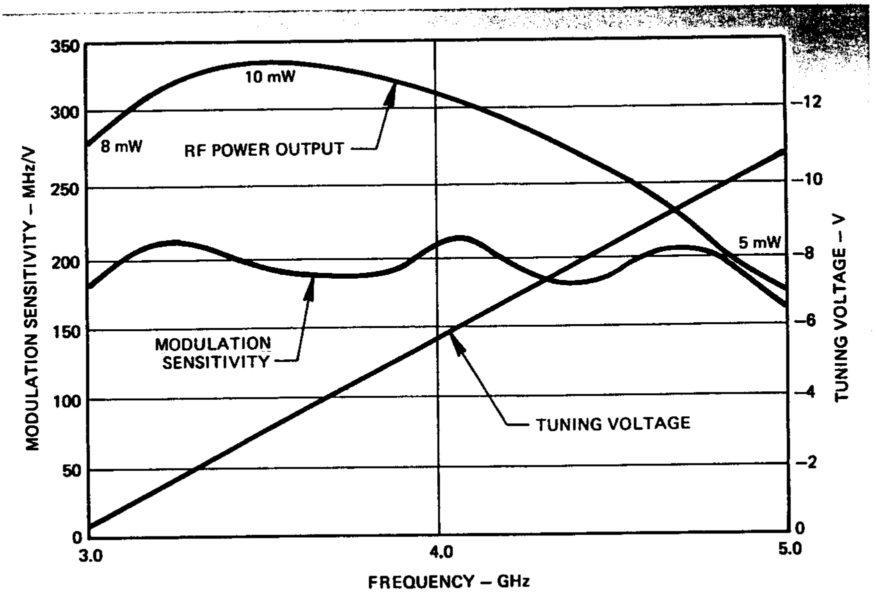

Figure 6. Power output, tuning voltage and modulation sensitivity characteristics of a 3.0-to 5.0-GHz fundamental HVTO subsystem.

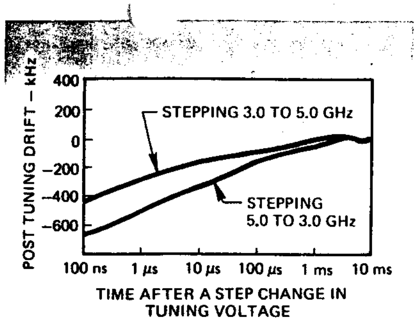

Figure 7. Post-tuning drift characteristics of a 3.0-to 5.0-GHz fundamental HVTO subsystem.

tuning voltage range for this oscillator ranges from -0.2V at 3 GHz to -10.7V at 5 GHz. The modulation sensitivity variation ratio is less than 1.3:1 across the band, and the minimum power output is 5 mW. This unit does not contain any amplification circuitry. The maximum post-tuning drift is less than 680 kHz from 100 ns to 10 milliseconds for any step change in tuning voltage in the band.

The power output, tuning voltage, and modulation sensitivity characteristics of a 7.7- to 10.3-GHz HVTO are illustrated in Figure 8, and its post-tuning drift characteristics are shown in Figure 9. The modulation sensitivity variation ratio is less than 1.5:1 across the band and the minimum power output is 1 mW. This unit does not contain any amplification circuitry. The PTD of this oscillator is less than 500 kHz for all steps within the 7.7- to 10.3-GHz range from 100 nsec to 10 msec after a step change in tuning voltage.

Comparison of Abrupt and Hyperabrupt Varactor Oscillators

The tuning voltage characteristics of two fundamental 2.6- to 3.9-GHz oscillators — one employing abrupt and one hyperabrupt varactors — are illustrated in Figure 10A. The inherent linearity of the HVTO can readily be seen by comparing the two tuning voltage characteristics as well as their modulation sensitivity curves (Figure 10B). As shown in Figure 10C, the power output of the abrupt junction varactor oscillator is higher than an equivalent hyperabrupt varactor oscillator without additional amplification. This is primarily due to the fact that the hyperabrupt varactor has a lower Q than an otherwise equivalent abrupt junction device.

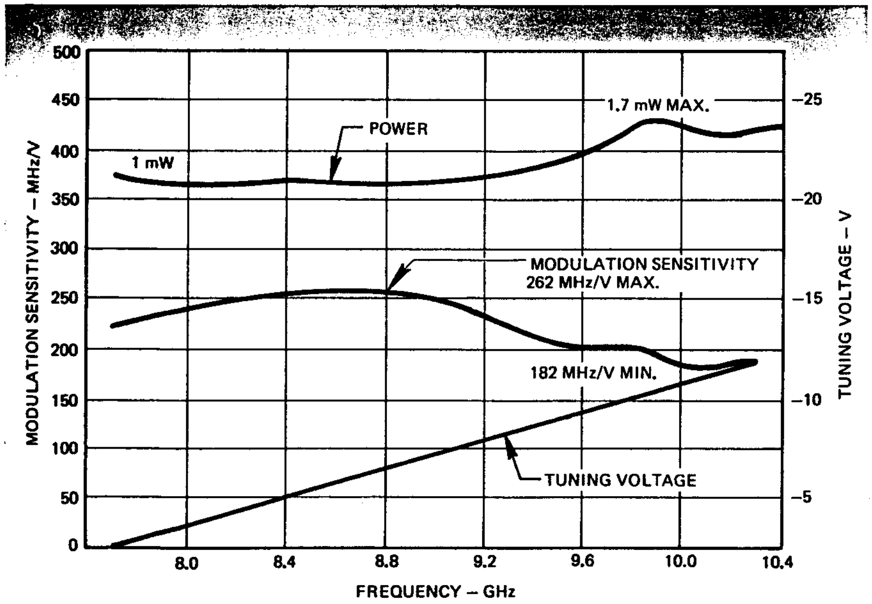

Figure 8. Power output and tuning characteristics of a 7.7-to 10.3-GHz HVTO.

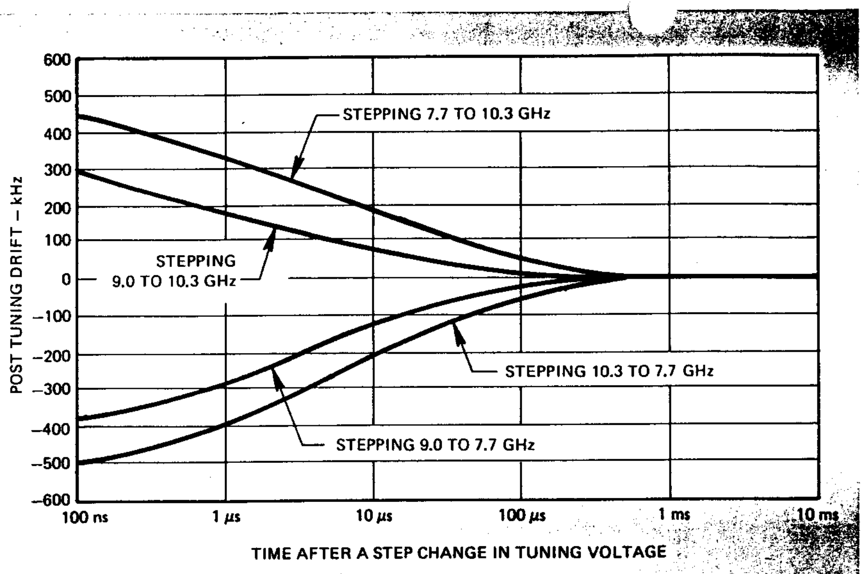

Figure 9. Post-tuning drift characteristics of a 7.7-to 10.3-GHz HVTO.

Circuit Technology

Initially, hyperabrupt varactor-tuned oscillators were built utilizing discrete, packaged transistors and varactors. Today, with the advent of microstrip oscillator technology, smaller, lighter weight HVTO's can be built. Combining this technology with microstrip amplifier designs yields products similar to that shown in Figure 11. This integral oscillator/amplifier operates from 2.6 to 3.9 GHz and is housed in a Watkins-Johnson Company developed "Minpac." Such units may be directly integrated into larger microstrip circuits or may be placed in housings having SMA connectors. The Minpac provides a convenient package which can easily be hermetically sealed.

Circuit Description

A schematic of the basic oscillator circuit used for Watkins-Johnson Company's hyperabrupt varactor-tuned oscillators is shown in Figure 12. Fundamental push-pull circuits are used up to 5 GHz, while doubling push-push circuits are used to 12 GHz. A "grounded base" configuration is used to provide a stable reference to the transistors and the varactor diodes, primarily to improve post-tuning drift. Figure 13 shows a simplified version of this schematic with the significant circuit parameters designated.

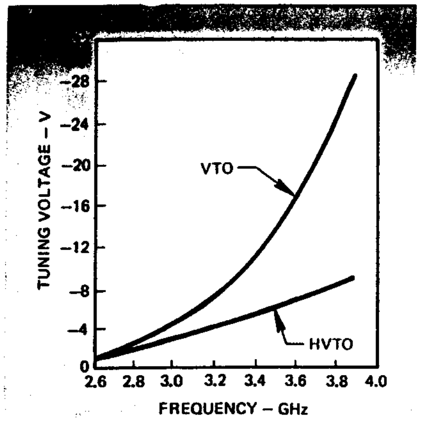

Figure 10A. Comparison of the tuning characteristics of a HVTO and VTO.

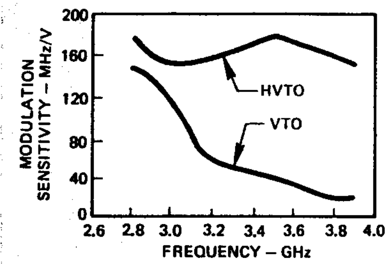

Figure 10B. Comparison of the modulation sensitivity characteristics of a HVTO and VTO in the 2.6-to 3.9-GHz range.

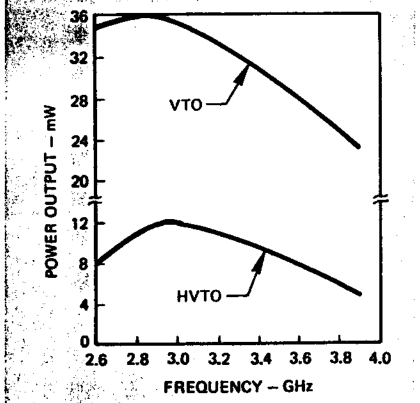

Figure 10C. Comparison of the power output characteristics of a 2.6-to3.9-GHz HVTO and VTO.

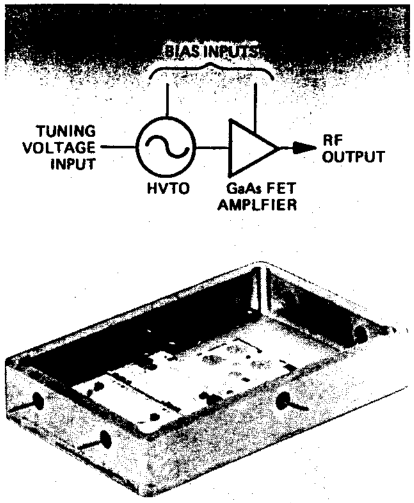

Figure 11. 2.6-to 3.9-GHz oscillator/amplifier in MINPAC.

The resonant frequency of the series circuit in Figure 13 is:

$$F = \frac{1}{2\pi\sqrt{L_p C_T}}$$

$$\text{where } C_T = \frac{C_t C_j(V)}{C_t + C_j(V)}$$

F = Frequency of Oscillation
C_t = Transistor Input Capacitance
$C_j(V)$ = Varactor Capacitance
L_p = Effective Series Inductance from Tuning Inductances, Coupling and Load

By substituting the varactor capacitance formula,

$$C_j(V) = \frac{C_j(0)}{(1+\frac{V}{\phi})^{\gamma}},$$

into the frequency equation and utilizing a circuit design such that

$$V >> \phi \text{ and } (V+\phi)^{\gamma} >> \frac{C_j(0)\phi^{\gamma}}{C_t}$$

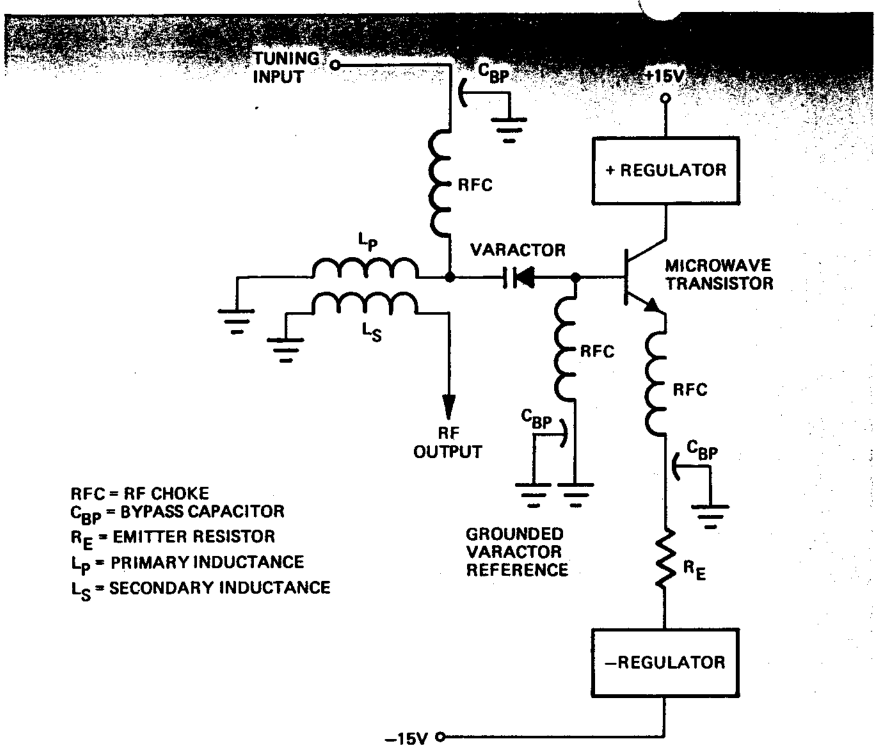

Figure 12. "Grounded Base" oscillator design to improve short term stability.

the frequency equation simplifies to

$$F = A\,[V^{\gamma}]^{0.5}$$

$$\text{where } A = \frac{1}{2\pi\sqrt{L_p C_j(0)\,\phi^{\gamma}}}$$

For an abrupt junction varactor (γ=0.5),

$$F = AV,^{0.25}$$

whereas for a hyperabrupt varactor (γ=2),

$$F = AV.$$

As a result, the frequency is approximately a linear function of varactor reverse bias voltage.

For presently available hyperabrupt varactors, γ ranges from 1.1 to 1.6;

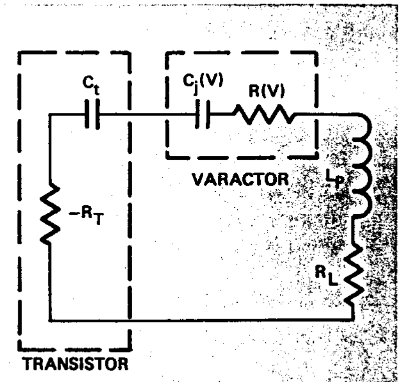

Figure 13. Simplified schematic of the varactor tuned oscillator.

however, over a given frequency band the transistor capacitance also varies as a result of changes in RF bias. Consequently, the γ of the effective capacitance C_T is approximately equal to 2.0, resulting in a linear tuning characteristic over bandwidths up to 45%.

Varactor Description and Characteristics

The linear performance of the hyperabrupt varactor-tuned oscillator (HVTO) has been made possible primarily because of improvements in the hyperabrupt varactor diodes and circuit design techniques using these devices. The hyperabrupt varactor diode has been available for some time, but not at performance levels acceptable for microwave oscillator work. New devices have now become available, due to the development of a mesa structure which makes possible the manufacture of low-capacitance diodes with higher Q and higher breakdown voltage.

A junction diode consists of two layers of semiconductor material which have been doped with impurities so that one layer has a deficiency of electrons and the other a surplus. These layers are designated as "p" and "n" layers, respectively. In the "n" layer, the surplus electrons are free to migrate under the influence of an electric field or applied voltage, thus leaving a net positive charge. Similarly, in the "p" layer, the deficiency of electrons leaves holes which behave as though they were mobile positive charges. Holes are also free to leave the area under the influence of external electric fields, resulting in a net negative charge.

Where the two materials meet, their respective charge fields extend across the junction and influence the current carriers in the opposite material. The positive charge from ions in the "n" material tends to repulse the holes in the "p" material, and the negative charge of the "p" material particles pushes the free or loosely bound electrons in the "n" material away from the junction. By thus removing the current carriers from the junction areas, a depletion region is formed through which current cannot flow until the repulsion of carriers is overcome by the application of a suitable voltage of the correct polarity.

As shown in Figure 14, the depletion region behaves as though it were a battery of a voltage equal to the junction potential, ϕ. For current to flow through the diode, it is necessary to overcome this voltage by a greater voltage of the opposite polarity. If an external voltage is applied with the same polarity as the contact potential, such as V in Figure 14, the depletion region can be made larger or smaller by increasing or decreasing the external voltage. In this manner, the reverse biased diode behaves like a parallel-plate capacitor. The depletion region becomes the dielectric, and the boundaries of the current areas simulate the two plates of the electrodes of the capacitor. The capacitance value will vary with the area of the junction, the nature of the semiconductor material and the applied voltage. As the reverse voltage increases, the two capacitor plates are pushed farther apart, thus reducing the effective capacitance of the junction. As the bias is lowered, the two plates draw closer together and thus increase the capacitance.

The difference between an abrupt junction and hyperabrupt junction varactor is that the concentration of the "n" material is constant across the depletion region in an abrupt diode, and it is nonlinear in a hyperabrupt diode, as shown in Figures 15A and 15B. This is accomplished by ion implantation or nonlinear epitaxial growing techniques. As the reverse voltage is increased, the characteristics of the nonlinear "n" material cause a greater capacitance change in the hyperabrupt varactor than in the abrupt junction varactor for a constant voltage change.

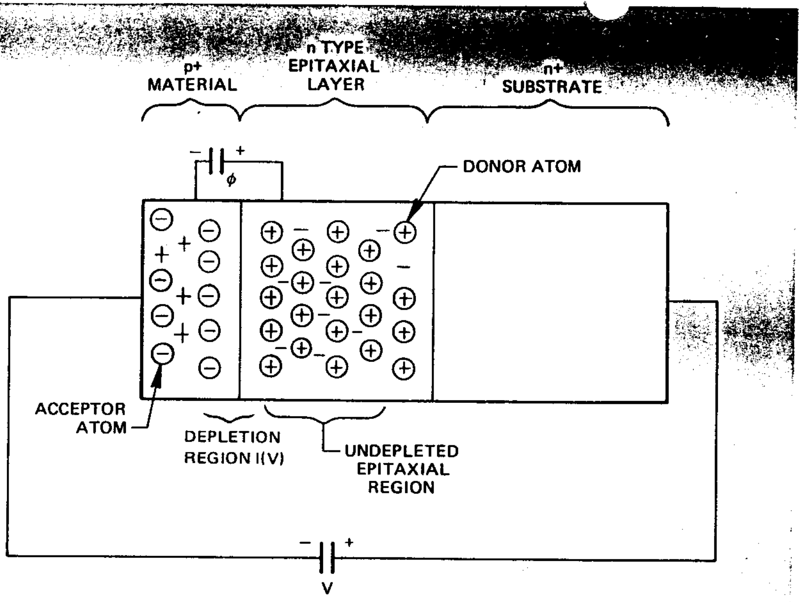

Figure 14. A pn junction varactor diode.

The capacitance of a varactor diode may be expressed by the equation

$$C_j(V) = \frac{C_j(0)}{(1 + \frac{V}{\phi})^{\gamma}}$$

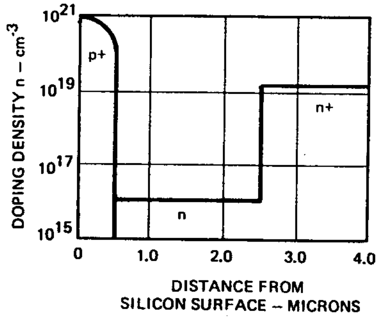

Figure 15A. Doping density for an abrupt junction varactor.

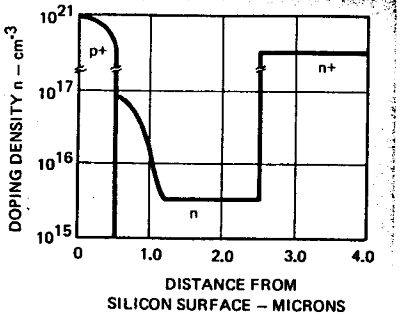

Figure 15B. Doping density for a hyperabrupt varactor.

where $C_j(V)$ = Varactor Capacitance
V = Reverse Bias Voltage
ϕ = Contact Potential
γ = Slope of Varactor C-V Characteristic

The junction capacitance is an inverse function of the reverse bias voltage raised to the γ power. The value of γ is determined by the doping profile of the epitaxial layer. For abrupt diodes, $\gamma = 0.5$, whereas it is approximately 2.0 for hyperabrupt varactors due to the nonlinear concentration of the "n" material. A comparison of the capacitance characteristics of an abrupt and hyperabrupt diode having the same capacitance value at zero volts is shown in Figure 16.

The Q (quality factor) of a varactor is expressed by the equation

$$Q = \frac{1}{2\pi F R(V) C_j(V)}$$

where F = Frequency
R(V) = Varactor Resistance
$C_j(V)$ = Varactor Capacitance
V = Reverse Bias Voltage

As shown in Figure 15, the average doping concentration of the undepleted epitaxial region is higher approximately by a factor of two in an abrupt junction varactor than in a hyperabrupt diode. Consequently, the series resistance is higher for the hyperabrupt diode as depicted graphically in Figure 17, and by the equation

$$R(V) = \frac{\rho}{A}\,[L-l(V)] = \frac{[L-l(V)]}{A N_d q \mu}$$

where ρ = Resistivity of undepleted epitaxial region
L-l(V) = Length of undepleted epitaxial material
L = Epitaxial layer thickness
N_d = Impurity concentration in the "n" material
μ = Carrier mobility
q = Electronic charge
V = Applied reverse voltage

Therefore, at low reverse bias voltages the Q of an abrupt junction varactor is higher than an equivalent (same $C_j(0)$) hyperabrupt varactor, as shown in Figure 18. However, at higher reverse voltages the Q of the hyperabrupt varactor increases above that for the abrupt varactor due to the more rapid decrease in $C_j(V)$ for the hyperabrupt device. Over the linear tuning range (-1 to -10V), the Q is lower and, consequently, the power output of a hyperabrupt oscillator is typically lower than an equivalent abrupt junction oscillator.

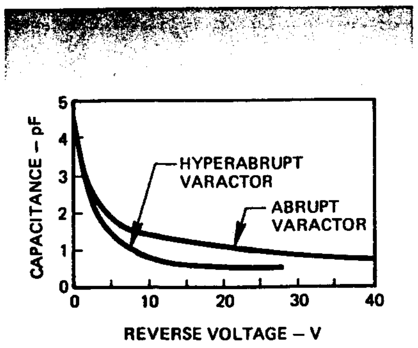

Figure 16. Capacitance characteristics of an abrupt and hyperabrupt varactor.

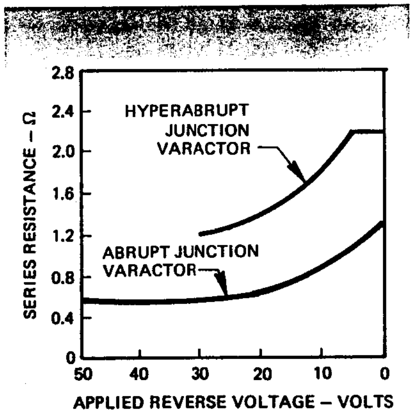

Figure 17. Series resistance for an abrupt and hyperabrupt varactor.

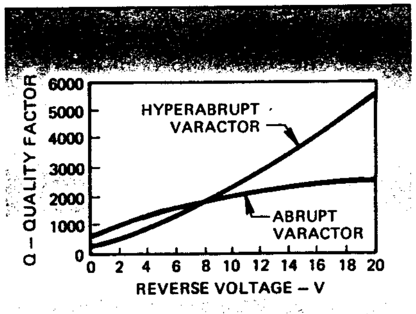

Figure 18. Quality factor vs. voltage for an abrupt and hyperabrupt varactor, f=50 MHz.

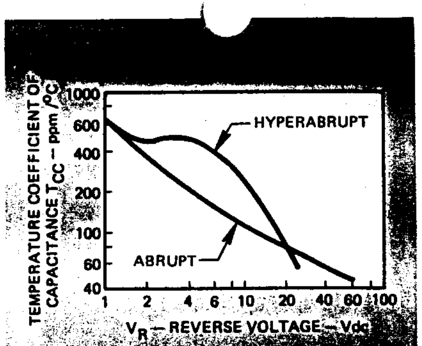

Figure 19. Temperature coefficient of capacitance vs. tuning voltage, abrupt junction diode and hyperabrupt junction diode.

The capacitance temperature coefficient (T_{cc}) of a varactor is expressed by the equation

$$T_{cc} = \frac{1}{C_j(V)}\left(\frac{d\,C_j(V)}{dT}\right) = \frac{-\gamma}{V+\phi}\left(\frac{d\phi}{dT}\right)$$

where $C_j(V)$ = Varactor capacitance
T = Temperature
ϕ = Contact potential
γ = Slope of varactor C-V characteristic

As shown in Figure 19, the T_{cc} of an abrupt junction varactor is lower than an equivalent (same $C_j(0)$) hyperabrupt varactor. The flattening of the T_{cc} near 4V for the hyperabrupt varactor is attributed to the rapid increase in γ at that point. This indicates that hyperabrupt varactor-tuned oscillators will have higher thermal drift than equivalent abrupt junction oscillators.

Conclusion

Hyperabrupt varactor-tuned oscillators have been developed which exhibit linear tuning characteristics and are capable of being tuned at very high speed, with low PTD characteristics.

The hyperabrupt varactor-tuned oscillator offers the following advantages over the linearized abrupt varactor tuned oscillator: lower PTD, faster settling time, less fine-grain modulation sensitivity variation, smaller size, higher MTBF, and lower cost.

Further advancements in diode and circuit technology are expected to yield oscillators of higher power and with broader tunable bandwidths than are presently available. GaAs material should prove to be ideal for such applications.

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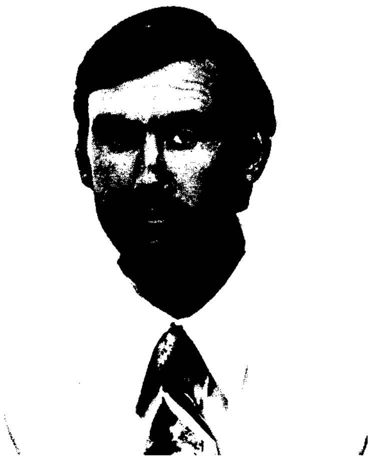

Biography

Richard M. Beach is currently the Head of the Product Engineering Section in the Solid State Department of Watkins-Johnson Company, Stewart Division. He is responsible for the development of wideband, fast-settling, low-drift oscillators as well as narrow-band, low-noise oscillators for military applications. Under his direction, VTO's for several military applications have been developed including the ALQ-122 Warning Receiver, the ALQ-136 Receiver, and the USM-406 Test Set. Also accomplished under his direction were the development of high-speed, low-drift linearizer circuits, computer-controlled VTO test equipment, and VTO load isolators.

NOTES