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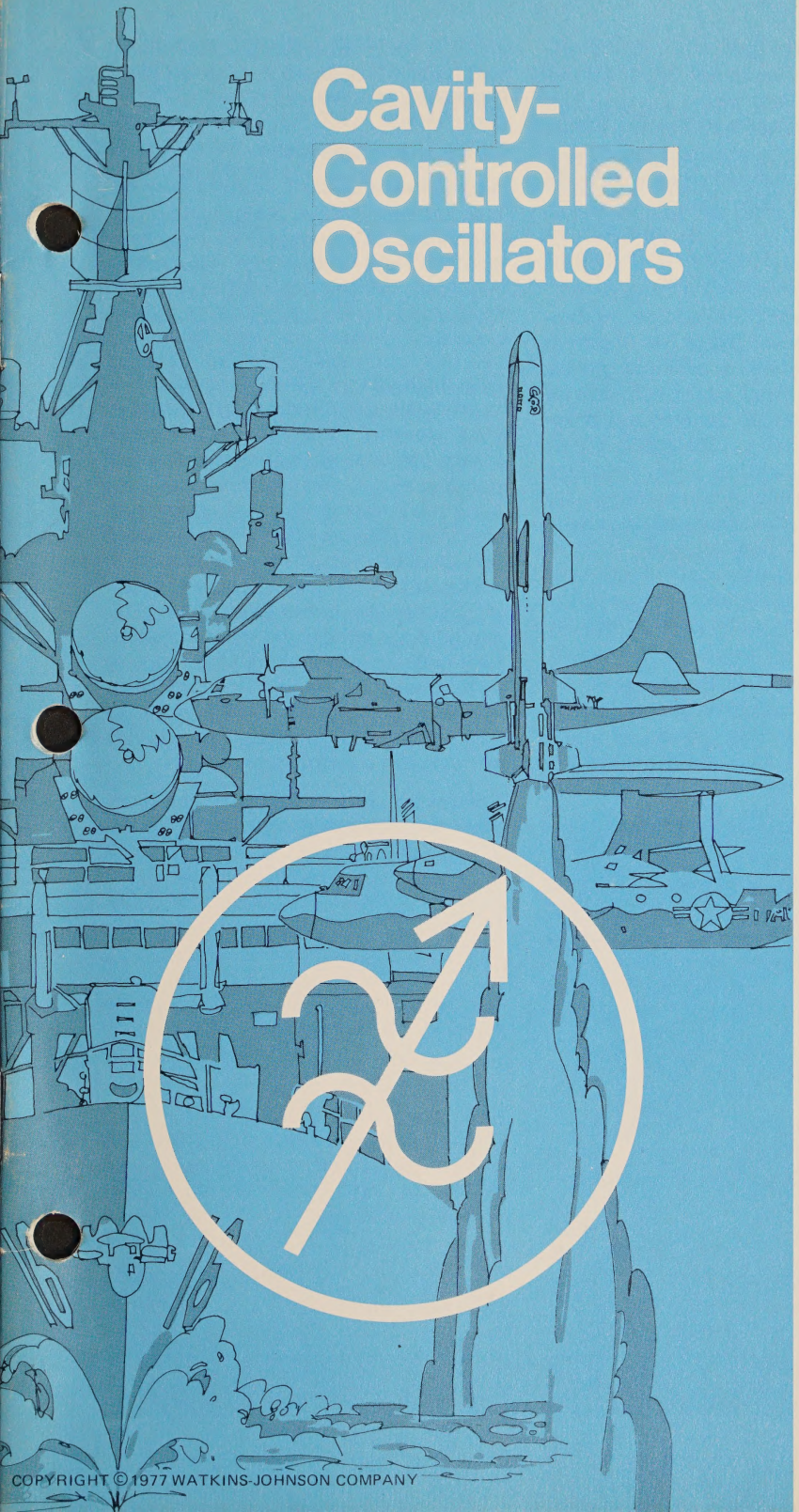
Cavity-Controlled Oscillators



WATKINS-JOHNSON COMPANY Tech-notes

The microwave cavity is one of the oldest circuit elements used in the generation of microwave energy. The first microwave tubes utilized a cavity to operate on an electron beam in a manner which caused oscillations. In the last decade or so, the use of microwave semiconductors in conjunction with microwave cavities has begun to exhibit significant potential.

One important difference exists, however, between the old electron beam method of microwave power generation and that which is used with semiconductors. In the electron beam concept, the cavity is an intrinsic part of the amplification and feedback generating mechanism necessary for oscillation. In the semiconductor concept, the amplification and, in most cases, the necessary feedback are built into the semiconductor device, and the cavity is used only for frequency control.

Microwave cavity oscillators are distinguished from other types of microwave oscillators by virtue of their superior frequency stability. They are the most stable type of oscillator capable of generating fundamental frequency energy in the microwave range. A properly-designed cavity oscillator, well isolated from environmental and input influences, can approach the stability of a crystal oscillator at magnitudes higher in fundamental frequency than that obtainable from crystal oscillators.

Although the cavity oscillator concept is not new, the number and performance of active devices available has increased. GaAs FET's, Gunn diodes, bipolar transistors, avalance devices and tunnel diodes are all compatible with the cavity oscillator concept to provide microwave energy for specific applications. A wide mechanical-tuning capability coupled with a small degree of electronic-tuning capability provide the cavity oscillator with performance compatible with many modern system requirements. Cavity oscillators have found their way into radar, communications, surveillance and control systems as well as fuses, jammers and receivers.

Solid-State Sources

Microwave solid-state sources may fall into any one of three general categories, depending on the degree of frequency stability or frequency tuneability required. In general, high stability is obtained at the sacrifice of frequency tuneability.

The high-stability type of solid-state sources always require a crystal reference source. The term "reference source" is used with crystal-controlled microwave oscillators because even overtone crystals have a maximum operating frequency of a few hundred MHz. Therefore, crystal-controlled oscillators must be frequency multiplied into the microwave range. This can be done either by direct multiplication or by phase locking the source to a harmonic of the crystal oscillator. Frequency stabilities in the order of one part in 10^{10} or better are possible with crystal control.

Solid-state sources falling in the intermediate-stability category may utilize a crystal or a high-Q cavity as the frequency control element. A small degree of voltage tuneability is possible in this category, ranging up to a few tenths of a percent. In addition, an intermediate stability may be designed to provide up to an octave of mechanical tuneability. The stability of this category of oscillators may range up to one part in 10^6 or better.

The low-stability category of solid-state sources covers such wideband devices as varactor-tuned, pin diode-tuned, or YIG-tuned oscillators, and intermediate bandwidth hybrid oscillators consisting of a cavity strongly coupled to a voltage-variable reactance.

Although the low-stability, solid-state sources contain the hybrid group of oscillators which feature a degraded, cavity-type performance, this article will be limited to the intermediate-

stability category of cavity controlled oscillators; those whose frequency stability characteristics are controlled by a high-Q cavity. This type of oscillator, which operates at 4 GHz, is shown in Figure 1.

Applications

Since a cavity oscillator can be designed with a small degree of electronic tuning, it can be locked to a given frequency by automatic frequency control. In this application, a discriminator is used at the intermediate frequency (IF) of a superheterodyne receiver. Any deviation in the IF from the center of the discriminator causes an error signal which is fed back to the voltage tuning port of the cavity oscillator to correct the frequency. If the voltage tuning is made sufficient to compensate for cavity oscillator drift with temperature, time, or supply voltage variations, the frequency will remain locked for long periods of time over widely varying conditions. This can be an important factor for wideband mechanically-tuned receivers or high sensitivity receivers with narrow IF bandwidths.

Radar Guidance and Fuses

The advantage of mechanical tuning and automatic frequency control becomes more obvious in the consideration of beam riding or radar guided missiles, or radar-type fuses. When jamming is a possibility, the exciter can be mechanically tuned to a frequency at which jamming is least likely, and the oscillator then locked to the IF.

Spot Jammers

Electronic tuning may also be used to generate a precise spot of noise for jamming purposes. In this application, the cavity's output frequency is modulated with noise to the desired bandwidth and then mechanically adjusted to the frequency of the threat to be jammed.

Communications Systems

Cavity oscillators with electronic tuning

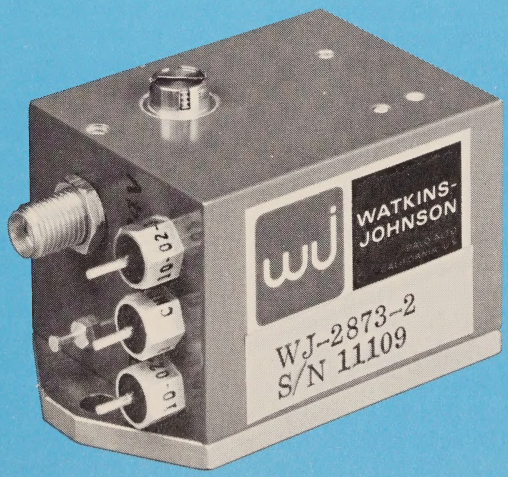


Figure 1. Solid-state, mechanically and electronically-tuned, cavity oscillator.

capability can be frequency modulated with voice, video or digital information for point-to-point communications. When frequency stability equivalent to that of a crystal oscillator is required, the cavity oscillator may be phase locked to a crystal reference in a narrow bandwdith phase lock loop and then modulated directly at frequencies outside the bandwidth of the control loop. This is often the type of exciter used in frequency division multiplex (FDM) communications systems.

Stable Local Oscillators (STALOS)

The electronic tuning capability may be used to provide a stable local oscillator (LO) in high sensitivity or wideband receiver systems. In this application the oscillator may also be phase locked to a stable crystal reference. In the high sensitivity case, the oscillator is locked to a stable reference and operates as the LO for a very narrow bandwidth IF. In the case of a wideband receiver, the oscillator may or may not be locked to a more stable reference, and acts as the first LO in a wideband system. For example, fixed frequency cavity oscillators may be set at 8 and 10 GHz as first LO's, where the second LO covers a 1.7- to 3.7-GHz range, with a 300 MHz second IF. The first LO's will then receive any signal within the 4- to 8-GHz or 10- to 14-GHz range and convert it into the range of the second IF. This principle can be used to cover any frequency range required without the necessity for wideband, high-frequency sweeping LO's.

Doppler

Since the cavity oscillator can be made to operate very stably for a relatively short time, it performs well in doppler applications. Most doppler applications do not require the long-term stability of a crystal, but do require very good short-term stability. Any short-term frequency jitter constitutes noise in a doppler system. This noise must be low enough to keep from masking the intended return. Uses are found for the high-Q cavity oscillator in doppler-type motion detectors such as police radar and security systems.

Performance Characteristics

The output power from a cavity-controlled semiconductor oscillator will be determined primarily by the characteristics of the active device. It is reasonable to conceive of a stable cavity which undergoes no significant physical changes with time, temperature or mechanical shock, in which case power output will be exclusively a function of active device parameters. Absolute power output and power output variations are the primary criteria for the selection of one of a wide variety of active devices available for use in cavity-controlled oscillator circuits. Some of these devices include bipolar transistors (for frequencies up to 10 GHz), Gunn diodes (6 GHz and above), avalanche devices (low to medium power above 6 GHz), tunnel diodes (very low power up to tens of GHz), and GaAs FET's (tens of milliwatts up to 20 GHz). A relative comparison of the power output from the various active devices is shown in Figure 2.

Power Stability

The stability of the power output is dependent upon certain factors inside and external to the unit, including bias voltage changes, temperature variations, possible start-up problems, environmental factors, and aging effects.

In any system, the active device in a cavity oscillator will experience some variation in applied voltage with a resultant power output variation. Of the active devices available, the GaAs FET and the IMPATT diode are the least sensitive to small variations in applied voltage. Bipolar-transistor sensitivity falls between these devices and that of tunnel diodes and transferred electron devices (Gunn diodes), which

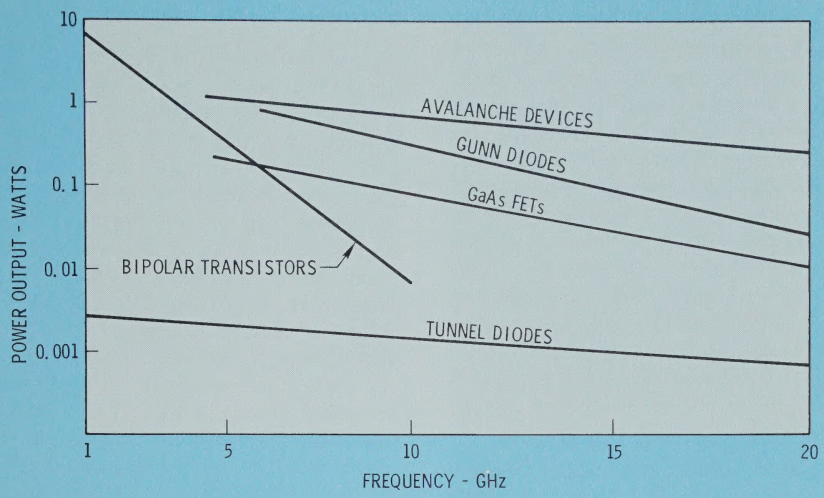


Figure 2. Approximate output power capability of various solid-state active devices available for use in cavity-controlled oscillators.

are the most sensitive. All of these devices exhibit significant variations in performance characteristics when subjected to larger variations in supply voltage. For this reason, supply voltages for semiconductor oscillators are generally held within relatively narrow limits, usually a few percent at most.

All of the active devices available will exhibit significant power output variations with widely varying temperatures. There is a wide variation in the temperature performance of the various types of active devices as well as between various lots of the same type of active device. A 3-dB variation in output power over an ambient temperature range of −30°C to +70°C is not unusual, but variations of twice or half this number often result from lot-to-lot variations in a particular active device.

Any of the active devices commonly used in cavity oscillators may experience a condition where oscillations will not restart when the applied voltage is removed and then reapplied. This usually occurs because the characteristics of the active device are not constant with temperature. The negative resistance of the active device is usually somewhat higher at elevated temperatures than at lower temperatures. Therefore, it is possible to start oscillations in a semiconductor oscillator at a given temperature by applying power and operate it at a lower temperature than the temperature at which oscillations will start, but when supply power is removed and reapplied at the lowered temperature, the oscillations will not restart.

Although well-designed, solid-state cavity oscillators are the least likely of all types of oscillators to exhibit degradation of the power output from mechanical shock or vibration, the degree of coupling between active device and cavity can strongly affect output power and, consequently, this coupling must be designed to be very stable during shock and vibration. The same situation exists with the coupling between the cavity and the load.

Power output changes with time can

be expected to occur in any device including semiconductor active devices. However, the use of high reliability active devices in conjunction with stable, durable, passive devices can reduce the expected variation to insignificance. This is not to say that the possibility of output power variations can be ignored, however, because some semiconductors, such as certain GaAs FET's and varactors, have built-in, reversible, time-related instabilities. Ion buildup on the periphery of a varactor junction or in the substrate of a GaAs FET can change the output power of a cavity oscillator significantly.

The output power from a cavity oscillator is very strongly influenced by the match between the oscillator and its load. Cavity oscillators are designed to have the highest possible Q for a given active device and required output power. For this condition, the effective resistance coupled into the cavity from the load must be as low as possible. Under these circumstances, any load mismatch is effectively multiplied by the apparent mismatch between the cavity and the output transmission line. Therefore, the power actually received by the load can vary quite dramatically with changes in load mismatch or with phase changes of the same magnitude load mismatch. This occurs because the power reflecting back and forth between the oscillator's output mismatch and the load mismatch can add or subtract from the actual power output of the oscillator. For this reason, a seemingly small load mismatch can cause relatively large power variations to the load when its phase is varied. This effect is especially evident when long lines are used between the oscillator and its load.

Frequency Stability

The output frequency of a cavity oscillator is controlled almost exclusively by the characteristics of the cavity. Its frequency stability, however, will be affected by changes in bias voltage to the active device, temperature effects, load VSWR variations, and environmental factors.

In a well-designed, high-Q cavity close to resonance, a very small change in frequency will result in very large changes in cavity reactance. Therefore, the reactance changes that occur in the active device as a result of voltage variations will be compensated by the cavity with only a small frequency change. For example, a cavity oscillator with a Q of 1000 may shift in frequency less than one part in 10^4 per volt change in applied voltage, whereas the shift in a wideband varactor-tuned oscillator with a Q of 50 can be expected to be at least 20 times worse, or about 0.2% per volt. This is not to say that either the cavity or the varactor-tuned oscillator would continue to perform if the applied voltage were changed one volt. Either may tolerate no more than a tenth of a volt variation without a degradation in performance. Figure 3 shows typical frequency pushing characteristics of a bipolar-transistor type of cavity oscillator operating at approximately 4 GHz.

Since the high-Q cavity oscillator is only lightly coupled to the load, the frequency effects of load mismatch are minimal. Light coupling can be con-

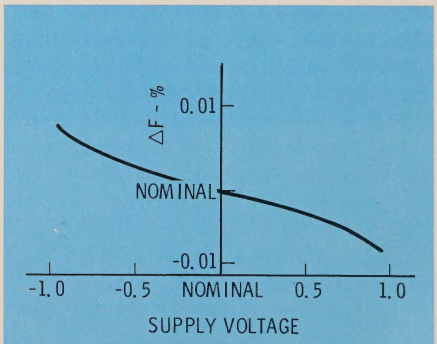


Figure 3. Typical frequency pushing with supply voltage for a high-Q cavity oscillator operating at about 4 GHz.

sidered as being a relatively large reactance in series with the load. In Figure 4, the reactance X_1 is the fixed, effective reactance due to light load coupling, X_2 is the reactance of a mismatched load and R_L is the resistive portion of the load impedance. Since in a high-Q cavity the magnitude of X_1 is large compared to the combined magnitude of X_2 and R_L, the frequency variation from changes in X_2 and R_L is minimal. The higher the Q of the cavity, the higher the relative magnitude of X_1, and the less effect load mismatches will have on the frequency of the cavity.

Figure 5 shows typical worst-case frequency pulling vs. load mismatch for a high-Q cavity oscillator operating at about 4 GHz. The reflection coefficient of the load is signified by Γ_L.

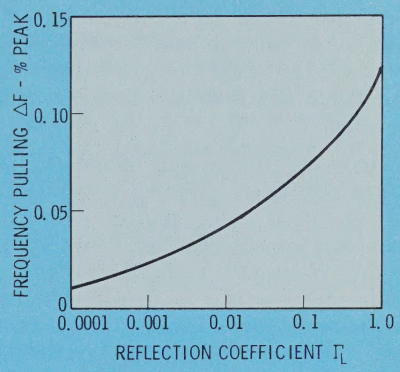


Figure 5. Typical worst-case frequency pulling with load mismatch for a high-Q cavity oscillator operating at about 4 GHz.

For a well-designed cavity oscillator with an effective Q in excess of 500 the frequency drift with temperature will be almost entirely a function of the temperature coefficient of the cavity. Metals commonly used in the design of cavity oscillators will have temperature coefficients in the range of 10 ppm/°C (parts per million per degree Celsius) to 30 ppm/°C. This means that a well-designed — but not compensated — high-Q cavity oscillator can be expected to drift between −10 ppm/°C and −30 ppm/°C, since the cavity enlarges with increasing temperature, causing a decrease in frequency. This frequency drift is normally a straight-line function of temperature except at the high temperature extreme, where changes in the active device may be quite severe, as shown in Figure 6.

Frequency drift with time should be

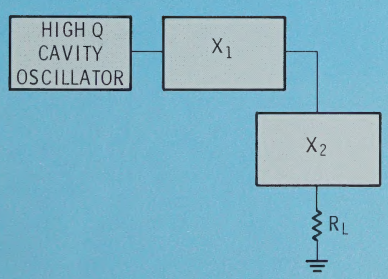


Figure 4. Circuit depicting effective reactance due to light coupling (X_1), combined with load reactance (X_2) and load resistance (R_L).

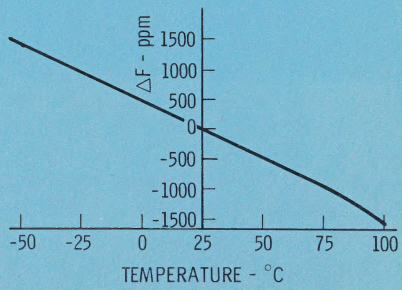


Figure 6. Typical frequency drift with temperature of a high-Q cavity oscillator operating at about 4 GHz.

minimal in a well-designed cavity oscillator using high reliability semiconductor and passive components. Permanent changes of a few parts per million in the first year are reasonable to expect.

Mechanical shock and vibration can cause significant frequency variations, especially if the applied vibration excites a mechanical resonance in the cavity. Normally, a 15-20g mechanical vibration applied to a well-designed cavity will generate only a few parts per million of frequency variation. However, amplification of this effect by a factor of 10 or higher is possible from the mechanical stresses resulting from a mechanical resonance excited by vibration. Unfortunately, even a well-designed cavity will have at least one mechanical resonance at some frequency. The areas in a cavity oscillator where frequency variations due to mechanical vibration are most likely to be generated are in the reactance which couples the active device to the cavity and in the reactance which couples the load to the cavity. Since these are comparatively high reactances, even small percentage changes can cause significant variations in frequency. Consequently, care must be exercised in the design of cavity oscillators to minimize the effects of mechanical resonance on these two reactances.

If a varactor is used to provide a small degree of electronic tuning, great care must be exercised in the selection of a method of coupling the varactor to the cavity. This coupling is usually a large reactance, and even small percentage changes due to vibration or mechanical resonances can cause significant frequency variations.

Noise

Random fluctuations in the amplitude and frequency of any oscillator result in AM or FM sidebands that appear in the form of noise. Of the two types of noise that occur in solid-state oscillators, the spectrum resulting from random frequency fluctuations is the dominant one. Thus, the presence or absence of frequency modulation (FM) noise is the best indication of oscillator performance, although amplitude modulation noise may be a factor in some cases.

FM noise results from two primary sources. One is the "thermal" source, which is a wideband source and results in a "white" noise spectrum. The other is the so-called "flicker" source, which is relatively narrow band and results in approximately a 1/F type spectrum; that is, the level in a given bandwidth or the equivalent carrier deviation decreases with distance from the carrier. The spectra resulting from the two types of noise are shown in Figure 7.

It is apparent from Figure 7 that the dominant noise source close to the carrier is flicker noise, whereas the dominant source far from the carrier is the thermal noise.

FM noise is specified either as the amplitude of noise with respect to the carrier in a given bandwidth at a certain frequency separation from the carrier or as the rms deviation of the carrier which results from a signal with a certain amplitude at a given

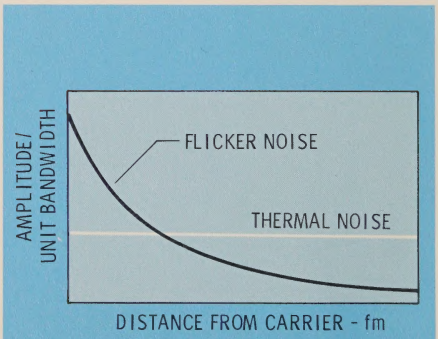


Figure 7. Spectra resulting from thermal and flicker noise sources.

frequency separation from the carrier. The two are related by the expression:

$$\frac{N}{C} = \frac{(\Delta f)^2}{(f_m)^2}$$

which defines the noise power (N) to carrier power (C) ratio as a function of rms deviation (Δf) of the carrier and modulating frequency (f_m). For any noise measurement to have meaning, an associated measurement bandwidth must be specified.

Since all active semiconductor devices exhibit a voltage- and current-variable reactance, small, random variations in either parameter will result in small, random frequency variations which manifest themselves as noise sidebands. Therefore, bias supplies must have relatively low noise characteristics so they will not significantly contribute to the noise of the oscillator.

In cavity oscillators, the most significant factor influencing close-in FM noise is loaded Q. All other factors remaining equal, FM noise is inversely proportional to loaded Q. This means that every effort to improve loaded Q improves the noise performance. The two most significant factors influencing loaded Q in cavity oscillators are: (1) load coupling (power output) and (2) varactor tuning. Requirements for low noise invariably result in low output power and minimal voltage tuning.

The type of active device used also influences noise performance. In oscillator applications, bipolar transistors, Gunn diodes and tunnel diodes are considered low-noise devices. Avalanche devices and FET's will usually produce somewhat higher noise levels, all other factors being equal.

Figure 8 shows comparative noise performance between a cavity oscillator with varied load coupling, and wide-

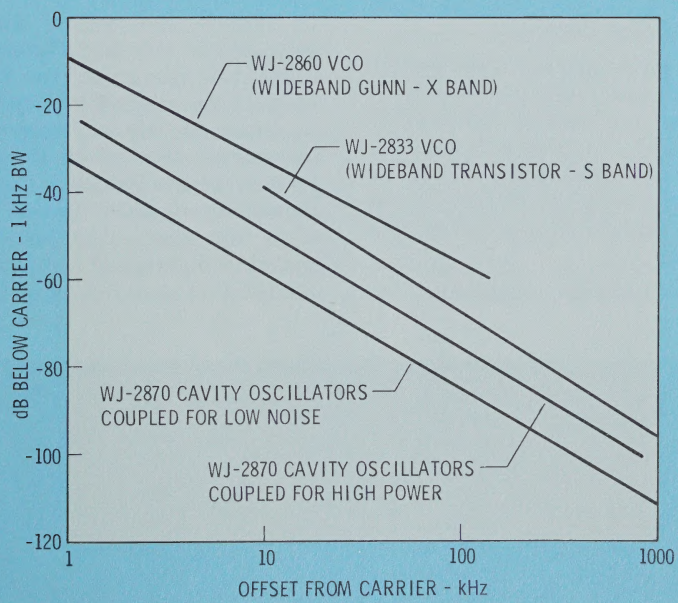


Figure 8. Comparative noise performance of a cavity oscillator and two types of wideband tuneable oscillators.

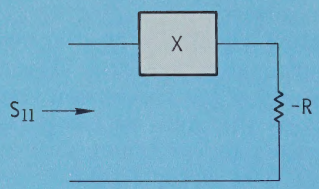


Figure 9. Series negative resistance model of one-port active device.

band Gunn and bipolar transistor oscillators.

Circuit Descriptions

Any active device can be described as a negative resistance in series with a reactance at any given frequency. Therefore, one-port devices, such as Gunn diodes, tunnel diodes and avalanche devices, can be modeled as shown in Figure 9, with only one S-parameter, S_{11}. Negative resistance is indicated by the magnitude of S_{11} being greater than unity.

Two-port active devices can also be modeled as series one-port devices if the proper terminal is selected as common, and one port is terminated in the proper impedance. Figure 10 shows a two-port active device (bipolar transistor) modeled as a series one-port active device.

With most bipolar transistors, an inductive reactance (X_1) in the emitter-to-collector port will make the magnitude of S_{11} (base-to-collector) greater than unity, indicating a negative resistance. In a similar fashion, the GaAs FET can be modeled as a one-port active device with negative resistance.

To achieve oscillation with the series one-port negative resistance model, it is only necessary to terminate this port in an impedance whose reactance is the conjugate of S_{11} and whose resistance is equal to the absolute value of the active device's negative resistance.

Cavity Model

Several types of cavities are suitable for frequency control of a solid-state oscillator. TE, TEM or TM types may be used, depending primarily on output frequency and designer preference. All types are utilized as parallel tuned circuits when high Q is a design goal.

Thus, a cavity utilized to control frequency in an oscillator circuit is a parallel-tuned circuit with a very high Q. That is, the ratio of reactance to resistance is very high. When operated exactly at resonance, the impedance of a cavity is purely resistive. When operated slightly off resonance, the impedance of a cavity is very highly reactive, either inductive or capacitive, depending on which side of resonance it is operated. Therefore, a cavity operated slightly off resonance can be modeled in a series equivalent as a

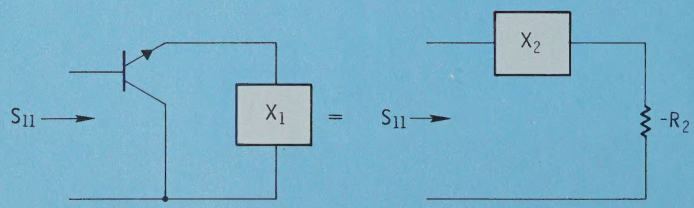


Figure 10. Bipolar transistor modeled as a series one-port device.

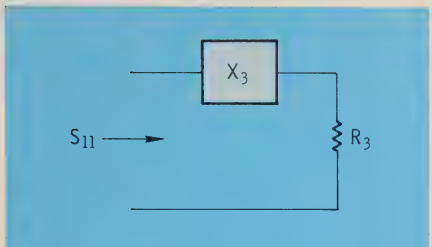


Figure 11. Off-resonance, one-port series equivalent model of a cavity.

one-port passive device as shown in Figure 11.

For a high-Q cavity slightly off resonance, X_3 will be very large and will change very rapidly with frequency. This is the factor which provides stability in an oscillator.

Coupling the Active Device and the Cavity

Since the reactance shown in the model of the active devices is usually much lower in practical devices than the reactance of a cavity near resonance, the cavity would have to be operated far from resonance to provide a conjugate match. Furthermore, the reactance far from resonance does not change as rapidly with frequency as it does close to resonance. Therefore, it is desirable to couple the active device to the cavity with a large reactance which is opposite to the reactance from the cavity. Figure 12 shows the desired coupling arrangement.

In a case where $X_A = -j20$ ohms; for operation slightly below resonance, the $+jX_3$ of the cavity might be +j1020 ohms. Then a coupling capacitance ($-jX_C$) of −j1000 ohms will provide the necessary conjugate reactance to the active device. Furthermore, if the active device's reactance changes slightly with applied voltage or temperature, only a very small change in frequency will bring the circuit back to a conjugate match.

The effective negative resistance of the active device decreases when oscillating into saturation. Therefore, the active device coupled to the unloaded cavity will oscillate heavily saturated to match the low resistance of the cavity. As the load is coupled into the cavity, the active device comes out of saturation and its negative resistance increases to match the resistance of the coupled load. If the load is coupled too tightly, the active device will not achieve the necessary negative resistance, and oscillations will cease.

Electronic Tuning

Electronic tuning of cavity oscillators is usually accomplished by capacitively coupling a varactor to the cavity. Since a varactor is a voltage-variable reactance, the frequency of the cavity will be voltage variable to some extent.

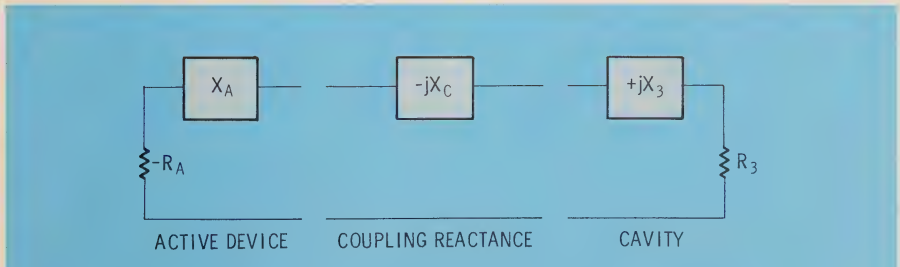
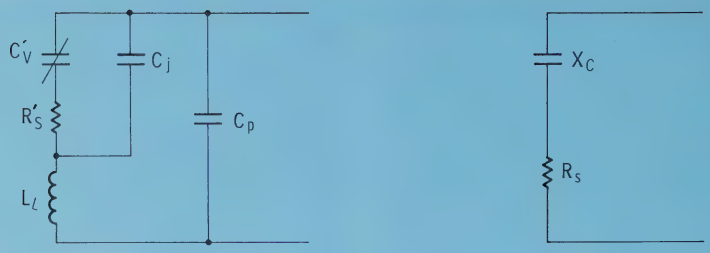


Figure 12. Desired coupling arrangement between the active device and cavity for high-Q performance.



C'_V = VOLTAGE VARIABLE CAPACITANCE

C_j = FIXED-JUNCTION PARASITIC CAPACITANCE

R'_S = SPREADING RESISTANCE

L_L = LEAD INDUCTANCE

C_p = PACKAGE CAPACITANCE

X_C = EFFECTIVE VOLTAGE VARIABLE CAPACITANCE

R_s = EQUIVALENT SERIES RESISTANCE

Figure 13. Equivalent circuit and simplified equivalent circuit of a varactor.

Figure 13 shows the equivalent circuit and simplified equivalent circuit of a typical packaged varactor.

The degree of electronic tuning obtainable is very limited if a high Q is to be maintained. This is because the inherent Q of most varactors is very limited in the microwave range. Available Q's range from about 100 for varactors used in the 1-GHz range to less than 10 for varactors used in the 10-20 GHz range. In essence, the Q of the oscillator will be determined by the Q of the varactor as enhanced by its coupling reactance.

For example, a varactor operated at 4 GHz and 4 volts reverse bias might have a Q of 50 with a capacitive reactance of about 50 ohms, which represents an equivalent series resistance of about 1 ohm. In order to couple this varactor to an oscillator whose loaded Q is 500, without seriously deteriorating the oscillator Q, the varactor's Q must be enhanced to at least 10 times the oscillator Q, or about 5000. Therefore, the reactance coupling the varactor to the cavity must be about 4950 ohms capacitive. This is shown in Figure 14.

Now, if the varactor is operated over a voltage range that results in a 4:1 change in capacitance, the approximate overall reactance change in the circuit will be -j4975 to -j5050, or only about 1.5%.

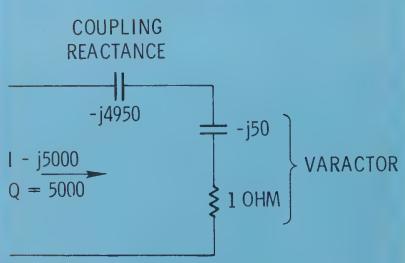


Figure 14. Q enhancement by the use of high coupling reactance.

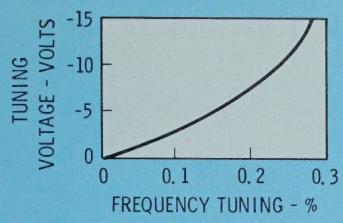


Figure 15. Typical voltage tuning curve using a varactor, lightly coupled to a cavity oscillator.

Since frequency varies as the square root of reactance, and the total reactance is increased by the net reactance of the loaded cavity, a voltage tuning range of a few tenths of a percent is all that can be attained in the practical case without degrading the overall Q. Since higher Q varactors are available at lower frequencies, this value would be somewhat higher. The converse is true at higher frequencies.

The varactor's capacitance is approximately a square-law function of voltage and, consequently, the voltage tuning response will exhibit the typical varactor-tuning curve shown in Figure 15.

The modulation sensitivity of a varactor-tuned oscillator, which indicates the frequency deviation resulting from a certain modulating signal, is therefore a function which decreases with increasing varactor voltage or increasing frequency. Figure 16 is a graph of tuning voltage and modulation sensitivity vs. output frequency at the mechanical tuning band extremes of a 10% bandwidth mechanically-tuned oscillator operating at 4 GHz which has a 40-MHz electronic tuning capability.

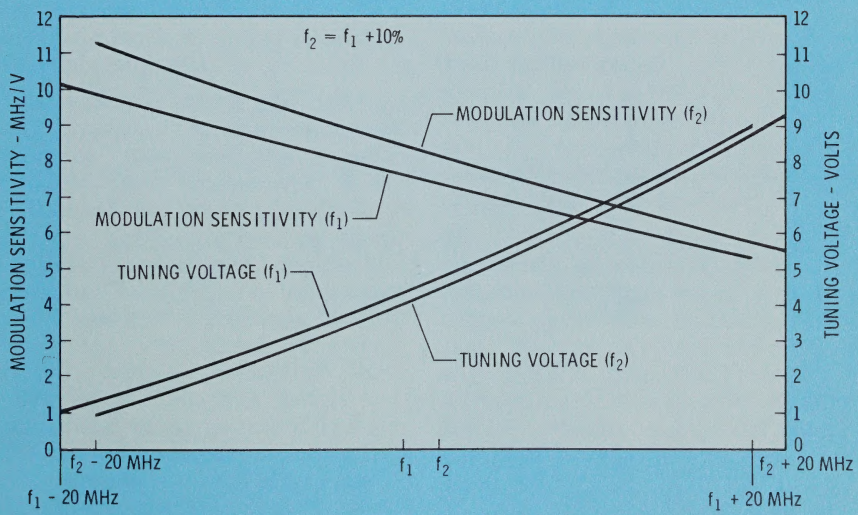


Figure 16. Curves of tuning voltage and modulation sensitivity vs. frequency at band extremes of a 10% bandwidth mechanically-tuned oscillator operating at 4 GHz.

Conclusion

Cavity-controlled, semiconductor oscillators can be designed to provide the low noise inherent in a high-Q cavity and, at the same time, since no vacuum is necessary, wideband mechanical tuning of frequency can be accomplished, as well as narrow-band electronic tuning. With the use of solid-state active devices, cavity oscillators can be made small, rugged and reliable, with low input power requirements.

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Mr. Bushnell is responsible for the direction of selected solid-state research and development efforts at Stewart Division. This includes development of wideband voltage-tuned sources, local oscillators, and transmitters from VHF through Ku-band, as well as associated peripheral equipment.

He has extensive design and development experience in the microwave electronics field on the system, subsystem and component level. Mr. Bushnell has held responsibilities and made significant accomplishments in system analysis and compatibility testing of the B-58 Hustler ground support checkout equipment, design, development and testing of several parametric amplifier subsystems from L through X-band, and design and development of numerous solid-state microwave components, including isolators, circulators, oscillators, multipliers, filters, shapers, discriminators, and noise generators.

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Mr. Buswell has been a frequent contributor of articles to the Watkins-Johnson Tech-Notes as well as to other microwave journals. He holds a B.S.E. from Michigan Technological University, a M.S.E. from the University of Michigan, and is a member of IEEE, GMTT, Eta Kappa Ku, Tau Beta Pi, and Phi Eta Sigma.

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