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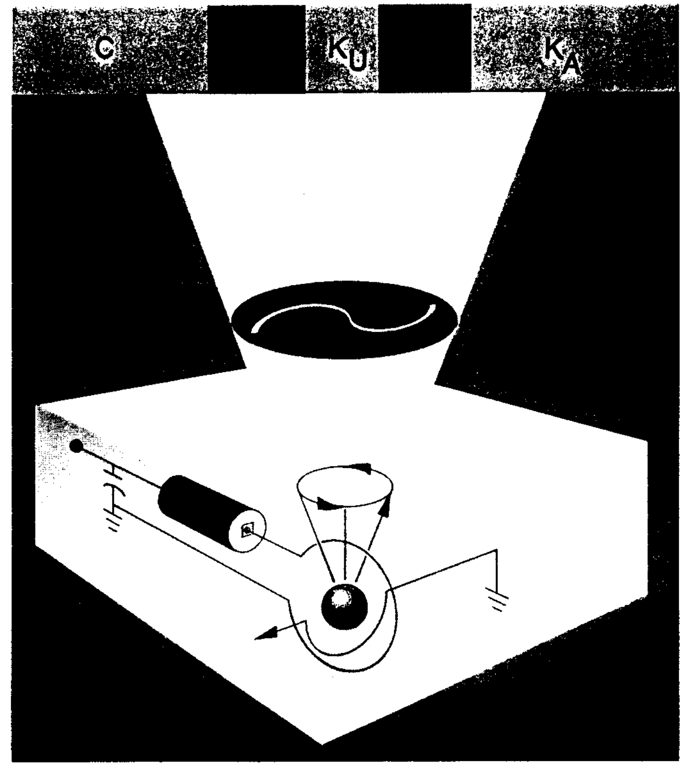
Tech-notes

# YIG-tuned bulk GaAs Oscillators




Ten years ago practical broadband microwave frequencies above 6 GHz were achieved by thermionic devices. These devices were large, required high operating voltages and exhibited a shorter lifetime than the emerging solid state devices.

Advances in crystal growth technology led to the production of the single-crystal Yttrium Iron Garnet (YIG) material. Because of the material's high "Q" resonance characteristic over wide frequency ranges, the YIG was soon used as the tuning element in devices, such as, the YIG filter. More recent, however, is the use of the semiconductor bulk Gallium Arsenide (GaAs) as a source of microwave power. By combining the YIG's linear tuning property with the broadband oscillation of the bulk GaAs device, a tunable broadband microwave signal results. Today it is possible for one YIG-tuned bulk GaAs oscillator to tune an octave frequency band and, with only a few oscillators, tune frequencies from C-band through Ka-band.

This article discusses some of the more important factors which influence the YIG-tuned bulk GaAs oscillator's performance. It describes the oscillation produced by the bulk GaAs device, the frequency tuning of the YIG sphere in a magnetic field and the coupling structure needed to yield an output signal. Two applications illustrate the oscillator's versatility in various systems and, a series of parameters are used to explain the oscillator's tuning characteristics.

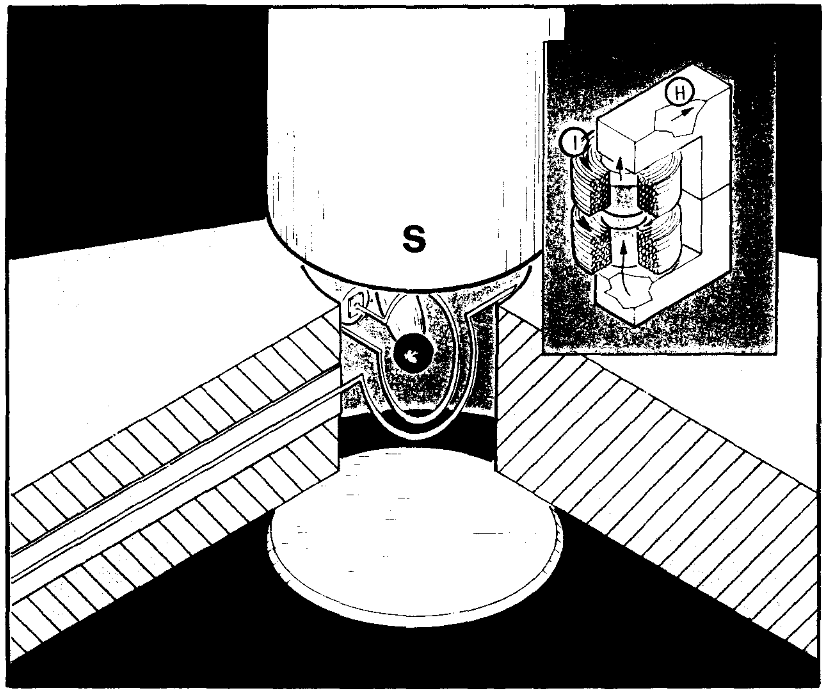



Fig. 1. A simple electromagnet producing a uniform magnetic field across the YIG sphere and RF coupling loops. The sphere is bonded to a rod which permits the sphere to be rotated in the magnetic field and the coupling loops.

### Three Main Components—YIG Sphere, bulk GaAs Device and Electromagnet

The tunable microwave signal obtained from the Yttrium Iron Garnet-tuned, bulk GaAs oscillator is the result of the tunable resonance characteristic of the YIG sphere and the broadband oscillation characteristic of the bulk GaAs device. These two components determine the oscillator's major operating parameters. A magnetic structure is required to produce a magnetic field across the YIG sphere so that frequency tuning can be achieved. Thus, the overall performance of the YIG-tuned bulk GaAs oscillator is influenced by the interrelationship of these three main circuit components.

YIG tuning magnets are simple electromagnets with a single air gap, Fig. 1. The current (I) through the two series connected coils provides the required magnetic field (H) across the gap. Placed between the poles of the electromagnet is the YIG sphere, bulk GaAs oscillator and RF output coupling structure, also shown in Figure 1.

Since the primary requirement is to provide a uniform magnetic field across the sphere, this gap region is very critical. A variation in the magnetic field occurs even across a gap separation of only a few thousandths of an inch. However, this variation must not cause an uncertainty in the resonance frequency of more than a few MHz, otherwise undesirable tuning modes can be generated. At the higher operating frequencies, this translates into a maximum field variation of no more than few gauss. For example, the field variation in Ku-band is less than 0.1 percent.

Since parasitic elements in the oscillator circuit become self-resonant at microwave frequencies, care is taken to reduce these parasitics by eliminating the bulk GaAs device packaging. As shown in Figure 1, the bulk GaAs device coupling loop is formed merely by extending the gold wire which is bonded to the device.



### Oscillation from a Bulk GaAs Device

A semiconductor chip of bulk GaAs with ohmic contacts, Fig. 2a, represents the active component in the YIG-tuned oscilator. When a dc voltage is applied to the device, the current first increases linearily and then oscillates after the electric field within the material reaches a certain threshold value. As shown in the active bulk GaAs circuit, Fig. 2b, the space charge grows as time elapses, with excess electrons forming either an accumulation or dipole layer in the material. This space charge layer nucleates at the cathode, travels through the material and is collected by the anode. This process repeats with new space charge layers forming at the cathode causing the current oscillations. The optimum frequency of operation for the oscillator is determined by the GaAs length (L) and carrier concentration.

The current oscillation caused by the space charge instability in the active region is referred to as the transferred-electron effect. This effect, which is also called the bulk-effect, is observed in a number of semiconductor materials, however, GaAs is the most widely used material for fabricating devices.

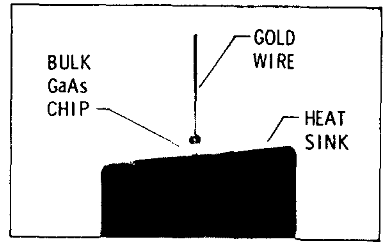
### The YIG Sphere

The sphere, Fig. 3a, is the most practical geometry for a YIG resonator because it is easily oriented in a magnetic field, and the resonant frequency is not strongly dependent upon its orientation. Also, the sphere is a convenient geometry to manufacturefrom the crystal. The diameter of the YIG sphere used in oscillators range in size from 0.012 to 0.037 inches.

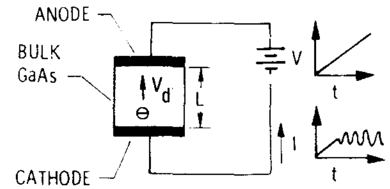
Since no harmonic resonances are generated, as in a transmission line resonator, very broad tuning ranges of more than a frequency decade are achieved. The tuning property of the YIG material is superior to other tuning devices (such as varactor-tuned oscillators), because of its low losses (high Q) at microwave frequencies.

### YIG Reonator - Linear Tuning

The YIG resonator can be explained in terms of spinning electrons that create a net magnetic moment in each molecule within a YIG crystal. Application of an external dc magnetic field causes the magnetic dipoles to align themselves in the direction of the field, thus producing a strong net magnetization (Ms), Fig. 3b. Any magnetic force at right




a. Magnified view of a 6 mil square chip of bulk GaAs bonded between two contacts. The device shown is fabricated at W-J's Solid-State Division.




b. An active circuit: the frequency of oscillation is equal to $v_d$/ L, where $v_d$ is the velocity with which the charge layer travels and L is the length of the active region.

Fig. 2. The two-terminal bulk GaAs device.

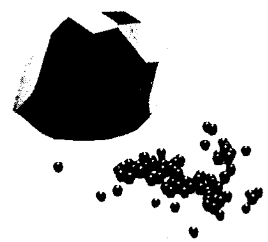


Fig. 3a. A YIG crystal grown at Watkins-Johnson Co. and, highly polished YIG spheres. Sphere diameters shown range from 0.037 to 0.012 inches.

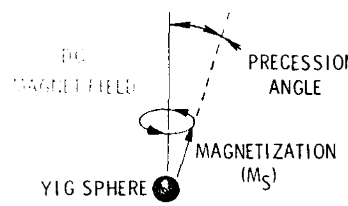



Fig. 3b. YIG Magnetization spin motion.

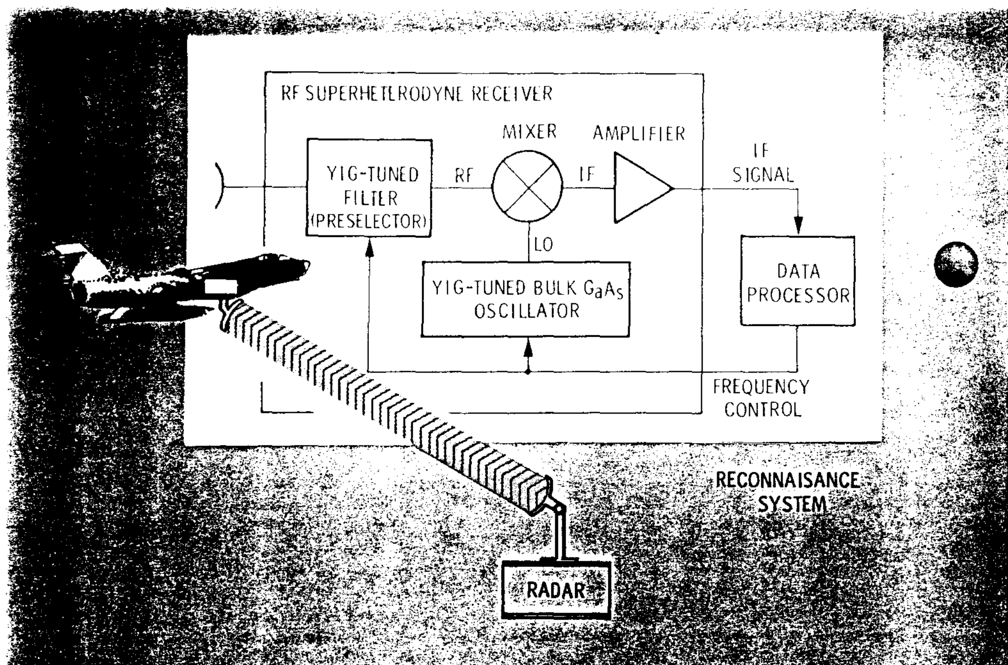



**Fig. 4. A simplified reconnaissance (recon) system using a RF superheterodyne receiver. The major components of the receiver consist of a YIG-tuned oscillator, YIG-tuned filter and, a mixer.**

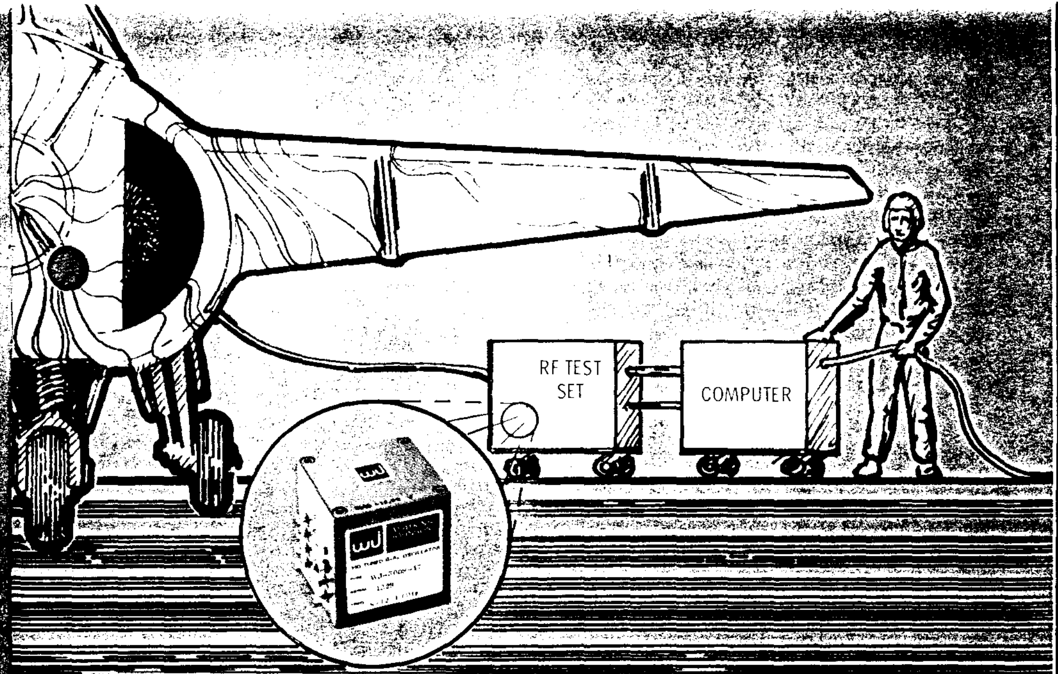



**Fig. 5. An application of the YIG-tuned bulk GaAs oscillator used as the key element in computer-controlled test equipment. Actual size of the WJ-5008 oscillator shown is 2.0x2.0 x2.2 inches.**

angles to the field results in a precession of dipoles around the field. The rate of precession depends on the strength of the magnetic field and, to a degree, on the basic properties of the material.

Such lateral forces result from RF magnetic fields applied perpendicular to the dc magnetic field, Fig. 3c. When the frequency of these RF fields coincide with

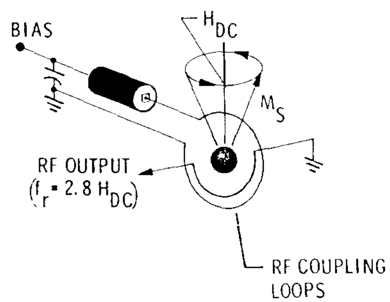



**Fig. 3c. YIG resonator coupling to the active circuit and RF output loop.**

the materials natural precessional frequency, strong interaction results. This interaction is known as the resonance phenomenon.

For spherical resonators, the equation for resonant frequency is:

$$f_r = \gamma (H_o \pm H_a)$$

where $H_o$ is applied dc bias field measured in Oersteds, $H_a$ is an internal field within the crystal known as the anisotrophy field, and $\gamma$ is the charge-mass ratio of an electron (or gyro-magnetic ratio) which has a value of 2.8 MHz/Oersted.

By proper orientation of the crystalline axis of the spherical resonator, the temperature dependence of the "anisotrophy" field may be eliminated. RF coupling to the YIG is achieved by concentrating the RF magnetic field in the vicinity of the sphere with a coupling loop. Othogonality between bias field and RF magnetic field must be maintained during coupling and is shown in Figures 1. and 3C.



## Reconnaissance and Test Equipment Applications

A reconnaissance oriented receiver operates within the acquisition and signal parameter measurement routine of the system shown in Figure 4. Here the prime attention is given to instantaneous identification and precession measurement of several signal parameters, such as, frequency, amplitude, pulse width, FM deviation, and direction of arrival. Along with an increased number of signals in a geographical area there has been an increase in the complex masking techniques that further tasked the operator's ability to make accurate decisions to define the signal. The superheterodyne receiver coupled with a data processor as an operator assistant accomplishes in "near realtime" signal acquisition and identification.

State-of-the-art receivers generally consist of an electronically scanned preselector (YIG-tuned filter), a solid-state YIG-tuned bulk GaAs oscillator and, a mixer.* By separating the filter and oscillator frequencies by an amount equal to the IF frequency (for example 160 MHz) the mixer will track the output of both YIG devices by a constant frequency difference (IF).

Frequency Control of the oscillator requires only a low dc voltage of approximately 15 volts, and the inherent linear tuning of both YIG devices allows "tracking" over an octave or more, even with wide temperature variations. Because of the output power from the oscillator is high enough, optimum mixer conversion loss and noise figure performance can be held even with the degrading effects of temperature variation.

Figure 5 illustrates a portable test system recently created for shipboard use in testing a major ECM system. In this application the computer-controlled test set is wheeled up to the aircraft along with the appropriate software and antenna coupler for that craft. The YIG-tuned oscillator is the key element in the RF chain. The oscillator's microwave signal is modulated and controlled to simulate a threat radar signal and thus test the reaction of the ECM system. Since the oscillator can cover any frequency band over a wide range, the test equipment can be versatile. Usually only a change in the computer software

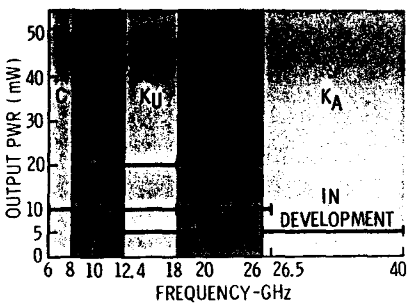
**Refer to July/August 1974 issue of Tech-notes for operation of the mixer device.*

is required to accommodate the testing of different systems.

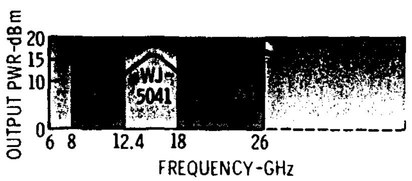
**Operating Frequency Range**

The frequency range and minimum output power available from a few standard oscillators is shown in the chart of Figure 6a. Also shown is the frequency range and anticipated power level of a single, discrete solid state YIG-tuned GaAs oscillator currently in development at the Watkins-Johnson Company. Each oscillator shown in the chart is a fundamental oscillator, that is, the frequency available at the oscillator output terminal is the frequency of the bulk GaAs device.

Typical output power curves for three W-J fundamental oscillators are shown in Figure 6b. Each curve illustrates the




a. **Frequency Range of octave band oscillators.**




b. **Output Power Characteristics of the WJ-5008, WJ-5041 and WJ-5600 oscillators.**

**Fig. 6. Frequency Range and Output Power Characteristics of YIG-tuned bulk GaAs oscillators.**

output power over very wide tuning ranges. For example, in applications as a local oscillator, these flat output power characteristics are desired in order to optimize the performance of the interfacing equipment.

The high spectral purity due to the YIG's Q (with Q between 2000-3000 for X-band), as well as the low noise characteristics of the GaAs device, makes these oscillators suitable as local oscillators in spectrum analyzers, or in critical applications such as microwave spectroscopy.

**Optimized Frequency of Operation**

Reliable broadband GaAs devices are created by a fabrication technique that forms a high quality bulk GaAs Chip for low thermal resistance bonding, Fig. 7. Bulk GaAs is formed by growing a

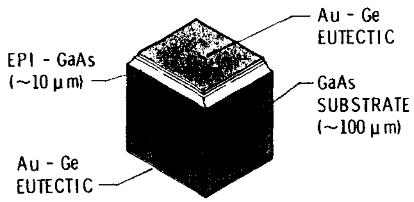



**Fig. 7. A chip of bulk GaAs.**

thin single-crystal layer of doped GaAs (epi-layer) upon a single-crystal of high quality GaAs substrate. The epi-layer is doped with an electron concentration in the order of $10^{15}$ electrons per $cm^3$, whereas, the substrate is doped in the order of $10^{18}$ electrons per $cm^3$. In order to "optimize" the frequency of operation, the epi-layer must have a definite thickness. For example, it is grown approximately 10 microns ($\mu$m) for X-band operation.

By using a unique "direct metallization" process developed at Watkins-Johnson Co., the epi- and substrate sides of the GaAs material are metallized with low resistance and highly malleable gold surfaces. An evaporation process applies a micron dimension layer of Gold-Germanuim (Au-Ge) eutectic and Nickel (Ni) to both GaAs sides. Next, alloying at temperatures exceeding 500°C causes Au-Ge diffusion into GaAs. This results in the formation of a thin highly doped layer that provides an extremely strong bond (with low resistivity) to the epi- and substrate surfaces.

Bonding the chip's epi-side to the heat sink (as shown in Figure 2a) decreases the thermal resistance of the device. During operation power densities of 50 mega-watts per $cm^2$ are developed within the epi-layer. This heat is efficiently dissipated through the gold surfaces, and ensures a safe device junction temperature.

**The Magnetic Circuit**

A linear relationship between the resonant frequency and the magnetic field is achieved if the leakage flux in the air gap is kept to an absolute minimum. This low leakage requirement is achieved by the symmetric coils of the electromagnet shown in Figure 8. The

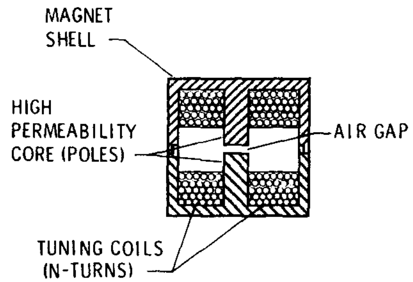



**Fig. 8. Magnet structure of the electromagnet used in YIG devices.**

geometry of this symmetric type structure minimizes the flux leakage from the gap region and provides a high degree of self-shielding from external fields. A high permeability material forms the core of the electromagnet but serves only as a flux conductor, since the gap reluctance determines the relationship between current and flux. However, the core material properties of conductivity and hysteresis are very important to the tuning characteristics of the oscillator.

The conductivity of the core material affects the tuning characteristics by altering the dynamic relationship between the tuning current and the magnetic field. It permits the flow of eddy current in the pole pieces and RF circuit, which causes the "sweep delay"

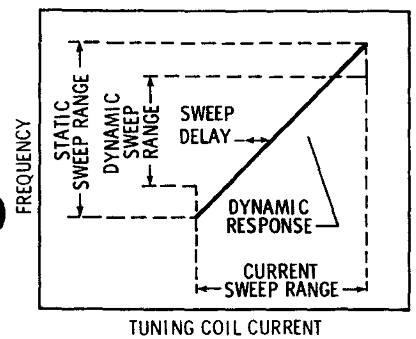



**Fig. 9 Dynamic tuning response of a YIG-tuned oscillator.**

characteristics of YIG devices, Fig. 9. Using ordinary magnetic materials, sweep delays of 80 to 100 microseconds are obtained. Shorter delays may be achieved by a laminated magnetic structure, but it has the disadvantage of being difficult to compensate against thermal expansion. This tendency of the tuning characteristics to drift with temperature is caused by the basic thermal expansion of the material. For the commonly used nickel magnetic steel, this expansion causes a shift in frequency and tuning sensitivity of approximately 10 parts per million per °C. This drift can be compensated by designing the magnetic path to include a section of material with a different coefficient of thermal expansion than the primary material used. By proper selection of geometry and expansion rates, the air gap exhibits essentially a zero coefficient of thermal expansion.

The power required to drive the electromagnet is determined by the RF portion of the oscillator, but the terminal impedance of the oscillator can be changed significantly without altering the physical RF performance. Coil power is independent of the coil tuning sensitivity and wire gauge used. Tuning sensitivity can be achieved in a single electromagnet by changing the number of wire turns. If the wire size is also changed (to keep the volume of the coil approximately constant) the required power remains approximately constant.

The terminal characteristics of an electromagnet do change with the tuning sensitivity. Both the inductance and the resistance of the fixed volume coil changes in proportion to the square of the number of turns of wire (N), while the tuning sensitivity varies directly with N. Since the terminal voltage required to sweep the electromagnet is given by:

$$E = L\frac{di}{dt} + Ri$$

where both L and R are directly proportional to the square of N and i inversely proportional to N, the magnitude of the voltage that must be applied to the coil to provide a constant sweep rate varies proportionally to N.

An example of the flexibility in coil parameters is given in Table 1, which compares the tuning sensitivity of three different magnets with essentially the same air gap.

**Table 1. Comparison of X-band oscillator coil parameters**

| Tuning Sensitivity | Coil Resistance | Coil Inductance |
|---|---|---|
| 17MHz/mA | 5 ohms | 85 mH |
| 25MHz/mA | 12 ohms | 210 mH |
| 50MHz/mA | 45 ohms | 800 mH |

### Tuning Characteristics

An oscillator with good tuning linearity over the entire operating band permits an accurate setting of the desired frequency in a test set application, accurate frequency determination in a local oscillator application, or accurate frequency versus time sweep for an applied linear ramp waveform. The high Q and linear tuning characteristics of the YIG resonator make it the dominate frequency controlling component. Therefore, overall linearity of the YIG-tuned oscillator is excellent, typically 0.1 percent, which is an order of magnitude better than other electronically tuned oscillators. In other applications the fine grain linearity of the oscillator is of interest and, in these cases, incremental linearity is measured. The tuning characteristics of the YIG-tuned oscillator is defined by the following parameters.

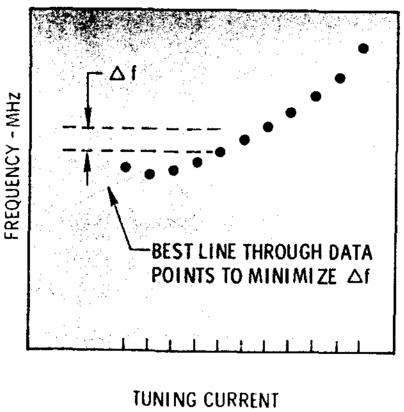
### Overall Linearity

Overall linearity is defined as the maximum deviation from the best fit straight line to the measured tuning curve, Fig. 10a. At each current point the actual frequency is measured and the difference between the theoretical and measured frequency is recorded as a positive or negative deviation. The best fit line to the tuning curve is that line which minimizes the deviation of the actual tuning curve from the straight line. This deviation is usually specified as ±Δf MHz deviation from best fit straight line. For example, the deviation is approximately ±10 MHz over full X-band and ±12 MHz over full Ku-band. Oscillators with a wider (or narrower) tuning range than the standard full band oscillators may have proportionally poorer (or better) overall linearity.

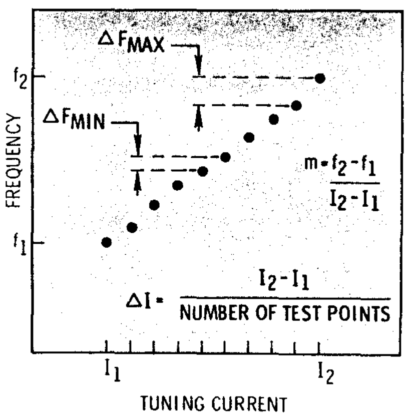
### Incremental Linearity

The current tuning range is divided into small, equal increments and the change in frequency, ΔF, for each change in current, ΔI, is measured. Incremental linearity is defined as the maximum change in ΔF and is given by:

$$\Delta F = \frac{\Delta F\ \text{max.} - \Delta F\ \text{min.}}{m\Delta I}$$




**a. Overall Linearity in terms of ±Δf MHz from best fit straight line.**




**b. Incremental Linearity, $\frac{\Delta F_{max.} - \Delta F_{min}}{m\ \Delta I}$ %.**

**Fig. 10. Tuning Characteristics.**



and is illustrated in Figure 10b. Incremental linearity is therefore a specification of the oscillator's fine grain linearity. As an example, for frequency increments of 300 MHz in the 8-18 GHz range, the incremental linearity is less than 1.5 percent.

### Hysteresis

In those applications where it is necessary to reset the oscillator's frequency to some previous value, the direction from which the frequency is approached should be considered. Hysteresis is defined as the maximum frequency difference obtained when tuning to a particular current value from both the low end and the high end current extremes, Fig. 10c. The hysteresis is taken at mid-band after cycling the oscillator from the low end to the high end, then back to the low end to establish the hysteresis loop. Hysteresis in the tuning curve is due to losses in the magnetic material, with values ranging from 10 MHz for full X-band oscillators to 15 MHz for Ku-band oscillators.

### Frequency Modulation

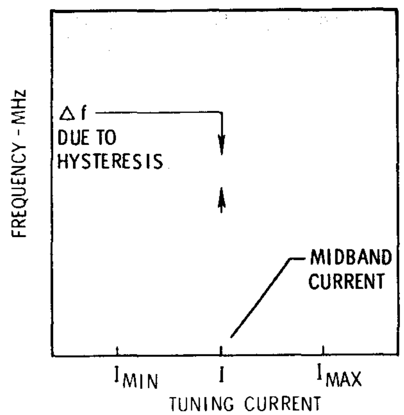
In certain applications the response of the main tuning coil is too slow to provide tuning over a small frequency range at very fast rates. These applications, however, can be satisfied by placing a small coil very close to the YIG sphere. This smaller coil permits frequency deviations to occur at faster rates since the coil is "air core" and is kept a reasonable distance from the metal surfaces.

The performance of a core material meeting most phase lock application requirements is seen in curve A of Figure 10d. The center frequency of the oscillator can be deviated ±50 MHz and the response falls approximately 3 dB when the modulating frequency is in the 300 to 500 KHz region. The maximum deviation is limited by the current carrying capacity of the fine wires used to form the small coil. Nominal tuning sensitivities are 50 to 100 KHz/mA.

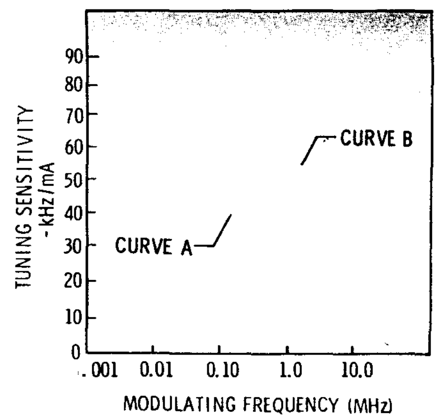
Newly developed coupling techniques permit extension of the flat response to much higher modulating frequencies—as shown in curve B of Figure 10d. As shown, the response does not tend to fall rapidly until modulating frequencies of 10 MHz are reached. This performance is useful for ECM applications as well as certain communication applications since the YIG tuning characteristics permit true linear frequency modulating characteristics.

### Sweep Rate

The magnetic circuit that is required to produce the uniform field for extremely linear tuning, also affects the maximum rate at which the oscillator's frequency can be swept. The element which limits the sweep rate is normally the tuning coil inductance. The larger the value of coil inductance (L), the lower the sweep rate. A sweep rate of 100 repetitions per second is sufficient for most reconnaissance receiver and commercial test




**c. Hysteresis, MHz.**




**d. Tuning Sensitivity, kHz/mA**

equipment applications. Sweep rates as high as 1000 Hz can be achieved by using special techniques to reduce the coil inductance. However, by incorporating these techniques to optimize the sweep rate, usually results in a reduction of the oscillator's tuning sensitivity and, increases the power required to tune the oscillator.

**Sweep Delay**

The tuning characteristics of the YIG-tuned oscillator change as the sweep rate is changed. As the sweep rate is increased, there exists a lag between the output frequency and the tuning current. This lag is referred to as the sweep delay and, is due to the properties of the magnetic circuit and eddy currents induced inside the magnet structure. Since the resonant frequency of the YIG sphere responds to the magnetic field, the frequency will also lag the tuning current. Figure 9 illustrates the current versus frequency sweep delay for both the static and dynamic operating conditions.

Typical delay times are 100 $\mu$sec in X-band and 200 $\mu$sec in $K_u$-band, or 44 MHz and 112 MHz respectively of frequency lag using a 10 millisecond sweep range. The lag is relatively constant over X-band frequencies, reaching this constant level within a few tenths of a millisecond of the start of the sweep. Sweep delay becomes most important when tracking between two or more devices is required.

**New Directions**

Today's system applications are being satisfied by the integration of several discrete device components. As the technology is developed, the integration of components, such as, mixers and IF amplifiers, as well as leveling circuitry and digital to analog converters within the oscillator will produce a dicrete "super component". This new device can then become the major system component. The result of this integration will be improved system performance at lower cost.

As refinements are made in the GaAs device and circuit technology, it is expected that a single oscillator will cover wider frequency ranges. For example, double octave coverage from one oscillator will permit the system user to reduce the existing number of components, thus improving reliability. In addition to wider frequency coverage, it is anticipated that the output power of standard band oscillators will increase by an order of magnitude. Along with wider frequency ranges and higher output power, the maturity of the rapidly growing YIG-tuned GaAs oscillator industry should permit lower prices for existing devices which will open up new commercial and military applications.



**Acknowledgement**

This issue results from the combined efforts of members of the technical staff at W-J's Solid State Division and Reconnaissance Systems Division. Some of their articles on this subject are found in the references that follow.

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