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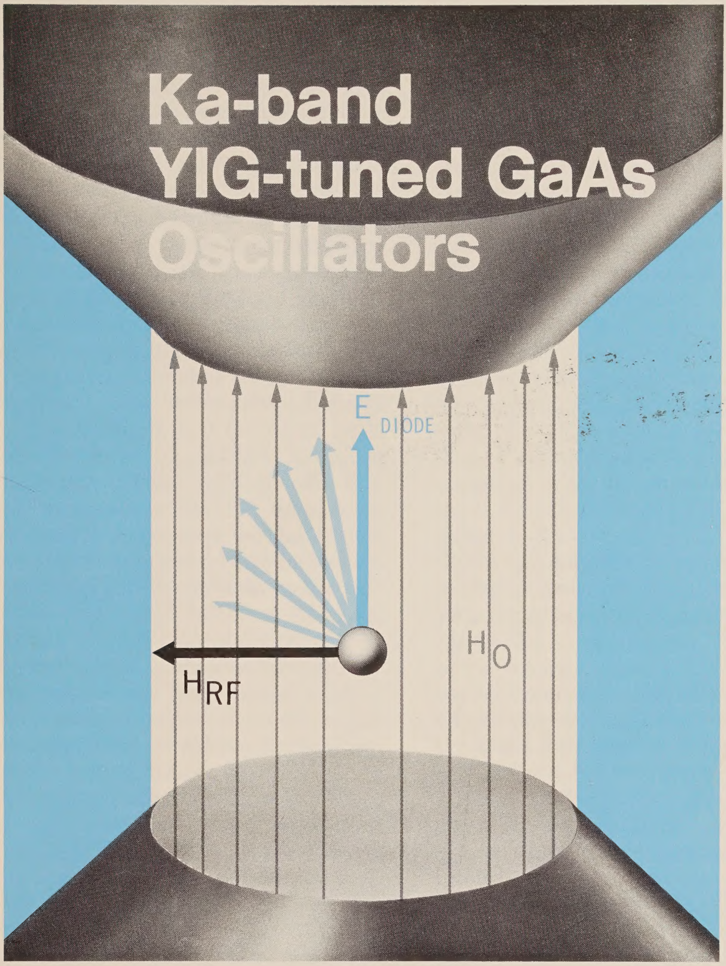
Ka-band YIG-tuned GaAs Oscillators



Within the past year advancement in YIG device and GaAs diode technology has extended the operating frequency range of the YIG-tuned GaAs Oscillator from K band through Ka band. Development of this 26.5 to 40 GHz fundamental oscillator is primarily due to refinements in the areas of the Gallium Arsenide (GaAs) semiconductor material, RF coupling circuit and, magnetic tuning circuit. Combining the Ka-band oscillator with lower frequency YIG-tuned oscillators will immediately open-up to military and commercial applications a tunable, solid state source for wideband receivers, synthesizers, sweepers and test equipment operating into the millimeter-wave range.

Our September/October 1974 issue of Tech-notes featured the Yig-tuned oscillator's GaAs diode active component, Yttrium Iron Garnet (YIG) resonator, RF coupling circuit and linear tuning characteristics. The center of attention in this article is on those areas of technology which further advanced the state-of-the-art.

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New applications of broadband reconnaissance receivers are demanding wideband tunable sources of excellent frequency accuracy and high reliability. The recently developed YIG-tuned GaAs Oscillator, covering 26.5 to 40 GHz can be considered as a further advancement of the state-of-the-art. It replaces the backward-wave oscillator tube as a local oscillator source in a tunable millimeter wave receiver.

The development effort of this solid-state source was applied to basically three separate areas:

- GaAs Diode Evaluation
- RF Circuit
- Magnetic Tuning Circuit

Although these areas can be considered independent from each other, the overall design concept cannot be neglected.

Diode Evaluation
The GaAs diode design is basically the same as previously used in K band.[1] It was found, however, that more stringent control was necessary to produce optimum Ka-band diodes. For instance, adjusting the epi-layer thickness to the proper value is more critical in Ka band than in lower bands. In addition, small changes in diode mesa size (epi side of GaAs chip) results in substantial variations in band coverage. The requirements of a reasonable operating current, a reliable operating temperature, a reasonable impedance to match the circuit and, optimum power output resulted in a design with a $10^{-4} cm^2$ mesa on a $2.25 \times 10^{-4} cm^2$ GaAs chip. The diode epi side is thermal compression bonded to a gold-plated, copper heat-sink and a 1.5 mil wire is thermal compression bonded to the other side. The diode is then mounted in a small coaxial cartridge and evaluated in a waveguide test cavity. The cavity consists of a section of WR-28 waveguide short-circuited on one side with a non-contacting adjustable plunger, while the other side is iris coupled to the load.

The power output is measured at 39 GHz. Diodes with an output power higher than 10 mW are selected as the oscillator's active component. Good correlation is found between power output measured in the test cavity and actual performance in the Yig-tuned circuit.

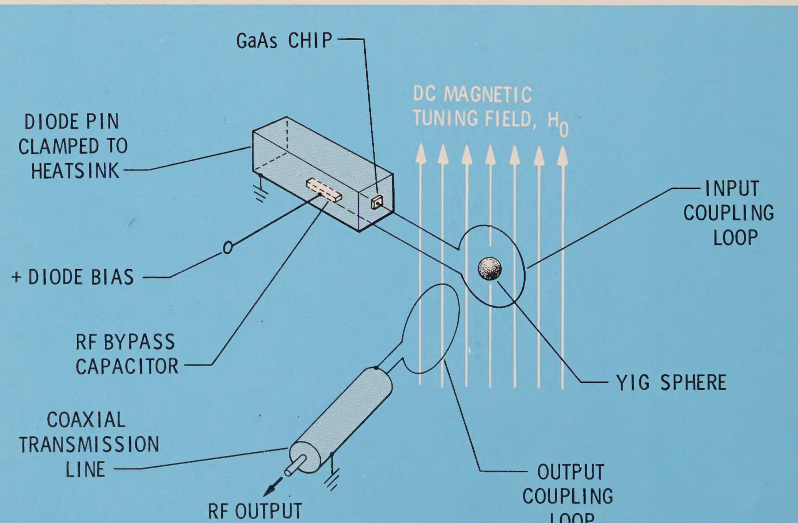


Fig. 1. YIG Resonator Coupling to the Active Circuit and RF Output Loop Coupling to the Load.

RF Circuit

The GaAs diode represents the active component, or the generator of the RF circuit. The RF energy flows from the generator to the spherical YIG resonator and to the load, Figure 1. Proper impedance transformation is accomplished by adjusting the coupling of the input and output loop to the YIG resonator in order to satisfy the oscillation condition. The frequency of oscillation is determined by the applied dc bias field which is orthogonal to the RF magnetic field.

The YIG resonator's inherent tuning linearity of ±.05% is drastically degraded by the parasitic circuit elements, self-inductance of the input coupling loop and, diode capacity. The self-resonance of the circuit, with the YIG removed, must therefore fall substantially above the operating frequency range. As a result, the concept of minimizing the path length of the RF current is introduced. The RF current in the input loop is directly returned to the diode through a dc blocking capacitor. The RF current in the output loop is returned to the transmission line. The surrounding cylindrical cavity which encloses the RF circuit is therefore free of conduction currents. Its only purpose is to suppress radiation losses. The unperturbed resonant frequency of the cylindrical cavity, TM_{010} mode, is much above the operating frequency. The input and output loops are orthogonal to each other in order to minimize loop-to-loop coupling. The output loop is connected to a short length of 47 mil diameter 50-ohm coaxial line. The center conductor of the line is probe coupled to a section of WR-28 waveguide. The Voltage Standing Wave Ratio (VSWR) of this transition is optimized by positioning a movable short in the waveguide resulting in a mismatch of less than 1.2:1. Although the output coupling is broadband, the low frequency coverage is limited by the cutoff wavelength of the particular waveguide size.

The RF circuit which consists of the YIG resonator and the two coupling loops constitutes a narrow-band tunable transformer.[2] Maximum power transfer from the GaAs diode generator to the load can be achieved for any impedance by adjusting the coupling parameters of the two loops as long as the coupling conditions are physically realizable. A YIG resonator can be considered as a microwave cavity with inverted coupling loops. Whereas in a regular cavity coupling is achieved inside its volume, coupling to the YIG resonator is done on the outside. An increase in coupling can be achieved with a smaller loop, or for a given loop size with a larger YIG sphere, since coupling is proportional to sphere volume. The large impedance transformation ratio between load and GaAs diode can be satisfied by a strong input loop coupling and weaker output loop coupling. There is a limit to how much the coupling can be increased since an excessively small loop diameter increases the losses in the YIG resonator, thus reducing the unloaded Q. This will produce discontinuous tuning or noise within the oscillator. Also, excitation of higher order spurious magnetostatic modes will occur.[3] A loop-to-sphere diameter ratio of at least 1.5 must be maintained for spurious-free operation. Increasing the sphere volume will increase the coupling but will also increase the parasitic self-inductance of the coupling loop and the circuit resonance will eventually fall within the operating frequency range.

These coupling problems can be alleviated by selecting diodes of higher negative resistance. Small signal impedance measurements[4] indicate that the diode parameters can have a strong effect on the negative resistance. Measurements recently taken show that the magnetoresistance effect can not be neglected since it influences the RF impedance of the diode. This effect will be discussed in detail under the Magnetoresistance Effect Section.

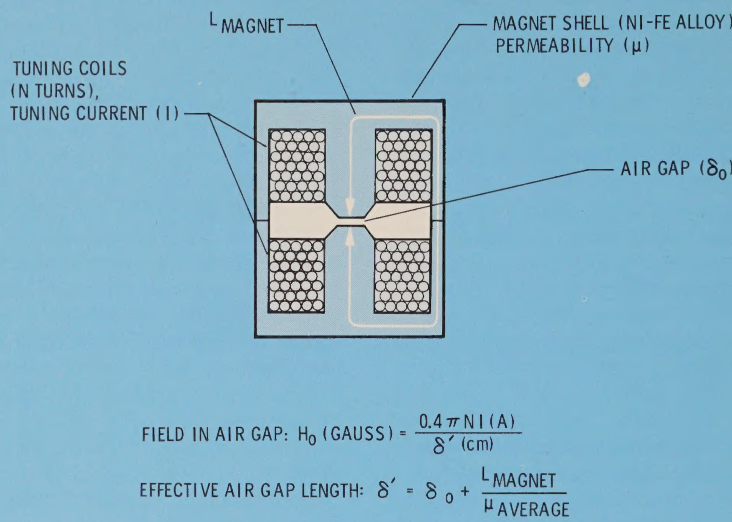


Fig. 2. Magnet Structure with tapered Pole Pieces.

Magnetic Tuning Circuit

The basic relationship between gyromagnetic resonance (YIG resonance) and applied dc tuning field H_o is:

$$f(\text{MHz}) = 2.8H_o\ (\text{Gauss})$$

This means, that in order to tune the YIG resonator to 42 GHz, a field of 15 kGauss is required. The magnet structure of the YIG-tuned oscillator is shown in Figure 2. Good tuning linearity can be maintained only if saturation effects in the magnetic material are eliminated, or if the average permeability (μ) of the material remains constant with increasing tuning current (I). A change in permeability with temperature will also result in a frequency shift. Since the field in the air gap, δ_0, is inversely proportional to the effective gap length, δ', an efficient magnetic circuit design must minimize the air gap. The coil tuning power is also proportional to the square of the gap length. A gap length of 50 mil allows a noncritical RF circuit configuration. The tuning current is 1.1 A to reach 40 GHz with a tuning power of 8.5 watts.

The magnet shell consists of a soft magnetic, high permeability nickel-iron alloy. The pole tips are tapered in order to improve the magnetic design, and to allow the placement of a larger heatsink close to the GaAs chip.

The saturation characteristic of various magnet shell designs is determined by measuring the field in the gap as a function of coil current. The measurement of these large magnetic fields by conventional means, (e.g. Hall Probe), could result in poor accuracy. A YIG resonator probe is utilized instead. It consists of a tiny YIG resonator loosely coupled to a 47 mil coaxial transmission line. The resonant frequency, which is proportional to the magnetic field in the gap, is observed with a swept input signal. The absorption dip in reflected power from the YIG probe is then compared with the marker of a calibrated wavemeter. The accuracy is determined only by a wavemeter since the resonance of the YIG probe is very sharp.

The incremental linearity for a 1 GHz step, measured at the low and high end of Ka band, differed by less than 30 MHz. These differences are considered adequate because of the limitation in resolution.

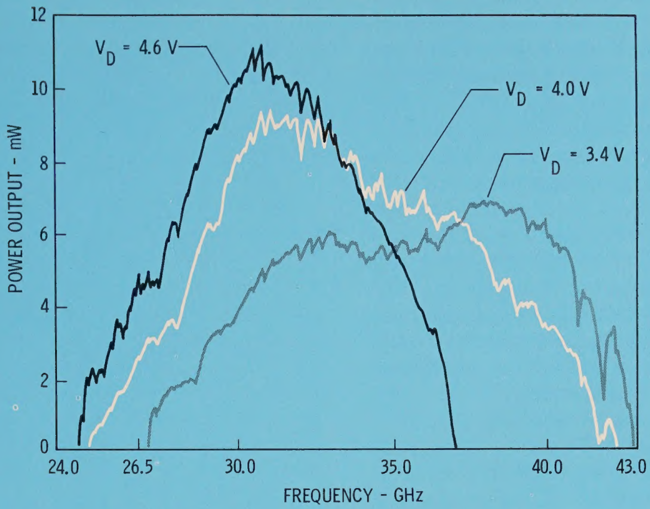


Fig. 3. Power Output of a YIG-tuned GaAs Oscillator (WJ-5610-1) for diode bias voltages at 3.4, 4.0 and 4.6 volts.

RF Performance

The three main variables which characterize a good YIG-tuned oscillator design are power output, frequency accuracy and, spectal purity.

• The power output for three different diode voltages is shown in Figure 3. Although full waveguide band coverage is possible for a fixed bias voltage, optimum performance can be achieved by linearly programming the diode bias. Power output at 70°C can be reduced by as much as 3 dB at the high-end frequency. This is caused by weaker input coupling to the YIG resonator and lower diode efficiency. A power output of 2 mW is adequate for proper mixer operation in a Ka-band tuner but, for commercial use in a test instrument, 10 mW of power is required.

• The frequency accuracy is determined by tuning linearity error and frequency drift with temperature as shown in Figure 4. It does not include hysteresis error or frequency pulling with load mismatch. The frequency error caused by tuning nonlinearity at room temperature is 40 MHz. Approximately 30 MHz is contributed by the magnetic circuit as determined by YIG probe measurements of the shell.

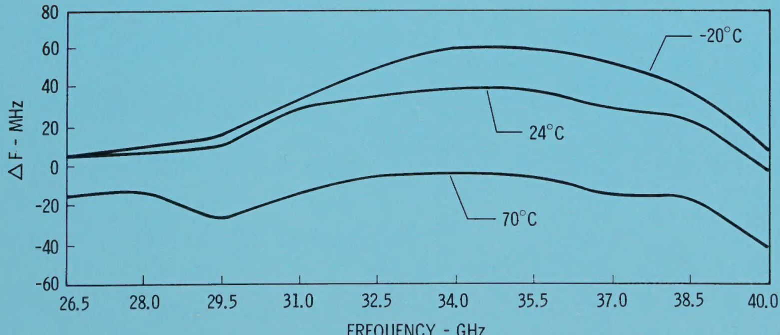


Fig. 4. Frequency Accuracy of a Ka-band Oscillator for baseplate temperatures at −20°C, 24°C and 70°C.

This proves that YIG tuning is inherently linear with the magnetic field even at these frequencies, and that the parasitic circuit resonance of this new RF circuit design is well above the operating frequency range. The frequency error caused by frequency drift with temperature is about 60 MHz.

• The spectral purity is characterized by a spurious-free output signal and low noise modulation of the carrier. Direct noise measurements have not yet been taken; however, excellent low noise performance of the YIG-tuned oscillator was observed in a WJ-1140 Ka-band tuner. A single-sideband noise figure of 8 dB was measured from 28 to 38 GHz. An incidental FM of 40 kHz is caused mainly by the noise of the driver circuit. A summary of oscillator performance for the WJ-5610-1 YIG-tuned oscillator is listed in Table 1.

Magnetoresistance Effect

A YIG-tuned oscillator operating in Ka band requires a tuning field as large as 15 kGauss. This magnetic field is applied either orthogonal or parallel to the E-field of the GaAs diode, depending on the mounting position of the diode in the circuit. In the present configuration of Figure 1, the GaAs chip is mounted on the vertical face of the pin, and orthogonality exists between the two fields. The carriers in the GaAs semiconductor material are therefore deflected, and the net effect is a reduction of the negative differential mobility of the device.[5] This change can be observed by measuring the dc characteristic of the diode with and without a magnetic field of 14 kGauss, as shown in the curves of Figure 5. Although the reduction in diode current amounts to less than 8 percent at 3.5V, the change in diode current dropback or its negative slope is substantially reduced. The reduction in diode current is proportional to an increase in resistance (magnetoresistance) since the diode voltage is kept constant. It is experimentally verified that the resistance change is proportional to the square of the magnetic field.[6]

During the course of diode evaluation it was observed that a good correlation exists between the negative slope of the diode dc characteristic and RF performance in the waveguide test cavity. Therefore, the RF performance must degrade substantially with the

FREQUENCY RANGE	26.34 to 40.16 GHz
OPERATING ENVIRONMENT	-20°C to 70°C
OUTPUT POWER, MINIMUM	2.4 mW @ 70°C
OUTPUT POWER VARIATION	6.5 dB
FREQUENCY LINEARITY	± 20 MHz
FREQUENCY DRIFT	50 MHz
HYSTERESIS	50 MHz
PUSHING FACTOR	15 MHz / VOLT
TUNING SENSITIVITY	37 MHz / mA
COIL INDUCTANCE	80 mH
COIL RESISTANCE	7 ohm
SIZE	2 x 2 x 2.5 INCHES
WEIGHT	40 OUNCES
OPERATING VOLTAGE	5.2 to 3.4 VOLTS DC
OPERATING CURRENT	880 mA

Table 1. Summary of the WJ-5610-1 YIG-tuned Oscillator Performance.

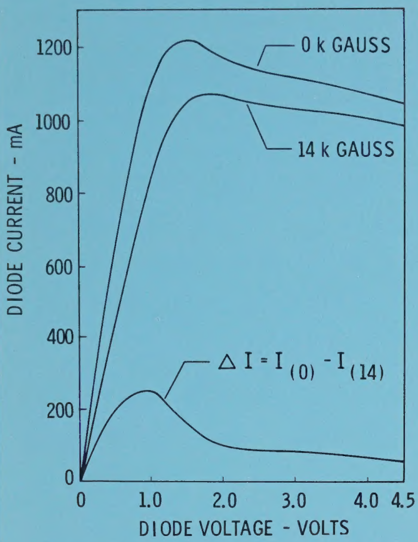


Fig. 5. Diode dc characteristics with and without Magnetic Field and Diode E-Field orthogonal to the Magnetic Field.

magnetic field applied in the worst direction.

The diode power output for two different couplings, that is, different iris diameters is shown in the curves of Figure 6. The power output is measured with the diode mounted in a waveguide test cavity while under the influence of a variable magnetic field applied orthogonal to the diode E-field. In the optimum case, the oscillator suddenly ceases above 12 kGauss; however, when the output is decoupled the power output is reduced but never quenched. This behavior can be qualitatively explained by a reduction in the negative resistance of the diode with the applied magnetic field. The sum of the negative diode resistance and the transformed load resistance must always be somewhat negative in order to satisfy the oscillator starting condition. Oscillations will stop when the diode resistance under the influence of a strong magnetic field becomes less negative such that the overall real part of the impedance is now positive. In the weaker coupled case this will not occur, since the transformation ratio is so large that a net negative real part remains. The reactive part of the diode impedance changes very slightly, resulting in a positive frequency shift of 10 to 15 MHz with maximum applied magnetic field.

A YIG-tuned circuit was evaluated in a 0.900 inch gap of a 4-inch electromagnet with tapered pole pieces.

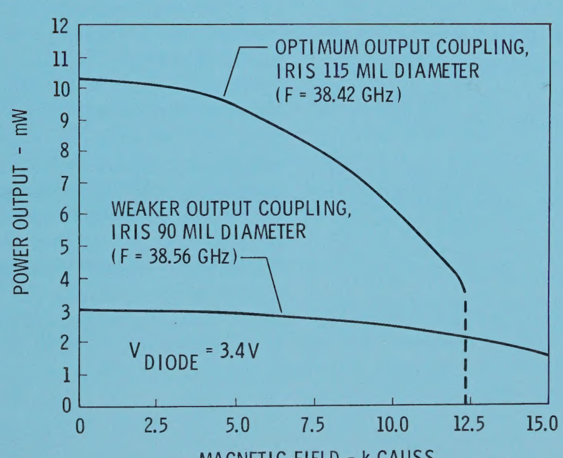


Fig. 6. Power Output to the Test Cavity Oscillator in a magnetic field and Diode E-Field orthogonal to the Magnetic Field.

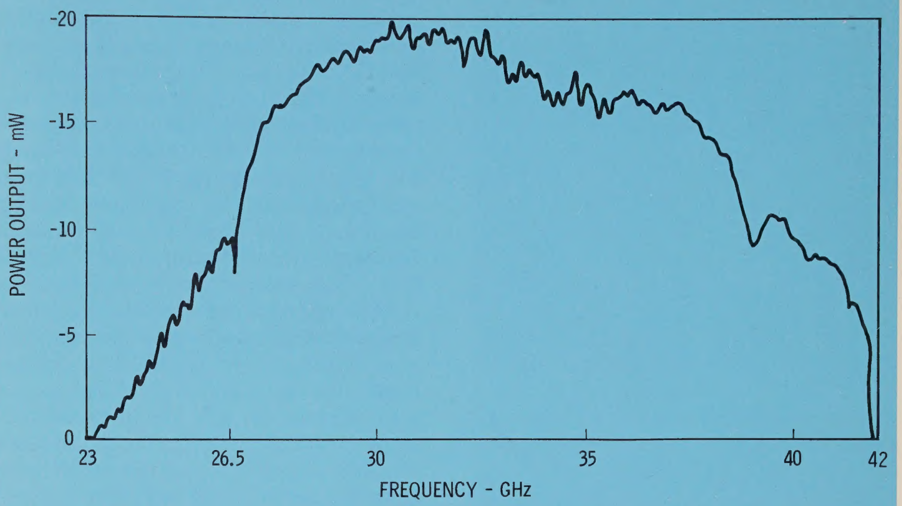


Fig. 7. Power Output of a Ka-band Oscillator with Diode E-Field parallel to the Magnetic Field. The Curve is obtained by programming the diode bias from 3.5 volts to 4.6 volts.

The magnetic field was adjusted for 40 GHz operation. The circuit was then rotated in the gap for minimum and maximum magnetoresistance effect. The output of the oscillator was fed through a small coaxial line to a waveguide test setup and the power measured as a function of rotation. These test results indicate that the power output can be increased by 3 dB when the magnetoresistance effect is eliminated. The YIG sphere orientation was optimized for both positions; also different sphere sizes and changes in input coupling were investigated for a given fixed output coupling.

The recent development of a new diode pin configuration now allows the magnetic tuning field to be parallel with the diode E-field. The result is a substantial improvement in power output and frequency coverage, as shown in Figure 7.

Future Developments

The addition of an FM coil to allow phase locking of the frequency for applications from spectroscopy to frequency synthesis. A FM coil has been incorporated within a WJ-5610-4 YIG-tuned oscillator and its characteristics are summarized in Table 2. An increase in power output in Ka band to 10mW at elevated temperature: A source with this output power level will be suitable for application in microwave sweepers. Better diodes have shown full Ka-band output power of 10 mW at 70°C. Extended low-end frequency coverage: The restriction is presently in the coax-to-waveguide transition; the cut-off frequency of the WR-28 waveguide. A unit with coaxial output covering 18 to 40 GHz is under development. Higher frequency coverage is possible with the present design technique.

Table 2. FM Coil Performance of the WJ-5610-4 YIG-tuned Oscillator.

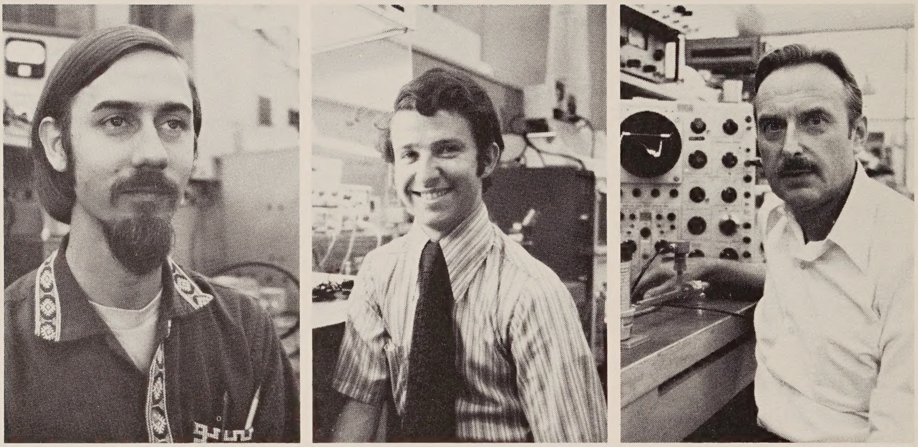
TUNING SENSITIVITY, (DC)	70 kHz/mA
FREQUENCY DEVIATION	±50 MHz
FREQUENCY RESPONSE (50% of DC SENSITIVITY)	200 kHz
MAXIMUM CONTINUOUS TUNING CURRENT	800 mA
COIL RESISTANCE	0.2 ohm
COIL INDUCTANCE	0.2 µH

Summary and Conclusions

Optimization of GaAs diode parameters results in broadband performance over full Ka band. The low thermal dissipation achieved guarantees reliable operation at 70°C. Refined circuit technology minimized the reactance of parasitic elements and proper impedance transformation has resulted in excellent tuning linearity. The extension of this technology to a higher frequency coverage is possible.

The efficient magnet structure with composite high permeability magnetic alloys exhibit negligible saturation effects. The reduction of the air gap to an absolute minimum kept the tuning coil thermal dissipation in reasonable limits. The magnetoresistance effect demonstrates its importance to RF performance. It is mandatory, especially at higher frequency operation, to orient the GaAs chip such that this effect cannot take place.

These advancements in state-of-the-art YIG devices should open up Ka band to system designers for development of high frequency equipment such as receivers, sweepers and synthesizers.[7].



Authors: William Green (left), **Walter Wilser** (center) and **Kurt Zublin** (right) are members of the technical staff at W-J's Solid State Division.

Bill Green is engaged in R&D of broadband Yig-tuned transistor and bulk-effect oscillators. He recently developed the first single bulk GaAs oscillator covering 6 to 16 GHz. Mr. Green also has designed and fabricated Hi-Rel Yig oscillators. Bill graduated from Cornell University with a BSEE degree and is a member of Eta Kappa Nu, Tau Beta Pi, Phi Kappa Phi and Alpha Sigma Phi.

Walter Wilser received his BA degree from Northeastern University and his MS and Ph D at Cornell University. He currently is responsible for advanced GaAs device development and fundamental GaAs materials research, and is developing a low stress metal sputter deposition process applicable to fused silica substrates. He has developed GaAs bulk-effect diodes which provide 10 milliwatts power output over the 26 to 40 GHz range. Walter is a member of the American Physical Society and Phi Kappa Phi.

Mr. Zublin is currently Project Engineer for the development of Yig-tuned GaAs oscillators covering the 26.5 to 40.0 GHz range. Previously he developed a GaAs Field Effect Transistor Oscillator which was varactor tuned over a 1.5 GHz portion of the X-band range. His work significantly advanced the state-of-the-art of GaAs FET components for receiver systems. Kurt holds a Diploma degree in EE from the Federal Institute of Technology, Zurich, Switzerland, and has done post-graduate study at Stanford University.

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