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Wideband YIG-tuned Oscillators

WATKINS-JOHNSON COMPANY
Tech-notes

Today's sophisticated military systems requirements demand increased power and wider band coverage from microwave signal sources. YIG-tuned transistor oscillators continue to provide the broadest band coverage available, with low phase-noise characteristics and excellent tuning linearity. Significant progress has been made in all these areas, but today's requirements for advanced military systems call for further improvement. Additionally, equivalent or better electrical performance, using fewer components to reduce the overall package size and weight, less overall power consumption, and improved reliability are important and desirable objectives in new development efforts.

Two fundamental problems are encountered in the development of truly wideband oscillators using GaAs FETs and silicon bipolar-junction transistors. The first is maintaining oscillation conditions over multioctave frequency ranges. The second, which is unique to YIG-tuned oscillators, is avoiding the spurious resonance associated with the inductance of the YIG coupling loop. Traditionally, both of these problems have been solved through the use of the common-gate and common-base topology. Simplified schematic diagrams are shown in Figure 1. The common-gate circuit used with a GaAs FET and the common-base circuit used with the silicon bipolar-junction transistor develop negative conductance (as seen by the resonator) only when the susceptance is inductive. This avoids the possibility of having a spurious resonance associated with the YIG coupling loop. Typically, device parasitics will force a change from inductive to capacitive susceptance at the high end of the negative-conductance band. However, the coupling loop inductance can usually be made small enough to avoid spurious resonances.

Silicon bipolar-junction transistors exhibit very broadband coverage (2 to 8 GHz, 3 to 13 GHz) when used in the common-base topology. This is primarily due to the high conductance of the devices. The drawback, however, is that available production bipolar transistors have a maximum frequency of oscillation of 15 to 16 GHz. This is strictly a device design/material limitation. Production GaAs FETs, on the other hand, are capable of oscillating well above 40 GHz, but are normally limited to only slightly greater than octave bandwidths when used in conventional YIG-oscillator circuits. This limitation is both device and circuit related. Achieving multioctave coverage in an oscillator above 16 GHz requires either a marked improvement in oscillator device technology or the development of alternative circuit techniques for GaAs FETs.

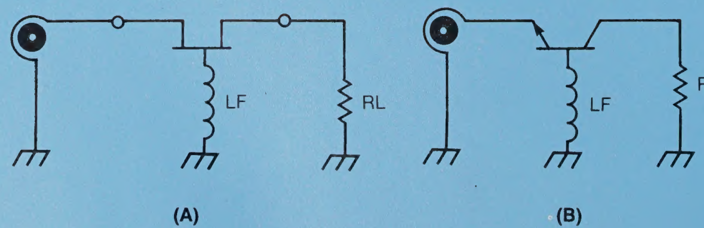

Figure 1. (A) Common-gate YIG-tuned oscillator using GaAs FET; (B) Common-base YIG-tuned oscillator using NPN, silicon, bipolar-junction transistor.

Objectives

The objective of present development work in GaAs FET oscillators at Watkins-Johnson Company is to develop and produce multioctave or wideband YIG-tuned oscillators with minimum power outputs of +13 dBm, that operate over a -54 to +85°C ambient temperature range.

For military missile applications, light weight and compact size is an essential requirement. The wideband YIG-tuned oscillator is designed as a 1.5-inch diameter package, with its total weight not to exceed 10 ounces.

Design Approach

The basic approach taken to realize wide bandwidth YIG-tuned oscillators is in the development of new circuit topologies that take advantage of the inherent properties of the GaAs FETs. This approach was taken because it promises a more timely solution to the problems that limit performance. The technology gained will be directly applicable to developing millimeter-wave broadband oscillators (8 to 26 GHz and 12 to 40 GHz).

A circuit topology that exhibits oscillation conditions over multioctave bandwidths is the common-source circuit. A simplified schematic is shown in Figure 2. The disadvantage of the common-source circuit is that the susceptance, as seen by the YIG, is capacitive. This allows for the possibility of spurious oscillations associated with the coupling-loop inductance of the YIG. The approach that was used to take advantage of the wide bandwidth of the common-source oscillator, without spurious resonances, was to "tailor" the frequency band of interest by control of the feedback capacitor C_F.

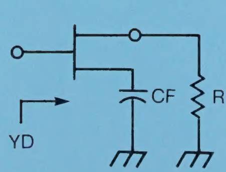

Figure 2. Common-source GaAs FET oscillator.

Tuning the series feedback element, C_F, was realized by replacing C_F with a second YIG resonator. A schematic diagram is shown in Figure 3. By placing both YIG resonators in the same magnetic structure, feedback and, therefore, oscillation conditions, are only present at the frequency of oscillation. As a result, no spurious oscillations can occur and broad tuning bandwidths are achieved. Considerable extension of tunable bandwidths has already been accomplished with dual-YIG circuits. Coverage has been obtained from 6 GHz to well beyond 18 GHz.

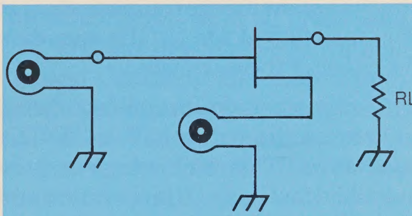

Figure 3. Two-YIG realization of the common-source oscillator.

The approach taken to obtain even wider band coverage is a variation of the two-YIG circuits. The feedback resonator was eliminated and the source was directly coupled to the gate resonator. Figure 4 shows a coupled-source topology which provides band coverage from 4.0 to greater than 20 GHz, limited only by the buffer amplifier capabilities.

Results obtained with both the dual YIG circuit and the coupled-source oscillator strongly suggest the possibility of 2 to 18 GHz operation. A more

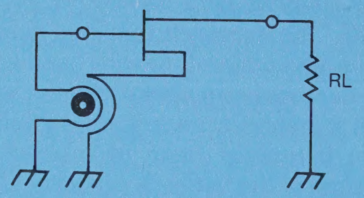

Figure 4. Coupled-source oscillator.

complete characterization of both of these oscillators should lead to a model that will allow a more complete study of the feasibility of 2 to 18 GHz operation for either of these circuits.

Presently, a balanced amplifier is being utilized as the buffer in 6 to 18 GHz oscillators. This technology can be stretched for 5 to 18 GHz operation and should be effective for high-power requirements in the 6 to 18 GHz range. The 4 to 18, or 4 to 20 GHz range, however, required development of a distributed amplifier. Computer-aided-design results and hardware tests indicate that the distributed amplifier has excellent bandwidth potential and the capability for high output power. Figure 5 illustrates a schematic diagram of a distributed amplifier.

Development work has already been completed on a compact 1.50-inch diameter package for the 6 to 18 GHz YIG-tuned oscillator. Extending the coverage from 4 to 18 GHz required redesign of the magnet to accommodate two stages of distributed amplification. The magnetic structure was required to accommodate the BeO substrate for the coupled-source type oscillator.

Experimental Results

Figure 6 shows the coupled-source oscillator topology being used for

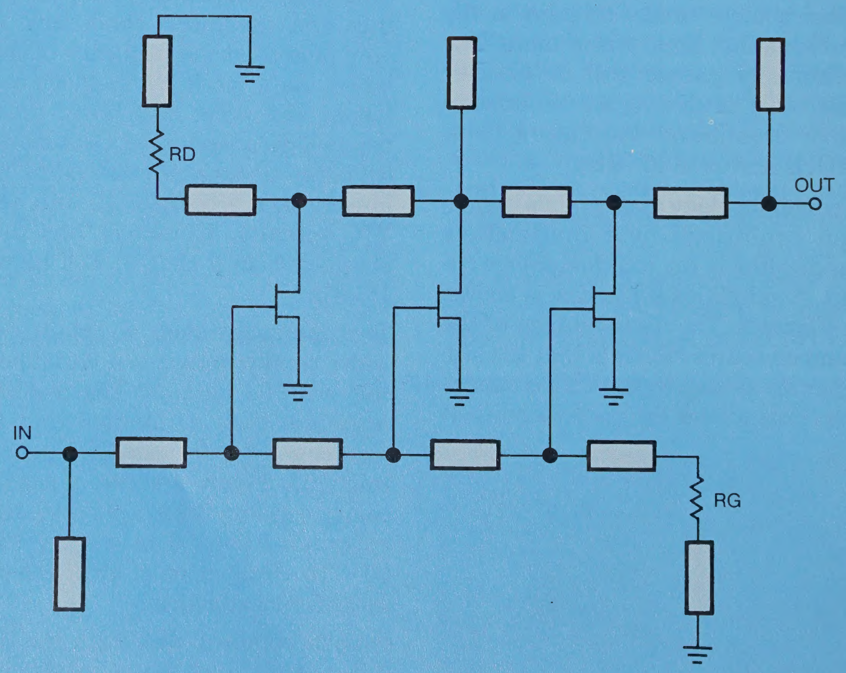

Figure 5. GaAs FET distributed amplifier.

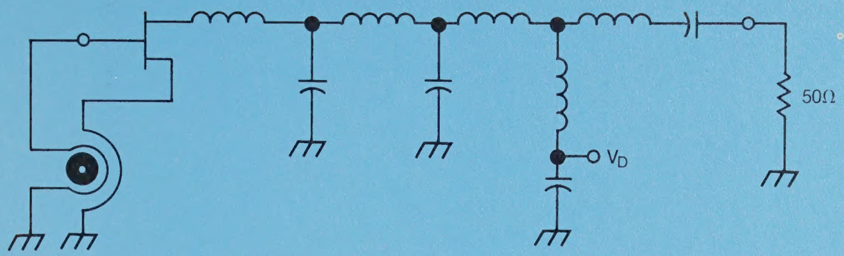

Figure 6. Coupled-source oscillator (3.5 to 19.5 GHz).

2.0 GHz to 19.5 GHz coverage. The active device is a recessed-gate GaAs FET with approximately 0.5 μm $\times$ 300 μm gate dimensions. The YIG resonator is 14 mils in diameter with a saturation magnetization of 1000 gauss. Output matching is accomplished with a four-element low-pass network with provisions for dc biasing and blocking. The match was formulated using small-signal modeling in conjunction with large-signal data collected from load-pull measurements. Figure 7 shows performance data for the coupled-source oscillator. Although the coupled-source oscillator topology has provided very wideband coverage, discontinuities due to YIG-sphere moding have prevented continuous coverage over the entire 2 to 18 GHz range. Extremely low harmonics and highly linear tuning are both characteristic of the coupled-source oscillator topology.

Figure 8 shows a production prototype of the coupled-source oscillator with a 2 to 18 GHz distributed amplifier being used as a buffer. The oscillator circuit is fabricated on BeO substrates and utilizes laser-drilled holes for grounding. Because of the high thermal conductivity of the BeO, the FET can be mounted directly on the substrate and no carrier is required. This approach yields a simple and inexpensive oscillator assembly which needs only to be clamped to the magnetic housing.

The development work on broadband, FET, YIG-tuned oscillators at Watkins-Johnson Company has made significant progress during the past year. The dual-YIG oscillator circuit has provided band coverage from 6 GHz to well beyond 18 GHz, limited only by the present buffer amplifier design. Several prototype units were fabricated and tested. The tests exceeded the initial developmental specification requirements, providing minimum power output of greater than +17 dBm and operating over the temperature range of -54°C to +85°C. The tuning of the feedback element, C_F, with a YIG resonator, provides the broad tuning range of this type of circuit, with band coverage extending to frequencies beyond 26.5 GHz. The main disadvantage of this type of circuit is the time required to rf-align the circuit and tune the two YIGs. Proper orientation of both spheres to their temperature-compensation axis is required over the wide military temperature range so that each tracks the other's resonant frequency as the oscillator is tuned. Figure 9 is a developmental specification for a 6 to 18 GHz YIG-tuned transistor oscillator. Figure 10 shows the data of a demonstration unit which provides a minimum of +17 dBm over the same frequency range. Several similar prototypes have been built in engineering, and documentation work has been completed for transfer into

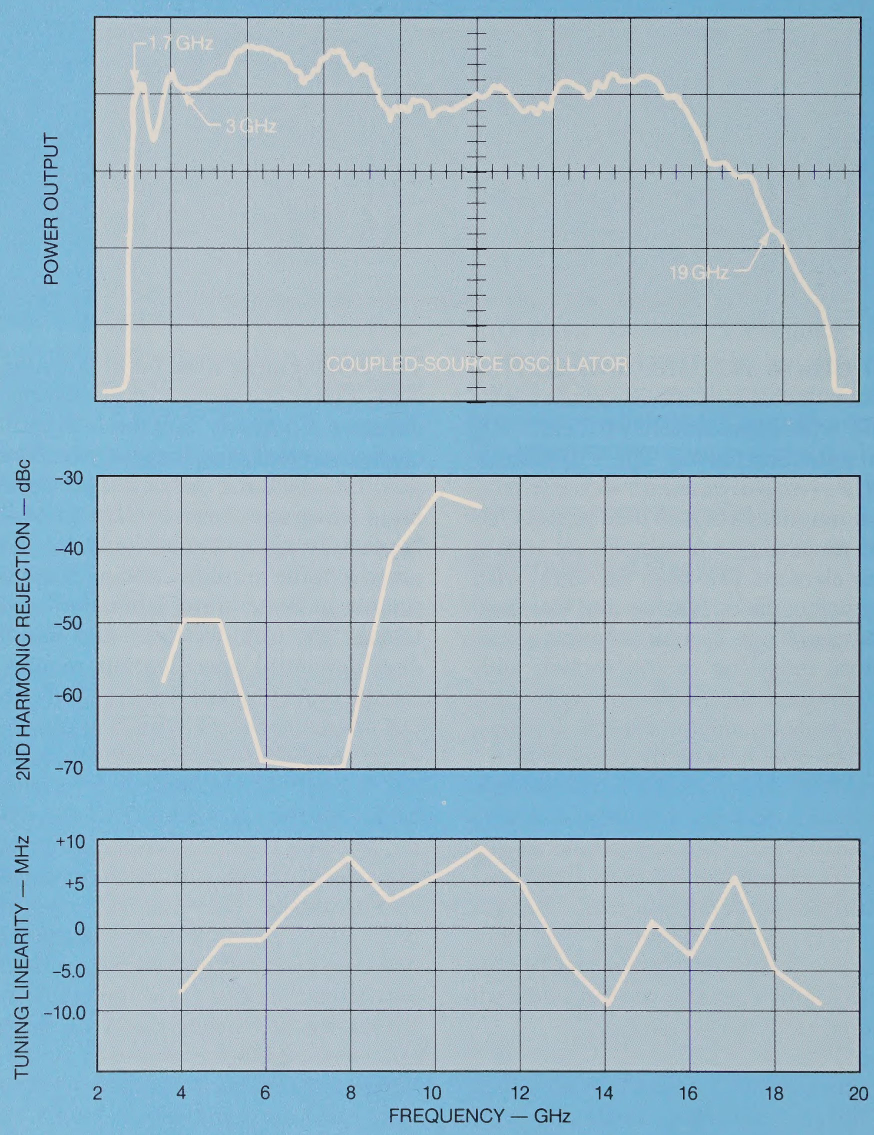

Figure 7. Performance data for coupled-source oscillator.

production. Work is also being done to develop a 4 to 18 GHz oscillator using the coupled-source structure shown in Figure 7. This circuit was more adaptable to the extension of the low-end tunable bandwidth. The parallel coupling technique employed in this type of circuit provides increased coupling to the YIG sphere, which is heavily doped with gallium. Gallium reduces the saturation magnetization ($4\ \pi ms$), which determines the lower frequency limits of operation and also reduces the Q of the sphere's microwave resonance. Data which illustrates the coupled-source oscillator operating from 4 to

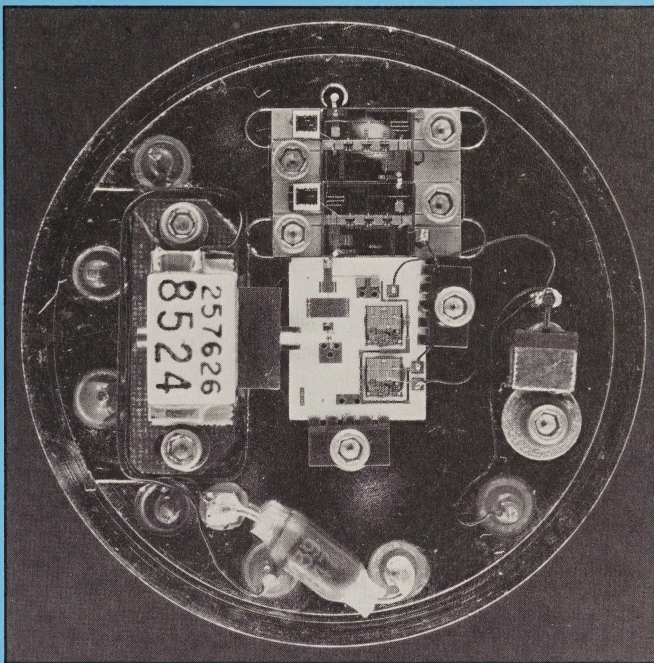

Figure 8. Photo of a 2 to 18 GHz distributed amplifier.

18.0 GHz, over the temperature range of –55 to +85°C, is shown in Figure 11. A developmental specification of the coupled-source oscillator is shown in Figure 12.

Beryllium Oxide (BeO) substrates are used in the coupled-source oscillator circuit to reduce the overall circuit cost. Using BeO substrates eliminates the need for a metal substrate carrier and reduces the overall assembly time required. The high thermal conductivity of beryllia, with its high thermal capacity and linear coefficient of expansion, makes it an ideal material for mounting field-effect transistor chips as well as other passive components. Holes are laser drilled, sputtered and plated on the BeO substrates where rf grounds are required. At higher frequencies and for broadband circuits, it is imperative that rf ground paths be kept as short as possible to reduce the transmission-line effects and minimize inductance. This state-of-the-art MIC construction technology is essential for reliable broadband operation. Some of the problems encountered during processing of the BeO substrate are that the line width cannot be made less than approximately 2 mils wide. Also, when a resistive network is used, and tantalum nitride is deposited on the substrate, the grain size of the substrates affects the ohms-per-square resistance value of the network. Presently, the best available BeO substrates have a grain size variation of between 10 to 15 microns. Because of the graininess of BeO substrates, it is still necessary to use an alumina oxide (AL_2O_3) or fused silica as substrate material where very narrow circuit pattern lines are required.

The coupled-source oscillator is being produced in Engineering, with all the

RF CHARACTERISTICS	Typical	Guaranteed
Frequency Range	6.0 to 18.5 GHz	6.0 to 18.0 GHz
Power Output (1.5:1 VSWR), Min.		+17 dBm
Output Variation, Max.	±2 dB	±3 dB
Frequency Accuracy[1]	±25 MHz	±30 MHz
Spurious Output Suppression		
2nd Harmonic, Min.	-12 dBc	-10 dBc
Inband Spurious, Min.	-60 dBc	-50 dBc
Incidental FM[2, 3]	10 kHz	
Pushing Factor, Max.		0.5 MHz/V
Pulling Figure (2.0:1 VSWR), Max.		1.0 MHz
Warm-up Time	5 minutes	

TUNING CHARACTERISTICS

Primary Input	
Sensitivity	18 MHz/mA
Hysteresis	17 MHz
Coil Resistance	8 Ohms
Coil Inductance	100 mH
Secondary Input	
Sensitivity	125 kHz/mA
Bandwidth (3 dB)	100 kHz
Deviation (continuous)	±60 MHz
Maximum Continuous Current	500 mA

ELECTRICAL POWER REQUIREMENTS

Oscillator Bias	+15 Volts @ 250 mA, Max., Steady State
Heater[4]	+28 Volts @ 450 mA, Max., Surge; 200 mA, Max., Steady State at Min. Temperature

ENVIRONMENTAL SPECIFICATIONS

Operating Temperature[5]	+10 to +60° C

MECHANICAL PARAMETERS

Size, Excluding Connectors	1.75 Inch Dia. × 1.50 Inches High
Weight	20 Ounces
RF Output Connector	SMA Jack
Electrical Connections	Solder Terminals
Outline Drawing Number	296892

NOTES:

1. Maximum deviation from straight line to the set of tuning curves at +10°C, +25°C and +60°C including effects of nonlinearity and temperature drift, but excluding pulling and hysteresis. Frequency accuracy applies after the specified warm-up period.
2. Measured for design verification. Data is not supplied with individual oscillators.
3. Excluding IFM-generated by fluctuations in tuning or bias power supplies.
4. YIG heater is self-regulating proportional — controlled.
5. Temperature is measured on the oscillator mounting surface.

Figure 9. WJ-6810-310F YIG-tuned transistor oscillator.

documentation being updated as refinements are made to the oscillator circuits to minimize rf alignment time.

To fully develop a 2 to 18 GHz coupled-source oscillator requires further characterization of the rf circuit and transistors. Experiments have indicated that the rf coupling-loop structure and method of coupling to the YIG sphere greatly influence the band coverage at the lower frequencies.

Tuning Current (mA)	Calculated Frequency (GHz)	Frequency Deviation (MHz)			Power Output (dBm)		
		-40° C	+25° C	+85° C	-40° C	+25° C	+85° C
334.00	6.000	1	0	3	19.3	19.2	18.8
	7.200	-3	-3	-3	21.4	21.3	21.0
	8.400	-3	-4	-3	21.2	21.1	20.9
	9.600	-5	-4	-2	20.8	20.8	20.8
	10.800	-2	-2	0	21.6	21.4	20.5
	12.000	-2	0	3	21.7	21.8	20.5
	13.200	-1	0	4	21.4	21.3	20.2
	14.400	1	4	8	21.7	21.6	20.6
	15.600	4	6	10	21.5	21.4	20.7
	16.800	1	1	3	21.4	21.2	20.5
1034.66	18.000	2	1	1	20.6	20.4	19.3

Linearity	±5 MHz	Tuning Coil Resistance	8 Ohms
Drift	7 MHz (Max.)	Tuning Coil Inductance	100 mH
Tuning Sensitivity	17.2 MHz/mA	Ground Isolation	Pass
2nd Harmonic Rejection	−10 dBc	Hysteresis	18 MHz
Spurious Rejection	7 to 60 dBc	FM Coil Sensitivity	300 kHz/mA

Figure 10. Data for 6 to 18 GHz.

Progress is being made in developing a very wideband distributed amplifier which provides sufficient gain over the frequency range of 2 to 18 GHz to meet the specification requirements of Figure 12. Typical gain utilizing two stages of cascaded amplification have yielded 9-dB minimum gain from 4 to 18 GHz, as shown in Figure 13. Figures 14 and 15 are gain and return loss curves of the same type of single-stage distributed amplifier with selected matched FET devices. By carefully selecting and matching FET parameters for high gmo, minimum C_{gs}, and high f_{opt}, it is possible to extend

Tuning Current (mA)	Calculated Frequency (GHz)	Frequency Deviation (MHz)			Power Output (dBm)		
		-55° C	+25° C	+85° C	-55° C	+25° C	+85° C
236.87	4.0	9	0	3	22.2	20.7	19.9
326.77	5.4	12	3	3	21.3	20.0	19.0
416.67	6.8	16	8	10	20.5	19.8	19.1
506.57	8.2	20	12	14	18.6	17.7	16.6
596.47	9.6	20	16	20	18.4	17.7	15.8
686.38	11.0	34	30	33	19.1	18.6	17.8
776.28	12.4	43	36	38	19.7	19.4	18.8
866.18	13.8	39	32	35	19.3	19.1	18.6
956.08	15.2	44	34	35	19.0	18.9	18.4
1045.98	16.6	39	26	25	19.5	19.2	18.8
1135.89	18.0	14	0	0	18.0	17.4	16.5

Linearity	±18 MHz	Tuning Coil Resistance	7.7 Ohms
Frequency Accuracy	±7 MHz	Tuning Coil Inductance	64 mH
Tuning Sensitivity	15.5 MHz/mA	Ground Isolation	Pass
2nd Harmonic Rejection	−10 dBc	Hysteresis	18 MHz
Spurious Rejection	−50 dBc	FM Coil Sensitivity	127.5 kHz/mA

Figure 11. Data for 4 to 18 GHz.

RF CHARACTERISTICS	Typical	Guaranteed
Frequency Range	4.0 to 19.0 GHz	4.0 to 18.0 GHz
Power Output (1.7:1 VSWR), Min.		+13 to +20 dBm
Output Variation (Matched Load)		
At Constant Temperature	5.0 dB	
Including Temperature Effects	8.0 dB	10.0 dB
Frequency Accuracy[1]	±25 MHz	±30 MHz
Spurious Output Suppression		
2nd Harmonic, Min.	-25 dBc	-20 dBc
Inband Spurious, Min.		-50 dBc
Incidental FM, Max.[2]		150 kHz
Pushing Factor, Max.[4]		0.5 MHz/V
Pulling Figure (1.7:1 VSWR), Max.		5.0 MHz
Warm-up Time, Min.[3]	3.0 minutes	
Magnetic Susceptibility, Max.		1.0 MHz/Gauss
TUNING CHARACTERISTICS		
Primary Input		
Sensitivity	18.0 MHz/mA	
Linearity, Max.	±20.0 MHz	
Hysteresis, Max.	20 MHz	
Coil Resistance, Max.		8 Ohms
Coil Inductance, Max.		110 mH
Secondary Input		
Sensitivity		250 kHz/mA
Bandwidth (3 dB)		100 kHz
Deviation (continuous), Min.		±100 MHz
Maximum Continuous Current		400 mA
ELECTRICAL POWER REQUIREMENTS		
Oscillator Bias	+15 Volts @ 180 mA, Max., Steady State	
Heater[5]	+28 Volts @ 450 mA, Max., Surge; 150 mA, Max., Steady State at Min. Temperature	
ENVIRONMENTAL SPECIFICATIONS		
Operating Temperature[6]		-10 to +60°C
Storage Temperature		-65 to +120°C
MECHANICAL PARAMETERS		
Size, Excluding Connectors		1.75 Inch Dia. × 1.50 Inches High
Weight	20 Ounces	
RF Output Connector	SMA Jack	
Electrical Connections	Solder Terminals	
Outline Drawing Number	TBD	

NOTES:
1. Maximum deviation from straight line to the set of tuning curves at -10°C, +25°C and +60°C including effects of nonlinearity and temperature drift, but excluding pulling and hysteresis. Frequency accuracy applies after the specified warm-up period.
2. Excluding IFM-generated fluctuations in tuning or bias power supplies.
3. As measured from the application of all oscillator power at -10°C.
4. Pushing due to bias voltage change.
5. YIG heater is self-regulating proportional — controlled.
6. Temperature is measured on the oscillator mounting surface.

Figure 12. Tentative developmental specification for the WJ-6830-XX YIG-tuned transistor oscillator.

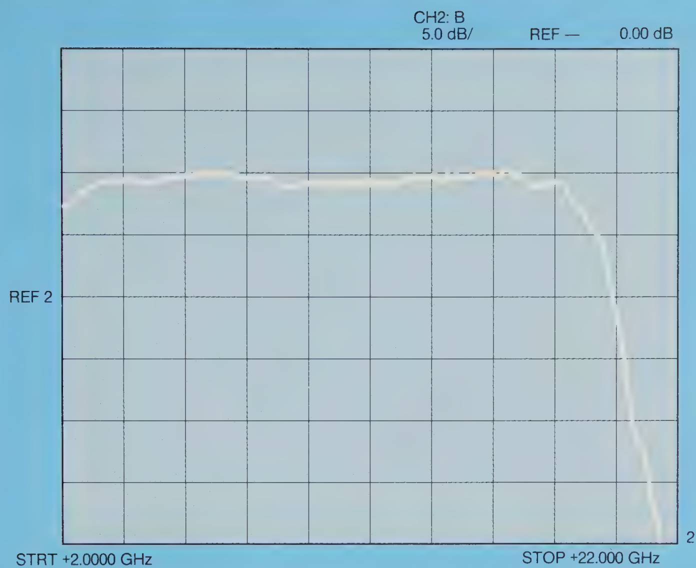

Figure 13. Typical gain utilizing two stages of cascaded amplification.

the gain from 18 GHz to 20 GHz, as shown in Figure 14,and up to 22 GHz, as shown in Figure 15. Modifications and improvements to circuit parameters are being made to improve the circuit yield and to be less sensitive to

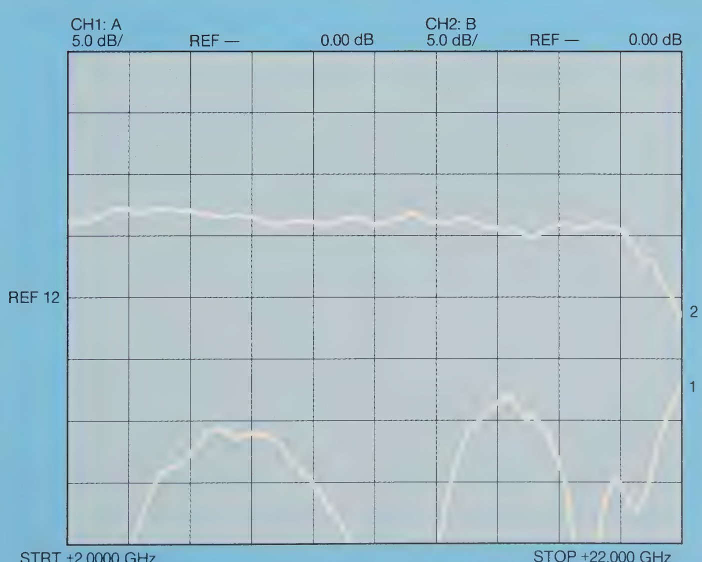

Figure 14. Gain and return loss curves of single-stage distributed amplifier with selected matched FET devices.

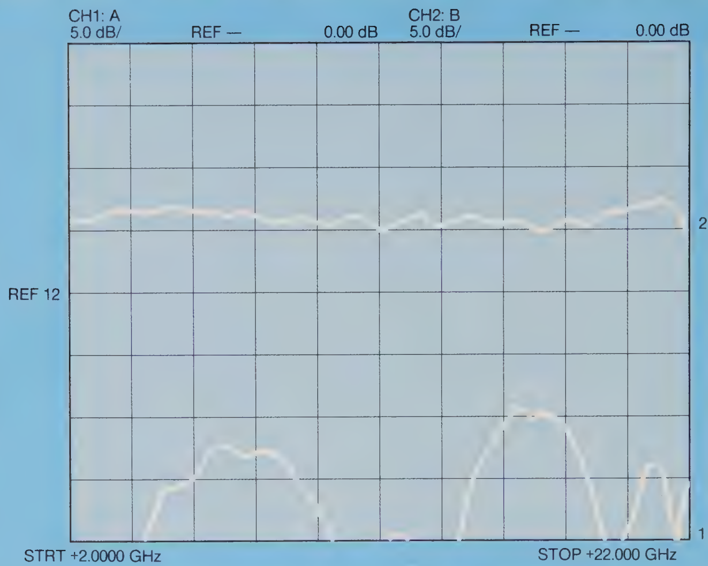

Figure 15. Gain and return loss curves of single-stage distributed amplifier with selected matched FET devices.

matched transistor parameters.

Presently, all of the developmental effort for the wideband YIG-tuned GaAs field-effect transistor oscillators is directed toward, and in support of military programs. The small size and light weight of these oscillators are ideally suit them for electronic countermeasures and missile guidance systems. YIG-tuned oscillators which can provide multioctave band coverage are essential for military systems to guard against enemy threats. Major programs requiring broadband YIG-tuned oscillators include ASTAAM (Advanced Seeker Technology Air-to-Air Missile), ADSM (Air Defense Suppression Missile), SPSR (Small Passive Superheterodyne Receiver), and Sidearm II.

The ultimate goal of achieving band coverage from 2 to 18 GHz will provide support for the military programs listed above.

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Notes

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