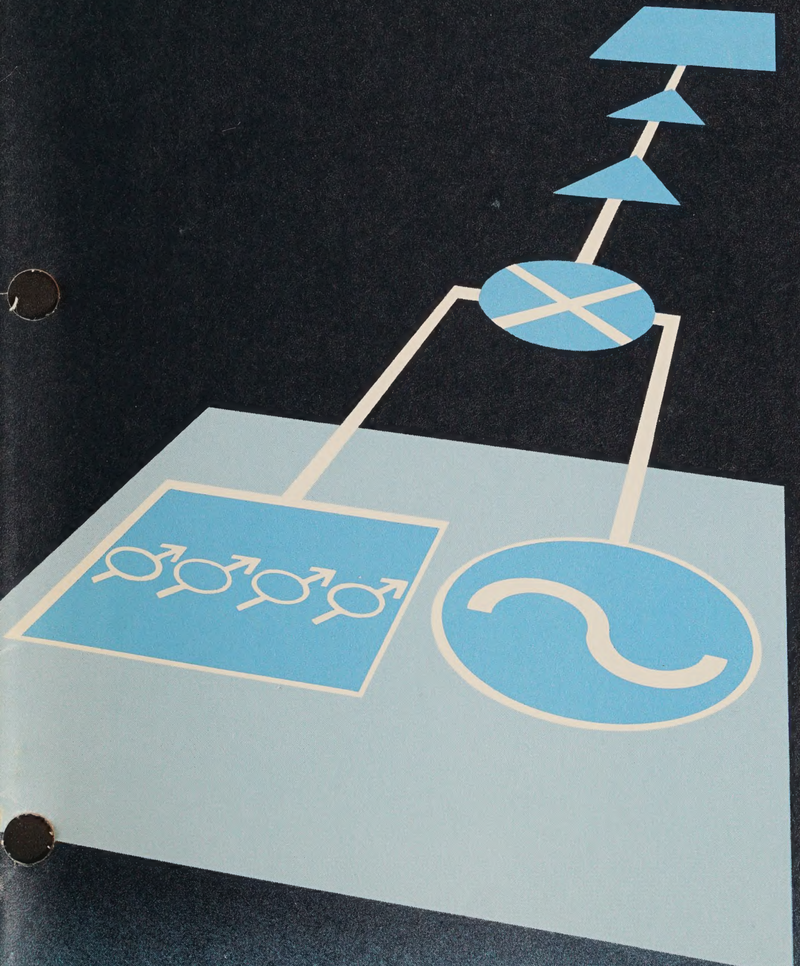
Vol. 4 No. 5 September/October 1977

YIG-Tuned Integrated Devices



WATKINS-JOHNSON COMPANY Tech-notes

The process of integrating standard microwave components such as oscillators, filters, mixers, or amplifiers into subassemblies enclosed in a compact package produces what might be called a "supercomponent" such as a frequency converter or receiver front end. There are a number of potential advantages to the systems manufacturer in the use of such supercomponents in place of the individual devices. First is the elimination of the common practice of system designers to overspecify a component's performance. This overspecification occurs because of the need to insure that the system specification will be met even if the worst-case performance of all the components occurs simultaneously. A supercomponent manufacturer can trade off performance among the various devices and still meet the requirements of the assembly. Second, overall performance may improve due to the common environment of the devices. The third advantage, of course, is smaller size and weight. A large fraction of the total size of the RF assemblies is made up of connectors, cabling, and housings. A supercomponent can eliminate much of this hardware and increase the density of electrical functions.

Receiver Front Ends

Superheterodyne front ends with narrow, instantaneous bandwidths are employed in many surveillance and spectrum analysis applications. In the front end shown in Figure 1, the RF input signal from the antenna passes through a YIG-tuned filter to a mixer. The preselector is typically a four-stage YIG filter with an instantaneous bandwidth of between 20 MHz and 70 MHz, depending on the operating frequency. Occasionally, a dual two-stage filter is used instead to allow the insertion of an RF amplifier between the second and third stages. This results in lower front end noise figure at some extra cost. The YIG-tuned LO (local oscillator) is generally a transistor oscil-

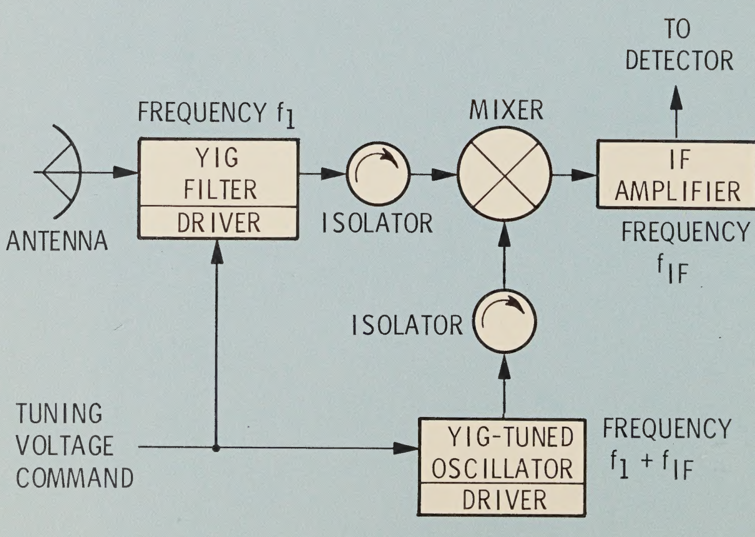


Figure 1. Typical RF front end.

lator through 8 GHz and a GaAs Gunn-effect oscillator in X and Ku-bands. The IF amplifier usually consists of two transistor stages totalling 30 dB gain. This, combined with the 6 dB mixer conversion loss and 4 dB preselector insertion loss, results in a net RF-to-IF gain of 20 dB. The mixer is a single balanced quadrature hybrid requiring LO drive levels of about +10 dBm. A double balanced mixer is not required since many of the dynamic range problems associated with single balanced mixers are eliminated through the use of the preselector.

The isolator between the oscillator and mixer is used to decrease the mismatch into which the oscillator must operate. A large mismatch can result in frequency pulling of the oscillator, or, in extreme cases, the oscillation may cease altogether. The isolator in the RF chain serves to eliminate gain ripple due to filter-mixer mismatch at the RF frequency and may also have the additional benefit of suppressing LO radiation at the RF input. In general, however, the frequency of the oscillator is sufficiently offset from the passband of the filter that LO radiation is not a major problem.

The YIG oscillators and filters common to these front ends are extremely linear, magnetically-tuned devices. The YIG sphere, which serves as the tuning element, is a resonator whose resonant frequency is directly proportional to the magnetic field which surrounds it. The magnetic field, in turn, is linearily related to the current used to generate the field. A typical magnetic circuit is shown in Figure 2. A pair of coils is wound around pole pieces made of high-permeability iron. The YIG sphere and RF circuit are located in the gap between the pole pieces. The outside walls of the magnetic shell provide a return path for the magnetic flux, provide for mechanical support of the RF circuit, and provide shielding from external magnetic fields.

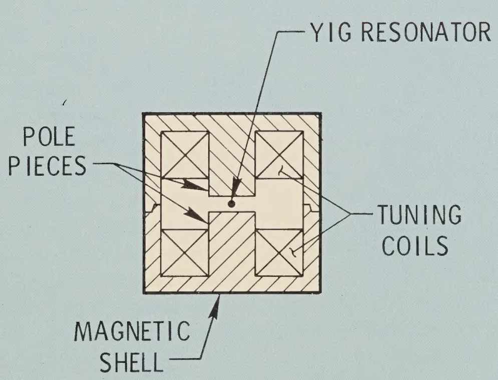


Figure 2. Magnetic structure of a YIG-tuned oscillator.

Tracking

Critical to the performance of the front end is the frequency tracking of the oscillator and filter. In most applications the IF frequency is defined by a narrowband IF filter located after the IF amplifier chain. A typical IF frequency might be 160 MHz. If the preselector bandwidth is 40 MHz, then a mistracking of 20 MHz between LO and filter results in a 3 dB increase in front end noise figure because the RF signal will be at the 3 dB point on the preselector's passband.

This mistracking can be caused by a number of factors, all of which influence the absolute frequency accuracy of the devices. Among them are the small non-linearity in the RF frequency compared to the tuning current (tuning nonlinearity), the different relative temperature drifts of the two devices and the different temperature behavior of the YIG driver circuits.

Tuning nonlinearity is the deviation in MHz from the best-fit straight line tuning curve. Generally, the YIG devices are very linear, with nonlinearities less than ±0.1%. The linearity of YIG oscillators is generally not as good as that of YIG filters. For example, in X-band the frequency error due to non-linearity might be of the order of ±8 MHz. Thus, if the RF bandwidth of a preselector is 40 MHz in X-band and a front end is tuned to 10 GHz, the real effective RF bandwidth becomes only 24 MHz if the oscillator non-linearity is ±8 MHz. If there is, in addition, some non-linearity in the preselector, the effective bandwidth will decrease further.

The most serious cause of tracking problems is the wide temperature range over which front ends are meant to operate (typically −54°C to +71°C). The frequency of a YIG device is dependent on temperature in two different ways. First, the resonant frequency of the sphere is temperature dependent. The temperature dependence is, in turn, a function of the orientation of the sphere in the field. Second, the field generated by the magnetic circuit is also temperature sensitive. This occurs because the iron forming the magnetic shell expands or contracts as the temperature changes, thereby changing the size of the gap in which the RF circuit is located. Since the field varies inversely with the gap, so does the frequency. Clearly, the tracking between an oscillator and a filter will degrade as the temperature varies due to the different drift characteristics.

The final consideration is YIG driver drift. A YIG driver circuit is basically a high input impedance (typically 10K ohms) voltage-to-current converter which allows a YIG device to be tuned with a precision voltage source rather than a current source. For a fixed input voltage, the output current which tunes the YIG will vary with temperature. This drift is different from one driver to the next due to the essentially random variation of the temperature coefficients of the driver's constituent resistors, operational amplifiers, and other components. Hence, a pair of YIG devices will generally suffer a relative drift over temperature due to variations in their respective drivers.

In conventional systems, several techniques are used to correct mistracking. One common technique is to wrap the devices in heater blankets to decrease the temperature range to which they are exposed and, hence, limit the relative drift. This method requires considerable heater power which may not always be available and also requires a rather long warm-up time to overcome the substantial thermal mass of the devices.

Another technique is to compensate the device drift through the use of a temperature sensitive circuit in the driver. A thermistor can be attached to the device to sense the temperature and adjust the driver current in such a manner as to compensate for the device's drift. This involves a rather complex alignment procedure, adding significantly to the cost of the front end.

One effective solution to tracking problems is to use an integrated YIG-tuned filter-oscillator. This device provides a means of control over the relative frequency of the oscillator and filter without the need to stringently control the absolute accuracy. The design objective is to eliminate relative mistracking to as great an extent as possible, to reduce the size and weight of the device, to decrease the tuning power required, and to maintain the ability to generate an arbitrary IF offset between the oscillator and filter. The last criterion rules out a single pole piece design with both devices in the same gap.

The design selected is shown in Figure 3. The magnetic circuit consists of a magnetic shell with two pole pieces, but a single main tuning coil. The preselector is mounted in one magnetic gap while the oscillator is located in the other. The main tuning coil tunes the two devices together across the frequency band. A small offset-coil is wound around the oscillator pole piece only. Current supplied to this coil generates an offset between the two devices which can be of arbitrary magnitude and sign.

Since the oscillator and filter are housed in a common shell and can be aligned to have comparable temperature coefficients, mistracking due to temperature effects is clearly not a problem. Furthermore, the dependence on driver accuracy is significantly reduced. The drift, or accuracy, of the main coil driver does not affect the relative frequeneies of the two devices. The tracking accuracy is governed solely by the offset coil

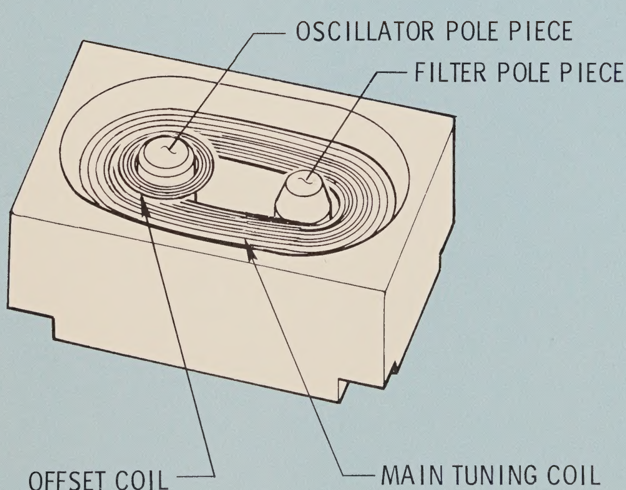


Figure 3. Design layout of a W-J YIG-tuned integrated filter-oscillator circuit.

driver. This driver is generating offset frequencies of the order of 100 MHz to 200 MHz, whereas a typical driver is usually required to generate current corresponding to frequencies of the order of 1 GHz to 20 GHz. Since in either case a driver-related frequency error of about 1 MHz can be tolerated, a 1% error in the "differential" driver is allowed, while a .01% error in the "absolute" driver is required. The excellent tracking accuracy of a Watkins-Johnson 1-2 GHz and 8-12 GHz filter-oscillator is displayed in Figure 4.

Physically, these devices measure approximately 2.55 x 1.4 x 1.57 inches in P, L and S bands and 2.2 x 1.8 x 1.5 inches in C, X and Ku bands. Tuning sensitivities are nominally 18 MHz/mA in the four lower bands, and 25 MHz/mA in X and Ku band, reducing the tuning current required by about 30% compared to the standard separate units (see Figure 5). A typical tuner utilizing an integrated filter-oscillator is illustrated in Figure 6.

An Integrated Front End

The next step in supercomponent integration is that of integrating the mixer and IF amplifiers with the filter-oscillator into a complete superheterodyne front end. The goal, of course, is to eliminate the isolators and connectors used in a conventional superheterodyne receiver in favor of a compact, lightweight RF-to-IF converter. Additionally, the integration of all these devices allows the use of complementary components rather than over-specified separate devices. Of necessity, a system designer must specify for worst case conditions. If, however, for example, the worst case filter insertion loss occurs at a frequency where the mixer conversion loss is very good, the combination may be able to meet the overall system specifications even though the individual components would not meet their specifications. This implies less alignment time for the individual components and potentially lower cost for the integrated devices.

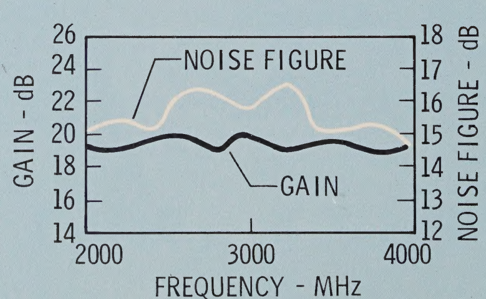


Figure 4. Tracking data of W-J YIG-tuned integrated filter-oscillator devices.

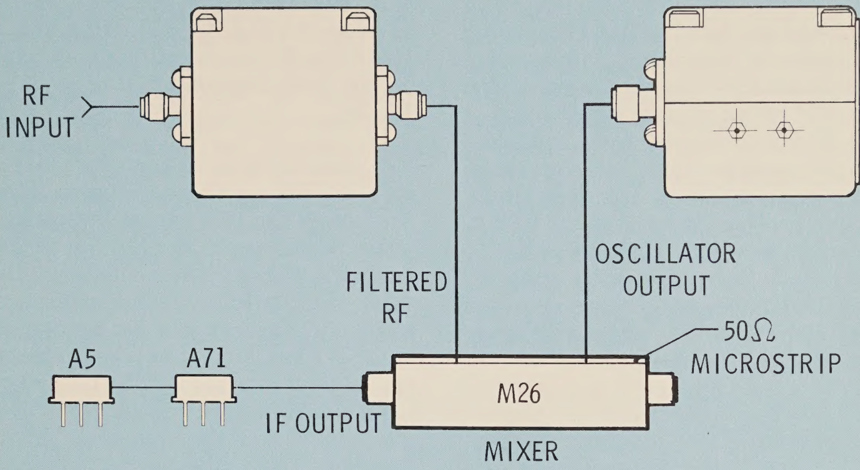


Figure 5. Physical appearance of the standard components (in separate packages) of a YIG-tuned front end.

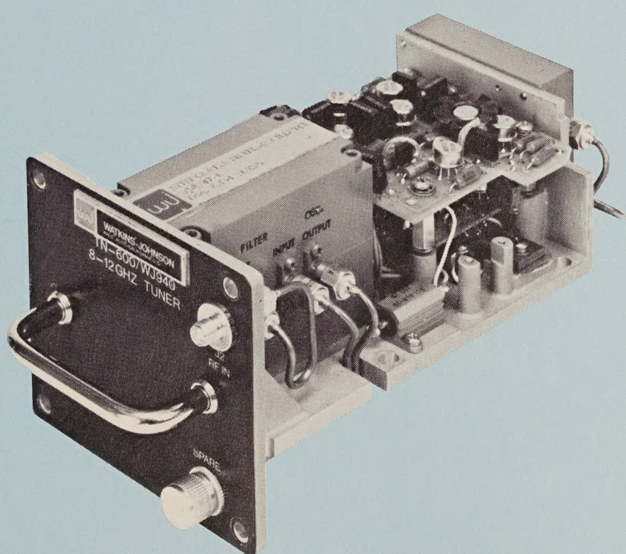


Figure 6. Typical tuner utilizing an integrated filter-oscillator device.

The most serious technical problem in the construction of a YIG integrated front end is the effect of eliminating the isolators between the mixer and preselector and between the mixer and LO. The mixer chosen for design of a W-J S-band integrated front end is the WJ-M26 biasable mixer, which provides a minimum of 15 dB L-to-R isolation. It also provides low RF input VSWR, typically less than 1.5:1 from 2.0 to 3.9 GHz and less than 1.7:1 from 3.9 to 4.0 GHz for an IF frequency of less than 300 MHz. The L-port VSWR was typically 2.0:1. To improve on this VSWR, a 3 dB attenuator was included in thin film on the mixer input port, reducing the effective VSWR to about 1.4:1. The IF amplifiers selected are a WJ-A71 first stage and a WJ-A5 second stage. The A71 is a low noise, high gain amplifier with a 2 dB noise figure, 18 dB typical gain, and -3 dBm output power at 1 dB gain compression. The A5 second stage has about 14 dB gain and a +7 dBm, 1 dB gain compression point.

The first integrated front end that was built was an S-band unit with an RF coverage of 2.0 to 4.0 GHz and a 160 MHz IF frequency. The goal was a 17 dB noise figure and 18 dB RF-to-IF gain.

The preselector and LO outputs attach to a substrate with two 50 ohm lines. The mixer can be replaced with a substrate containing a 50 ohm line which connects, either in the oscillator or the filter, directly to the IF port. This way both YIG devices can be pre-aligned without the mixer. After pre-alignment, the mixer is inserted and the final alignment performed on the mixer RF port and preselector to eliminate VSWR induced ripple. Connecting the IF amplifiers is a relatively straightforward procedure, since the frequency is only 160 MHz.

The electrical performance of the first W-J integrated front end is shown in Figure 7. Noise figure was approximately 0.5 dB better than the design

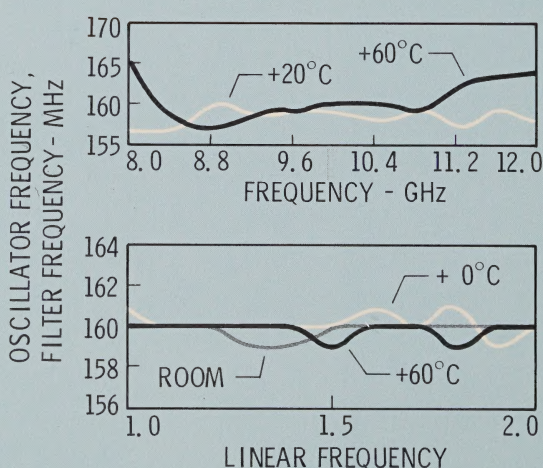


Figure 7. Electrical performance of a W-J YIG-tuned integrated front end.

goal, while gain proved to be about 2 dB better. The effective RF bandwidth was better than 15 MHz. Frequency accuracy was better than ±5 MHz over a 0° to +60° temperature range. The unit is housed in a compact structure approximately 2.6 x 2.6 x 2.0 inches, not including the drivers. YIG-tuned integrated front ends and filter-oscillators appear as shown in Figure 8.

Manufacturing experience has shown that integration of multiple RF devices can improve system performance and reliability, and can be cost effective when produced in sufficient quantities. And, they compare favorably with subassemblies composed of separate components, with the added benefit of smaller size and weight. Supercomponents are especially beneficial to the system designer who may have specific "black box" requirements for a certain subassembly, but hasn't the manpower to realize these requirements in house.

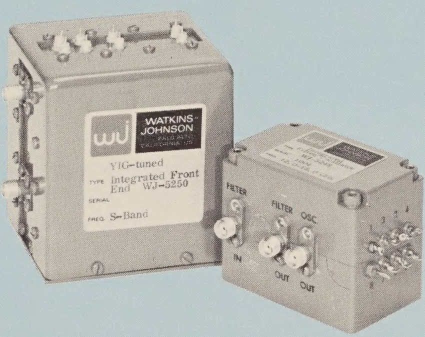


Figure 8. The integration of YIG-tuned front ends and filter-oscillator circuits diminish the overall size of subassemblies.

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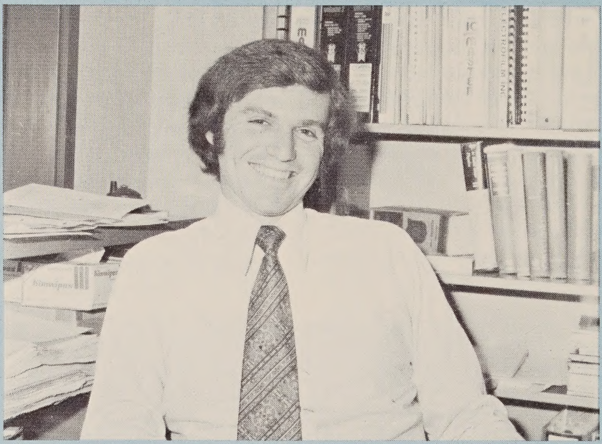
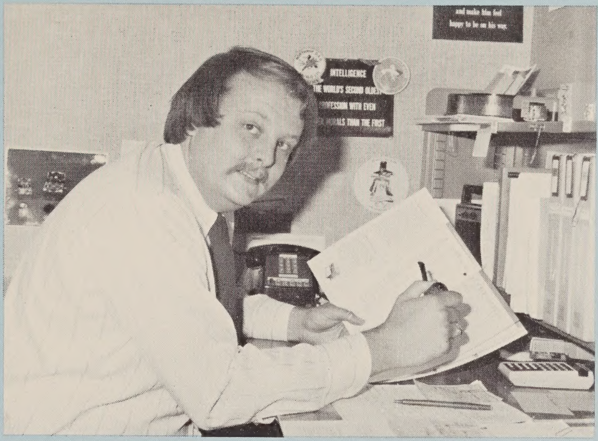


James C. Papp

Dr. Papp is Head of the Watkins-Johnson Company YIG Device Engineering Section. He is responsible for all product development and design of YIG devices, including band-pass and band-reject filters, harmonic generators, and transistor and bulk-effect oscillators. He is also responsible for engineering support for YIG devices being built by the Solid State Division's production department. Since becoming the Head of YIG engineering in August, 1976, the section has developed 2 to 6 GHz, 2 to 8 GHz and high power X-band and 18 to 40 GHz Gunn effect oscillators. In addition, band-reject filters in P through Ku bands have been developed and put into production. YIG driver electronics have been redesigned into thick-film hybrid form, thereby significantly reducing costs. In addition, a closed loop system allowing very accurate tracking of a YIG filter to a reference signal has been developed.

Prior to his assignment as Head, YIG Device Section, Dr. Papp was a Member of the Technical Staff and project Engineer on a program to develop the set of thin film YIG tuned transistor oscillators for the F-15 aircraft. The outgrowth of this program has been the development of a line of high performance thin film oscillators covering 2 to 12 GHz. He has also been in charge of development of integrated tracking filter/oscillators in all frequency bands from 0.5 to 18 GHz, as well as the development and production of a complete integrated front end incorporating filter, oscillator, mixer, and IF amplification. In addition, Dr. Papp has served as assistant program manager during the pilot production phase of the Wild Weasel program, which involved the manufacture of an integrated assembly of oscillators, harmonic generators, microwave amplifiers and mixers used in an aircraft direction finding system, and was also involved in the development of the first 26-40 GHz YIG oscillator.

Dr. Papp holds an A.B. and Ph.D. in physics from the University of California, Berkeley. He is a member of the American Physical Society, IEEE, and Phi Beta Kappa.



Robert "Val" Jackson

Mr. Jackson is an applications engineer for the Watkins-Johnson Company Signal Sources, Solid State Division. As applications engineer for the YIG Devices product line, he has sales and marketing responsibility for the southern portion of the United States.

Formerly, Mr. Jackson was a project engineer with the Scotts Valley Solid State Division, and was engaged in project engineering of ferrite isolators for internal use by the Scotts Valley and Palo Alto Divisions of the Watkins-Johnson Company. His primary assignment was production supervision and incorporation of design changes and manufacturing techniques to meet production schedules. In the isolator programs, Mr. Jackson's responsibilities included design changes, environmental testing, component failure studies, and supervision of personnel within the production group.

During a four-year tour of duty with the U.S. Navy, Mr. Jackson attended both basic and advanced Airborne Electronic Warfare schools, with emphasis in electronic countermeasures. His primary assignment was the operation, modification and maintenance of various airborne electronic warfare systems used on a variety of naval aircraft. Mr. Jackson was responsible for the operational performance and reliability of these systems during a one year tour of duty in Vietnam while assigned to the Naval Air Wing. He received numerous awards and decorations for his performance and support of electronic warfare during his military years.

Mr. Jackson holds a B.S.E.T. from the Oregon Institute of Technology, and is a member of the Association of Old Crows, Electronic Defense Association, IEEE, and Phi Theta Kappa.

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