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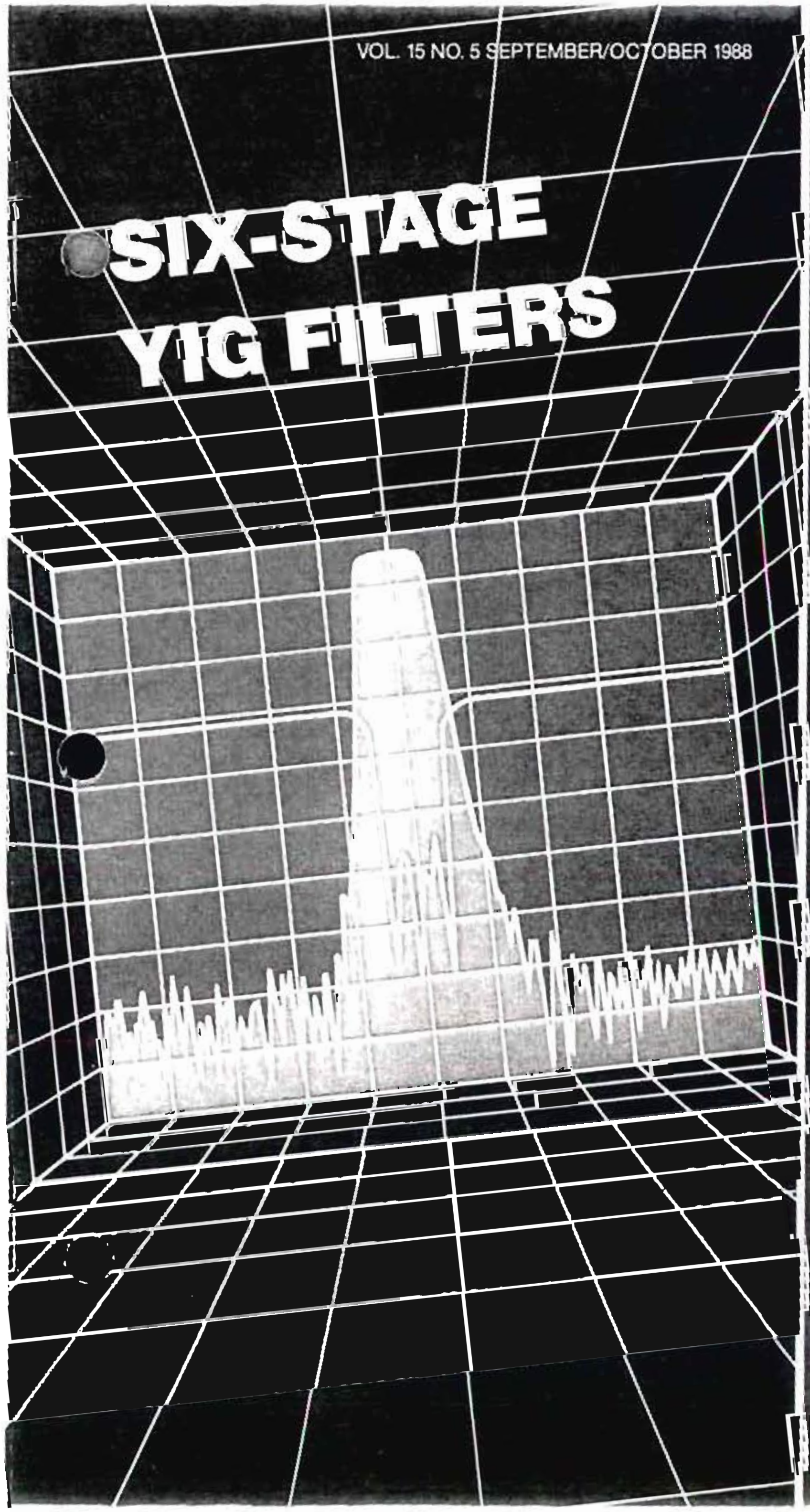
SIX-STAGE YIG FILTERS



WATKINS-JOHNSON COMPANY

Tech-notes

Magnetically tunable YIG (Yttrium Iron Garnet) filters have wide applications as preselectors in microwave recievers and spectrum analyzers. Multipole YIG filters with four or less stages have been the industry standard for twenty-five years. Five or six stage YIG-tuned bandpass filters were once thought to be unrealistic because of problems that besieged the nature of the design. Recent advancements at Watkins-Johnson Company, however, have resulted in the development of six-stage YIG-tuned bandpass filters covering the 500 MHz to 26.5 GHz frequency range (see Table 1). Six-stage YIG filters simplify many problems confronting systems designers by improving performance and providing greater flexibility for the user.

Yttrium iron garnet spheres serve as resonators in a host of magnetically tuned microwave devices such as bandpass and reject filters, oscillators, limiters and discriminators. The high unloaded Q, inherent tuning linearity, broad tuning range, temperature stability, manageable spurious resonse, good frequency tracking and small size make YIG spheres ideal tuning elements for microwave devices. The resonance modes are associated with specific crystallographic orientations of the YIG crystal. The 110 orientation is the fundamental resonance mode; however, weak spurious modes (representing other crystal axes) are unavoidably excited in YIG-tuned filters.

A simple one-stage YIG-tuned bandpass filter and its equivalent circuit are shown in Figure 1. Two coupling loops transfer rf energy into and out of the YIG sphere resonator, one loop connected to a source and the other to a load. The entire arrangement sits in the air gap of an electromagnet. When no static magnetic field is applied to the YIG crystal, the input and output loops are totally decoupled from each other, and there is no power transfer between source and load. In the presence of a steady magnetic field, however, a narrow frequency band of rf energy excites the electrons in the YIG lattice and they, in turn, produce a magnetic field which couples onto the output of the filter. The resonant frequency is related to the applied magnetic field by,

$$F(\text{GHz}) = 28B\ (\text{Tesla}).$$

Model Number[1]	Frequency Range (GHz)	Bandwidth, 3 dB (MHz, Min.)	Insertion Loss (dB, Max.)	Combined Passband Ripple & Spurious (dB, Max.)	Off-Resonance Isolation (dB, Min.)	Off-Resonance Spurious (dB, Min.)
WJ-5906-006[2]	0.5-1	20	8	1.5	90	80
WJ-5906-016	1-2	40	6	2	90	60
WJ-5906[2]	0.5-2	15	8	2	90	80
WJ-5907-006	2-4	40	4.5	1.5	90	80
WJ-5907	2-6	40	4.5	1.5	90	80
WJ-5907-016	2-8	40	4.5	1.5	90	60
WJ-5907-026	4-8	50	4	1.5	90	80
WJ-5908-026	6-12	60	4	1.5	90	80
WJ-5908-036	8-12.4	80	4	1.5	90	80
WJ-5908-046	12-18	100	4	2	90	60
WJ-5908	6-18	100	4	2	90	80
WJ-5908-076[3]	6-18	500	6	2	90	70
WJ-5908-056	8-18	100	4	2	90	80
WJ-5908-066	6-26	60	4.5	2	90	80
WJ-5909	2-18	40	7	2	90	80
WJ-5909-006	2-26.5	30	7	2	90	70

Notes:
1. All models 1.7-inch cube.
Operating temperature range +10 to +60°C
Limiting level +10 dBm on all models.
2. Limiting level +5 dBm.
3. Limiting level > 0 dBm.

Table 1. Six-stage YIG-tuned bandpass filters.

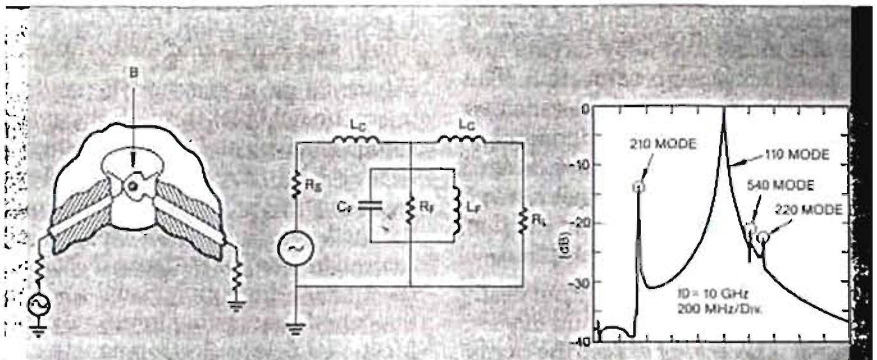


Figure 1. Single-stage YIG-tuned bandpass filter along with a simplified equivalent circuit of main resonance 110 mode. Other resonances (tracking-spurious-responses), not included in the model are also shown. The intrinsic L, C and R values are a function of such parameters as sphere volume, loop geometry, unloaded Q, free-space permeability and saturation magnetization. The resonant frequency is defined as, F(GHz) = 28B (Tesla). Multisection tunable filters are created by cascading sections. L_c is the coupling-loop inductance.

This phenomenon is explained in great detail in technical literature [1,2,3], but the most effective model for understanding its use in filters requires reducing the ferrimagnetic effects of the YIG sphere to an equivalent circuit, as shown in Figure 1. Physical parameters such as sphere volume, loop geometry, free-space permeability, saturation magnetization, and unloaded Q can be used to calculate effective RLC values for use in a filter model. A multistage filter can then be modeled by cascading of the simpler one-stage model.

Obstacles to Multistage Design

Some important components of a YIG filter and rf structure are illustrated in Figure 2. The electromagnet consists of a tuning coil driven by a constant-current driver. The field in the air gap is determined by the total number of turns, the drive current, and the gap length. The pole faces must be exactly parallel to ensure that each spherical YIG resonator sees the same B-field (magnetic field) magnitude. At 18-GHz, for example, a change in gap length of only .0001 inches in a 0.050-inch air gap will cause a 36-MHz frequency shift. Also, if gradients become too large, tracking-spurious-responses (the 210, 540, and 220 modes in Figure 2c) and crossing-spurious-reponse amplitudes can become prohibitive.

Tracking-spurious-responses are weakly-coupled resonances in the form of passbands that remain at a fixed offset from the main (110) resonance. They represent holes in the off-resonance isolation.

Crossing-spurious-responses are resonances in the form of stopbands that tune at a faster rate than the main resonance (110), actually intercepting the filter passband and distorting its shape (see Figure 2c). Any field non-uniformity will affect their amplitude.

The magnet core is typically machined out of a nickel-iron alloy having low hysteresis and high saturation. The tuning linearity of YIG filters is due almost entirely to magnet characteristics. For optimum magnet design, the shortest possible air gap is always desirable because it reduces saturation effects and dc-power consumption.

A short air gap, however, is not desirable from the rf structure point of view, where it is necessary to keep the cavity walls several sphere diameters away from the spheres. RF currents on the cavity walls couple fields back to the resonators, creating spurious responses and shifting the resonant frequency.

The shaded area at the lower pole piece of Figure 2a is a temperature-compensating material with magnetic properties similar to the main core, but with a higher thermal expansion coefficient. It prevents the air gap from changing length as a function of temperature.

Figure 2d is a computer-generated magnetic-field plot through the cross section of a typical electromagnet used to tune YIG filters. Notice the flux-crowding in the corners throughout the shell, pinpointing possible areas of saturation. The flux patterns, including the leakage flux, give visual insight into what's happening in the magnet. Most YIG-device electromagnets are configured to have the outside wall serve both as a B-field return path and as a high-permeability shield (similar to the metal case of an antimagnetic watch) that prevents external magnetic fields (from power-supply transformers, for example) from coupling into the air gap, causing the YIG resonant frequency to shift.

The tuning-coil inductance, along with induced currents in the core (eddy currents), limit the rate at which the filter can be set to a new frequency. When the B-field changes state, the induced counter-emf$(-V_i)$ sets up circulating currents in the magnet. The direction of these currents is opposite that of the main coil current. The same is true for the magnetic field that results (see Figure 2a). When the opposing field decays to zero, the main tuning-field magnitude and the resulting filter passband frequency will have reached their final value. The rate of eddy-current decay depends on core and circuit-block conductivity and geometry. Pole-piece diameters must be kept to a minimum, while still ensuring field uniformity over the YIG spheres. Larger diameters mean higher induced currents when tuning the electromagnet.

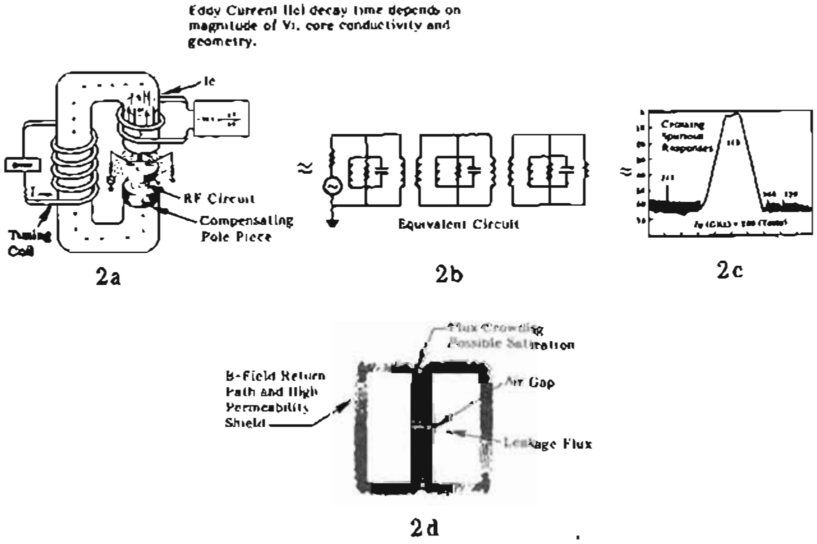


Figure 2. Simplified concept of a three-stage YIG-tuned bandpass filter showing the electromagnet, the rf structure and its equivalent circuit, and the filter's frequency response. Also shown is a computer-generated plot of magnetic-flux distribution throughout the cross-section of an electromagnet of the type typically used to tune YIG filters.

Six-Stage YIG-Tuned Bandpass Development

A great deal of trial-and-error has been applied to six-stage filter development. However, the development of a YIG-filter computer model complimented the empirical appraoch. With this model, it is possible to "tweak" each coupling loop and sphere independently, and tune the filter over a desired frequency range for a quick look at passband shape at any frequency (see Figure 3). The model allows the cascading of many filter sections. The actual rf alignment of YIG filters in a production environment requires the combination of knowledgeable, skilled individuals and methodical production processes.

Traditional filter alignment techniques such as measuring end-resonator band-

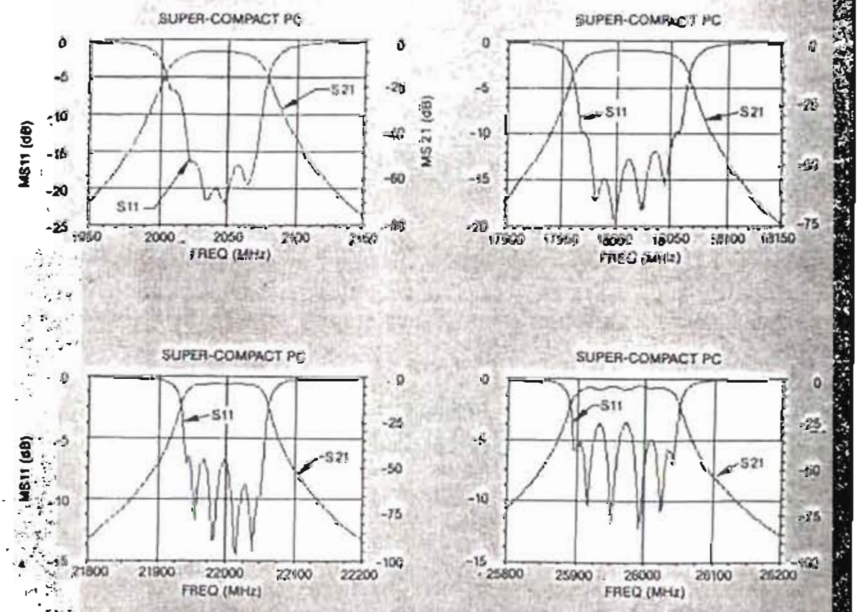


Figure 3. Computer-generated frequency-response curves showing return loss (S11) and insertion loss (S21) characteristics of a six-stage YIG-tuned bandpass filter. The bandwidth growth and varying bandpass shape is largely due to the changing electrical length of the coupling loops over frequency.

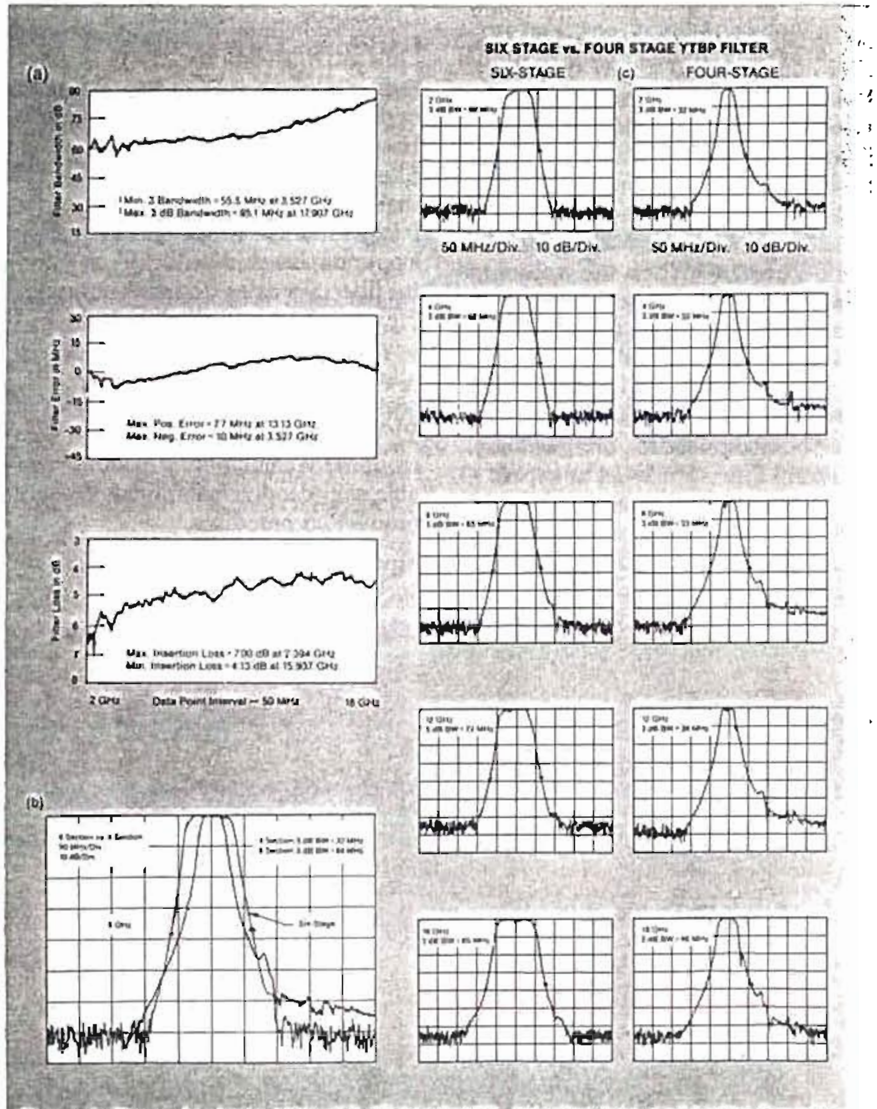


Figure 4. Figure 4a shows plots of 3-dB bandwidth, insertion loss, and tuning linearity taken at 50-MHz steps. The incremental variations in loss and bandwidth seen towards the low end of the tuning range result from crossing-spurious-responses tuning through the passband. The minimum bandwidth and maximum insertion loss often occur at frequencies where the filter passband and crossing-spurious-responses intercept.

Figure 4b. In this four- and six-stage overlap plot, the six-stage filter has approximately twice the 3-dB bandwidth of its four-stage counterpart, but considerably less 70-dB bandwidth.

Figure 4c. Comparison of six-stage and four-stage YIG-tuned bandpass filter frequency responses as the filters tune over the 2-18 GHz frequency range. The filters have equivalent 50-dB bandwidth. Note the greater 3-dB bandwidth of six-stage filters.

widths and interstage coupling coefficients can be applied; however, the filter will likely have maximum flatness at the low end of the tuning range and have ripple at the high end.

After the basic passband shape is achieved, there is still the problem of dealing with crossing-spurious-responses, temperature-induced detuning, bandwidth growth, and other problems that become more complicated as more resonators are added. In the six-stage design, more pole-piece area is required. Spheres in some models are separated by as much as 0.600 inches or as little as .040 inches.

Achieving uniformity of the magnetic field at the location of the YIG spheres is a high priority in the design and production of six-stage bandpass filters. In the past, design engineers have used a tiny YIG sphere attached to a miniature coaxial line as a precise magnetic probe to map the magnetic field in the air gap. A micrometer-driven x-y carriage was used to adjust the position of the probe within the magnetic circuit. This cumbersome, time-consuming technique has been replaced by computer modelling programs which calculate and display local field gradients as well as warn the engineer of the onset of saturation of the magnetic circuit. The greater number of spheres and the increase in the pole-face area of six-stage YIG filters require magnetic-shell geometries and machining processes that are specifically selected to provide uniformly flat, smooth, parallel surfaces, to precise tolerances.

Six-stage filters offer many benefits to the system designer. In all cases, the steeper skirt selectivity of 36-dB/octave versus the 24-dB/octave of a four-stage filter is a definite advantage. In cases where the filter bandwidth is constrained by the image-rejection specification, the impact of filter selectivity is considerable. For example, Figure 4 compares a six-stage filter that has twice the 3-dB bandwidth of its four-stage counterpart. Notice that the six-stage 75-dB bandwidth is less than the four-stage 75-dB bandwidth. The steeper selectivity allows larger effective 3-dB bandwidths, which can minimize several system concerns. Problems associated with local oscillator mistracking, non-linearities, post-tuning drift, temperature drift, hysteresis, and dynamic tracking become more manageable, and do not require the use of expensive electronic correction circuitry.

In reciever applications, where local-oscillator radiation back through the rf filter can broadcast the receiver's position to other listening devices, a six-stage filter in the front end will significantly improve the attenuation of such unwanted signals. The amount of rf leakage through a YIG passband filter circuit is largely a function of the number of stages. Additional stages provide better isolation. The off-resonance isolation of all six-stage models is approximately 40 dB greater than that of four-stage devices and is considerably better than 100 dB.

Tracking-spurious-response attenuation is a function of coupling-loop geometry, resonator material, overall filter bandwidth and the number of sections in the filter. Increasing the number of resonators will have the greatest effect. All six-stage models in Table 1 have >80-dB tracking-spurious-response suppression. In some models, a slightly higher dissipation loss and optimized coupling results in <2:1 vswr within the 3-dB bandwidth points over the entire tuning range (see Figure 5).

The development of the six-stage bandpass filter has advanced the state-of-the-art of YIG-filter technology. The list of improved parameters is extensive, and includes improved matching cap-

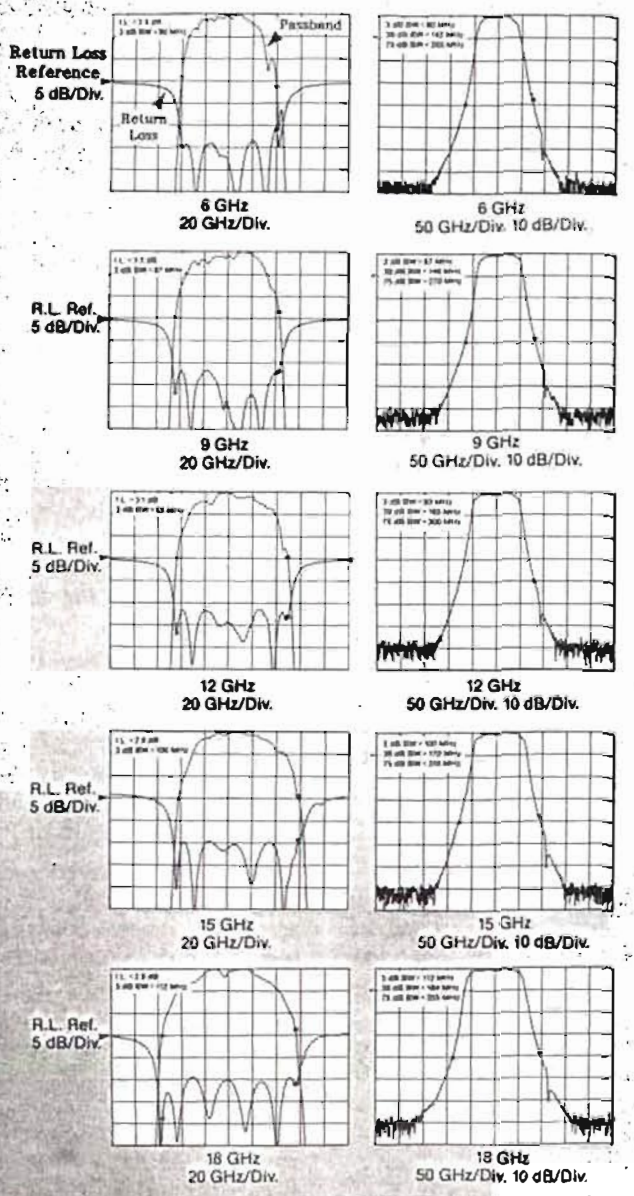


Figure 5. Plots of the frequency response of a WJ-5908-020 as it tunes over 6-18 GHz. The slightly higher dissipation loss and steeper response within the 3-dB bandwidth make it possible to achieve less than 2:1 vswr over its entire 3-dB bandwidth at all frequencies. The passband shown on the left, plotted at 1-dB/division, changes shape and the bandwidth grows as the filter is tuned towards the high end of its frequency range. This is the result of the changing electrical length of the interstage coupling loops and of the small crossing-spurious-responses that can be seen tuning through the passband.

ability, wider bandwidth, better spurious-response rejection, improved off-resonance isolation, and increased skirt selectivity. The six-stage filter promises systems designers, as well as users, increased design margin and better overall system performance.

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Mr. Korber designed and produced the industry's first eight-stage YIG-tuned band-reject filters and, more recently, the first six and seven stage YIG-tuned bandpass filters covering the 500 MHz to 26 GHz region. He is presently working on the development of a seven-section 2-40 GHZ YIG-tuned filter.

Mr. Korber immigrated from the Netherlands in 1954, served four years in the U.S. Navy, is a graduate of U.S. Navy Radar School and of Philco-Ford Technical School.