# A Ferrimagnetically-Tuned Parametric Amplifier

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*Abstract*—**A parametric amplifier can normally be tuned only over relatively restricted frequency ranges. One of the basic reasons for this tuning difficulty is that more than one frequency range is of importance for, in addition to the signal frequency, a pump frequency and one or more sum or difference frequencies must be considered. In this paper a tunable negative-resistance parametric amplifier is described which uses ferrimagnetically-tuned signal and idler circuits, together with a fixed-frequency pump source.**

**This amplifier is unique in two respects. One is that the amplifier is electrically tuned through the use of yttrium iron garnet (YIG) resonators. Secondly, useful low-noise performance has been achieved over a tuning range of almost one octave. This amplifier thus successfully demonstrates that the technique of magnetic tuning with YIG resonators can be applied to a device as complex as a parametric amplifier in much the same manner as it has been applied in the past to microwave band-pass and band-stop filters.**

## Introduction

A PARAMETRIC AMPLIFIER can normally be tuned only over relatively restricted frequency ranges. One of the basic reasons for this tuning difficulty is that several frequencies are of importance: In addition to the signal frequency, a pump frequency and one or more sum or difference frequencies must be considered [1], [2]. If significant power flow occurs only at the signal and difference frequencies, an equivalent negative resistance is created at the signal and difference frequencies. When this condition is realized it is possible to construct an amplifier by circulator-coupling the signal circuit, or to construct a frequency converter with gain by taking the output at the difference frequency. If significant power flow occurs only at the signal frequency and sum frequency, a positive resistance is introduced at the signal frequency, but power gain is possible by taking an output at the sum frequency. This device is commonly termed an up-converter.

In the construction of an electrically-tunable parametric amplifier, a variety of approaches can be used:

1) Use a fixed-tuned broadband signal circuit, an electrically-tunable pump source, and a fixed-tuned difference or sum frequency circuit.
2) Use a fixed-tuned broadband signal circuit, a fixed-tuned pump source, and an electrically-tunable difference or sum frequency circuit.
3) Use an electrically-tunable signal circuit, a fixed-tuned pump source, and an electrically-tunable difference or sum frequency circuit.

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The first approach has the advantage of requiring no electrically-tunable circuits, but only a tunable pump source. A tunable pump source, however, is necessarily more complex than a fixed-tuned source, and uniform pumping of the nonlinear reactance (here assumed to be a semiconductor diode) over a wide range of pump frequencies is much more difficult than with a fixed-frequency pump. This latter factor is of considerable concern for the case of the negative-resistance parametric amplifier where small changes in diode pumping can result in large changes in amplifier gain.

The second approach has the advantage of a fixed-tuned pump, and is probably the simplest approach to the construction of an electrically-tunable parametric amplifier. The tuning range, however, is necessarily limited by the bandwidth of a fixed-tuned signal circuit. For many applications this approach may yield adequate tuning ranges, particularly if multiple-tuned signal circuits are used.

The third approach is perhaps the most difficult one, requiring simultaneous tuning and tracking of two resonant circuits. Nonetheless, this method has the potential of a very wide tuning range, since its tuning is not dependent upon a fixed-tuned circuit resonance.

In this paper a tunable parametric amplifier using the last of these approaches is described. This amplifier is unique in two respects. One is that the amplifier is electrically tuned through the use of yttrium iron garnet (YIG) resonators [3], [4]. Secondly, useful low-noise performance has been achieved over a tuning range of almost one octave. This amplifier thus successfully demonstrates that the technique of magnetic tuning with YIG resonators can be applied to a device as complex as a parametric amplifier in much the same manner as it has been applied in the past to microwave band-pass and band-stop filters.

## Design Considerations

The amplifier configuration used in this study is thus of the negative-resistance, nondegenerate type, using a varactor diode for the nonlinear reactance [1], [2]. In many respects the amplifier is of conventional design. The signal circuit operates in S-band with a fixed-tuned pump at 17 Gc/s. Two YIG resonators are coupled to the diode to form the tunable resonant circuits at the signal frequency and the idler frequency. Separate magnetic bias circuits are used to tune the signal and idler resonators with proper tracking of the two achieved electronically by means of the associated tuning control circuitry.

A schematic representation of the amplifier is shown in Fig. 1. The signal and idler circuits are of coaxial construction. Between the signal input and the varactor is a conventional low-pass filter structure which is cut off at the pump and idler frequencies. On the opposite side of the varactor, a length of shorted coaxial line is used to couple to two appropriately placed YIG resonators, one for the signal circuit and one for the idler circuit. Pump power is coupled to the diode through a simple single-tuned waveguide bandpass filter.

There are two major design considerations involved in the placement of the YIG resonators: the position of the resonators with respect to the varactor, and the degree of coupling of the resonators to the varactor. These parameters can be best understood by considering the equivalent circuit of a YIG resonator coupled to a TEM mode transmission line. Such an equivalent circuit is shown in Fig. 2 [5]–[7]. On the basis of this equivalent circuit, it can be determined that the proper spacing of the signal circuit YIG resonator is at the end of a shorted transmission line, approximately a quarter wavelength from the varactor. Under this condition the equivalent circuit of the varactor and the YIG resonator at the signal frequency is as shown in Fig. 3. The resonant frequency is given by:

$$\omega = \left(\frac{C_0 C_m L_m}{C_0 + C_m}\right)^{-1/2} \approx (C_m L_m)^{-1/2} \quad \text{when } C_m \ll C_0. \quad (1)$$

We thus see that the resonant frequency of the signal circuit is completely determined by the YIG resonator if sufficient coupling of the YIG resonator is achieved so that the condition $C_m \ll C_0$ is satisfied.

A further condition on YIG resonator coupling is obtained by considering the effect of YIG resonator loss. In order that YIG resonator loss not degrade amplifier performance, we require that

$$R_m \ll R_s. \quad (2)$$

Relating diode loss to cutoff frequency $f_c$ and YIG resonator loss to the unloaded $Q$ of the resonator, we have

$$R_m = \frac{1}{2\pi f C_m Q_{\text{YIG}}}$$
$$R_s = \frac{1}{2\pi f_c C_0}. \quad (3)$$

Therefore

$$\frac{R_m}{R_s} = \frac{f_c}{f}\frac{C_0}{C_m}\frac{1}{Q_{\text{YIG}}} \ll 1. \quad (4)$$

For proper operation of the amplifier, the following conditions must therefore be satisfied:

$$1 \ll \frac{C_0}{C_m} \ll \frac{f}{f_c} Q_{\text{YIG}}. \quad (5)$$

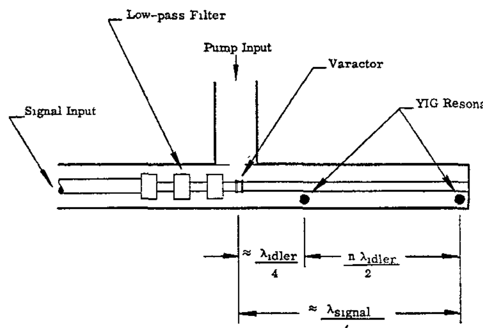


Fig. 1. Schematic representation of the parametric amplifier.

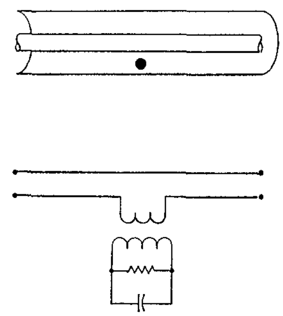

Fig. 2. Equivalent circuit of a YIG resonator coupled to a TEM mode transmission line.

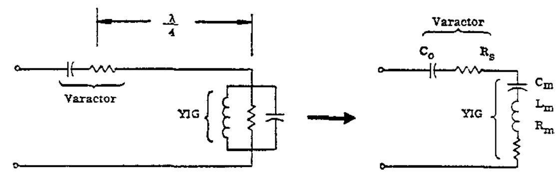


Fig. 3. Equivalent circuit of the varactor-YIG combination.

At S-band, typical values would be

$$f = 3 \text{ Gc/s}$$
$$f_c = 100 \text{ Gc/s}$$
$$Q_{\text{YIG}} = 2500.$$

Therefore

$$\frac{f}{f_c} Q_{\text{YIG}} \approx 75$$

which is sufficiently large to satisfy Equation (5).

The idler circuit is of almost identical configuration. Again a quarter-wavelength spacing between varactor and YIG resonator is used. In this case, it is not possible to have a short circuit in the coaxial line immediately after the resonator. Proper operation can be achieved, however, if the distance between the YIG resonator and the shorted line is approximately an integral number of half-wavelengths at the idler frequency. The position of the low-pass filter is also of concern so as to effectively short the input line at the correct location.

The design considerations involved in the choice of pump frequency, diode characteristics, signal circuit input impedance, etc., are the same as for a conventional parametric amplifier and hence will not be treated here.

## Amplifier Construction

The experimental parametric amplifier is shown in Fig. 4. A conventional coaxial three-port circulator with an operating range of 2 Gc/s to 4 Gc/s is used at the input of the amplifier. Following the circulator is a four-section coaxial low-pass filter of 50 ohms characteristic impedance and a design cutoff frequency of 9 Gc/s. Immediately following the low-pass filter is the varactor diode; a diffused junction silicon diode with the following characteristics:

Junction Capacitance = 0.4 pf at −4 v
Total Capacitance = 0.64 pf at −4 v
Cutoff Frequency = 200 Gc/s at −4 v.

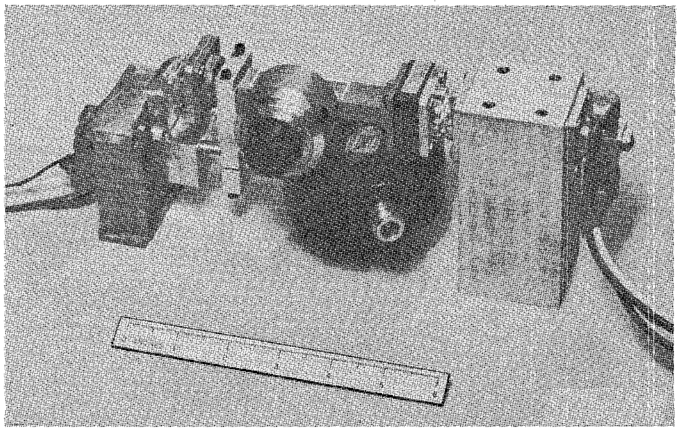

Fig. 4. Experimental parametric amplifier.

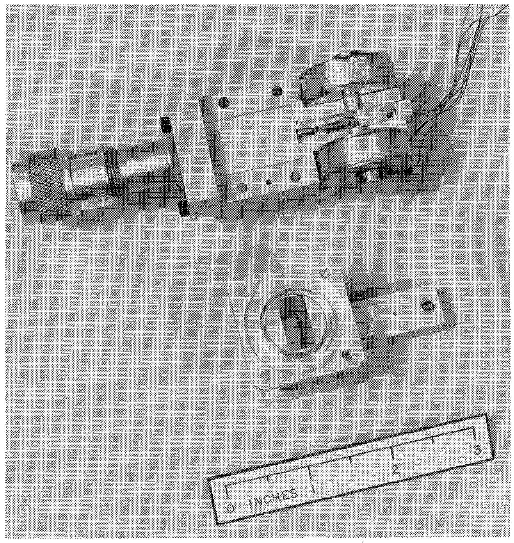

Fig. 5. Disassembled view of the parametric amplifier.

The interior of the amplifier, as depicted in Fig. 5, shows the region subsequent to the varactor which contains the two YIG resonators. The YIG resonator nearer the varactor is the idler resonator, while the signal circuit resonator is the YIG sphere contained within the coupling loop. Pump energy from the 17 Gc/s klystron is coupled into the varactor through a single-tuned band-pass cavity of 150 Mc/s bandwidth centered at 17 Gc/s built into the cover plate of the amplifier. Sufficient isolation of the idler frequency is insured by constructing the pump cavity of waveguide which is cut off at 16 Gc/s, and by preceding the band-pass filter by a length of waveguide which is also cut off at 16 Gc/s.

One practical problem associated with this approach to a tunable parametric amplifier is how to supply two relatively independent but controllable magnetic fields which are physically in close proximity. The relationship between the applied magnetic field and the resonant frequency of the YIG resonators is to a good approximation given by

$$f = 2.8B$$

where $f$ is in Mc/s and $B$ is in gauss. Thus a field of about a kilogauss is required for the signal circuit resonator, and a field of about 5 kilogauss is required for the idler resonator. Furthermore, when the signal circuit's magnetic field is increased, the idler circuit's magnetic field must be decreased, since a fixed pump frequency is used.

It was possible to adequately satisfy these requirements in the limited space available by making the two magnetic circuits orthogonal. Permanent magnets were used to establish the magnetic field required for mid-band operation, and tuning coils were used to change the field about those values.

The performance characteristics sought for in this amplifier were low-noise performance (2.5 dB) at high gain (about 20 dB) over a large tuning range (about one Gc/s) without adjustment of the pump. Tuning was to be accomplished electrically by means of a single control signal. These objectives imposed stringent requirements on the entire RF structure. Not only did adequate coupling have to be achieved between varactor and YIG resonator, but also a high degree of uniformity in coupling had to be achieved over a large range in frequency. Such uniformity was required, because at high gain small variations in coupling will result in large variations in gain. Furthermore, all circuit resonances not associated with the YIG resonators had to be removed from the signal and idler circuits. Such fixed-tuned resonances would limit tuning range by the introduction of pronounced tuning nonlinearity and gain variation (or oscillation).

An additional important consideration introduced by the use of YIG resonators is the excitation of "higher-order" magnetostatic modes [4]. Such "higher-order" modes are present in all ferrimagnetic resonators and are characterized by nonuniform distributions of magnetization within the ferrimagnetic sample. These higher modes can become degenerate in frequency with the principal mode, causing coupling irregularities and corresponding gain irregularities. It is therefore important that the coupling structures used minimize the excitation of these distorting modes.

Starting with the basic RF configuration shown sketched in Fig. 1, a practical circuit was obtained experimentally which adequately satisfied the major re-

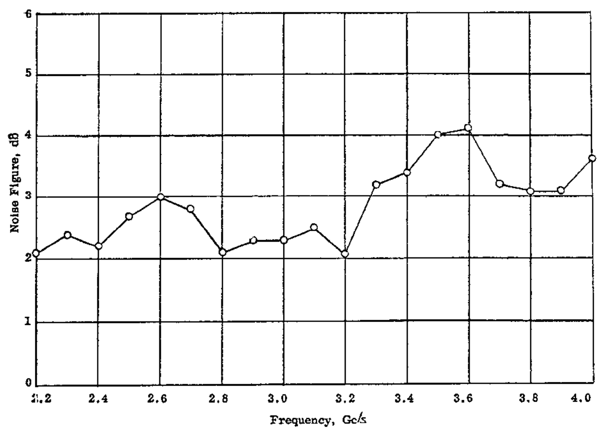


Fig. 6. Noise figure performance of the ferrimagnetically-tuned parametric amplifier, including contribution of 9 dB noise figure second stage. Optimized tuning, with pump level adjusted to give 25 dB gain.

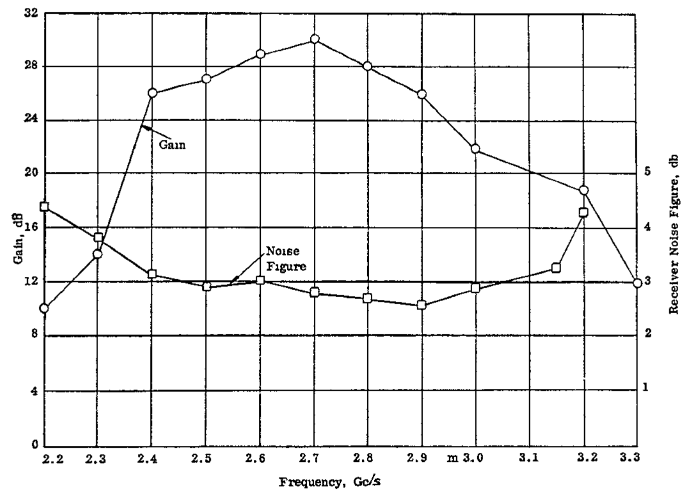


Fig. 7. Gain and noise figure performance of the ferrimagnetically-tuned parametric amplifier. "Single-knob" tuning, fixed pump level, 14 dB noise figure second stage.

quirements outlined earlier. Coupling to the signal circuit resonator was effected by means of a $1\frac{1}{2}$ turn loop. Through the use of such a loop it was possible to achieve tight coupling to the YIG sphere while at the same time minimizing the excitation of magnetostatic modes. The idler sphere was placed between the RF center conductor and ground plane, centered in a radial depression in the center conductor. Again, with this configuration it was possible to achieve adequate coupling to the YIG resonator without exciting magnetostatic modes.

It was not possible to eliminate completely a passive circuit resonance in the idler circuit. This resonance, which is believed to be a diode resonance, caused both gain variation and tuning nonlinearity.

## Test Results

The completed parametric amplifier was tested in two modes of operation. In the first mode, adjustments were made at each frequency checked to optimize amplifier performance. Independent tuning of signal and idler circuits was used to eliminate tracking error, and adjustment of pump power was made to maintain 25 dB gain except when a lower noise figure could be obtained at a lower value of gain. A conventional single-ended mixer was used as the second stage with a nominal noise figure of 9 dB and IF frequency of 30 Mc/s. The resulting noise figure measurements are plotted in Fig. 6. The instantaneous bandwidth varied between 8 Mc/s and 17 Mc/s.

These results indicate that the best performance was obtained over the frequency range 2.2 Gc/s to 3.3 Gc/s, with useful performance extending to 4 Gc/s. Thus it was possible to achieve operation over almost an octave in frequency.

In the second mode of operation, "single-knob" tuning was employed with no adjustment of pump power. The second stage in this case was a receiver with a nominal noise figure of 14 dB and an IF frequency of 160 Mc/s. In this mode of operation satisfactory performance was achieved over the tuning range of 2.2 Gc/s to 3.3 Gc/s. Gain and noise figure for this mode are plotted in Fig. 7. The overall receiver noise figure was higher in this case because of the higher second stage noise figure and because of the fall-off of gain at the ends of the tuning range. A decrease in bandwidth to 5 Mc/s at the low end of the tuning range occurred as a result of tracking error from imperfect compensation of idler circuit tuning nonlinearity.

## Conclusion

The principal result of this study has been the demonstration of the usefulness of YIG resonator tuning techniques in the construction of low-noise parametric amplifiers. Such devices are capable of electrical tuning over wide frequency ranges without significant degradation of noise performance. These techniques should be useful at frequencies above approximately 2 Gc/s, when adequate values of YIG resonator $Q$ relative to varactor $Q$ can be achieved.

## Acknowledgment

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