AN INVESTIGATION OF JUNCTION DIODE PARAMETRIC AMPLIFIERS AT MEDIUM RADIO FREQUENCIES

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PREFACE

The Parametric Amplifier is presently one of the most widely discussed devices in the field of electronics. It has the capability of amplifying radio-frequency power with circuitry that is remarkably simple and economical compared to vacuum tube amplifiers. The theory and basic principles underlying their operation have been reported at least one hundred years ago. The relatively recent development of semiconductor junction diodes has provided the means for useful application of parametric phenomena. With the exception of digital computer applications, the majority of the reported experimental results have been in the region between approximately one hundred megacycles and ten kilomegacycles.

After a rather intensive perusal of practically all the available literature on parametric amplifiers, I decided that an interesting and useful study would be the investigation of the heretofore neglected medium radio-frequency portion of the spectrum. To the best of my knowledge, parametrically amplified reception of the standard broadcast band has not been disclosed previously.

The circuits, techniques, and observations reported in this thesis will, I hope, fill a portion of the apparent gap in the application of these amplifiers.

I am indebted to the United States Air Force for making this study possible. Indebtedness is also gratefully acknowledged to Professor

L. S. Pedrotti of the Physics Department, Institute of Technology, United States Air Force, who, in 1953, inspired my interest in much of the theory involved in this study.

I express my sincere thanks to Professor P. A. McCollum, my adviser, for his helpful criticisms and many valuable suggestions. My thanks are also due to Dr. H. T. Fristoe, my secondary adviser, for his keen interest in the subject and for the loan of some diodes manufactured by Texas Instruments Inc.

Appreciation is expressed to the following firms for their generosity in furnishing samples of their diodes: Continental Device Corporation, 12911 Cerise Avenue, Hawthorne, California; Microwave Associates, Inc., Burlington, Mass.; Pacific Semiconductors, Inc., 10451 West Jefferson Blvd., Culver City, California

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CHAPTER I

INTRODUCTION

A Semiconductor Junction Diode Parametric Amplifier may be described as an electronic device which uses the non-linear parameters of a diode junction to amplify radio-frequency power. Regardless of the particular application, if the desired output exceeds the input, the device may be thought of as an amplifier. In specific circuit configurations, it may be used as an essentially single-frequency amplifier, frequency converter, or sub-harmonic and harmonic generator.

There are many physical analogues of the simplest form of the electronic parametric amplifier. Among them are included a child's playground swing and a flexible footbridge. In the case of the playground swing, a child "pumps" energy to the swing system at the proper time to cause the amplitude of the swing to build. In the footbridge example, the unwritten regulation that soldiers break step while crossing a bridge is based on the prevention of a disastrous collapse that is possible if the amplitudes of bridge oscillation are permitted to build.

Historical Background

The basic theory and analysis of parametric amplifiers is not by any means a recent development. There have been many contributions, however, the work of R. V. L. Hartley (1936) is considered most applicable to the semiconductor diode type of parametric amplifier. Hartley analyzed an electromechanical system in which one plate of a capacitor was elastically supported so as to form a mechanically resonant system. The electrical portion of the system was a simple resonant circuit. His analysis shows that sustained oscillation is possible when proper frequencies and impedances are present in the system.

Manley and Rowe (1956) extend the theory to include non-linear elements in general. The only assumption in their analysis is that the non-linear element has a single-valued characteristic. Rowe (1958) analyzed the small-signal theory and concluded that the amount of non-linearity of the element used determines the bandwidth.

Although this thesis does not concern itself with sub-harmonic generation specifically, the following historical background is significant and is included for the sake of completeness.

McLachlan (1947) indicates on page 2 that the earliest recorded rigorous analysis of a type of parametric amplification is the now classical experiment of F. Melde. In 1859, Melde described the oscillation of a string which was excited by a tuning fork. He noted that under proper conditions the string would oscillate once for every two cycles of tuning fork oscillation. Lord Rayleigh (1894) described sub-harmonic oscillation in connection with Melde's experiment. Ludeke (1953) reports the experimental results of sub-harmonic generation in mechanical systems with orders as high as the 1/9th sub-harmonic.

Probably one of the greatest potentials of sub-harmonic generating parametric amplifiers is the application to the digital computer field. Wigington (1959) has analyzed the patent application of the late Professor J. von Neumann. Professor von Neumann suggested the non-linear capacitance of a semiconductor junction as the non-linear element of a phase-locked oscillator. Goto (1959) gives a description of the Parametron, a digital-computer component, which uses periodically varying inductance as the non-linear element in an operational computer. Leenov and Uhlir (1959) conclude that the non-linear capacitor is superior to the non-linear resistor in the generation of harmonics. Leeson and Weinreb (1959) have analyzed harmonic generator circuits very similar to the experimental circuits described in Chapter IV of this thesis.

Chapter II of this thesis covers the depletion-layer capacitance of a PN junction diode in a simplified form. An equivalent circuit of the junction is shown and an expression for the junction capacitance is developed. The linearization of the depletion-layer capacitance in Chapter II serves as the basis for the theory of the lossless Parametric Amplifier developed in Chapter III. Rather than building and analyzing one specific circuit based on the theoretical model and then comparing the two, a decision was made to conduct a more general investigation of several different circuit configurations. This choice, although probably much more time consuming, yielded a better overall understanding of the parametric amplifier.

Chapter IV shows several experimental circuits and the techniques used during the experiments. Although medium radio frequencies were used in the experiments, the theory and circuitry are applicable to any frequency range in general. During the course of this investigation, numerous application possibilities came to mind. The reception of the standard broadcast band stations was first experienced by the author on 19 July 1959 during some preliminary experiments. The reception of intelligence with the aid of parametric amplifiers in the general frequency range used in this thesis has not been reported previously. Although no noise measurements were made, a qualitative comparison of the reception of a particular station with and without the experimental amplifying converter showed a noticeable reduction in noise background with the amplifier operating. It was also observed that some stations could be received with the amplifier operating while only background noise was present without the amplifier, at the same frequency. Quantitative gain measurements show amplification to within approximately 2 db of the predicted theoretical values at selected frequencies. It appears to the author that the parametric-amplifying converter has practical applications in the medium radio-frequency portion of the spectrum. Particularly attractive features include simplicity, economy, and reliability.

CHAPTER II

SEMICONDUCTOR JUNCTION CAPACITANCE

PN Junctions

The theory of semiconductor junction capacitance has been presented by Torrey and Whitmer (1948), Shockley (1949), and later by Uhlir (1956, 1958).

Two of the most widely used semiconductor materials are Germanium (Ge) and Silicon (Si). At ordinary room temperatures, pure Ge and Si are poor electrical conductors. It is a well known fact that the conductivity of a material may be increased with the addition of energy; by increasing the temperature or applying an external field for example. Another mechanism used to increase conductivity in semiconductors is the addition of closely-controlled amounts of certain impurities. These impurities may be added during the crystal growth process.

If a trace of Arsenic (As), or some other pentavalent element, is added to pure tetravalent Silicon, an excess of electrons is available for conduction. This type material is designated "N" (negative) type. On the other hand, if Boron (B), or some other trivalent element, is added to the pure Silicon, an effective deficiency of conduction electrons results. This material is designated "P" (positive) and conduction is by holes. Fig. 1 shows a sample of P material joined with a sample of

N material and the resulting junction formed between the two. The movement of holes and excess electrons, in the absence of any applied external fields, is called diffusion and is due to thermal energy. In the junctions illustrated later, a plus sign indicates a hole and a minus sign indicates an excess electron.

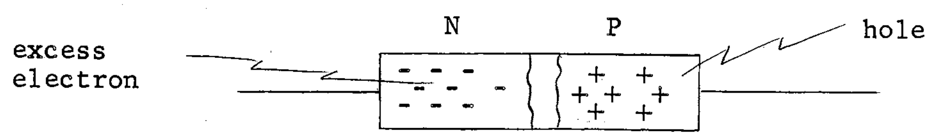


Fig. 1. Simple PN Junction.

In the immediate vicinity of the junction, diffusion continues until the Fermi levels are aligned and equilibrium is attained. This neutral region is called the depletion layer. In other words, there is a depletion of holes and a depletion of excess electrons in this region. The electric field in the layer is referred to as a barrier. The potential difference between the sides of the depletion layer is called the barrier height or contact potential and is measured in volts.

With the depletion layer free of holes and excess electrons, it may be thought of as an effective dielectric. The sides of the depletion layer may be considered as two plates of a parallel-plate capacitor. The usual definition of capacitance is the ratio of the charge on one conductor to the potential difference between them. Quantitative values of the depletion-layer capacitance depend on specific values of the relative permittivity and geometry of the layer.

When an external field is applied to a PN junction, as is indicated in Fig. 2, a condition of forward bias exists. The holes and excess

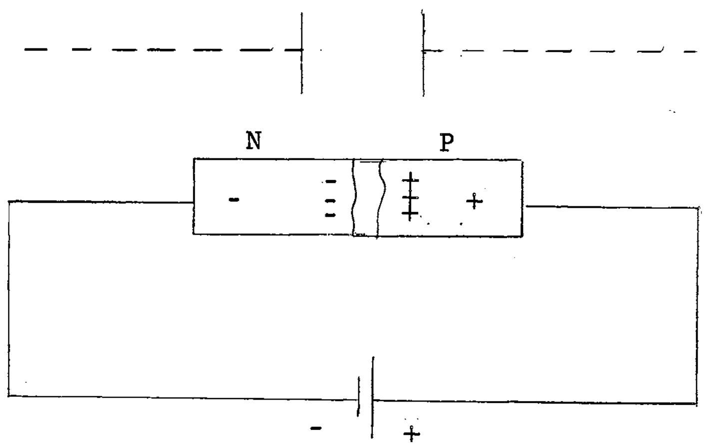


Fig. 2. Forward-Biased PN Junction.

electrons are repelled toward the junction. The depletion-layer capacitance is effectively increased. Current flows in the external circuit. If excess forward bias is used, excessive current will cause increased thermal agitation and eventual breakdown of the crystal structure.

When an opposite external field is applied, as is shown in Fig. 3, the condition of reverse bias exists.

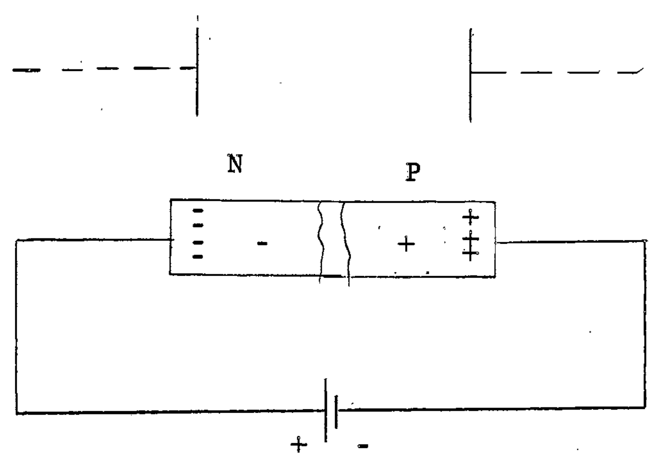


Fig. 3. Reverse-Biased PN Junction.

The holes and excess electrons are repelled away from the junction. The depletion-layer capacitance is decreased. Current in the micro-ampere range flows in the external circuit because of leakage and finite resistance of the material. Excessively high external fields cause breakdown of the crystal structure.

With the application of a periodic external field and reverse bias simultaneously, as indicated in Fig. 4, the depletion-layer capacitance also varies periodically.

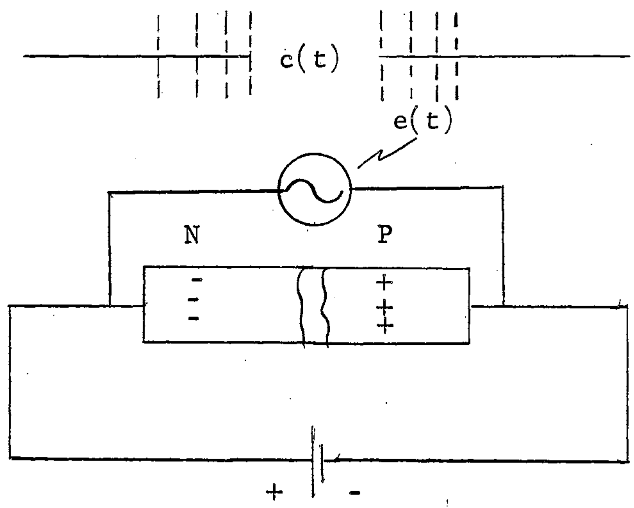


Fig. 4. PN Junction with Periodic External Field and Reverse Bias.

The reverse bias establishes the operating point or steady value about which the periodic portion varies. This action is analagous to physically pulling apart the plates of a two-plate capacitor. The energy required for the separation is supplied by the generator e(t).
The application of a periodic voltage larger in the magnitude than the bias may cause heavy conduction in the forward direction. This depends on the respective magnitudes of the bias and periodic voltage. Likewise, if the diode is reverse biased near the breakdown voltage point, periodic breakdown may occur with large periodic voltages. When a time-

varying capacitance effect is desired, as in a parametric amplifier, the magnitudes of reverse bias and periodic voltage should be adjusted so that neither conduction nor breakdown occur. The time-varying capacitance of the diode, as depicted in Fig. 4, is the electrical equivalent of the mechanical time-varying capacitance of Hartley (1936). The characteristics of a junction diode have been examined extensively. The charge and capacitance vs voltage characteristic is non-linear as shown in Fig. 5. The equivalent circuit discussion which follows shows how the characteristic may be effectively linearized.

Equivalent Circuit of a Diode Junction

The response of a non-linear element depends on the characteristics of the element and the complete range of all inputs to the element. The response of a specific element will in general be applicable only to that element. The powerful Superposition Theorem does not hold in the non-linear analysis. However, a non-linear function of one or more variables may be linearized, if the function is analytic, by assuming a small variation and expanding the function in a Taylor's series about the operating point. Second and higher-order derivatives may be neglected. (Gaines, 1958). Fig. 5 below shows the characteristic curve of a typical junction diode.

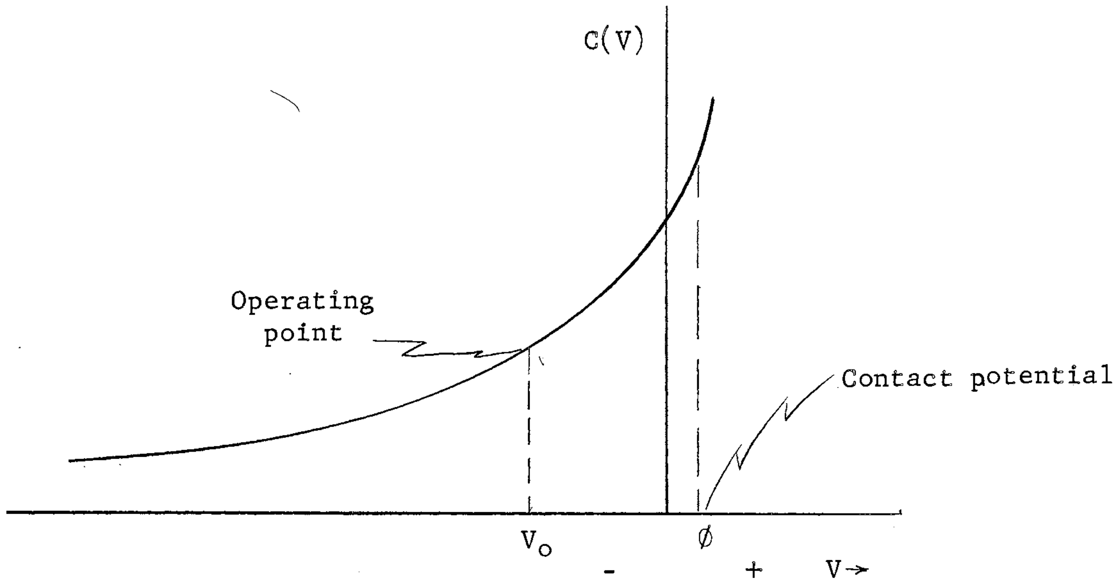


Fig. 5. Junction Diode Characteristic.

Torrey and Whitmer (1948) briefly discuss the depletion layer of a semiconductor on page 75. They show that the depletion-layer capacitance may be expressed as a function of the applied voltage as

$$C(V) \propto \frac{1}{\sqrt{\emptyset_o - V}} \tag{1}$$

This may be written as

$$C(V) = K(\emptyset_o - V)^{-n} \tag{2}$$

The operating point may be defined as V_o.

$$V_o = \emptyset_o - V \quad \therefore \quad C(V) = K(V_o + v)^{-n} \tag{3}$$

Where

$\emptyset_o$ is the contact potential difference of the barrier.
V is the applied voltage.
v is a small variation about V_o.
n, K are constants that depend on the geometry and composition of the junction.

By substitution, the capacitance as a function of voltage may be expanded in the Taylor series

$$C(V) = KV_o^{-n} - nKV_o^{-n-1}v + \ldots\ldots\ldots\ldots \tag{4}$$

with the restrictions that $\frac{v}{V_o} < 1$, and $0 < n < 1$.

The capacitance at the operating point may be defined as

$$C_o = KV_o^{-n} \tag{5}$$

Then with v being sinusoidal, as shown in Fig. 4, the time-varying capacitance may be written as

$$C(t) = C_o - \frac{nC_o}{V_o} V_m \sin(\omega t) \tag{6}$$

With the substitution

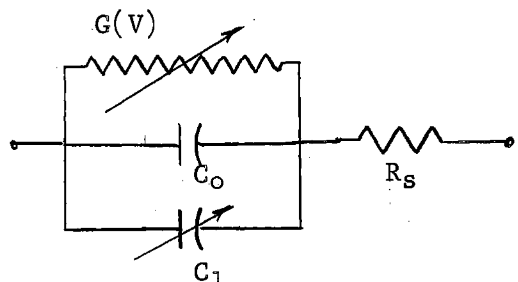
$$C_1 = -\frac{nC_o}{V_o} V_m \tag{7}$$

The final expression becomes

$$C(t) = C_o + C_1 \sin(\omega t) \tag{8}$$

This is merely the equivalent of two capacitances in parallel. For and equivalent circuit, Torrey and Whitmer (1948) show on page 97, a simplified version of Fig. 6, below.

(A) Forward Bias

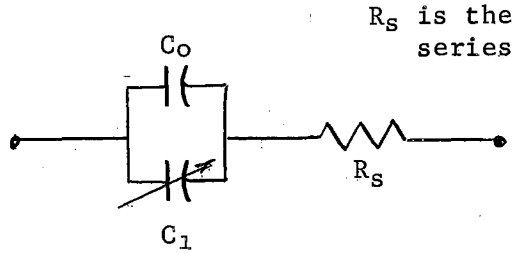


$\frac{v}{V_o} \geq 1$

G(V) is the shunt conductance

R_s is the internal series resistance.

(B) Reverse Bias



$0 < \frac{v}{V_o} < 1$

Fig. 6. Equivalent Circuit of a Diode Junction.

The shunt conductance, with reverse bias applied, may be neglected at high frequencies because it is effectively shunted by C_o. It should be noted that other parameters such as inductance and capacitance of the connecting leads and package may be present. The equivalent circuit above is for the junction area. The value of R_s depends on the impurity distribution and lead contacts. Uhlir (1958) has shown, by means of a Smith Chart plot, that the equivalent circuit in Fig. 6B is valid for small signals. The small-signal impedance for small values of reverse bias is primarily capacitive. The absence of shot noise in a primarily capacitive impedance is an attractive design feature.

A figure of merit may be defined as a cut-off frequency, f_c, as

$$f_c = \frac{1}{2\pi R_s C_o} \tag{9}$$

This definition is different from that of Uhlir in that C_o is used rather than the value of capacitance at maximum reverse bias, C_{min}. The quality factor, Q, may then be defined as

$$Q = \frac{1}{2\pi f R_s C_o} \tag{10}$$

This definition of Q is valid only for small excursions about the operating point and reverse bias. For a high value of f_c or Q, R_s, the series resistance, should be extremely low. A low value of R_s implies a low volume of the depletion layer. A small-volume depletion layer poses problems in the manufacture and limits the value of a reverse-bias voltage that may be applied before "punch-through" or break-down occurs. Limiting the reverse-bias voltage in turn limits the dynamic range of capacitance.

Butler and Roberts (1959) have compiled a rather extensive listing of characteristics of commercially available diodes. The highest cut-off frequency for a particular unit shown is 77 kilomegacycles with an R_s of 2.3 ohms. The figures of merit will undoubtedly improve with the development of new manufacturing techniques and materials.

As a general circuit component, the semiconductor junction diode has many advantages in its favor. Among them are small size, reliability, long life, fast response at high frequencies, low power consumption, and relative ease of economical mass production. On the disadvantage side, it appears that low power handling ability compared to vacuum tubes and other devices is the major disadvantage. With respect to the parametric amplifier application, the junction diode closely approximates a lossless capacitor.

CHAPTER III

THE THEORETICAL PARAMETRIC AMPLIFIER

Manley and Rowe (1956) have derived two independent equations relating powers at different frequencies in a non-linear element. Weiss (1957) developed the identical equations for a quantum-mechanical system such as a Maser. Salzberg (1957) derived the same equations without the use of the Fourier analysis. These same equations apply to the Dielectric Amplifier of Mason and Wick (1954) and the Ferromagnetic Amplifier of Tien and Suhl (1958).

Before delving into the mathematical background, it is desirable to have a clear physical picture of how gain is achieved in parametric amplifiers. Consider the simple system depicted in Fig. 7.

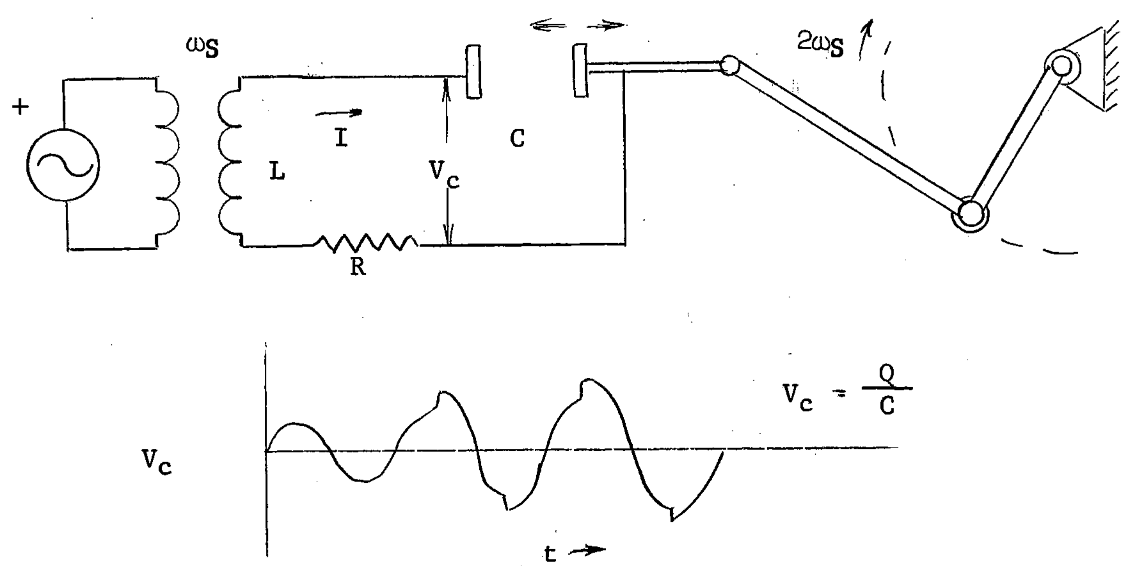
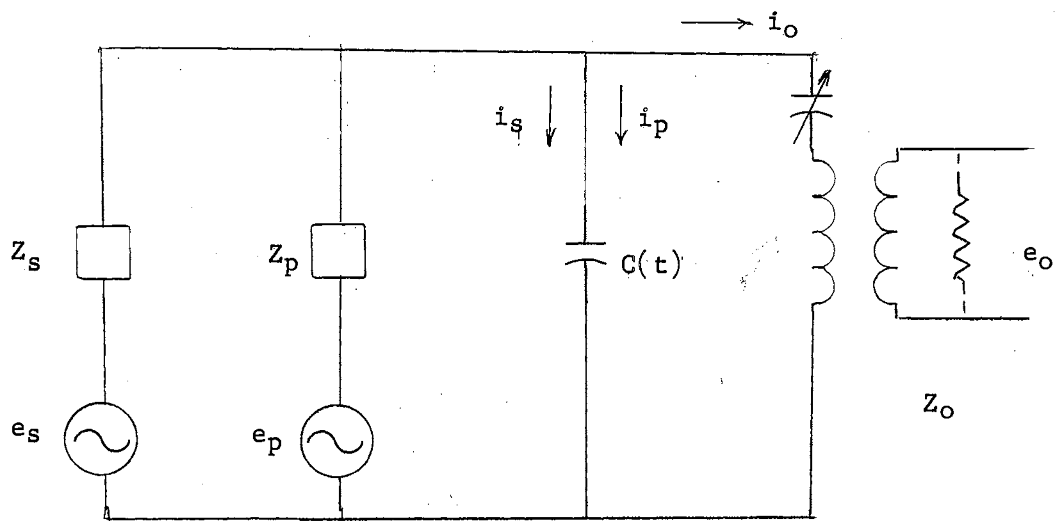


Fig. 7. Simple Electromechanical System.

The capacitance of the sinusoidally-excited resonant circuit is varied mechanically. Energy is expended by the mechanical pump in overcoming the force of electrostatic attraction between the capacitor plates. If the pump is adjusted so that the capacitor plates are pulled apart when the capacitor voltage, V_c, is at a maximum, an effective increase in this voltage results. As the capacitor voltage and charge go through zero in the cycle, the plates are returned to their initial position. No energy is required for this return because there is no electric field between the plates. When the voltage V_c reaches a negative maximum, the plates are separated again, and the process continues as before. In a lossless system, the voltage would continue to build indefinitely. It would result in an infinite voltage and continued variation would require an infinite mechanical force. In the physically realizable case, the amplitude builds until the mechanical energy supplied by the pump is equal to the electrical energy dissipated. In electronic parametric amplifiers, the mechanical pump is replaced by a local oscillator, also referred to as a pump.

A circuit of a simple electronic parametric amplifier using a lossless capacitance as the non-linear element is shown in Fig. 8. The impedances are considered ideal filters with zero impedance at the frequency indicated by their respective subscripts and infinite impedance at all other frequencies. The load impedance, Z_o, is frequency selective and is adjusted to the frequency $f_o = mf_p \pm nf_s$, where m and n are positive integers in general. Only steady state conditions are considered. Because the capacitance, $C(t)$, is considered lossless, no real power is dissipated. With two sources and one passive load, the only real power dissipated is in the load Z_o. Inspection of the circuit shows that the summation of powers must equal zero. The subscripts indentify the following components; s for signal; p for pump; o for output. On an average power basis

$$P_s + P_p + P_o = 0 \tag{11}$$



1) C(t) is a lossless capacitance whose charge vs voltage characteristic is non-linear.
2) $e_s = E_s \sin(\omega_s t + \Theta_s)$, $e_p = E_p \sin(\omega_p t + \Theta_p)$.
3) Z_s has zero impedance at frequency f_s, infinite impedance at all other frequencies.
4) Z_p has zero impedance at frequency f_p, infinite impedance at all other frequencies.
5) Z_o has zero impedance at frequency f_o, infinite impedance at all other frequencies.
6) $\omega = 2\pi f$, Θ designates the phase angle.
7) $f_o = mf_p \pm nf_s$, m, n, are integers.

Fig. 8. Simple Theoretical Parametric Amplifier.

The instantaneous power, in general, is defined as

$$p = e(t)i(t) \tag{12}$$

The average power is the time integral of p

$$P = \frac{1}{T}\int_0^T ei\, dt, \text{ Where T is a period equal to an integral number of cycles.} \tag{13}$$

If e(t) and i(t) are sinusoids,

$$P = \frac{E_m I_m \cos\Theta}{2}, \text{ where } \Theta \text{ is the phase angle between voltage and current.} \tag{14}$$

In the case of the parametric amplifier, from equation 11,

$$E_s I_s \cos\Theta_s + E_p I_p \cos\Theta_p + E_o I_o \cos\Theta_o = 0. \tag{15}$$

Only like-frequency voltage and current contribute to the average power. The impedance of a lossless capacitor may be written as

$$Z = X_c = \frac{1}{2\pi fC} = \frac{E_m}{I_m} \tag{16}$$

With $I_m = 2\pi fCE_m$, dimensionally CE_m may be defined as the charge, Q_m. After substitution of these quantities into equation 14,

$$P = E_m \pi f\, Q_m \cos\Theta \tag{17}$$

This relates the average power to the voltage and charge at a frequency f. Further dimensional analysis permits defining

$$W = \pi E_m Q_m \cos\Theta \ \frac{\text{joule}}{\text{cycle}} \tag{18}$$

Making this substitution into equation 17, the average power into a lossless capacitor is

$$P = fW \text{ watts.} \tag{19}$$

Equation 15 may now be written as

$$W_s f_s + W_p f_p + W_o f_o = 0 \tag{20}$$

Making the substitution $f_o = mf_p \pm nf_s$, m and n integers,

$$W_s f_s + W_p f_p + (mf_p \pm nf_s) W_o = 0 \tag{21}$$

This may be rewritten as

$$f_s (W_s \pm nW_o) + f_p (W_p + mW_o) = 0 \tag{22}$$

In general, f_s and f_p are not equal to zero. Therefore,

$$W_s \pm nW_o = 0, \text{ and} \qquad W_p + mW_o = 0 \tag{23}$$

Substituting from equation 19

$$\frac{P_s}{f_s} \pm \frac{nP_o}{mf_p \pm nf_s} = 0$$

$$\frac{P_p}{f_p} + \frac{mP_o}{mf_p \pm nf_s} = 0 \tag{24}$$

$$\frac{-P_o}{mf_p \pm nf_s} = \frac{P_p}{mf_p} = \frac{\pm P_s}{nf_s}$$

Although many other possibilities exist, for the purposes of this thesis, only the cases where m = n = 1 will apply. Therefore,

$$\frac{P_s}{f_s} \pm \frac{P_o}{f_p \pm f_s} = 0 \tag{25}$$

$$\frac{P_p}{f_p} + \frac{P_o}{f_p \pm f_s} = 0 \tag{26}$$

$$\frac{-P_o}{f_p \pm f_s} = \frac{P_p}{f_p} = \pm \frac{P_s}{f_s} \tag{27}$$

P_s is positive at the sum frequency and negative at the difference frequency.

These last three equations relate the average power at the various frequencies for the simple parametric amplifier with two sinusoidal sources, a lossless non-linear reactance, and a passive frequency-selective load. Positive power is indicative of the flow into the reactance. Negative power denotes flow out of the reactance. These equations are the equations of Manley and Rowe. The derivation in this thesis is an expanded hybrid of the work of Manley and Rowe and the simplified analysis of Salzberg. These power relations are independent of the degree of non-linearity of the reactance. The magnitudes of the individual powers can be determined only by detailed analysis of a specific circuit. In the theoretical case, if the load Z_o is a pure reactance, including a short and open circuit, no real power is absorbed and no power is exchanged between the sources. Power is exchanged between the reactance and each generator at their respective frequencies.

Parametric Amplifier Equivalent Circuit

The equations of Manley and Rowe imply the existence of a "hidden" source within the reactance. Many articles in the literature refer to the "effective negative conductance" that appears at the difference frequency. Consider the circuit of Fig. 9, with the load temporarily removed.

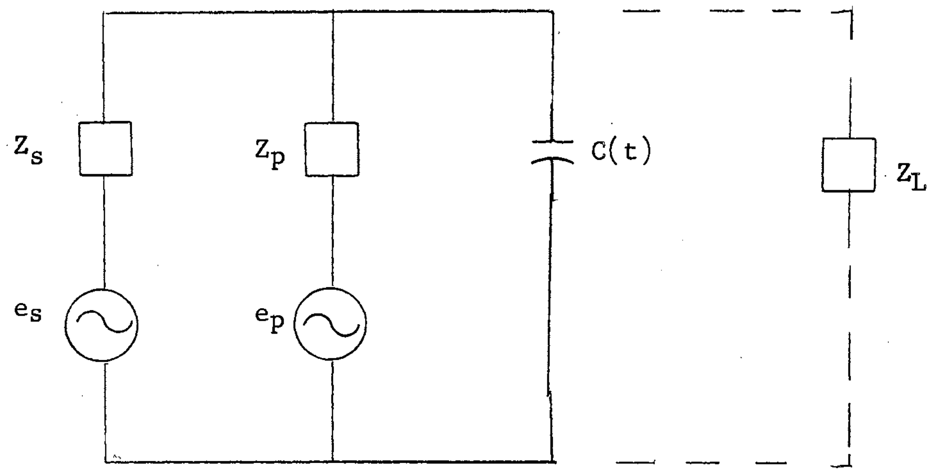


Fig. 9. Lossless Parametric Amplifier Without Load.

With the previous assumptions that Z_p and Z_s are ideal filters and $C(t)$ is lossless, by superposition, the voltage across $C(t)$ is

$$v(t) = V_p \sin(\omega_p t + \theta_p) + V_s \sin(\omega_s t + \theta_s) \tag{28}$$

and

$$\frac{d}{dt}(v) = \omega_p V_p \cos(\omega_p t + \theta_p) + \omega_s V_s \cos(\omega_s t + \theta_s) \tag{29}$$

From 8, with the assumption that $V_p \gg V_s$

$$C(t) = C_o + C_1 \sin(\omega_p t + \theta_p) \tag{8}$$

$$\frac{d}{dt}(C(t)) = \omega_p C_1 \cos(\omega_p t + \theta_p) \tag{30}$$

The charge may be expressed as

$$q(t) = C(t)v(t) \tag{31}$$

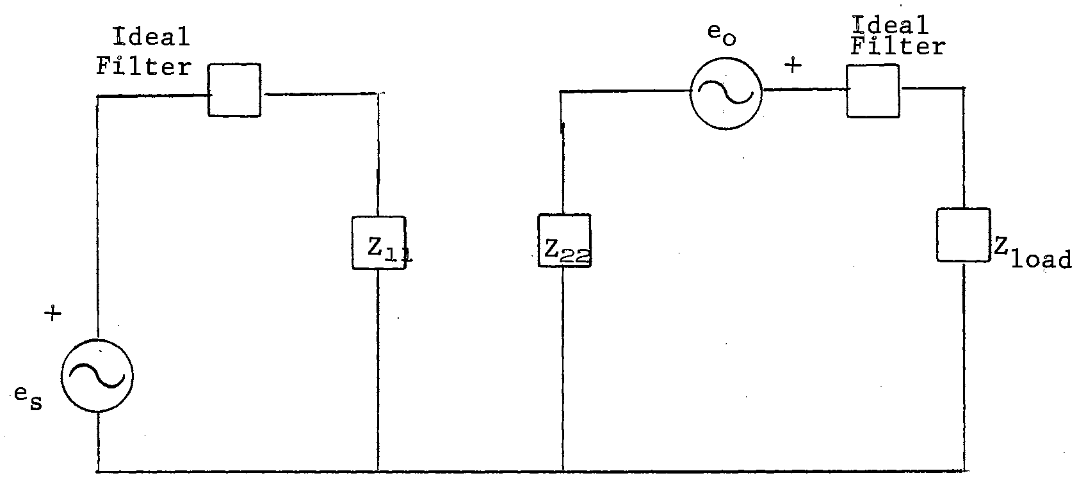
From which the current

$$i(t) = C(t)\frac{d}{dt}(v) + v\frac{d}{dt}(C(t)) \tag{32}$$

yields the following components

$$
\begin{aligned}
i(t) = \; & \omega_p C_o V_p \cos(\omega_p t + \theta_p) \\
& + \omega_s C_o V_s \cos(\omega_s t + \theta_s) \\
& + \omega_p C_1 V_p \sin \left[(\omega_p + \omega_s) t + \theta_p + \theta_s\right] \\
& + \omega_p C_1 V_p \sin \left[(\omega_p - \omega_s) t + \theta_p - \theta_s\right] \\
& + (\omega_p + \omega_s) \frac{C_1 V_s}{2} \sin \left[(\omega_p + \omega_s) t + \theta_p + \theta_s\right] \qquad (33) \\
& + (\omega_s - \omega_p) \frac{C_1 V_s}{2} \sin \left[(\omega_p - \omega_s) t + \theta_p - \theta_s\right]
\end{aligned}
$$

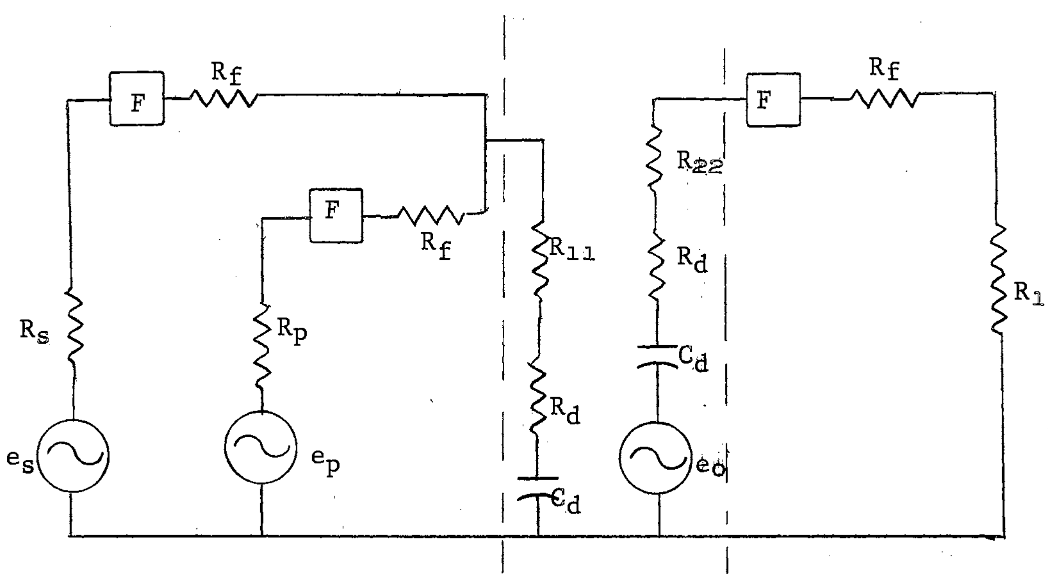
Considering only the frequencies involved, the two fundamentals appear in addition to the sum and difference frequency. If, by suitable filtering, only the sum or difference frequency is permitted to appear, and this frequency is designated f_o, an equivalent circuit may be drawn. The restriction of allowing only the sum or difference frequency to appear is purely arbitrary and depends on the desired application. By applying the principle of duality, it may be shown that if the two fundamental currents flow through the lossless non-linear capacitor, equation 33 becomes an expression for voltage and voltages having the same frequency components as the current equation appear. Again the choice is arbitrary. In any event, the theoretical parametric amplifier has a signal applied on which a desired operation is to be performed. The pump energy drives the lossless non-linear capacitor which results in an output signal at a desired frequency.



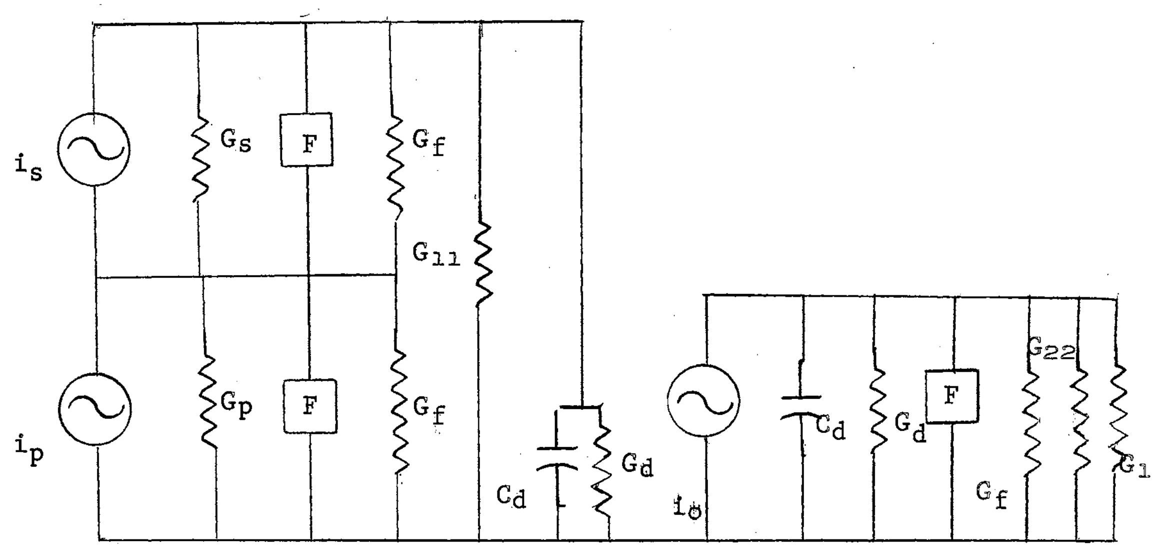
Z_{11} and Z_{22} include the effects of the diode, pump, and bias and load.

Fig. 10. Equivalent Circuit of a Simple Parametric Amplifier.

If the load is at resonance, and approximately ideal filters are assumed, the following equivalent circuits should be valid when losses are included.



(A) Lossy Equivalent.



(B) Dual of Lossy Equivalent.

$\boxed{F}$ indicates an approximate ideal filter

i = current	e = voltage	o = output
R = Resistance		f = filter
G = Conductance		$_{11}$ = input
C = C_o, the diode capacitance		$_{22}$ = output
s = signal		1 = load
p = pump		d = diode

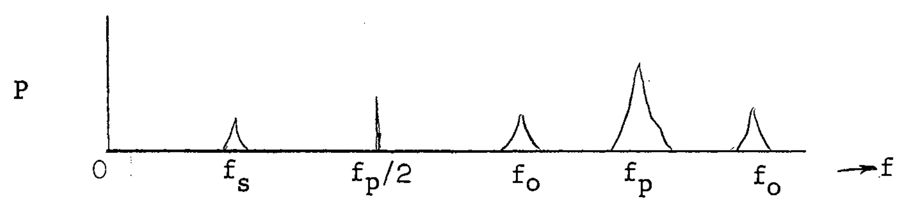
Fig. 11. Equivalent Circuits Including Losses.

Quantities with the subscripts $_{11}$ and $_{22}$ are included to account for losses such as wiring, bias circuit, losses due to only approximate-ideal filters and other losses. Somewhat similar circuits have been analyzed by Rowe (1958), Leenov (1958), and Heffner and Wade (1958).

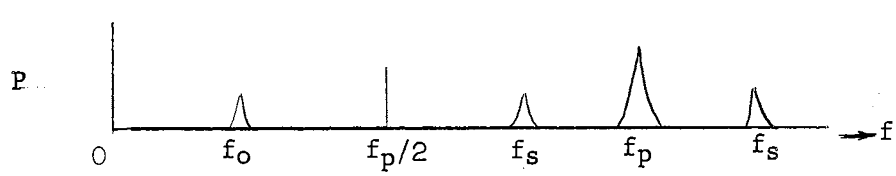
The equivalent circuits were derived without any stipulation as to the relative positions of each of the frequencies in the spectrum. The relative positions of the frequencies with respect to each other are of fundamental importance and, depending on the application, the positions establish the possibility of power gain or loss.

Frequency Relationships

The analysis of Hartley (1936) shows that if two sources, each with a different frequency, supply power to the circuit of Fig. 8, the higher-frequency source will supply most of the power and the lower-frequency source will supply very little power. This immediately leads to the possibility of using microwatt signals as the low-frequency source and a higher-powered local oscillator for the higher frequency source. A detailed examination of the Manley and Rowe equations shows the relationship between the various frequencies. For the purposes of this thesis, the local oscillator power present in the circuit will always be greater than the signal power. Two general cases which depend on the position of output frequency in the spectrum are shown graphically in Fig. 12 below.



(A) Modulator, $f_s < f_p$.



(B) Demodulator, $f_o < f_p$.

Fig. 12. Modulator and Demodulator Relationships.

The modulator and demodulator may be examined in greater detail by considering all frequencies terminated reactively except f_p, and either the sum or difference frequency containing f_s or f_o. Consider the modulator spectrum shown in Fig. 13 below.

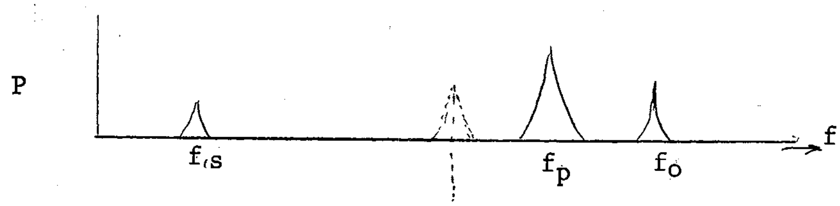


Fig. 13. Modulator Spectrum.

The output frequency, f_o, is the highest frequency and is the sum of the pump and signal frequencies. For this case, equations 25 and 26 may be written as

$$\frac{P_s}{f_s} + \frac{P_o}{f_o} = \frac{P_p}{f_p} + \frac{P_o}{f_o}$$

$$- P_o = \frac{f_o}{f_s} P_s \qquad - P_o = \frac{f_o}{f_p} P_p \tag{34}$$

The theoretical power gain may be defined as power input at a frequency f_s to the power output at f_o:

$$G_p = - \frac{P_o}{P_s} = \frac{f_o}{f_s} = \frac{f_p}{f_s} + 1 \qquad f_p > f_s \tag{35}$$

These equations show that it is possible to transfer power from the low frequency, f_s, to a higher frequency f_o. Both the signal and pump contribute to the output. The stable power gain shows that for a high gain, a wide spread in frequency is desirable.

The demodulator spectrum shown in Fig. 14 below is an example of ordinary superheterodyne-receiver conversion.

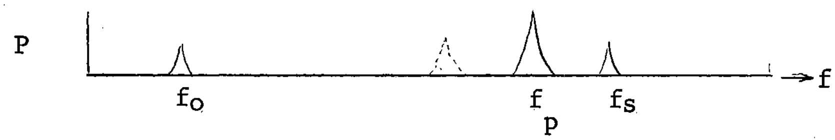


Fig. 14. Demodulator Spectrum.

The output frequency, f_o, is the lowest frequency in the spectrum and is the difference between the signal and pump frequencies. The equations remain the same as the Modulator case with the exception that

$$f_o = f_s - f_p \tag{36}$$

The theoretical power gain is now

$$G_p = \frac{f_o}{f_s} = \frac{f_s - f_p}{f_s} = 1 - \frac{f_p}{f_s} \qquad f_p < f_s \tag{37}$$

Although power is available at the frequency f_o, the gain is less than unity and a loss is evident. A great spread in frequency between f_o and f_s indicates a corresponding loss.

The remaining case is shown graphically in Fig. 15 below. In addition to being the biggest power, the pump is also at the highest frequency.

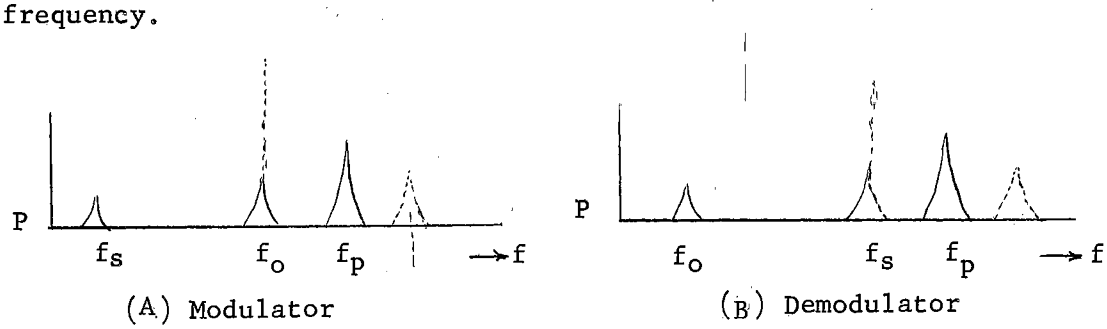


Fig. 15. Modulator and Demodulator Spectrums.

The frequency relationship is

$$f_o = f_p - f_s \tag{38}$$

Solution of the Power equations yields

$$G_p = -\frac{f_o}{f_s} = -\frac{(f_p - f_s)}{f_s} = 1 - \frac{f_p}{f_s} \qquad f_p > f_s \tag{39}$$

The negative gain indicates a potential instability and the possibility of oscillation. The pump supplies power to the load and signal source, thus effectively increasing the signal power. It should be noted that classical circuit analysis fails after oscillation starts and impedance matching is not possible. In practical applications, an important case arises where f_o is equal to f_s. This is the simplest form of parametric amplifier and oscillation is possible in one of two modes in addition to non-oscillating amplification. After oscillation has started, the gain is not limited to -1 as implied by equation 39 above. Theoretical gain in the lossless case approaches infinity. In the practical case, R_s, the series resistance of the diode, and other losses limit the gain to a finite value.

For the harmonic or sub-harmonic generator, the signal circuit may be removed and only the pump and load remain. The load is made frequency selective and only the desired harmonic or sub-harmonic exists in the theoretical case.

In summary, the following assumptions were made concerning the theoretical amplifier:

(1) the non-linear time-varying element was lossless, i.e., R_s was equal to zero,

(2) the filters were ideal. The only real power was dissipated in the load at a frequency f_o,

(3) the pump power was greater in magnitude than the signal power.

In the real parametric amplifier, the last assumption is readily made valid; the first two are approached. R_s precludes the exact short-circuit of harmonics and some power is dissipated. The assumed infinite impedance of open-circuit harmonic loads cannot be met in practice and additional power is lost.

CHAPTER IV

EXPERIMENTAL CIRCUITS AND OBSERVATIONS

Of all the possible frequency combinations indicated in Chapter III, the sum-frequency mode of conversion was chosen as the primary area of investigation. This mode was chosen because of the predicted inherent stability and because it includes frequency conversion in addition to amplification. Based on the frequency ranges of the components, instruments, and equipment available, an output frequency of 40 megacycles (mc) was chosen. The signal frequency, f_s, was in the 1 mc region. This choice of frequencies made it possible to investigate both the sum and difference modes easily. The pump frequency, f_p, was approximately 39 mc for the sum mode and approximately 41 mc for the difference mode.

One model of a 20 mc amplifier, with the pump at 40 mc, was constructed for the purpose of observing time signals from the National Bureau of Standards station WWV. This circuit was also operated as a 20 mc harmonic generator by pumping at 20 mc and taking the output at 40 mc.

All of the experiments were conducted in a laboratory on the fourth floor of the Engineering Building on the Oklahoma State University campus; an elevation of about 60 feet above ground level. It should be pointed out that no antenna was required at this location.

Measuring Techniques

The primary measuring instruments included a General Radio Type 1001-A Standard Signal Generator, which was used as the signal source; a Measurements Corporation Megacycle Meter (grid-dip meter) as the pump source; and a Tektronix Type 545 Oscilloscope, with a 53/54 L plug-in unit, as the output indicator. The effective values of the inductors and capacitors used in each circuit were measured by the use of a Boonton Radio Corporation Type 160A Q Meter. A communications type radio receiver was used to audibly identify particular signals.

In dealing with small-signal levels, as in these experiments, proper calibration of the instruments is extremely important. A temperature-stabilizing period of approximately one hour was used prior to calibration. The line voltage to all of the instruments was monitored. The oscilloscope was calibrated by using its internal calibrator and the probe was properly balanced. The signal generator output was checked against the oscilloscope calibration at various frequencies and no significant discrepancies existed below 20 mc. Above 20 mc an unresolved ambiguity arises because the upper frequency limit of the oscilloscope is being approached and the accuracy of the signal generator output is decreased. For the experiments in this thesis, the signal generator was chosen as the standard reference.

The receiver was aligned in accordance with the manufacturers instructions. A calibration curve of the receiver intermediate frequency (i-f) amplifier output vs antenna terminal input voltage at 40 mc was linear. The minimum discernible signal was approximately 6 microvolts input; noise was predominant in the output. It should be pointed out that with the receiver i-f output at 455 kc, and the signal generator chosen as the standard, the apparent ambiguity mentioned previously resolves itself.

Three different methods of gain measurement were investigated. The most obvious is the direct method, where the signal generator output is assumed standard and the experimental amplifier is connected between the generator and oscilloscope. Direct gain measurements are possible with the circuits to be described. However, in addition to the involved, but necessary, oscilloscope calibration, the direct method has another disadvantage that appears with the simple circuits that follow. The filters used were not ideal, and with the pump near 40 mc, both pump and signal appeared at the output. Nevertheless, the signal component is identifiable and appears superimposed on the pump component as is shown in Fig. 16 below.

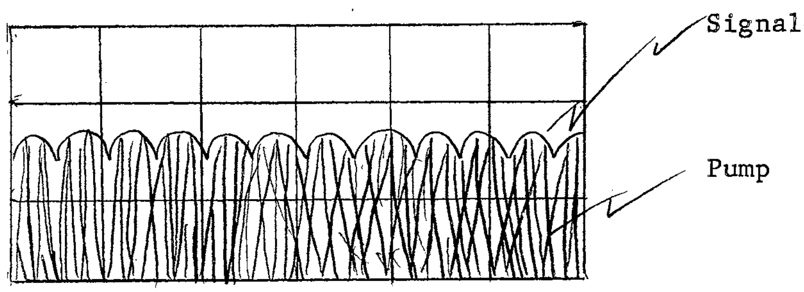


Fig. 16. Superposition of Pump and Signal Voltage.

With loose inductive coupling of the receiver to the amplifier, audio identification is possible in addition to the apparent traveling of the signal wave as the signal generator frequency is varied very slowly. This method positively identifies the signal component visually and audibly. As a further check, loss of the signal may be effected by individually turning off the signal generator, pump, or removing the diode from the amplifier.

The second method of measuring gain was accomplished by connecting the oscilloscope to the output of the last i-f stage of the calibrated receiver. With the signal generator output known and considered the standard, the gain of the receiver and the loss of the oscilloscope probe are known constants and the unknown gain of the experimental amplifier is readily determined. It should be noted that the receiver AVC circuit should be disabled, and RF sensitivity and other controls must remain exactly as they were during calibration. Fig. 17 is a block diagram of this measurement method.

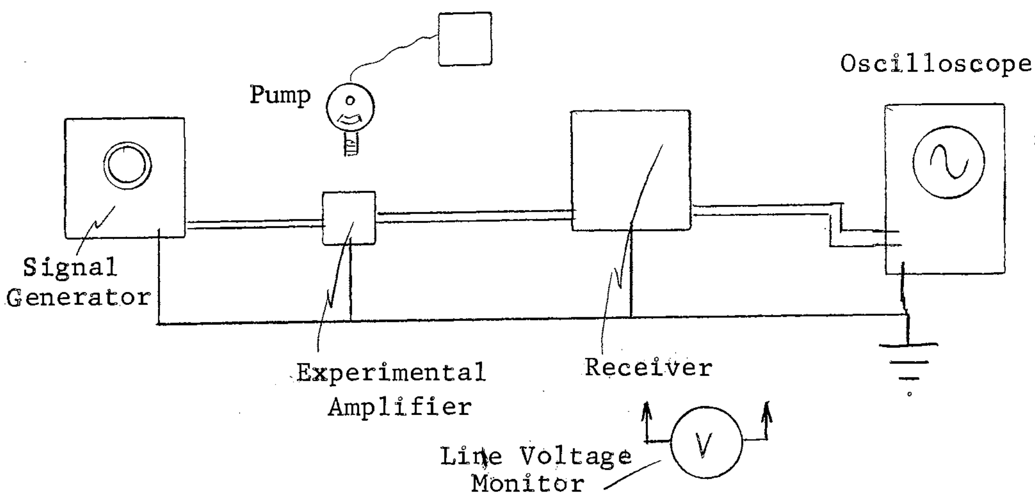


Fig. 17. Block Diagram of Amplifier Gain Measurement.

Some small error in a gain vs frequency plot is probably introduced by this method, because it is necessary to relate the gain of the experimental amplifier to the receiver output through the receiver calibration plot.

The third method is essentially the same as the second, except the output may be measured at the receiver audio amplifier instead of the i-f amplifier. In either of these methods, the receiver acts as a very effective filter for the output of the experimental amplifier.

In all of the circuits that follow, 1/32 inch copper sheet was used as the chassis. The pump and output circuit capacitors were of the small trimmer variety. The pump and output circuit inductors were self-supporting and made of No. 16 enameled copper wire, wound on a 5/8 inch diameter form. Although the inductors were not optimized with respect to diameter/length ratio, typical air-core values of Q at 25 mc were approximately 270. The signal circuit inductors, both round and rectangular ferrite core types, were of commercial manufacture. The signal circuit capacitors were ordinary single-section variables with air dielectric. The inductors were mounted mutually perpendicular to each other.

Circuits

The following single diode circuits, based on the lossy equivalents shown in Fig. 11, were constructed.

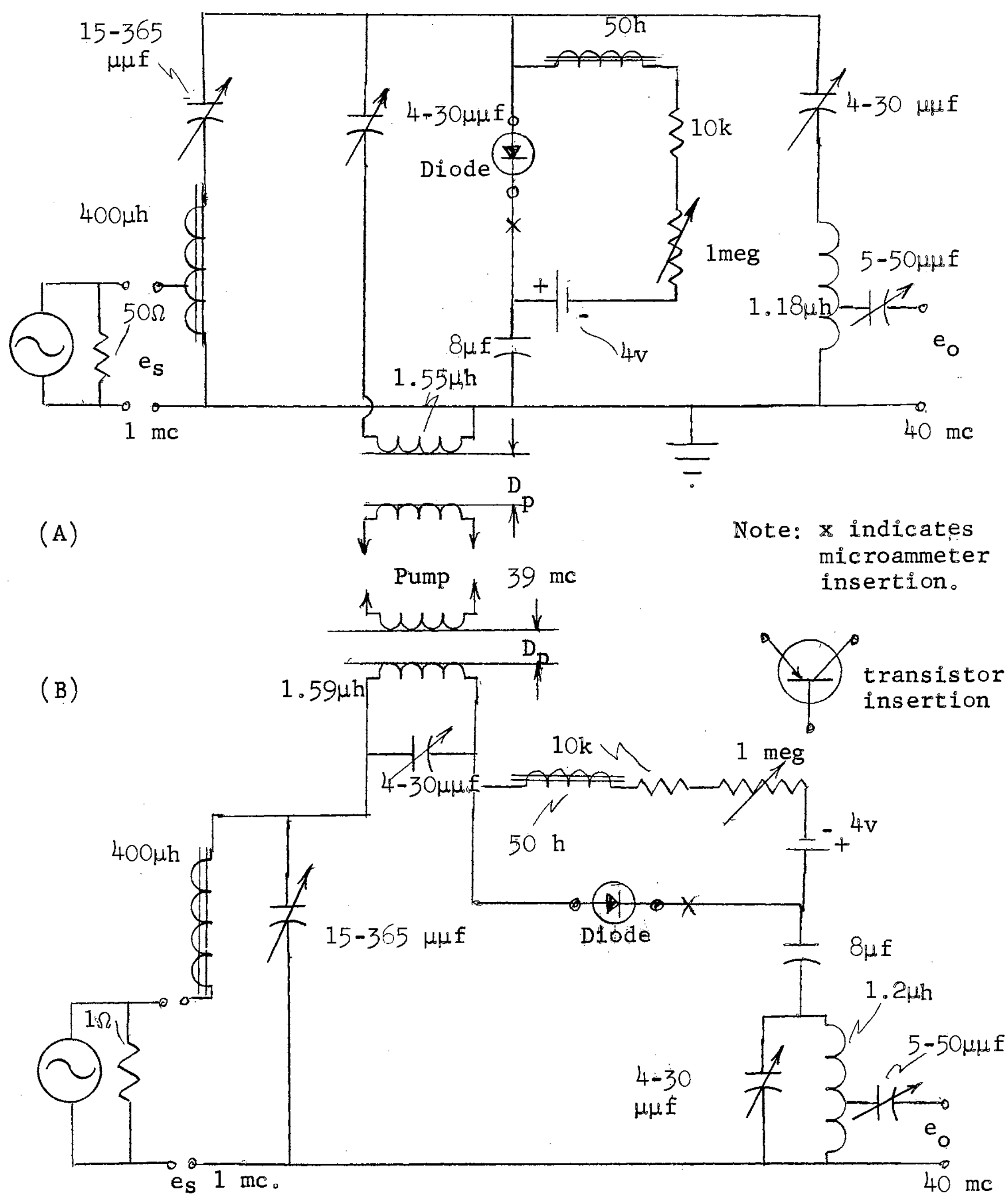
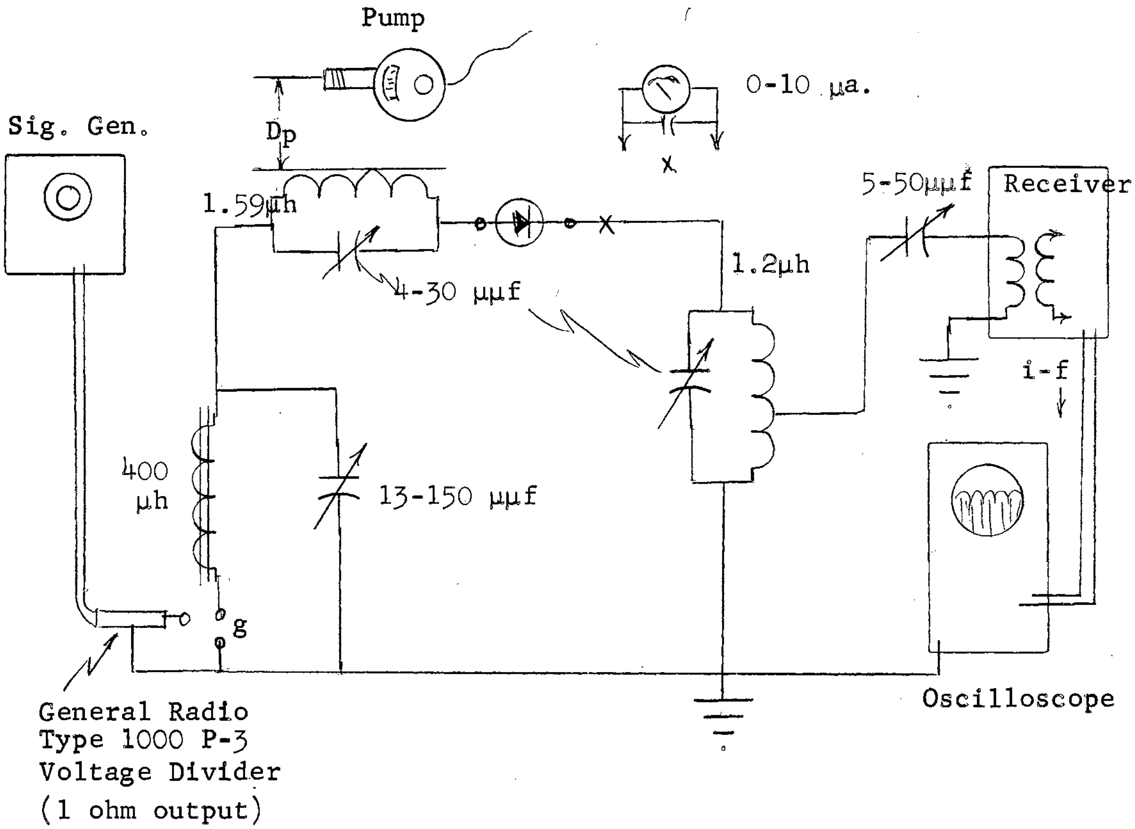


Fig. 18. Experimental Circuits Using a Single Diode.

The 8 μf capacitor in both circuits was an effective short circuit at all the frequencies involved, and it served to isolate the bias voltage from the rest of the circuit. The capacitor was a sub-miniature type rated at 6 volts d-c. The 50 henry reactor in the bias circuit was an effective open circuit at all the frequencies involved. It was a sub-miniature type with a d-c resistance of 4400 ohms.

It was noted that, in the configuration of Fig. 18A, a closer pump distance, D_p, was required than that at B for the same relative output. With a coupling distance of approximately 1 inch, the 1 megohm variable resistance served to vary the diode capacitance. With the pump at 39 mc, several different stations in the broadcast band could be tuned in by varying the bias control alone. With the coupling distance equal to approximately 2 inches, the bias control could be varied for an optimum setting, as was indicated by the observed signal on the oscilloscope and the audio output of the receiver.

Both configurations were operated in the unbiased condition in addition to using bias. The unbiased version of the circuit in A of Fig. 18, produced a distorted output accompanied by a loud hum (comparable to the familiar 60 cycle hum) in the receiver audio output. The dual circuit shown in B did not produce hum or distortion, and little difference was noticed between the biased and unbiased conditions. The excellent results obtained without bias prompted the construction of the circuit shown in Fig. 19. It should be noted that the same diode was used in both biased and unbiased circuits.



Note: Point g is grounded for reception of the broadcast band or connected to the signal generator for gain measurements.

Fig. 19. Unbiased Single Diode Circuit.

The self-biased method of operation is not completely understood, but considering the hypothetical junction shown in Fig. 3, it appears that holes are being stored and an effective negative bias results. Insertion of an a-c by-passed d-c microammeter in the above circuit showed that current was flowing. The current varied with D_p, the pump coupling distance; the closer the coupling, the greater the current. If holes are temporarily stored, the storage effect may be a function of frequency, although this was not observed. In any event, the effect appears to be desirable in this application, and the possibility of accentuating it requires more research and possibly changes in manufacturing techniques.

Because of the excellent results obtained with this circuit, it was selected for a more detailed examination. The optimum pump distance was approximately 2 1/2 inches. At this distance the d-c microammeter indicated 7 microamperes. With greater pump distances, the output was correspondingly less. At pump distances closer than 2 1/2 inches, a detuning effect was observed. The conversion and amplification process continued, but a small change in pump frequency was necessary for reception of a particular signal. At approximately 1/2 inch pump distance, a saturation effect was observed and the parametric process appeared to stop. Increasing the pump distance caused normal operation to recur without any additional adjustments.

Various pump frequencies were tried without any other changes in the circuit. Although there was a marked decrease in output, the amplifier functioned with the second harmonic of 20 mc as the pump frequency. During this time, the amplifier pump circuit remained adjusted to the original 40 mc frequency. This leads to the possibility of using the harmonics of lower-frequency pumps which may be more economical and more easily adjusted.

With the pump distance at approximately 2 1/2 inches, and all of the remaining equipment turned off, a battery-powered three-transistor audio amplifier with a 1N48 diode detector was inductively coupled to the amplifier output circuit. Among the many stations audible, the following were positively identified: WNOE, New Orleans, La.; KYW, Cleveland, Ohio; and KSL, Salt Lake City, Utah. This was accomplished without an outside antenna at approximately 10:00 p.m. on several different nights. The audio output was low compared to the output of an ordinary receiver. This is to be expected since no i-f amplification stages were used.

With the pump and signal circuits individually adjustable by the use of the trimmer capacitors, an optimum response was obtained for each frequency as opposed to an ordinary superheterodyne receiver where ganged tuning is employed. This does not, however, preclude ganged tuning in a parametric amplifier. For example, with the pump frequency at 39 mc and the signal at 1000 kc the response is shown in Fig. 20 below.

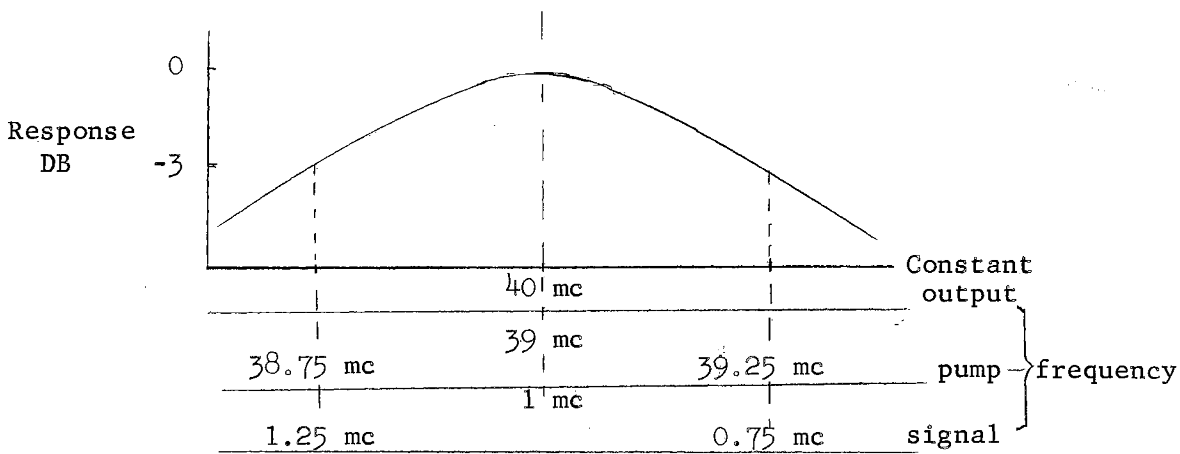


Fig. 20. Sum Frequency Output.

As indicated above, the output circuit was tuned to 40 mc and not disturbed; the signal circuit was adjusted to 1 mc optimum response with the pump at 39 mc. Without adjusting the pump or signal circuits, the pump frequency and signal generator frequency were varied approximately 250 kc to either side of their center frequencies before the response was down 3 db. It is important to note that, in the sum-frequency case, the pump frequency plus signal frequency must equal the output frequency at all times. For optimum response, the signal and pump circuits should be adjusted individually to their respective frequencies. The apparent bandwidth observed could be broadened to include the entire broadcast band with the additional loading of the signal circuit by an external antenna. In so far as the simplicity of ganged tuning is concerned, there are commercially available dual-section capacitors with one section at maximum capacity while the other section is at minimum. In the difference-frequency case, approximately the same bandwidth was observed. The difference-frequency output has the advantage of not inverting the signal frequencies; hence an ordinary dual-section capacitor of appropriate capacities may be used for ganged tuning.

When operated in the difference-frequency mode, this amplifier began to oscillate when the pump distance was decreased from 2 1/2 inches to about 2 inches. The action was comparable to a simple regenerative receiver. Each of the broadcast band stations received was accompanied by the familiar audio whistle superimposed and overriding the signal.

Table I shows the theoretical and experimental power gains at selected frequencies. For each of the experimental points shown, the signal and pump circuits were optimized. The pump distance was kept constant at 2 1/2 inches. The output frequency was constant at 40 mc. The signal generator output impedance was 1 ohm, and the output voltage constant at 20 microvolts. The diode was a unit specifically designed for parametric amplification.

TABLE I

SUM-FREQUENCY POWER GAINS

Signal Generator Frequency KC	Pump Frequency MC	Measured Power Gain DB	Theoretical Power Gain DB
600	39.4	14.0	18.5
800	39.2	14.1	17
1000	39	14.4	16
1100	38.9	13.8	15.6
1200	38.8	13.6	15.25
1400	38.6	12.8	14.6
1500	38.5	12.1	14.25
1600	38.4	12.0	14
2000	38	11.4	13

There are several reasons for not achieving the predicted theoretical gain. Among them are:

a) The diode was not lossless; R_s had some value greated than zero,

b) the filters were not ideal; some power was dissipated at other frequencies,

c) the lower sideband was assumed a perfect open circuit in the theoretical case; it was not so terminated in this circuit.

Knowledge of the pump power would have been advantageous. However, the ease of introducing the pump power, inductively over a wide frequency range, was the reason for choosing the grid-dip meter as the pump source.

Although extreme care was used during the conduct of this particular experiment, the methods used in arriving at the values of measured gain can be improved considerably. The signal generator frequency was assumed standard, and the pump frequency was determined by listening to the audio output of the receiver while varying the pump frequency until the signal was identified by the 400 cycle modulation superimposed on the signal generator output. This occurred at only one pump frequency so that in principle there is nothing wrong with this method of selecting frequencies. The oscilloscope was connected to the receiver i-f output, and the output indications were compared to the previously prepared calibration chart of the receiver. Some error is inherent in this method. Although the signal generator was assumed standard, there was no assurance that the indicated signal generator output voltage of 20 microvolts at 40 mc was as accurate as the indicated 20 microvolts at lower frequencies. Choosing a lower output frequency would have eliminated this possible discrepancy, but the theoretical and actual gains would also be lower.

It is conceivable that the general purpose broadcast band receiver of the future will contain a parametric amplifier very similar to the circuit of Fig. 19.

The following version of a balanced-mixer circuit was constructed.

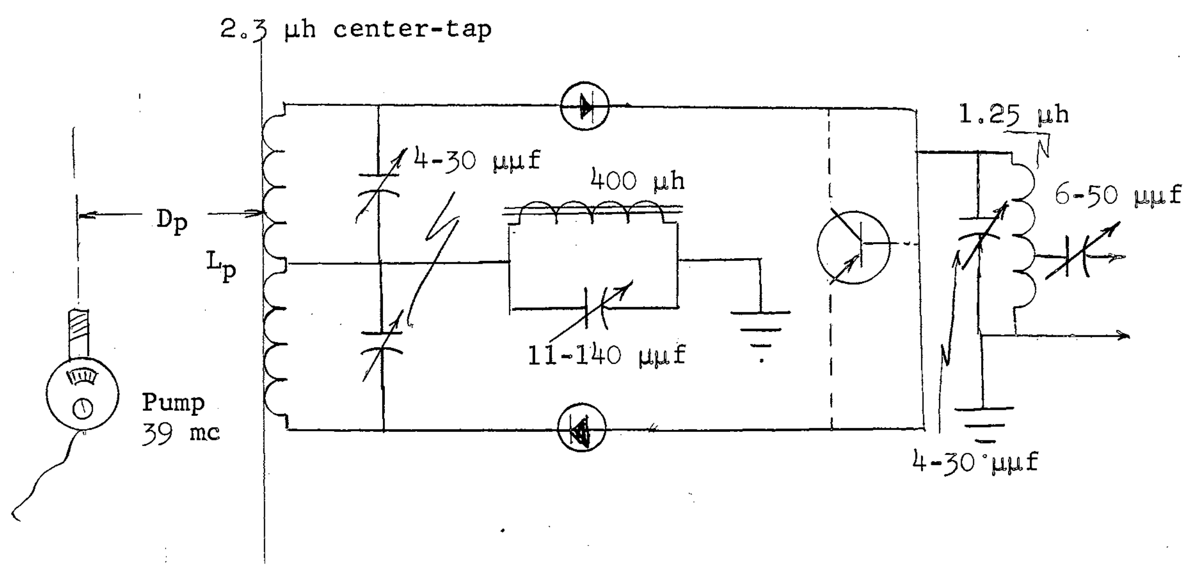


Fig. 21. Balanced Two-Diode Circuit.

This particular circuit appeared to require much less pump power than any of the other circuits tested. The diodes were operated in the unbiased condition. With the variable-frequency pump used, the output was taken at both the sum and difference frequencies. The amplifier oscillated with about 3 inches spacing between the pump and L_p, the pump circuit tank, at the difference frequency. The circuit was exceptionally easy to tune over the standard broadcast band. A power gain of 13.8 db was measured with the signal circuit at 1 mc and the pump circuit at 39 mc. The diodes used were computer types. The use of a transistor in place of the diodes did not yield favorable results.

The following is a circuit diagram of a 20 mc amplifier.

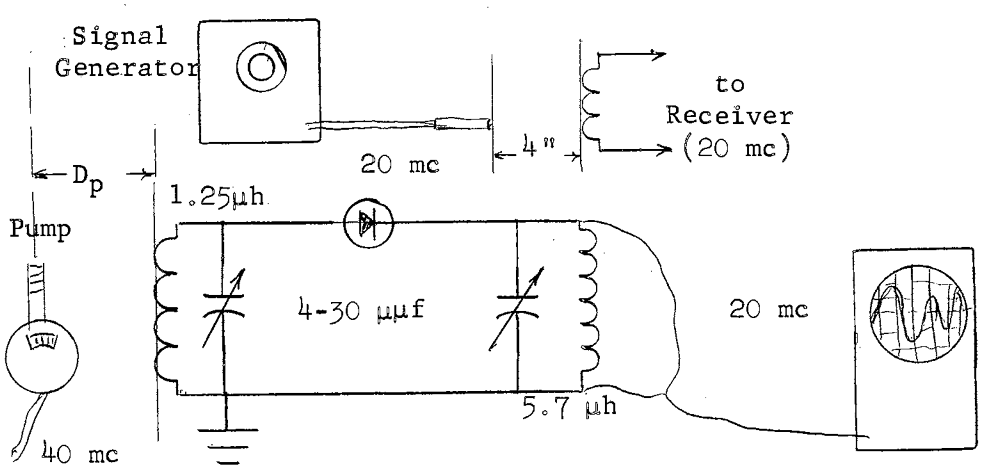


Fig. 22. 20 mc Amplifier.

This amplifier was extremely unstable and hand effects were severe. There was a stable point of operation, with amplification, when the pump coupling, D_p, was increased so that oscillation did not occur. As the distance, D_p was decreased, a point was reached were oscillation commenced and the meter of the grid-dip meter (pump) indicated that power was being supplied to the amplifier. Distancewise, the following sequence took place as the pump distance was decreased from about 12 inches to about 1/4 inch. From 12 inches to 8 inches, no significant change; at 8 inches to 6 inches, significant amplification was observed both audibly and visually on the oscilloscope; at about 6 inches, oscillation commenced and the amplifier action was very similar to that encountered in a simple regenerative receiver. Hand effects became very noticeable and there was a marked dip indicated on the pump meter; at about 5 inches, the familiar rushing sound associated with superregeneration was noted; at about 4 1/2 inches, a greatly amplified signal was observed, but the exact position of the pump was extremely critical and very severe detuning effects and loss of signal, as a result of the detuning, was noted. At distances less than approximately 4 inches, the amplifier appeared to saturate, and no amplification was observed although pump power was being supplied as indicated by the pump meter. This effect is not clearly understood. It is probable that the proximity of the pump caused such severe detuning that the proper frequency relationship for amplification did not exist. An alternative explanation might be that the diode was driven into the forward bias, hence, conducting region, which in turn may have cause detuning. No bias was used in this circuitry.

The waveform of the amplifier as observed on the oscilloscope appeared to contain both the 40 mc pump frequency and the 20 mc subharmonic. Although not measured, a definite amplification of WWV signal strength at 20 mc was observed without any antenna.

With the pump and output positions reversed, the second harmonic of the 20 mc pump was observed audibly at 40 mc. No further experiments with this configuration were conducted.

The following bridge-type circuit was constructed.

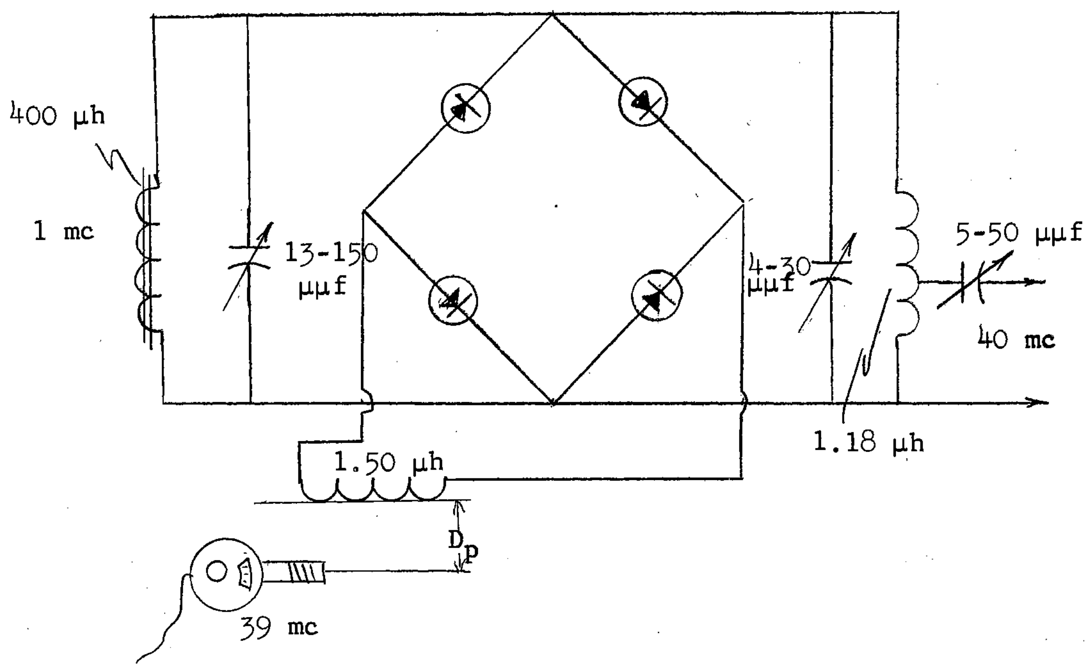


Fig. 23. Bridge-Type Circuit Using Four Diodes.

In principle, this circuit should have performed much better than it did. The low power gain of only 6 db is attributed to unmatched diodes. The diodes used in this configuration were of the general purpose power-rectifier type. This circuit should be investigated further with 4 matched diodes specifically designed for parametric amplification.

General Observations

Over 40 different diodes and transistors were checked for performance in the various circuits. Evaluation of specific diodes was not a part of this investigation, but a comment on diode quality is deemed appropriate. There is a marked difference in the amount of pump power required for a specific output with various diodes. Of the 15 transistors checked, one surface-barrier type with a cut-off frequency of 30 mc appeared superior to the rest. This was the best transistor available, and had the highest cut-off frequency. It is probable that some of the newer "mesa" types designed for UHF use would act as satisfactory parametric amplifiers.

All of the diodes checked were silicon junction types. One particular diode, specifically designed for this application, required an extremely small amount of pump power compared to all the other diodes and transistors. Mismatch and other losses are less evident when a diode designed for parametric amplification is used in the circuits described in this thesis.

Because the same circuitry was used in checking all of the diodes and transistors, both in the biased and unbiased conditions, the differences in required pump power may be interpreted as being an indication of different values of R_s, the diode series resistance, and the junction capacitance. These parameters in turn are an indication of diode suitability for parametric amplification.

When a parametric amplifier is operated over a band of frequencies rather than one specific frequency, exact impedance matching of each of the circuits (signal, pump, output, and diode) is not feasible. The practical solution to this problem is the choice of the highest quality diode available.

It is interesting to note that, with the circuit of Fig. 19 optimized at 1 mc signal frequency and 39 mc pump frequency, the minimum discernible signal generator voltage was 0.2 microvolt compared to approximately 6 microvolts without the amplifier operating. At these levels, noise was predominant, but the advantages of the amplifier became evident.

Although admittedly a crude technique, a hot 250 watt soldering iron was held about 1/8 inch away from a diode in the circuit of Fig. 18B. The following action was observed by listening to a broadcast station with the amplifier operating unbiased. Within about 45 seconds after heat application, a build in volume was noted. This was followed by an increase in a hissing noise and a decrease in signal volume. After an elapse of about 2 minutes, the signal and noise were both lost. At this time the heat was removed and almost complete recovery occurred after an elapse of approximately 30 seconds. With bias applied, similar action occurred except that complete loss of signal took about 3 1/2 minutes. Upon removal of heat, recovery occurred after an elapse of about 30 seconds. This action appears to indicate some independence of temperature in the biased condition. Application of heat in this manner was tried several times with the same diode and no significant changes were noted after each recovery.

CHAPTER V

SUMMARY AND CONCLUSIONS

Synopsis

The basic principles of parametric amplification have been known by the scientific world for almost a century. Much of the relatively recent interest in electronic parametric amplifiers has been stimulated by the development of low-loss semiconductor junction diodes. Diodes which are specifically designed for parametric amplifiers permit the use of simple circuitry and make possible a close approach to the theoretical lossless-circuit power gain.

Because the parametric amplifier has low loss and low noise characteristics at high frequencies, the majority of the reported experimental results have been in the region above 100 mc. Table II, on the following page, is a selected summary of previously reported experimental results. The entries are representative of the frequencies and areas that have been investigated.

The results obtained with the experimental circuits described in this thesis indicate that the junction diode parametric amplifier is well suited for amplification and frequency conversion of low-power medium radio-frequency signals. In addition to its simplicity, it is a narrow-band device compatible with the requirements for the reception of amplitude-modulated signals. Although the simple circuits described in this

TABLE II

SELECTED EXPERIMENTAL RESULTS

Type	Frequency K = 1000	Power Gain db	Bandwidth	Noise Figure db	Pump Power mw	Reference, Author, Source, Month, Year, Page
Balanced Si Diodes	f_s=1mc f_p=20mc f_o=21mc	Approx. 10	Approx. 10% f_s	------	-----	Salzberg, Proc. IRE June 1958, 1303.
VHF Ge Diode	f_o=380 mc f_p=600 mc	35	-------	Approx. 10	30	Chang, Proc. IRE July 1958, 1384.
Varactor Diode	f_p=1060 mc f_o=f_s=530 mc	10	0.6 mc	3.8	4	Kibler, Proc. IRE April 1959, 583.
Traveling wave	f_s=380 mc f_o=250 mc f_p=630 mc	10-12	10-20 mc	3.5	1-2	Engelbrecht, Proc. IRE, Sept. 1958 1655.
4 Terminal Ge Diode	f_s=214 mc f_p=150 mc	8	0.25 mc	2.5	100	Chang, Proc. IRE Jan. 1959, 81.
Ferrite Core Computer	f_s=f_o=f_p/2 f_p f_{clock} 6 mc 140 kc 2 mc 24 kc 200 kc 2 kc	----------	-------	-----	 120 30 5	Goto, Proc. IRE August. 1959, 1304.
Ge 1N23 Pt. Contact Diode	f_p = 4 Kmc f_o=f_s= 2 Kmc f_{clock}=100 mc	----------	-------	-----	---	Sterzer, Proc. IRE Aug. 1959, 1317.
Supperregenerative - Si Mesa Diode	f_p = 10 Kmc f_s = 780 mc f_{quench}=0.25 mc	56-85	1.5-2 mc	1	---	Younger, Proc. IRE June 1959, 1271.
Harmonic Gen. Ge Diode	f_p = 24 Kmc f_o = 48 Kmc	Power out 1.4 mw	--------	-----	80	Kita, Proc. IRE June 1958, 1307.
Microwave Si Diode	f_p = 12 Kmc f_o=f_s=6 Kmc	Approx. 18	Approx. 8 mc	5-6	---	Hermann, Proc. IRE June 1958, 1301.

study were not ideally filtered, qualitative results indicate an apparent noise reduction and quantitative measurements show a definite useful power gain.

In view of the apparent advantages of simplicity, economy of operation and construction, reliability, and practically unlimited life, it is concluded that serious consideration should be given to incorporating junction diode parametric amplifiers in future medium-frequency radio receivers.

Suggestions for Future Investigations

Numerous application possibilities came to mind during the course of this study. Naturally, the most obvious were derivatives of vacuum tube and transistor circuits. Bandspread and multi-band tuning techniques are well known, and the costs of vacuum tubes and transistors for frequencies below 100 mc are competitive. In the interest of economy and miniaturization, it appears desirable to use a transistorized oscillator for the pump source where low pump power is required.

The author has not been able to find any reports of audio or low radio-frequency experimental work in which diode parametric amplifiers were used. The possibility of investigating whistlers, and other very-low-frequency propagation, such as the 60 kc National Bureau of Standards Station at Boulder, Colorado is appealing.

It appears that any study of the structure of the ionosphere would be materially enhanced with the use of a parametric amplifier. The use of the 20 mc WWV signal in the passive detection of vehicles in flight, at radial distances of up to 1000 miles above the earth, has been reported by Krause (1958).

In addition to the possibility of using mesa transistors as diodes, the bridge-type circuit reported in this thesis deserves additional investigation with diodes designed for parametric amplifier applications.

The possibility of using high-Q quartz crystals or ceramics as filters at low frequencies should not be overlooked.

The use of transistors in future investigations may lead to a circuit configuration where a portion of the transistor is used as a low-loss diode and the remainder is used as an oscillator to supply the pump power.

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