APPLICATION NOTES

APPLICATION NOTE 35
MASERS AND PARAMETRIC AMPLIFIERS

INTRODUCTION

This Application Note is divided into three major sections:

1) Instrumentation
2) Masers
3) Parametric Amplifiers

The first section presents typical measurements and the major areas of activity in the Maser and Parametric Amplifier fields. Sections 2 and 3 give general information about the performance and operation of the units.

MASER-PARAMETRIC AMPLIFIER INSTRUMENTATION

Both the Maser and the Parametric Amplifier (MAVAR) operate at noise figures far below anything found in conventional amplifiers. This is an important advantage since in many applications system performance is limited by its noise figure.

Parameters that are usually measured are: gain, bandwidth, noise figure, signal frequency, signal power, RF pump frequency and RF pump power. These measurements, as such, are quite common. So, many hp instruments are in use already. For example, hp Signal Generators are used as RF pumps in some cases. Other suggested instruments are Model 415B Standing Wave Indicator, 416 Ratio Meter for gain measurement; hp frequency measuring equipment for bandwidth; 430C or 434A Power Meters for power measurements and Noise Figure Meters for noise figure in certain applications. In addition, general microwave instruments such as Attenuators, Adapters, Tuners and Detector Mounts are useful.

Hewlett-Packard has not yet had direct experience with the application of hp instruments to Maser and Parametric Amplifier measurements. So, for the time being, a match between available instrumentation and measurement requirements can best be obtained by a presentation of instrument capabilities by the field engineer and a customer evaluation of capabilities in terms of his measurement needs.

Areas of Activity:

Because of the significance of Masers and Parametric Amplifiers, many agencies such as corporations, universities, and military laboratories are conducting research. To provide a general idea of who is doing what, the following table has been included.[1]

TABLE I - ORGANIZATIONS REPORTED TO BE DOING MASER AND PARAMETRIC AMPLIFIER RESEARCH

ORGANIZATION	MASER			PARAMETRIC AMPLIFIER
	TYPE	FREQUENCY	MATERIAL	TYPE
Advance Industries	Solid State	S Band X	Ruby Ruby	-
Airborne Instrument Labs.	3-level, solid state	L (1. 2-1. 3 kmc)	Ruby	Diode and Traveling Wave
Air Force Cambridge Research Center	-	-	-	Ferrite
Armour Research Labs.	Solid State	X	Ruby	-
Bell Telephone Labs.	Traveling Wave 3-level, solid state 3-level, solid state	X X (9 kmc) X (6 kmc)	Ruby Lanthanum ethyl sulfate Lanthanum ethyl sulfate	Diode, Beam, Traveling Wave and Ferrite
California Institute of Technology	-	-	-	- Diode
Columbia University	3-level, solid state	X (3 cm)	Ruby	-
Evans Signal Laboratories	-	-	-	Diode and Beam
Ewen Knight	Traveling Wave (helix) 3-level, solid state 3-level, solid state 4-level, solid state	X (8 & 9 kmc) S (2. 3 & 3 kmc) X (8 kmc)	Ruby Ruby & Potassium chromicyanide - Ruby	Diode

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TABLE I - (Continued)

ORGANIZATION	MASER			PARAMETRIC AMPLIFIER
	TYPE	FREQUENCY	MATERIAL	TYPE
G. B. Electronics	-	-	-	Diode and Ferrite
General Electric	3-level, solid state 3-level, solid state	X (9. 19 kmc) S (2. 82 kmc)	Ruby Ruby	Diode
Harvard University	3-level, solid state	L (21 cm)	Postassium cobalticyanide & postassium chromicyanide	-
Hoffman Electronics	-	-	-	Diode
Hughes Aircraft	Molecular beam solid state	24 kmc X	Ammonia Lanthanum ethyl sulfate	Diode, Ferrite, electron beam
ITT Laboratories	-	-	-	Diode
Lavoie Laboratories	-	-	-	Diode
Lincoln Labs.	3-level, solid state (several) traveling wave traveling wave	from 0. 3 kmc to 3 kmc X (9-10 kmc) L (1-1. 4 kmc)	Potassium cobalticyanide Chrome cyanide & ruby Ruby	Diode
Arthur D. Little	Molecular beam	24 kmc	Ammonia	-
Martin Company	-	-	-	Ferrite
Microwave Associates	-	-	-	Diode
Microwave Engr. Labs, Inc.	-	-	-	Diode and Ferrite
Microwave Research Inst.	-	-	-	Diode and Ferrite
M. I. T.	Solid State	X (8. 4-9. 7 kmc)	Ruby	Diode and Ferrite
Philco	Double cavity, molecular beam traveling wave	- -	Ammonia -	Diode and Ferrite
Polytechnic Research & Development	Molecular beam	24 kmc	Ammonia	-
Raytheon Manufacturing Co., Waltham	-	-	-	Diode and Ferrite
RCA Princeton	Molecular beam 3-level, solid state	24 kmc X (10 kmc)	Ammonia Ruby	Diode and Traveling Wave
Sage Laboratories, Inc.	-	-	-	Diode
Signal Corps Engineering Lab.	3-level, solid state Molecular beam	up to X up to K	Ruby Ammonia	-
Stanford University	3-level, solid state 2-level, solid state traveling wave	S (3 kmc) - S (3 kmc)	Ruby, potassium chromicyanide - Ruby	Diode and Beam
Sylvania Research Laboratories, Bayside	-	-	-	Diode and Traveling Wave
Texas Instruments	3-level, solid state	X (9 kmc)	Potassium cobalticyanide, ruby	Diode
University of California	2-level, solid state 2-level, solid state 3-level, solid state	X (9 kmc) - -	Magnesium oxide Potassium cobalticyanide Ruby	-
University of Michigan	3-level, solid state 4-level, solid state	X (10 kmc) -	Ruby -	Diode and Ferrite
Varian Associates	Molecular beam 3-level, solid state	24 kmc 88 kmc	Ammonia Barium, strontium or lead titanate	- -
Westinghouse Corp.	2-level, solid state 3-level, solid state	C X	Neutron-irradiated Quartz	Diode and Ferrite
Wright Air Devel. Center	3-level, solid state	S (2. 8 kmc)	Potassium cobalticyanide	Diode
Zenith Radio Corp.	-	-	-	Vacuum Tube

MASERS, GENERAL

Microwave Amplification by Stimulated Emission of Radiation

Maser amplifiers utilize the energy in a molecular system rather than the flow of electrons which you are used to thinking about. In general, a Maser consists of a crystal or gas placed in a cavity (cavity Maser) or in a piece of waveguide (traveling wave Maser). Energy is obtained by making the cavity material increase energy levels in one set of conditions so that it will give up energy in another set of conditions. The energy change is the product of the microwave frequency of the radiating field and Planck's constant: $E = hf$

A pumping signal with a frequency corresponding to the energy difference between the lowest and the highest crystal energy level is supplied by an external oscillator to change the energy level of the crystal. Because the energy level of the electrons in the crystal can be changed by varying a surrounding magnetic field, the output frequency can be tuned.

The low noise of the Maser makes it useful in many applications such as radar, radio astronomy, telemetering, scatter and satellite communications. For example, in a radar system if a Maser amplifier is inserted between the antenna and the mixer in the receiver, the system sensitivity is effectively increased because the noise figure has been reduced.

Masers operate at various RF signal frequencies from a few hundred megacycles through 24 kmc. For example, it is reported that early traveling wave masers used by Bell Telephone Laboratories had the following characteristics: [1]

Signal Frequency	5.9 kmc
Bandwidth	350 mc
Max. Output Power	22 dbm
Pump Power	100 mw
Pump Frequency	18.9 and 19.5 kmc

Cavity Type Maser:

Cavity type Masers contain either a gas stream (ammonia) or a crystal (ruby) in the cavity. In either case electrons in the cavity material are forced to give up energy. The Maser using ammonia (commonly called a molecular beam Maser) can be used as an accurate frequency standard. However, its narrow frequency band, poor tunability, and low output power limit its usefulness as an amplifier.

Cavity Masers can have a single external coupling line with a circulator, or they can use separate input and output coupling. The circulator Maser has superior gain bandwidth products, but forward losses in the circulator detract from top performance. Since gain bandwidth is important, designers have usually concentrated on the one port circulator Maser to either eliminate the circulator at the expense of gain or to improve the circulator.

Traveling Wave Maser:

The traveling wave Maser is very promising. It has a slow wave structure instead of a cavity. Thus, it can be tuned over a wide bandwidth by varying the pumping frequency (input microwave frequency which causes a crystal to change energy levels) and the magnetic field. It has unilateral amplification which makes circulators unnecessary. Further, its crystal material volume is greater than that in the cavity Maser which makes more power output possible.

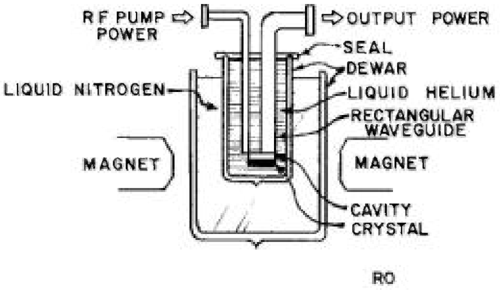

Figure 1. Typical Cavity Maser

Maser Operation:

A typical cavity Maser is shown in Figure 1. [2] The cavity containing the crystal is immersed in liquid helium contained in a Dewar (thermos). In order to conserve helium, the helium Dewar is sealed and it is immersed in liquid hydrogen. RF pump power is delivered to the cavity by the waveguide on the left and the signal from the antenna is delivered to the cavity by the waveguide on the right. Amplified signal from the Maser is also delivered through the right hand waveguide. Usually a circulator is used as shown in Figures 2 and 3. [2]

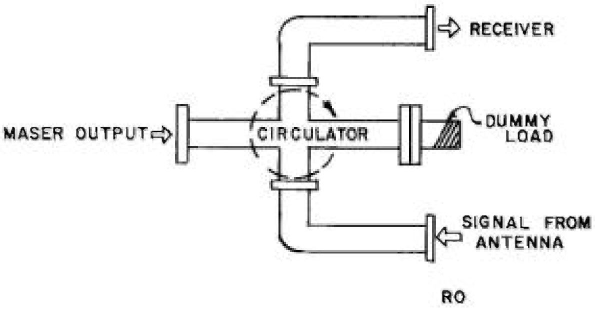

Figure 2. Circulator for Use with Maser

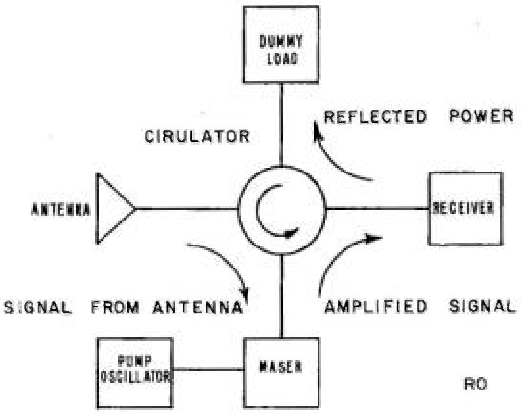

Figure 3. Block Diagram of Circulator Shown in Fig.2

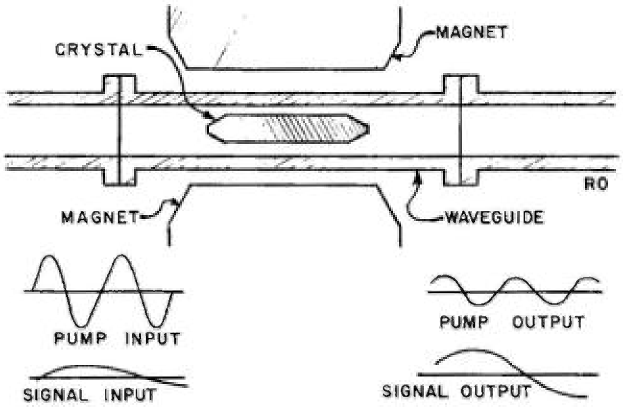

Figure 4. Cavity Material Orientation

The Maser action takes place in the cavity material which is shown in the center of the waveguide in Figure 4[3]. The waveforms show the amplification of the input signal at the expense of pump power.

MASER ACTION IN THE CRYSTAL

The key to the operation of the Maser lies in the interaction between high frequency radiation and matter.

According to the quantum picture of matter, every electron is essentially a small spinning magnet. In non-magnetic atoms paired electrons have opposite poles so that their magnetism is cancelled. However, in some substances the cancellation is incomplete and unpaired electrons result which makes the material paramagnetic. When paired electrons are placed in an external magnetic field the spinning electron can have just two positions according to quantum theory: 1) axis pointing in the same direction as the field 2) axis pointing in the opposite direction. The two positions represent different energy levels. The highest corresponds to the electron whose axis points in the direction of the field.

Radiation consists of photon particles carried by a guiding wave with a frequency related to the photon energy by Planck's equation $E = hf$. If the energy of the photon is exactly equal to the difference in energy between two states, a particle of radiation is produced when an electron falls from the higher to the lower energy state. When an electron rises to a higher energy level it absorbs a photon of the same frequency. Thus, when radiation passes through an assembly of electrons, there are three possibilities:

1. No interaction (energy of photon not equal to a difference pair of energy levels).

2. A photon collides with an electron in the lower state; radiation will be absorbed and the electron will rise to a higher state.

3. The photon will collide with an electron in the higher state, the electron will go down to a lower state and a new photon will be emitted.

Under normal conditions there will always be some changing of energy levels by the electrons resulting from chance collisions which raise them and from their natural tendency to seek the lowest energy level. Normally the lower states are more densely populated. Thus, when electrons are subjected to radiation (with the correct frequency) there will not be as many new photons generated as are absorbed and the output wave will be weaker than the input wave.

However, if the energy levels can be changed so that there are more electrons in the higher state, a photon beam (of correct frequency) would produce more drops than rises so more photons would come out than went in resulting in amplification.

The operation of the Maser involves putting most of the electrons in the upper state. Then if photons of the correct frequency pass through, they will drop, thus amplifying the input wave.

The three level paramagnetic MASER has a material with atoms containing more than one unpaired electron.

The solid state material is placed between the poles of a strong magnet and cooled to a temperature a few degrees above zero in a bath of liquid helium in order that most of its unpaired electrons will fall into the lowest state. (With more electrons in the lower state, the noise output is lower.) Then it is subjected to a microwave pulse (rf pump) which raises the majority of the electrons to a higher level. The difference between energy of the upper and lower levels depends upon the strength of the magnetic field. Thus, by adjusting the strength of the magnetic field the Maser can be tuned over a wide range of frequencies. A typical energy level diagram is shown in Figure 5.

The rf pump oscillator raises the electrons from energy level 1 to 3. $\Delta E_{1-3} = hf_{pump}$. Then, upon application of the signal, they drop from level 3 to 2 emitting photons. $E_{3-2} = hf_{signal}$. The electrons then relax from level 2 to 1, giving off energy to the crystal. These photons do not leave the cavity, however, because it will not support their frequency.

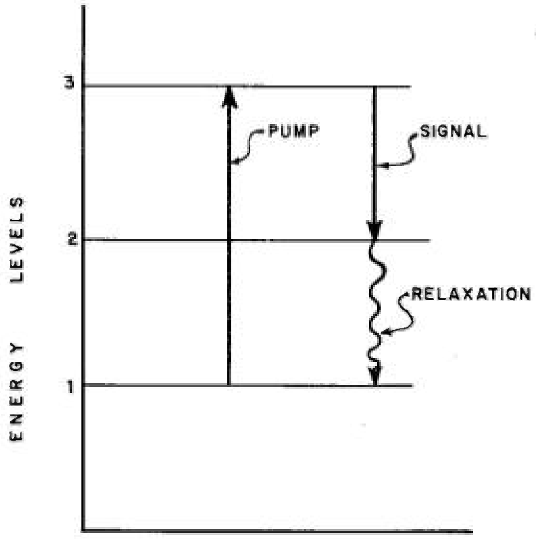

Figure 5. Effect of Pump and Signal Energy On Energy Levels

PARAMETRIC AMPLIFIERS

The Parametric Amplifier is similar to the Maser in that it has low noise, and it derives its energy from an RF pumping oscillator. However, the Parametric Amplifier achieves low noise amplification at room temperature and does not require liquid helium operating temperatures as the Maser does.

Since liquid helium cooling is not required, the Parametric Amplifier is simpler, more reliable, and more readily miniaturized than the Maser. It could, for example, contain only an rf pump, solid state diode and a piece of waveguide.

The Parametric Amplifier uses a variable non-linear reactance as its active element. The variable reactance may be a ferrite, semi-conductor diode, or an electron beam. The reactance used depends upon several considerations. For example, the ferrite device requires a permanent or electro magnet and operates at high power levels. Diode construction techniques are improving rapidly and offer a simple and compact low noise amplifier from K band down to DC.

An interesting variation of basic diode configuration uses four stages of diodes arranged so that a growing wave is generated as the signal travels through successive diode stages. The main advantage of this Traveling Wave Parametric Amplifier is an increase in bandwidth.

Parametric amplifiers, like Masers, operate at various microwave frequencies. Typical Parametric Amplifier Noise Figures, though higher than Maser Noise Figures, are lower than Noise Figures of conventional Microwave Amplifiers. Some typical reported performance figures for the four Parametric Amplifier types are shown in Table 2[4].

TABLE 2 - PERFORMANCE OF SOME TYPICAL PARAMETRIC AMPLIFIERS

TYPE	Pump Freq. (mc)	Pump Power	Signal Freq. (mc)	Signal Power	Noise Fig. (db)	Gain (db)	Bandwidth (mc)
Ferrite	9000	3 μs pulses 20 kw peak	4500	100 w	-	8	-
Diode	3500	100 mw	1200 or 2300	1.5 mw	4.8	19	1
Modulated Beam	8300	140 mw	4150	-	-	20	-
Traveling Wave	900	10 mw	400	-	3.5	10	100

Since Parametric Amplifier Noise Figures are low, they are ideally suited to low noise applications such as receiver operation. A typical application is shown in Figure 6 which is a block diagram of the front end of an International Telephone and Telegraph Corporation Laboratories receiver[1].

A 900 mc signal from an antenna is modulated with a 9.9 kmc pump signal in a parametric amplifier converter. A lower sideband signal of 9 kmc is mixed with a 9.07 kmc local oscillator signal giving a 70 mc IF signal. Reported performance is 20 db gain at a band width of 1-2 mc and a pump power less than 50 mw.

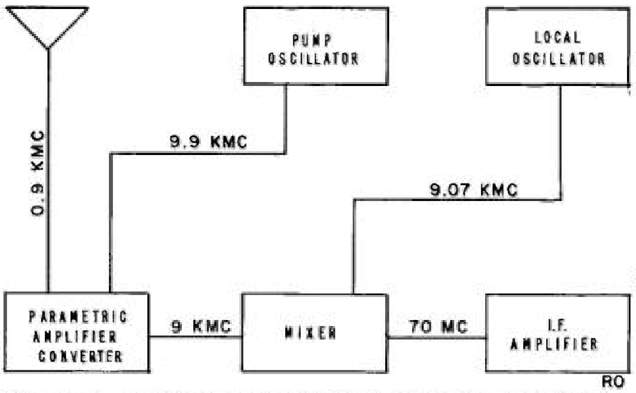

Figure 6. Typical Parametric Amplifier Application

PARAMETRIC AMPLIFIER OPERATION

The operation of parametric amplifiers hinges on the non-linear behavior of a reactive element.

Figure 7 shows a simplified equivalent circuit of a parametric amplifier with an inductive reactance element (L)[4]. (A ferrite would be used at microwave frequencies.)

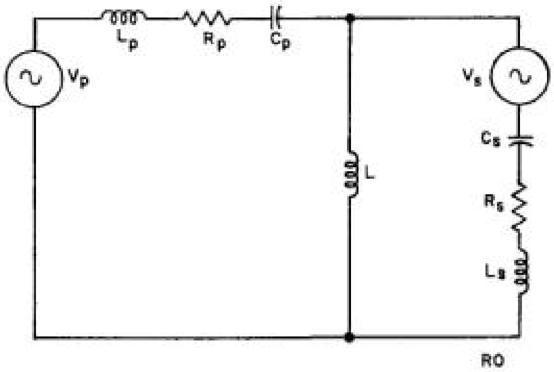

Figure 7. Simplified Parametric Amplifier Equivalent Circuit

A signal source V_s and a higher frequency RF pump V_p drive the non-linear reactance L. The inductor non-linearity causes upper and lower sideband frequencies. Now assume only four frequencies are permitted to flow through L; the pump frequency (f_p), the signal frequency (f_s) and the upper sideband (f_h) = $f_p + f_s$ and the lower sideband (f_ℓ) = $f_p - f_s$. The reactor is assumed to be a short circuit to all other frequencies. Then, analysis of the reactor power relationships shows[4]:

$$\frac{P_s}{f_s} = -\frac{P_h}{f_h} + \frac{P_\ell}{f_\ell} \qquad (1)$$

where positive P is power <u>leaving the reactor</u> and negative P is power <u>absorbed by the reactor.</u>

Now if we permit only power at the lower side band (P_ℓ) to exist in the reactor, equation 1 becomes:

$$P_s = P_\ell \frac{f_s}{f_\ell} = P_\ell \frac{f_s}{f_p - f_s}$$

Since P_s and P_ℓ are positive, power flows from the reactor at the signal frequency (f_s) and the lower sideband frequency.

Since you must maintain f for power to flow at the signal frequency, an "idler" circuit to absorb power at f_ℓ is added as shown in Figure 8[4]. Then with proper P_ℓ, f_s and f_ℓ relationship it is possible to obtain an amplification of signal power.

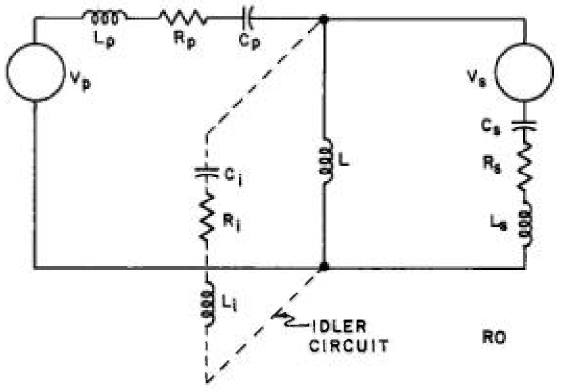

Figure 8. Parametric Amplifier with Idler Circuit

It can be shown that gain is equivalent to adding negative resistance in the signal circuit which is a function of pump power and is thus controllable.

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4. The Mavar: A Low-Noise Microwave Amplifier by Samuel Weber September 26, 1958 Electronics.

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