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LOW-NOISE SMALL-SIGNAL AMPLIFIER

D. Neuf and P. Lombardo

15 January 1963

Prepared under Navy, Bureau of Ships

Contract NObsr-87556

Interim Report No. 1

1 July 1962 to 25 October 1962

CUTLER-HAMMER
AIRBORNE INSTRUMENTS LABORATORY
DEER PARK, LONG ISLAND, NEW YORK
AIL DIVISION

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ABSTRACT

The present-day noise-figure limitations of electron tubes, tunnel diodes, and traveling-wave tubes do not permit their use in a low-noise S-band amplifier and, because cryostatic cooling techniques are not desired, the use of a traveling-wave maser is obviated. Therefore, the parametric amplifier is the only remaining practical low-noise S-band amplifier. The most successful broad-band parametric amplifier designed by AIL is the one-port difference-frequency amplifier, which uses the varactor diode self-resonance as the "idler" frequency. An evaluation is presented of two configurations of difference-frequency parametric amplifiers. The first breadboard models of both types of amplifiers are shown and practical data is presented. A recently published technique for broad-banding parametric amplifiers by means of two pumps is also evaluated.

I. STATEMENT OF PURPOSE

Contract NObsr-87556, Project SR-008-03-01, Task 9391, requires that research and development effort be conducted in the field of low-noise small-signal amplifiers with emphasis on four sample devices having the following specifications:

Frequency	Within S-band (2 to 4 Gc)
Gain	15 db (minimum)
Bandwidth	40 percent (minimum)
Noise Factor	2 db (maximum)
Dynamic Power Range	70 db
Cryostatic Cooling	None

II. TECHNICAL DISCUSSION

A. GENERAL

Parametric amplification is achieved by the use of a semiconductor P-N junction (varactor) that functions as a voltage variable capacitor. The varactor receives two voltages--one at a signal frequency and the other at a much higher frequency (pump frequency). The pump voltage at the varactor terminal is large and there is a large modulation of the diode capacitance at the pump frequency. The diode capacitance is nonlinear with voltage, and there is interaction between the pump and signal frequencies much in the same manner as normal heterodyning in a conventional crystal mixer. However, since the varactor is an almost pure capacitance, it permits interaction without any losses. In fact, depending on the type of external circuits, energy is transferred from the pump to the signal circuits without losing any of the modulation contained at the signal frequency. The increase in signal power represents the source of power gain for the varactor. Since the varactor too is nearly a pure capacitance, this gain is practically noise free. In practice, the small amounts of contact and spreading resistance are the source of amplifier noise (usually small).

A varactor can be used as an amplifier in several different ways. If amplification is required at the signal frequency, the interaction between the signal and pump frequency voltages can be considered as presenting a negative resistance at the signal frequency. Unilateral devices are presently available that exhibit a small insertion loss in one direction and high attenuation in the reverse direction

These devices (isolators) can be designed as circulators to isolate the input, amplifier, and output circuits. The simplest circulator has three ports--one for each of the referenced circuits. Because of its directive properties, the circulator can use the negative-resistance amplification available from the varactor. Such an amplifier is considered as operating in its regenerative negative-resistance mode.

In addition to the pump and signal frequency, the idler frequency is important in parametric amplifiers. The idler frequency is the difference between the signal and pump frequencies ($f_p - f_s$). Since the pump frequency is usually larger than the signal frequency, the pump and idler frequencies are reasonably close to each other. In practice, the varactor is tuned in one circuit at the signal frequency and in a second circuit at the idler frequency. The pump power is normally coupled through the idler circuit.

Although the parametric amplifier is usually thought of as a narrow-band device, it can be used as a broadband device as can be seen from equation 1 (reference 1).

The gain-bandwidth product of a one-port parametric amplifier with equal loading at f_s and f_i is:

$$G^{1/2}\beta = \frac{c_1}{c_0} \sqrt{f_s f_i} \qquad (1)$$

where

$\frac{c_1}{c_0}$ = nonlinearity ratio,

f_s = signal frequency,

f_i = idler frequency.

Equation 1 shows that a high value of idler frequency is desirable. In practice, a value of $c_1/c_0 = 0.35$ has been demonstrated on many programs at AIL.

Table I has been derived for an amplifier having a 15-db gain (for one, two, or three cascaded stages) and a signal frequency of 3 Gc.

TABLE I

GAIN-BANDWIDTH FEATURES

f_i	$G^{1/2}\beta$	3-db Bandwidth for an Overall Gain of 15 db (Mc)		
(Gc)	(Mc)	1 Stage	2 Stages	3 Stages
7.5	1650	300	700	930
10	1900	340	800	1100
15	2350	420	1000	1300
20	2700	480	1150	1500

Table I assumes that there is no bandwidth constriction because of the cascading arrangement, and that only single-tuned circuits are used.

Figure 1 is a typical circuit configuration using a one-port (negative-conductance) parametric amplifier with a circulator. The circulator is used to separate the forward and reflected (amplified) signals at the negative-conductance port. This type of amplifier can be further classified into either balanced or unbalanced configurations. Each circuit configuration has its own advantages and disadvantages; however, both are capable of large operating bandwidths and both will be maximized with respect to operating signal bandwidth.

B. CIRCUIT CONFIGURATIONS

1. BALANCED DIODE MOUNT

The balanced diode mount (two diodes) is an exclusive design of AIL and is presently being patented. A breadboard model of this mount has been designed and completely fabricated by our model shop (Figure 2), and is now being evaluated for performance.

Figure 3 shows the equivalent circuit for this mount. Its inherent wide-band capabilities can be attributed to the simple idler circuit, which consists of the two diodes in series between the ends of a small idler cavity. The bandwidth of the idler circuit is in the order of 1000 Mc. Therefore, it is possible to obtain a negative resistance at the signal frequency of at least 1000-Mc bandwidth.

Since this negative resistance has a small equivalent capacity in series with it, an inductance is added to resonate this capacity and thus leave a pure negative resistance. This is necessary before the diode resistance can be transformed into a value yielding more gain. The equivalent circuit of the diodes at the signal frequency is shown in Figure 4A. The method of tuning out the series diode capacity can be greatly improved with double tuning (Figure 4B). Without double tuning, the bandwidth of the signal circuit was typically 500 Mc; with double tuning the signal circuit bandwidth could be raised to at least equal the idler circuit bandwidth (1000 Mc). A two-section quarter-wave transformer is used to raise the diode negative impedance to a value that will yield a gain of 10 db.

2. SINGLE DIODE MOUNT

Figure 5 shows an unbalanced diode mount (one diode) constructed in our model shop. The equivalent circuit of this mount is shown in Figure 6. Unlike the balanced mount, the idler bandwidth of this mount is limited to about 10 percent of the idler frequency used because of the narrow-band performance of the quarter-wave open coaxial line used to provide the ground return for idler currents generated in the diode.

Typical idler resonant frequencies obtained from this mount have been on the order of 7 to 8 Gc. Corresponding idler bandwidths of 700 to 800 Mc were also obtained. If it were possible to obtain an idler resonance at 15 Gc, the idler bandwidth would be 10 percent or 1500 Mc, which is sufficient for a 40 percent amplification bandwidth at S-band. The signal circuit in the unbalanced mount is similar to that used in the balanced mount. Therefore, the same double-tuning techniques apply for broad banding the unbalanced mount.

Preliminary measurements have been made on the unbalanced mount using a new diode with low stray capacitance (manufactured by Solorac Corporation) and a 14-Gc idler resonance was obtained. This is very encouraging because it is now unlikely that the idler bandwidth will limit our signal frequency amplification.

C. BROAD-BANDING TECHNIQUES

1. CONVENTIONAL TECHNIQUES

Several techniques for broad banding now being investigated are feasible for obtaining an S-band parametric amplifier with an instantaneous bandwidth of 40 percent. These techniques are: (1) multiple tuned networks at the signal frequency port, (2) multiple tuned techniques at the idler port, (3) external resistive loading at the idler frequency, and (4) staggering (using two or more varactors) at the idler frequency. This final technique may be a combination of several of the techniques listed.

The initial starting point for all of these techniques is to obtain the broadest band parametric amplifier using only single-tuned circuits and then apply the same techniques to obtain the required 40-percent bandwidth.

2. BROAD BANDING BY DOUBLE PUMPING

A unique method of increasing the gain-bandwidth product of a parametric amplifier was recently described in the literature (reference 2). The method consisted of applying two pump frequencies separated by about 10 Mc to the varactor diode instead of the conventional single pump frequency. Rather startling improvements in the gain-bandwidth product of the parametric amplifier used were obtained in this manner.

The technique was investigated by AIL in an effort to determine if it could be applied to the development of a broad-band S-band amplifier. The results of our tests were disappointing because the improvement in gain-bandwidth product predicted was not apparent when other methods of measurement were used. In addition, the minimum detectable signal obtained from the double-pumped amplifier did not agree with the broad-band noise figure measurement.

D. CIRCULATOR DEVELOPMENT

During this report period, two circulator manufacturers have succeeded in developing three-port S-band circulators with bandwidths greater than 40 percent. Four of these circulators were ordered from the Melabs and are presently being used to evaluate the two breadboard varactor mounts. The Western Microwave Corporation has promised delivery of a circulator covering the complete S-band region (2 to 4 Gc).

In view of the technical breakthrough in circulator development accomplished by Melabs and Western Microwave, AIL has decided to drop its development program for a wide-band circulator for the S-band region and devote this effort to the wide-band diode mounts.

E. VARACTOR DIODES

Two types of varactor diodes are presently being used for application in this program:

Manufacturer	Model	Type of Junction
Microwave Associates	Pill	Silicon graded
Solrac	Cartridge	Gallium arsenide point contact

The Microwave Associates diode is presently being used in the balanced diode mount; the Solrac diode is being used in the unbalanced diode mount.

III. CONCLUSIONS

Engineering effort on the balanced and unbalanced diode mounts is proceeding, but it is not yet known which type of mount will be used for the final model. If neither mount is capable of 40 percent or greater bandwidth, an attempt will be made to stagger tune three or four 500-Mc bandwidth mounts. A theoretical investigation is being performed to determine which type of overall gain and noise factor will be expected from such a staggered triple or quadruple mount.

IV. PROGRAM FOR NEXT INTERVAL

Since the circulator development program has been dropped, the next report period will show much faster progress on the two varactor mounts. Effort will also be directed toward evaluating the gain, bandwidth, and noise-figure performance of the new low-capacitance Solrac diode used in an unbalanced diode mount, and the Microwave Associates diode used in a balanced diode mount.

V. KEY PERSONNEL

Brief biographies of the key personnel taking part in the program are included in this section.

PETER P. LOMBARDO

Mr. Lombardo received a B.E.E. degree from Brooklyn Polytechnic Institute in 1953 and is taking graduate courses at the same school.

Mr. Lombardo joined AIL in 1953 and is a Section Head in the Department of Applied Electronics. He has directed a number of parametric amplifier programs, including the ground station receivers for Advent and Syncom. This work required the development of parametric amplifiers, circulators, varactor multipliers, and limiters.

Other projects that Mr. Lombardo has worked on include the development of microwave harmonic and subharmonic generators using varactor diodes, experimental research on accurate broad-band temperature-limited diode noise sources, and the design of various IF amplifiers.

In addition, Mr. Lombardo has designed traveling-wave, backward-wave, and cavity-type parametric amplifiers; performed experimental work on broad-band amplifier coupling networks in the VHF, UHF, and microwave regions; and developed UHF and microwave receivers, low-noise vacuum-tube amplifiers, and parametric amplifiers for communications and radar applications.

DONALD A. NEUF

Mr. Neuf graduated from RCA Institutes in 1958 and is presently completing the requirements for a B.S.E.E. degree at Hofstra College.

Mr. Neuf joined AIL in 1958 and is an engineer in the Department of Applied Electronics. He has had considerable design and development experience with wide-band parametric amplifiers in the UHF, L-band, and S-band frequency regions. He also has participated in the Advent and Syncom parametric amplifier programs.

Other projects that Mr. Neuf has worked on include the design of octave-bandwidth low-noise UHF amplifiers using planar grid triodes and transistors and tunable and fixed-frequency preselectors using helical and stripline resonators. Mr. Neuf has also participated in the development of equipments used to study the ionosphere.

VI. REFERENCES

1. H. E. Rowe, "Some General Properties of Nonlinear Elements. II. Small-Signal Theory," IRE Proceedings, Vol 46, p 850-860, May 1958.

2. T. N. DeFilippis, D. Neuf, and P. Lombardo, "Further Comment on 'Double Pumped X-Band Parametric Amplifier with Extremely Large Gain-Bandwidth Product,'" IRE Proceedings, Vol 50, p 2378-2379, November 1962.

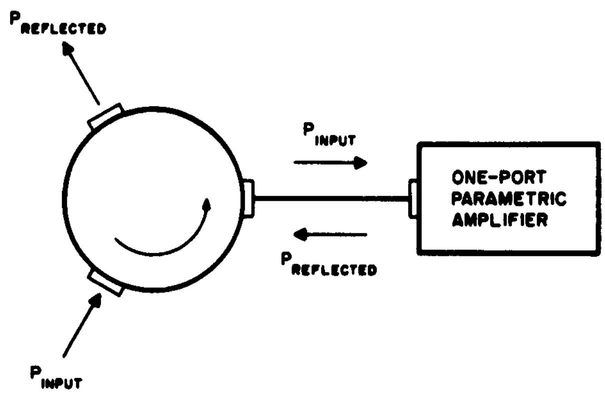


FIGURE 1. ONE-PORT PARAMETRIC AMPLIFIER WITH CIRCULATOR

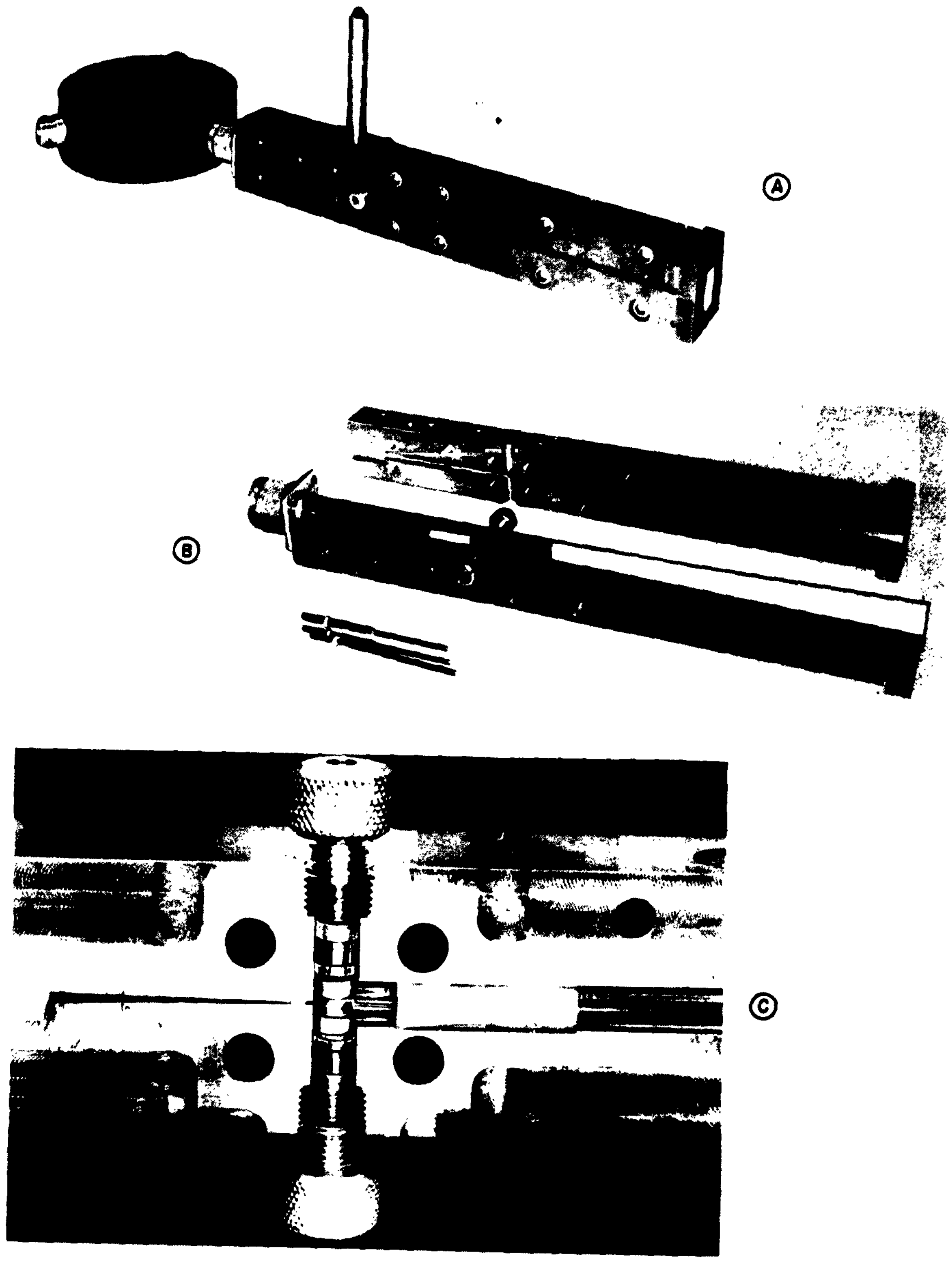
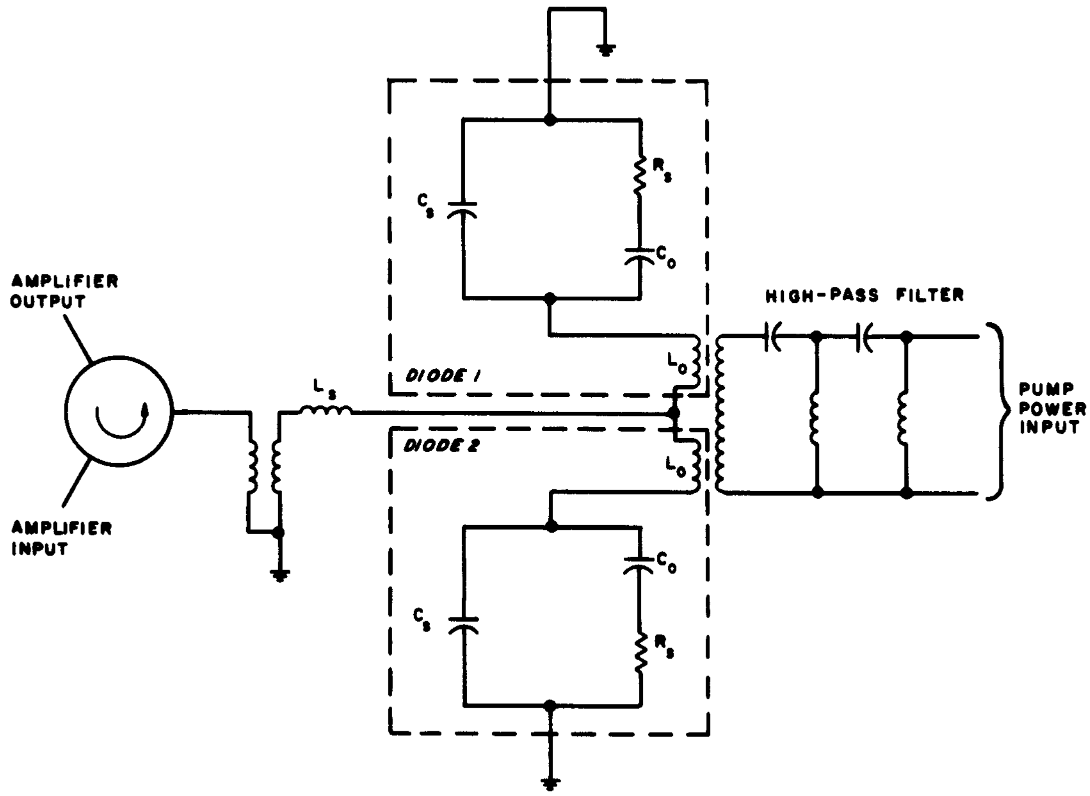


FIGURE 2. BALANCED DIODE MOUNT (TWO DIODES)



L_s = SIGNAL FREQUENCY TUNING INDUCTANCE
L_o = DIODE LEAD INDUCTANCE
C_o = JUNCTION CAPACITANCE
R_s = JUNCTION SPREADING RESISTANCE
C_s = DIODE STRAY CAPACITANCE

FIGURE 3. SCHEMATIC DIAGRAM OF BALANCED DIODE MOUNT

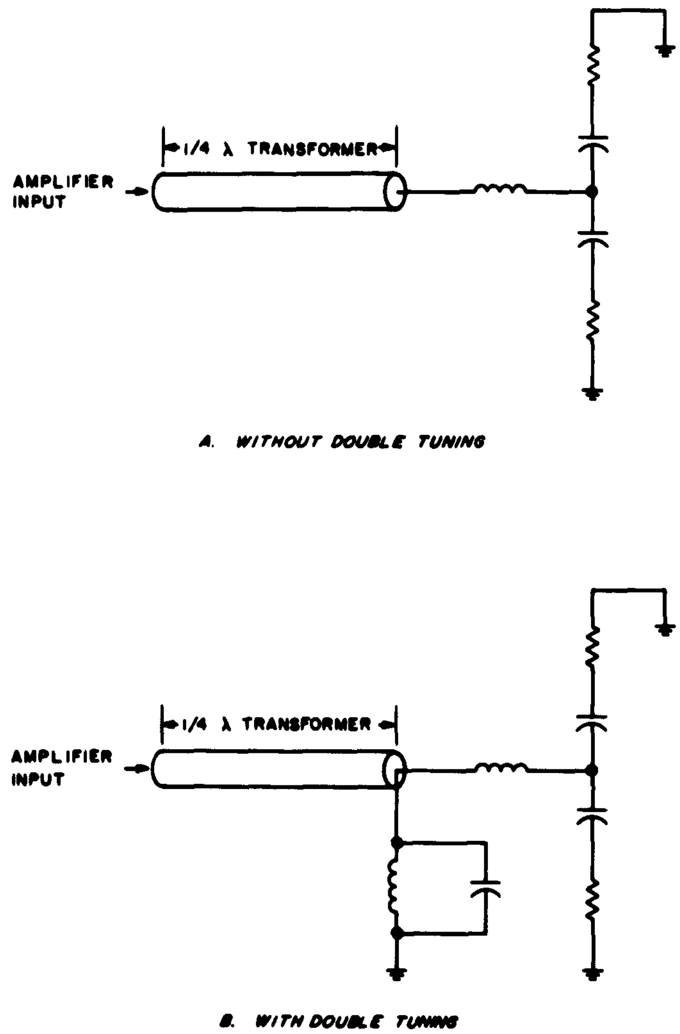


FIGURE 4. EQUIVALENT CIRCUIT FOR BALANCED DIODE MOUNT WITH DOUBLE TUNING

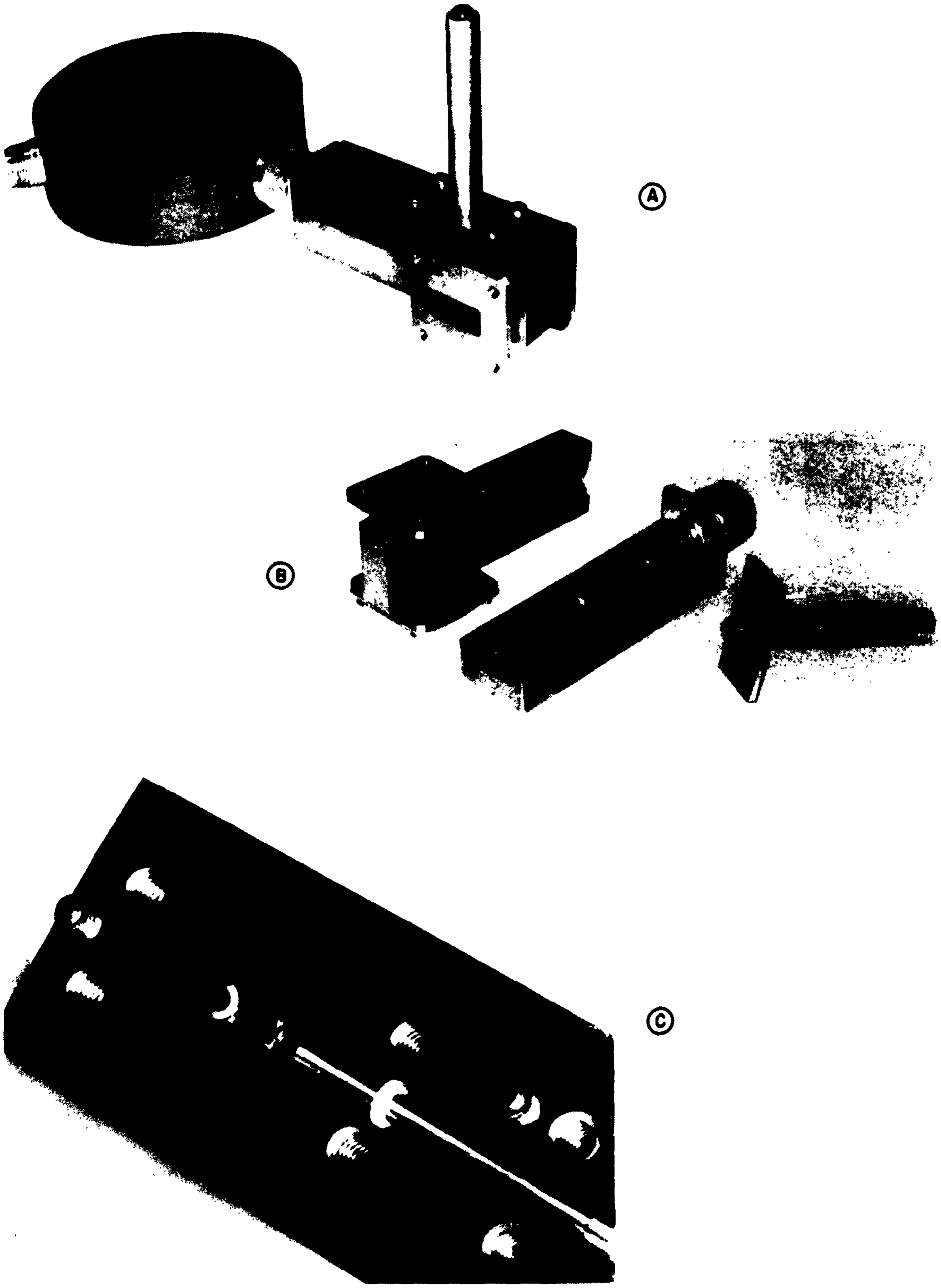
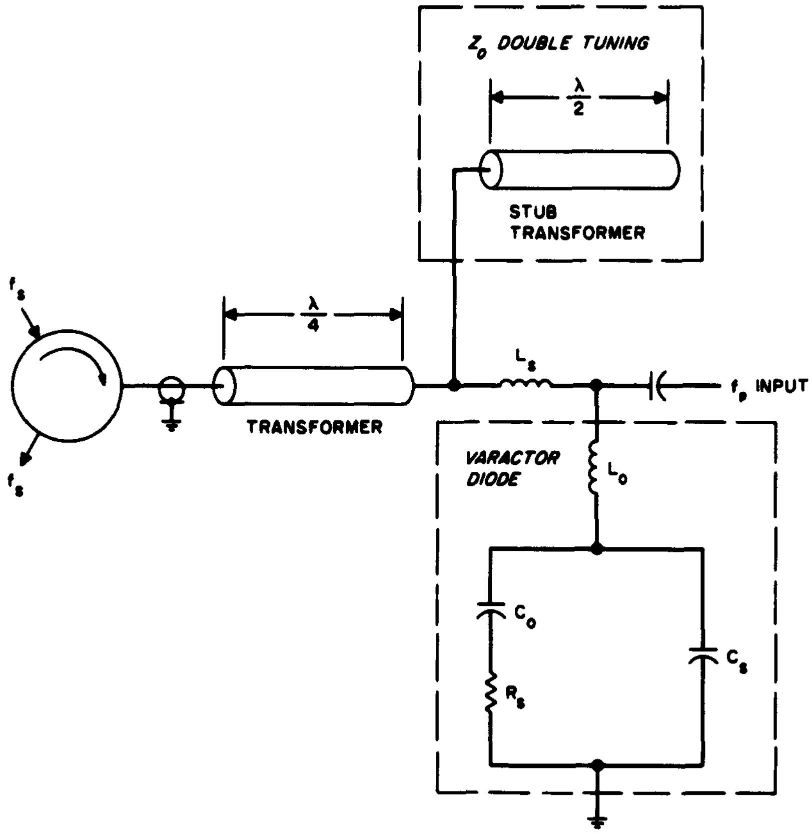


FIGURE 5. UNBALANCED DIODE MOUNT (ONE DIODE)



L_0 = DIODE LEAD INDUCTANCE

C_s = DIODE STRAY CAPACITANCE

C_0 = JUNCTION CAPACITANCE

R_s = JUNCTION SPREADING RESISTANCE

L_s = SIGNAL FREQUENCY TUNING INDUCTANCE

FIGURE 6. SCHEMATIC DIAGRAM OF UNBALANCED DIODE MOUNT

APPENDIX

FURTHER COMMENT ON "DOUBLE-PUMPED X-BAND PARAMETRIC AMPLIFIER WITH EXTREMELY LARGE GAIN-BANDWIDTH PRODUCT"

by

T. N. DeFilippis, D. Neuf, and P. Lombardo

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A recent letter to the IRE reported rather startling improvements in gain bandwidth product of parametric amplifiers by the use of a second pump. The purpose of this communication is to report on several important measurements made at AIL that were neglected by the author in the above referenced letter. Measurements made at AIL on a double pumped parametric amplifier indicate that 1) the sensitivity (not the broad-band noise factor) is degraded, 2) the amplifier generates a multitude of spurious outputs, and 3) the increase in gain-bandwidth is not real, but is only an apparent one dependent on method of measurement.

The parametric amplifier that was employed in our experiments used a MA 4254 varactor having a zero bias capacitance of 0.8 pf and operated at a signal frequency of 1800 Mc. The amplifier (with a single pumping) yielded a gain of 15 db with a 3 db bandwidth of 50 Mc. The measured over-all noise factor was about 2.2 db (with a second-stage noise factor of 11 db). Fig. 1A shows the measured performance of the amplifier with single pumping and double pumping (with a 10-Mc spacing between pumps). This measurement was made by use of a swept signal generator and a broad-band detector feeding a HP 130B scope. It was initially thought that the pump frequencies were leaking into the output detector producing unwanted responses, consequently, a low-pass filter having a cutoff frequency of 4000 Mc was added to the output (before the detector) and there was no significant change in the response.

A double-tuned 10-Mc wide band-pass filter was then inserted before the detector and the results are shown in Fig. 1B. The filter led to a decrease in apparent gain of the double-pumped parametric amplifier (shown in the middle curve), but it did not narrow the pass band as should obviously have occurred. The filter characteristis is also shown in Fig. 1B. The horizontal sweep corresponds to a frequency of 1.55 Gc at the low end and 1.9 Gc at the high end.

A noise factor measurement of the double-pumped parametric amplifier was made utilizing a helix noise generator, a double-tuned 10-Mc wide preselector, and a mixer followed by a 30-Mc preamplifier and post amplifier combination. It was found that careful adjustment of the local oscillator had to be made to avoid regions of high spurious output. Discrete points of high noise spikes were found to exist approximately every 10 Mc (the double-pump spacing) as the local oscillator and preselector were varied. Table I lists the measured results obtained with a single-pumped and double-pumped parametric amplifier. Although the broad-band noise factor was relatively good, the CW sensitivity (MDS) was severely degraded.

We have not had the opportunity yet of making any theoretical investigations of the double-pumped case; therefore, we can base our conclusions only on the experimental evidence that we have obtained.

We believe the reasons for the discrepancies are:

1) The beating of the two pump oscillators results in a forced on-off modulation of the gain (if we assume equal pump voltages applied to the varactor) at a rate equal to the difference frequency (or beat rate) at the double-pump spacing. When the pump frequencies are in phase, we get reinforcement of the voltage and an attendant high gain condition, and when the pump frequencies are out of phase we get cancellation of the pump voltage and a corresponding low gain condition. This modulation will take place at the difference frequency (the difference between the two pump frequencies).

2) Spurious outputs are generated when a fixed input frequency is applied to the varactor. These outputs will be present over the entire bandwidth of the input circuit and will be separated in frequency by the difference in pump frequencies. This conclusion would explain why a narrow-band filter inserted in the output does not narrow the over-all pass band. The presence of spurious outputs also explains the discrepancy between the broad-band noise factor and the CW sensitivity.

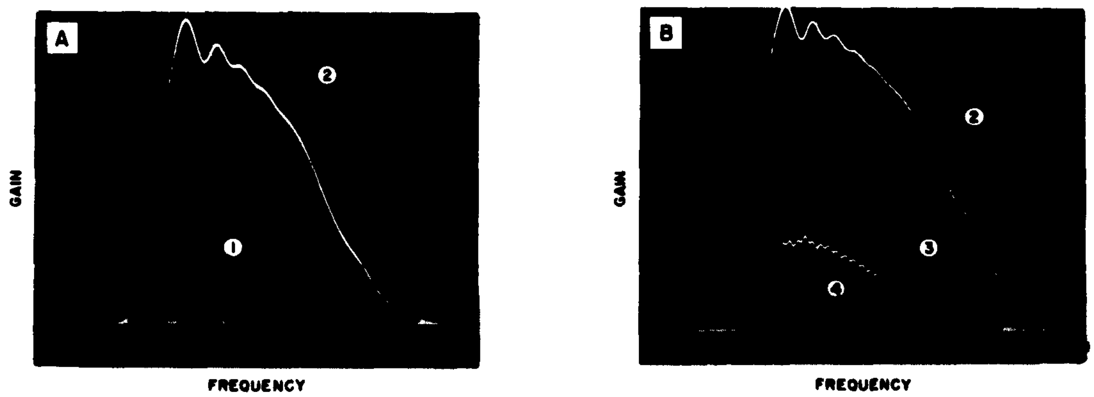
3) Spurious outputs are present (of low amplitude) when no input signal is present. These outputs are separated in frequency by the difference between the pump frequencies. Consequently, the CW sensitivity is determined partly by the proximity to one of the spurious outputs.

The double-pumping scheme has been shown to be of questionable value as a means for obtaining a low-noise broad-band parametric amplifier.

TABLE I

	Signal Frequency	Gain	Measured Broad-band Noise Factor	MDS*
Single pump	1800 Mc	15 db	2.2 db	-108.8 dbm
Double pump	1800 Mc	16.5	2.0	-102.8
Double pump	1800 Mc	22.0	1.9	- 85.8

* MDS (minimum discernible signal) was measured with a 2.0 Mc post receiver bandwidth.



(1) SINGLE-PUMPED CASE
GAIN = 15 DB

(2) DOUBLE-PUMPED CASE
GAIN = 30 DB
PUMP FREQUENCIES = 10.150 AND 10.160 GC

(3) OUTPUT RESPONSE WITH A DOUBLE-TUNED 10-MC PRESELECTOR ON THE OUTPUT TO THE DETECTOR

(4) RESPONSE OF THE PRESELECTOR ALONE

FIGURE I. GAIN AS A FUNCTION OF FREQUENCY

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