NATIONAL RADIO ASTRONOMY OBSERVATORY
Green Bank, West Virginia

Electronics Division Internal Report No. 74

WIDEBAND TUNABLE PARAMETRIC AMPLIFIERS

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JUNE 1968

NUMBER OF COPIES: 100

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ABSTRACT

Satellite communications and radio astronomical applications need large frequency bands, often exceeding the limits of instantaneous bandwidths of receivers. Tunable amplifiers can assist in this need. After a survey of various tuning methods this report describes the simplest method, which is by means of bias voltage. Analysis and experiment show 300 MHz electronic tuning range around 1.7 GHz (gain 15 dB, noise temperature 80°K, instantaneous bandwidth 25 MHz.) A new and simple method facilitates one octave tuning range. In agreement with the theory, tuning between 4 and 8 GHz is achieved using one single knob. Noise temperature varies between 80°K and 240°K, bandwidth between 45 MHz and 110 MHz at constant gain of 17 dB.

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1. INTRODUCTION

One of the key elements of low noise microwave receivers for satellite communications, as well as for radio astronomical observations, is the parametric amplifier. For amplification of signals within a wide frequency range one of two methods can be used, either amplifiers with a wide instantaneous bandwidth or amplifiers having a wide tuning range. For the time being a maximum of about 13% instantaneous bandwidth has been achieved with a gain of 12 dB in one stage. (1,2,3)

The second method, which permits coverage of several times larger frequency bands is to tune amplifiers. (1,4,5,6,7) Various methods exist which accomplish the desired tuning. However, only a few attempts have been made to analyze these methods and to choose the best one. This report, therefore, after some basic remarks, gives a survey of the various methods. Later on it will go into more detail about

(1) the purely electronic tuning by means of the bias voltage only, and

(2) a new method, which permits coverage of one octave band by means of a simple combined mechanical and electronic control. This method does not require a pump frequency change such as others do. (7)

The practical results on amplifiers which are tunable electronically over 20% frequency band around 1.7 GHz, and on an amplifier which is tunable between 4 and 8 GHz, confirms the theoretical predictions.

The data of these tunable amplifiers will be compared with wideband amplifiers which are not tunable.

In conclusion statements are made about the advantages and disadvantages of tunable amplifiers.

2. Fundamentals

If one wants to design tunable amplifiers one has to consider carefully the C/V-curve of the varactor diode.

For an optimized paramp the RF voltage of the driving pump source covers the whole range between the breakdown point of the diode and the forward limit of too high shot noise. The described varying pump voltage causes the capacitance modulation, which creates the desired negative impedance. One is interested particularly in the first Fourier-coefficient C_1 and the mean value C_M of the varying capacitance. The higher the ratio

$$\gamma = \frac{C_1}{2C_M}$$

is, the lower is the noise temperature and the greater the bandwidth.

Unfortunately, one has to consider for the practical varactor-diode a lot of stray reactances, which not only deteriorate the performance somewhat, but also determine the layout and features of the practical amplifier to a great extent. The signal circuit usually can be represented by the elements of Figure 1a. One of the major problems is the idling circuitry. It is advisable to use one of the self resonances of the diode for the idling to obtain the best noise and bandwidth results (8-12). In the case of the so-called series resonance (resonance of the junction capacitance C_M with the lead inductance L) one tries to shorten the case capacitance of the diode by an external short. Most of the balanced amplifiers utilize this kind of operation (Figure 1b). In the second case of the so-called "parallel resonance" (resonance of the junction capacitance C_M, the case capacitance C_c and the lead inductance L) one tries to provide an external open circuit for the diode within the idling bandwidth.

3. Various Possibilities of Tuning

3.1 Pump Frequency - Variation

Looking at the basic relationship for parametric amplifiers:

$$f_1 = f_p - f_2 \tag{1}$$

One can easily see that by varying the pump frequency f_p one can tune the signal frequency f_1, provided the signal bandwidth B_1 is large enough. This method has some disadvantages for operational amplifiers:

(1) The klystrons, which are commonly used as pump oscillators, usually require sophisticated mechanical and electronic two-knob adjustments for frequency changes.

(2) The pump circuits usually cannot be made broadbanded enough, without deteriorating the idling and signal circuits.

3.2 Mechanical Changes (Signal-Idling)

Mechanical tuning can be made in the signal and idling circuits. In the instance of idling tuning one can add an external capacitance to the diode case capacitance, whereas in the case of mechanical signal tuning it is more convenient to change the external inductance L_{ext} (Figure 1a) by moving the signal transformers. Both methods allow some tuning. Mechanical change of the signal circuit usually yields a wide tuning range. The disadvantages of mechanical tuning are common to both methods:

(1) Relatively poor reproducibility

(2) Extremely high mechanical precision required

(3) Deterioration of the performance is likely after several thousand tunings.

(4) Mechanical tuning is difficult in cooled applications

3.3 Voltage-Tuning

Electronic tuning of paramps by means of varying the varactor bias voltage is, from the viewpoint of operation, the most desirable. If one looks at Figure 1a, one can easily see that an increase of the bias voltage, which reduces the mean junction capacitance C_M, of the varactor results in raising the signal midband frequency. On the other hand, Figures 1c and 1d show that the idling midband frequency reacts in the same manner when the bias voltage is increased. At a constant pump frequency both tendencies seem to compensate each other, which would mean that the bias voltage does not affect the midband frequency of the paramp. Actually it does. Increasing the bias voltage can tune the amplifier midfrequency either upward or downward, depending on the mode of operatiion, the signal and idling bandwidths, and other things. If one wants to change the bias voltage one must avoid drawing the diode to either one of the mentioned forward and breakdown limits. It can be accomplished by reducing the pump voltage. This again automatically results in decrease of the dynamic Q-factor

$$\widetilde{Q} = \gamma Q = \gamma \frac{f_c}{f_1}$$

where f_1 is the signal and f_c the cutoff frequency of the diode. Later we shall see how this affects the bandwidth and noise temperature.

3.4 Combinations

The widest tuning ranges up to one octave can be achieved by applying two or more of three methods mentioned at one time. In addition, one always has to adjust the pump power, as in all the other cases. In any instance it is necessary either to adjust three knobs manually, or to provide an electronic servo system. This can be done by a simple method which will be discussed later.

4. Voltage Tuning

Because the bias voltage method of tuning is the simplest and safest for external adjustment, I will go into more detail about this method.

Voltage tuning makes it necessary to reduce the pump voltage and therefore causes a reduction of the γ factor. In a certain range one can compensate the deterioration of the Q factor by choosing a higher cutoff frequency. The basic requirement for tunable amplifiers is therefore to have varactors with as high cutoff frequencies as possible.

The next question is the ratio of idling to signal bandwidth. It is usually much easier to widen the signal circuit bandwidth than to widen the idling bandwidth. In addition, one gets wider tuning ranges from the idling circuitry because the influence of the capacitance C_M on the idling midband frequency is stronger than the one on the signal circuit midband frequency. One easily sees the reason for this fact if one compares the simpler idling circuits with the more complicated signal circuit.

Let us now investigate the influence on the bandwidth and the noise temperature. Figure 2 shows the relative gain bandwidth products dependent on the ratio of idling to signal frequency. Parameter is the dynamic Q. $\sqrt{GB}$ is computed for the two idling self resonances already mentioned. One can see that a reduction of the dynamic Q by a factor of 2, which is necessary, reduces the gain bandwidth product by about the same factor. The noise temperature reacts in about the same manner on Q factor changes: it deteriorates substantially, as shown in Figure 3.

5. Combined Single-Knob Tuning of the Signal and Idling Circuits

5.1 Principle

The following investigates how amplifiers can be tuned whose bias is varied together with their signal-circuit tuning. The technical realization of configurations where a linear relation exists between the bias V_D and the line length l_a is particularly easy (Figure 8b). For this purpose the relation between the bias V_D and the idling and signal frequencies, respectively, must first be studied. For the dependence of the mean junction capacitance, C_M on the bias V_D the well-known equation

$$C_M = \frac{C_{Mo}}{\sqrt{1 - V_D/\phi}} \tag{2}$$

for high doping and an abrupt transition is employed. C_{Mo} here is the mean barrier-layer capacitance at the bias $V_D = 0$ and ϕ the contact potential. In the case $f_2 = f_{E1}$ (idling frequency = series self-resonance frequency) one obtains for the signal frequency, using the Eqs. (1), (2)

$$\frac{f_1}{f_{1o}} = \frac{f_p}{f_{1o}} - \left(\frac{f_p}{f_{1o}} - 1\right) \cdot \sqrt[4]{1 - V_D/\phi} \tag{3}$$

Here f_{1o} is the signal mid-frequency at zero bias:

$$f_{1o} = f_p - \frac{1}{2\pi\sqrt{L\ C_{Mo}}} \tag{4}$$

The condition for the magnitude of l_a is that the impedance Z_1 in Figure 8b is purely resistive. From the condition $X_1 = 0$ the equation

$$\cot \frac{\omega_1\ l_a}{c} = Z_L\ \omega_1\ C_c + \frac{Z_L}{\frac{1}{\omega_1\ C_M} - \omega_1 L} \tag{5}$$

results for a resistive impedance $Z'_1 = R'_1 \ll Z_L$. It should be noted that the quantities C_M and ω_1 in Eq. (5) are not independent variables but are interrelated in a complex way via the Eqs. (2) to (4). The Eq. (5) was evaluated for an amplifier having the following data:

$f_{1o} = 8$ GHz	$C_{Mo} = 0.32$ pF
$Z_L = 50\Omega$	$f_p = 22.6$ GHz
$C_c = 0.48$ pF	$f_{co} = 293$ GHz ($V_D = 0$)
$L = 0.2$ nH	$\Phi = 1.1$ V
$L_{add} = 0.24$ nH	

The inductance L_{add} represents the external reactance for the idling circuit and lies in parallel to the capacitance C_c in Figure 1b. With these values one can get a nearly linear relationship between 1_a and V_D over one octave band. It is interesting to note that the modulation factor γ can keep an almost constant value of $\gamma = 0.1$ at a gain of 17 dB in a nearly frequency independent manner.

5.2 Frequency Dependence of Noise Temperature and Instantaneous Bandwidth:

The noise temperature referred to the ambient temperature T_a results as:

$$\frac{T}{T_a} = \frac{1}{f_p/f_1 - 1} + \frac{f_p/f_1}{\frac{\gamma^2 f_{co}^2}{f_1^2} \frac{\left(f_p - f_1\right)^4}{\left(f_p - f_{1o}\right)^4} + 1 - f_p/f_1} \tag{6}$$

Figure 6 plots the dependence of the noise temperature T on the signal frequency f_1 with different parameters f_p/f_{1o}. With increasing signal frequency the noise temperature rises. An increase in the pump frequency by a factor of two reduces the noise temperature merely by about 10%, as is evident from Figure 6.

Since all essential parameters (C_M, f_2, 1_a, f_c) change when the amplifier is tuned through its range, it can be anticipated that the total bandwidth of the amplifier also changes strongly. The bandwidth B_2 of the idling circuit, shown in Figure 1b is given by

$$B_2 = f_2^{\,2}\ 2\pi r C_M = \frac{f_2^{\,2}}{f_c} \tag{7}$$

Under the condition

$$Z_1' \ll Z_L \tan \frac{\omega_1 1_a}{c} \tag{8}$$

the variation of the signal-circuit reactance X_1 (Figure 8b) is found to be

$$\frac{dX_1}{d\omega_1} = L + \frac{1}{\omega_1^{\,2}\ C_M} + \frac{C_c + \dfrac{1_a}{cZ_L \sin^2 A}}{\left(\dfrac{1}{Z_L \tan A} - \omega_1 C_c\right)^2} \tag{9}$$

and the resistive part R_1 is found from the equation

$$R_1 = \frac{Z_L\ (m^2 + \tan A)\quad (1 + \tan^2 A)m}{(m+m \tan^2 A)^2 + (m^2 \tan A - \tan A + m^2 Z_L\ \omega_1 C_c + Z_L\ {}_1 C_c \tan^2 A)^2} \tag{10}$$

with the abbreviations

$$m = \frac{Z_1'}{Z_L} \tag{11}$$

and

$$A = \frac{\omega_1 \, l_a}{c} . \tag{12}$$

From the Eqs. (9) and (10) the signal bandwidth B_1 is found as

$$B_1 = \frac{R_1}{\pi \frac{dX_1}{d\omega_1}} \tag{13}$$

and the gain bandwidth product $\sqrt{G}\,B$ as (13).

$$\sqrt{G}\,B = \frac{2}{\frac{1}{B_1} + \frac{1}{B_2}} \tag{14}$$

These bandwidth calculations were carried out for the amplifier with the aforementioned data. The dashed curve of Figure 7 shows the result. A slightly rippled curve results, with the value of $\sqrt{G}\,B$ varying between 350 and 800 MHz. If the variation Z_1' with the frequency were considered, the values of the product $\sqrt{G}\,B$ would be lowered by about 20% at the band edges (4 and 8 GHz) in Figure 7. This then results in a slightly humped curve which is shown in dot-dash fashion in Figure 7.

6. Experimental Results on Amplifiers in the L- and C-Bands

6.1 Voltage Tunable Amplifiers:

Figure 4 (a and b) shows a tunable paramp, which has a coaxial input with a slot in the input line and a waveguide input containing a taper to a reduced height waveguide of only 20 mil height.

Figure 5 shows some results of this single ended amplifier, which operates around 1.65 GHz. Using different signal transformers Z_T one can accomplish tuning ranges between 120 and 300 MHz. As shown above, the smaller the tuning range is, the better are the noise temperature and the instantaneous bandwidth. The noise temperature, as measured, lies in the order of 70 - 80°K. If one would design this paramp for maximum instantaneous bandwidth, one would get about 60 MHz bandwidth in the instance of single tuning, and about 90 MHz in the instance of double tuning. Because of full pumping the noise temperature would lie between 30 - 40°K.

In a certain range the ratio of the noise temperature T and the tuning range Δf can be described by a constant

$$T \ / \ \Delta f = \text{constant} \tag{15}$$

In cooled receivers the contribution of the amplifier itself is usually less than 8% of the total system noise temperature. For these applications the tuning results only in a slight deterioration of the system noise figure. However, one can cover several times wider frequency ranges with these tunable amplifiers than can possibly be covered with the best amplifiers with large instantaneous bandwidths.

6.2 Full Octave Band Amplifier With One Combined Mechanical-Electronic Tuning Knob:

A balanced amplifier which can be tuned through the full octave band between 4 and 8 GHz is shown in Figure 8a. The 3-port circulator, which covers the same frequency range, is already linked to the signal input of the paramp. Its signal line has a slot into which a polystyrene pin is inserted. This pin, which can be moved to and fro by means of a micrometer, is linked to the two-step coaxial transformer. This changes the line length l_a between the diodes and the transformer (See Figure 8b). Attached to the micrometer screw is a multi-turn potentiometer for control of the bias V_D of the varactor. Eight revolutions of the screw are needed for tuning the amplifier from 4 to 8 GHz.

In the frequency range around 6 GHz the noise temperatures measured are around 150°K and near 4 GHz around 100°K. As Figure 5 shows, these values agree fairly well with the theoretically determined noise temperature.

The product gain x instantaneous bandwidth at a constant gain of 17 dB varies between 330 MHz and 1000 MHz, if the amplifier is tuned over the octave band. The humps of the measured curve as shown in the solid curve in Figure 7 are mainly due to mismatches of the circulator.

The pump power, which is fed into the amplifier via the pump waveguide (visible on the right side of Figure 8a) has to be changed by 7 dB to get the constant gain of 17 dB mentioned above.

Cooling tests with liquid nitrogen (77°K) revealed a good performance of the amplifier (including in particular the displacement of the transformer). Even when cooled the amplifier could be tuned through the full octave band.

6.3 Discussion of the Experimental Results and Comparison With Amplifiers Having Large Instantaneous Bandwidths:

In comparison with the voltage tuning method, described in paragraph 6.1, the combined mechanical-electronic tuning method, described in paragraph 6.2 requires a more difficult tuning mechanism (especially for remote tuning). However, it has the advantage of resulting in lower noise temperatures and wider tuning ranges.

The comparison of tunable amplifiers with amplifiers having large instantaneous bandwidths is as follows:

Amplifiers with large instantaneous Bandwidth B	Amplifiers with large tuning range Δf
$\frac{\sqrt{G'} \times B}{f} \lessneqq 50\%$	$\frac{\sqrt{G'} \times \Delta f}{f} = 2 \div 4.5$

CONCLUSIONS:

In conclusion, the main features of tunable paramps are:

The disadvantages of tuning:

1. Sacrifice of instantaneous bandwidth
2. Sacrifice of noise temperature

The advantages of tuning:

1. It results in a much safer operation in the case of cooled amplifiers, especially with regard to the amplifier described in paragraph 6.1; because no critical multituning is required, and VSWR-changes of the circulator have much less effect on the paramp.
2. Several times wider frequency ranges can be covered with one amplifier.

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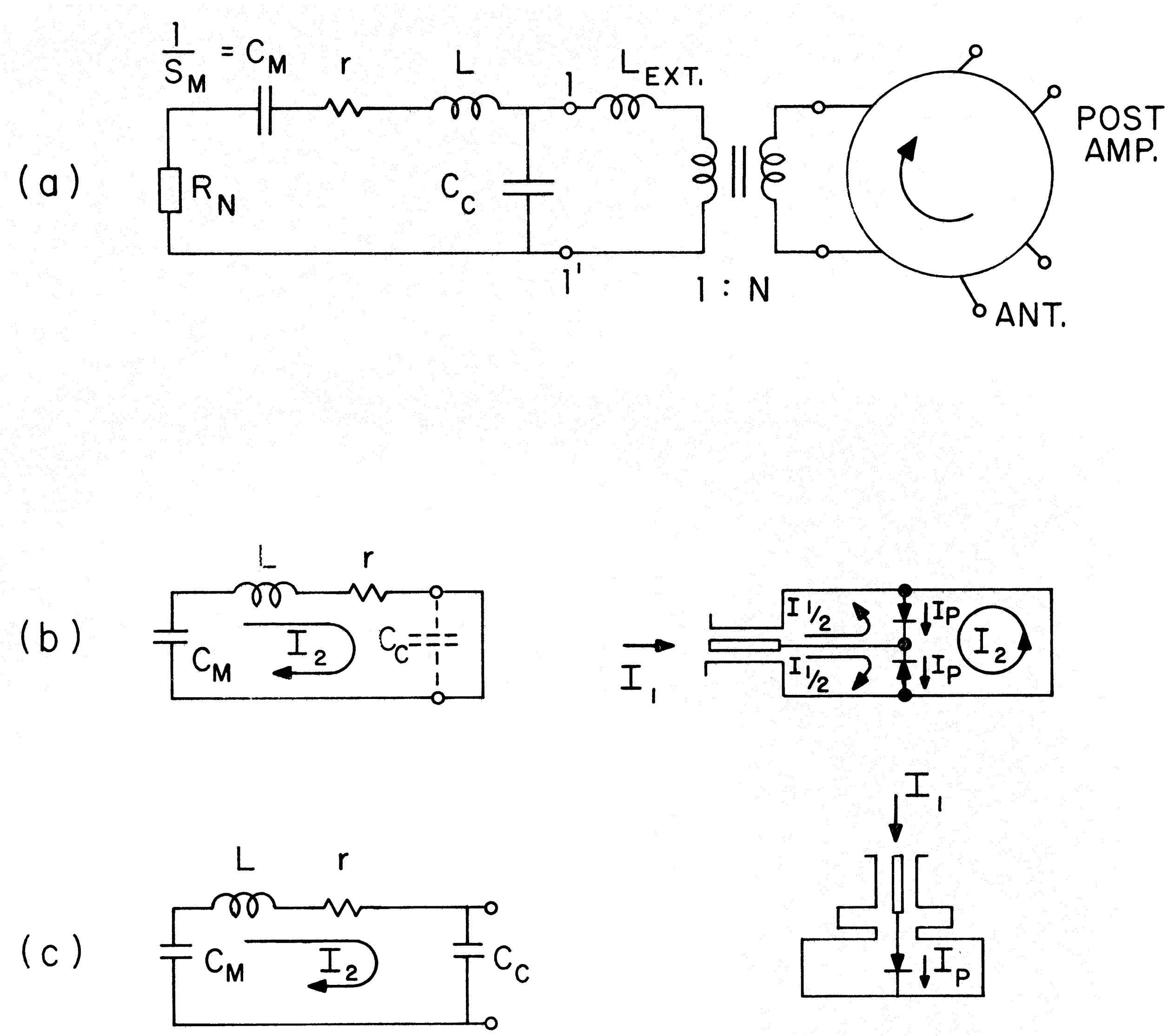


Figure 1: EQUIVALENTS CIRCUITS AND PRACTICAL CONFIGURATIONS FOR TUNABLE PARAMPS

(a) Signal Circuit
(b) Idling Circuit for series-resonance with a balanced realization
(c) Idling Circuit for parallel resonance with a single ended realization

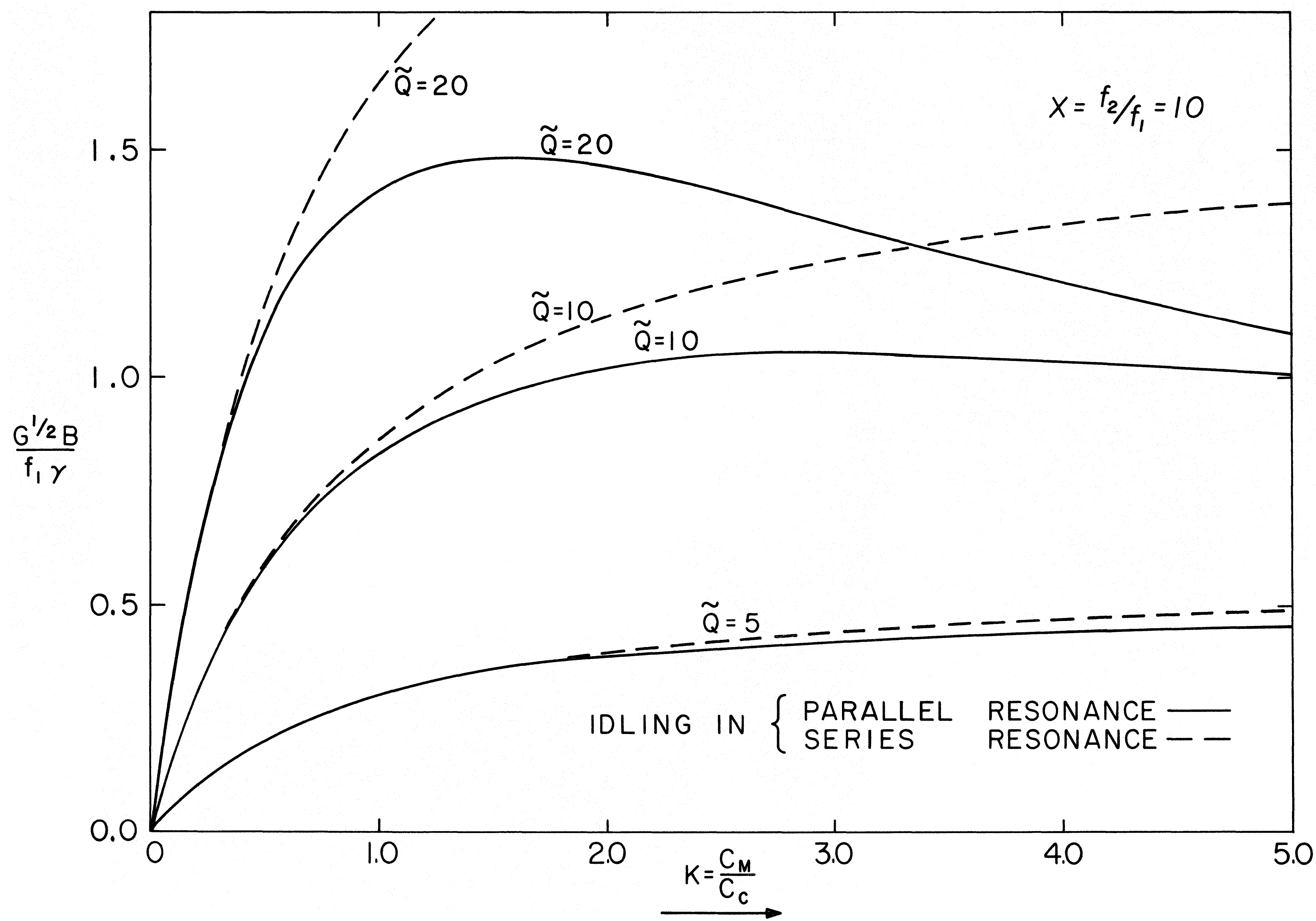


Figure 2: INFLUENCE OF TUNING BY MEANS OF BIAS VOLTAGE ON THE BANDWIDTH OF SELFRESONANT PARAMPS

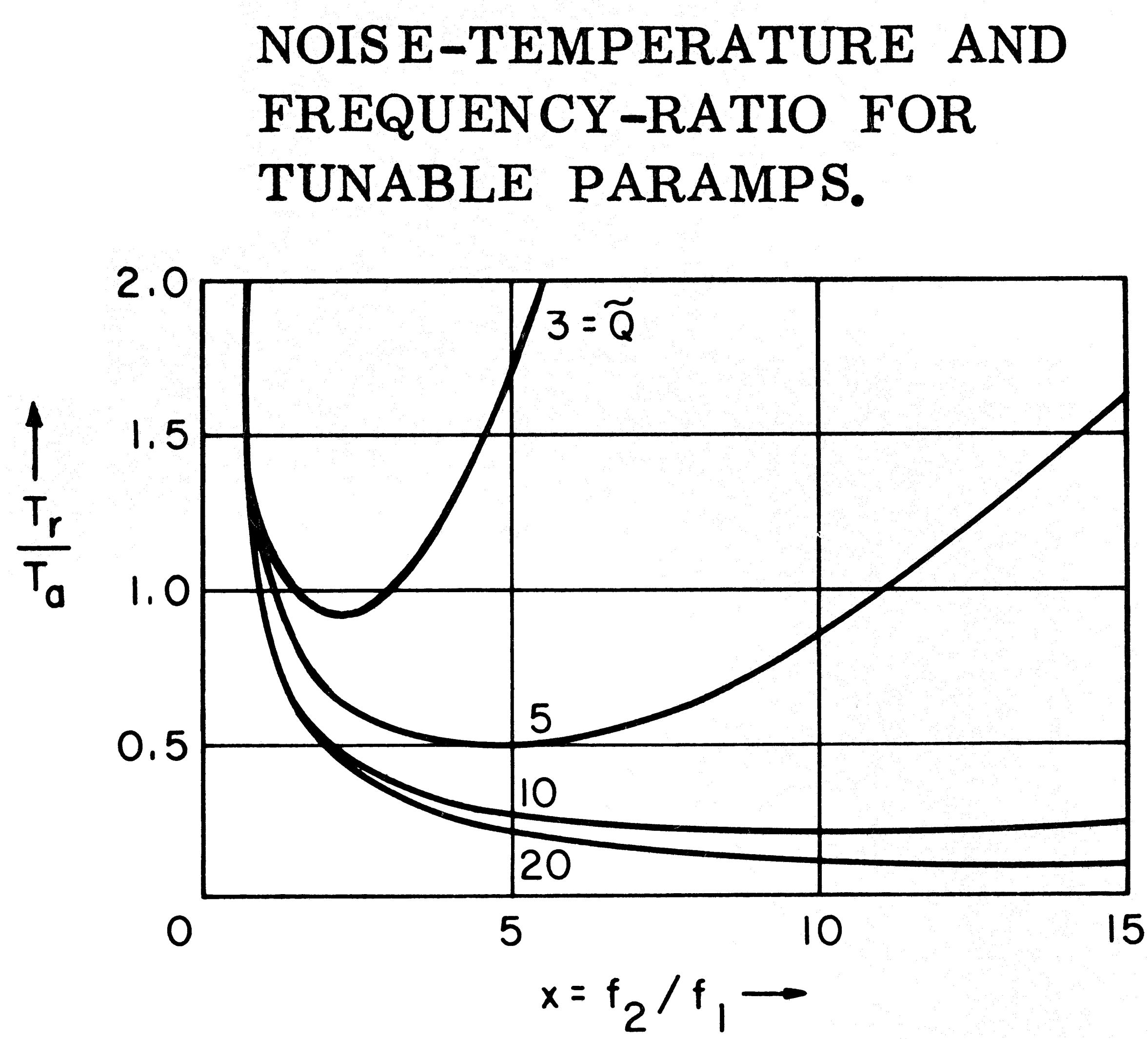
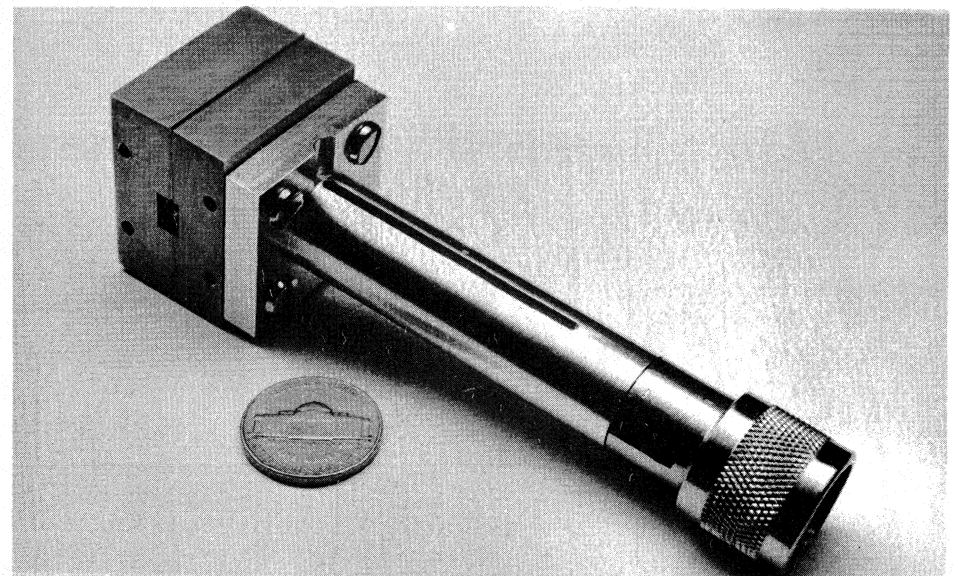


Figure 3: INFLUENCE OF TUNING BY MEANS OF BIAS VOLTAGE ON THE NOISE TEMPERATURE OF PARAMPS

(a)



(b)

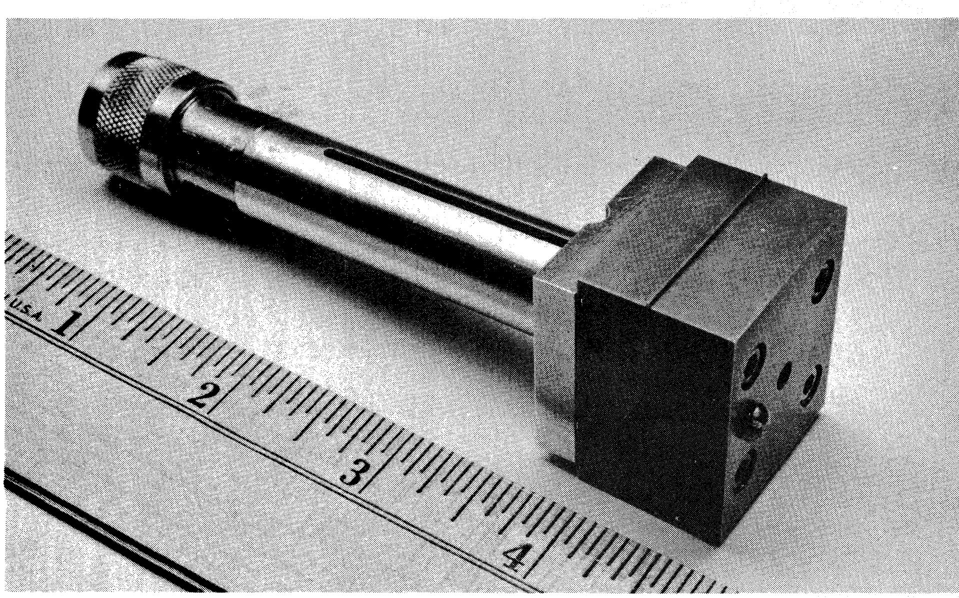


Figure 4: 18 CM PARAMP (Tunable by means of bias voltage around 1.65 GHz)

(a) View at coaxial input line and pump input
(K-band waveguide)

(b) View at diode holder (Middle screw on the right side)
And the reduced height (20 mil) waveguide with its short

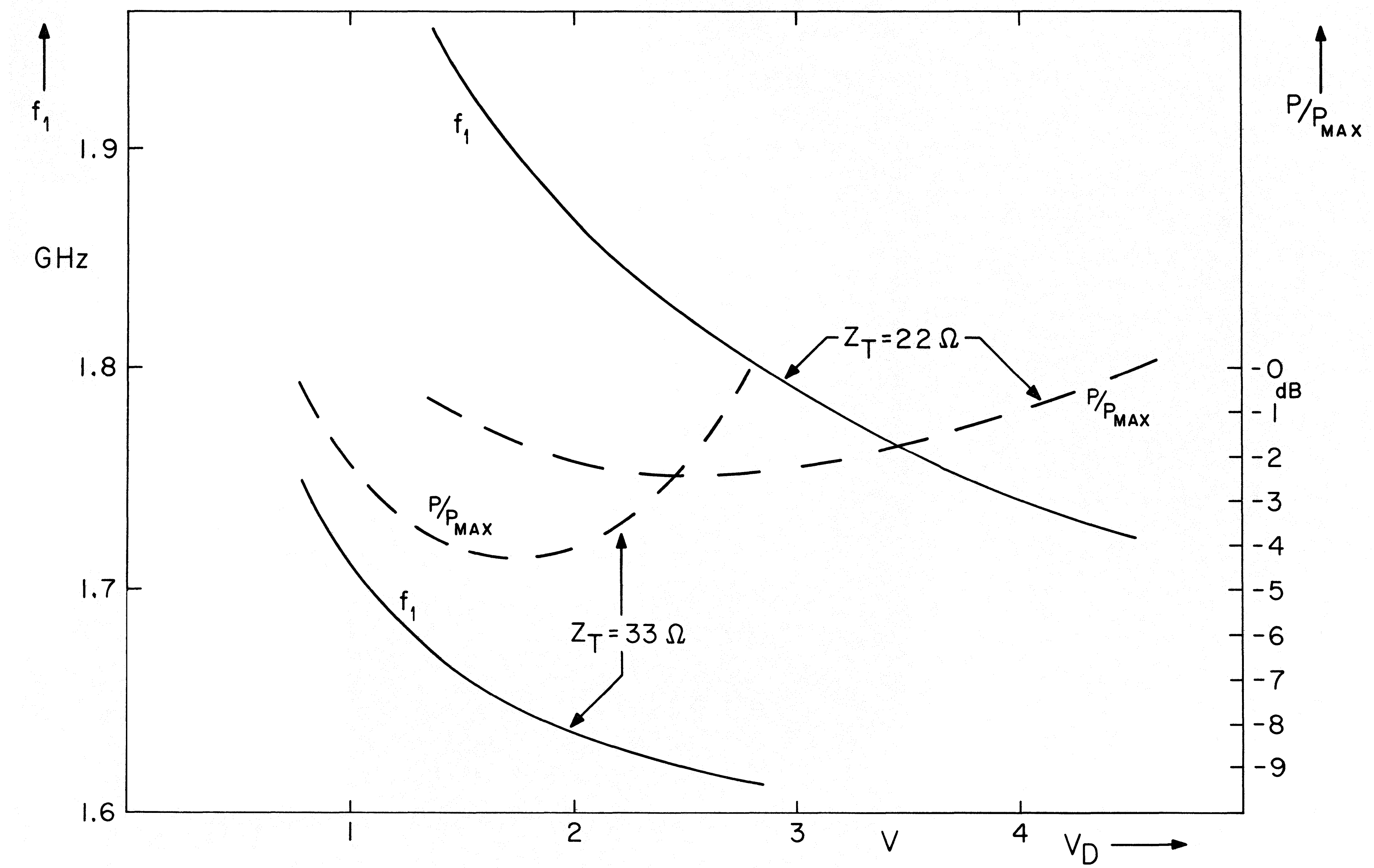


Figure 5: SIGNAL FREQUENCY RANGE FOR THE VOLTAGE TUNABLE 18 CM PARAMP

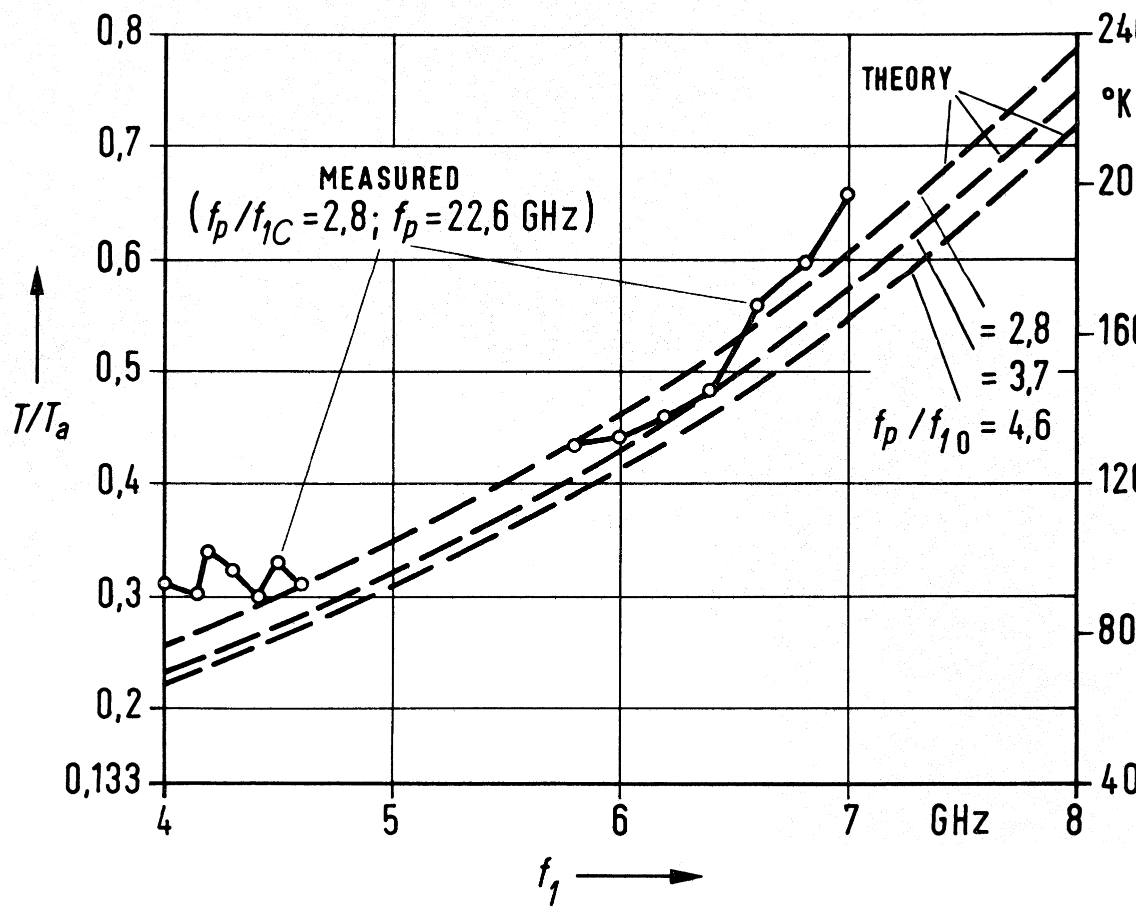


Figure 6: NOISE TEMPERATURE OF C-BAND PARAMP WHICH IS TUNABLE FROM 4 TO 8 GHz

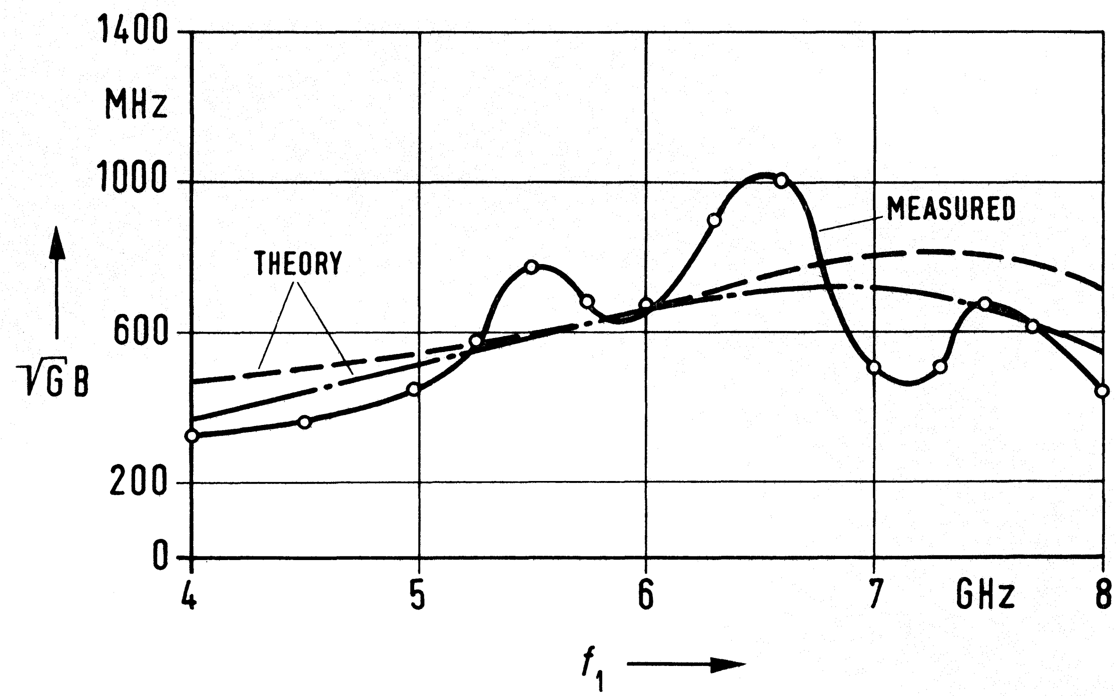
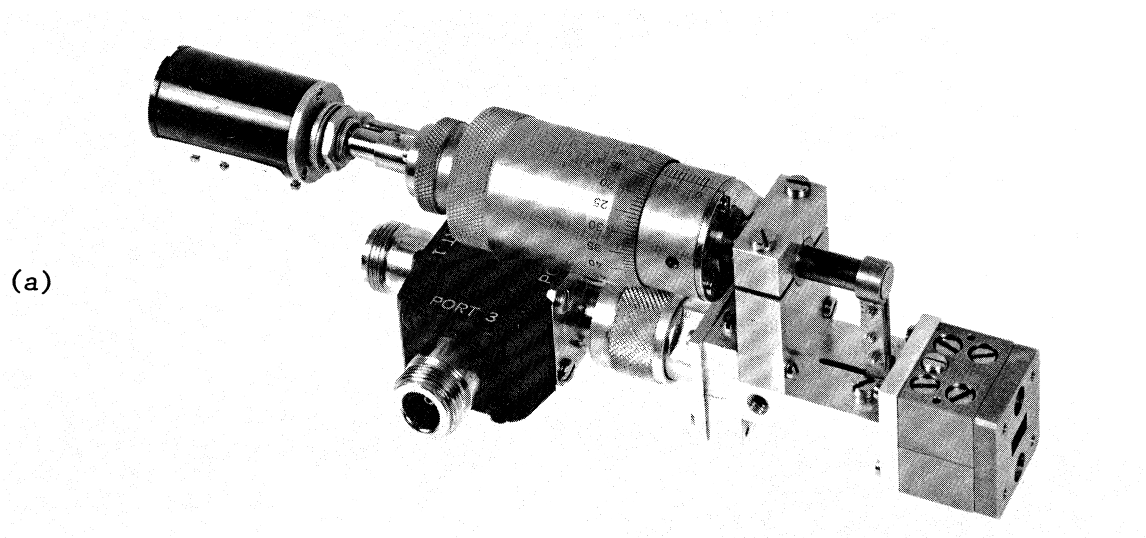


Figure 7: INSTANTANEOUS GAIN-BANDWIDTH PRODUCT $\sqrt{G}$ B OF THE 4 - 8 GHz - TUNABLE PARAMP

(G = Const = 17 dB)

(a)



(b)

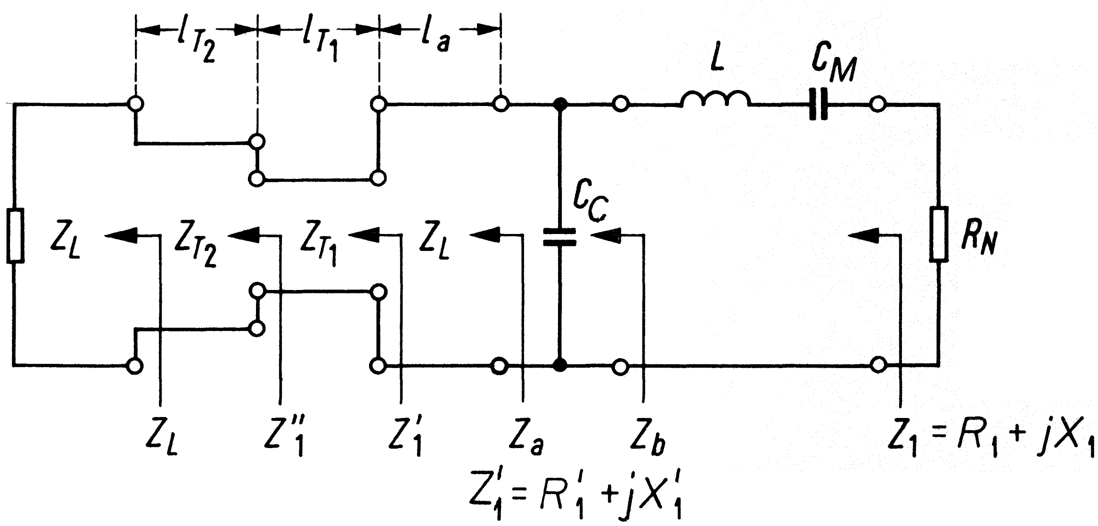


Figure 8: 4 - 8 GHz PARAMP (a) AND ITS EQUIVALENT SIGNAL CIRCUIT (b)