In fairness, it should be noted that, if the three-section two-way dividers are cascaded with zero line length between them, the VSWR of the cascade will be better than the worst-case condition of random length between the dividers. However, at higher frequencies, for physical realizability, a length of line between the cascaded dividers is desirable. The approach suggested in this short paper can still be applied to advantage.

Example 2: A four-way divider is required for 3.7–4.2 GHz. A three-section 4-to-1 impedance-ratio prototype was selected. With a normalized bandwidth of 0.2, the theoretical maximum VSWR is 1.02/1. With cascaded single-section transformer dividers, the VSWR over the same bandwidth would vary between 1.03/1 (with no length between the dividers), 1.24/1 maximum (with a quarter-wavelength between the dividers), and 1.12/1 maximum (with a half-wavelength between the dividers).

Fig. 2 shows impedance values for the two approaches. Fig. 3 gives typical performance of the three transformer-section design.

Summarizing, a significant improvement in the performance of a set of cascaded power dividers can be achieved by considering the entire chain as a multistep transformer, rather than designing each divider to be matched to 50 Ω at its input and output.

REFERENCES

[1] H. Yee, F. Chang, and N. Audeh, "A study of wideband *N*-way power dividers," Univ. Ala. Res. Inst., ASTIA AD693290, July 1969

A Coolable Degenerate Parametric Amplifier for Millimeter Waves

JOCHEN EDRICH

Abstract—**The first 20-K-cooled degenerate parametric amplifier for 46 GHz is described. New 20-K-cooled circulators and Schottky-barrier varactors are used. Its noise temperature of less than 60 K means almost an order-of-magnitude improvement over previous uncooled amplifiers.**

I. INTRODUCTION

Operational parametric amplifiers with signal frequencies up to 60 GHz and SSB noise temperatures in the order of 600 K have been reported previously [1]. This letter describes several new developments in the millimeter-wave range, which lead to a 20-K-cooled degenerate amplifier with a very low noise temperature. One of the unresolved problems in the field of cooled amplifiers was the lack of coolable circulators. Recently, a way has been found to construct broad-band-type junction circulators for the millimeter frequency range. At 46 GHz an insertion loss of 0.7 dB and an isolation of more than 20 dB over 3.5 GHz was achieved with single junction circulators when cooled down to 16 K [2].

II. VARACTOR

Theoretical and experimental studies were performed in order to determine the optimum diameter of the platinum–gallium arsenide Schottky-barrier junctions used in the amplifier. It turned out that a diameter of 2 μm constituted the best compromise between the requirements for low pump power, broad bandwith, low noise temperature, and reproducible and mechanically strong contacts. One problem which arises when the tiny gold-plated platinum dots are contacted with a pointed whisker is the stray capacitance of its tapered section against the grounded substrate. This capacitance C_s is shunting the junction capacitance C_j and the loss resistance r in the n-type epilayer, as can be seen from the sketch of the contacted junctions and its simplified equivalent circuit in Fig. 1(a) and (b), respectively. The value of C_s was determined using the method of images and curvilinear squares; both methods yielded in close agreement a value for C_s that is 10 percent of the junction capacitance C_{j0}, or approximately 0.001 ρF. The use of 1-μm junctions instead of 2-μm junctions would roughly quadruple the ratio C_s/C_{j0} assuming about the same whisker taper of 10°; this taper can hardly be made smaller—at least not in the area close to the junction which is mainly responsible for C_s. The large ratio C_s/C_{j0} of 1-μm junctions would result in a sizable shunt for the negative resistance appearing across junction capacitance C_j in Fig. 1(b). This, in turn, means a degradation in noise temperature and bandwidth as compared with the 2-μm junctions. The 2-μm diodes, however, have the disadvantage of requiring much more pump power because of their larger average junction capacitance.

In order to obtain a mechanically strong and yet elastic contact a very short whisker of only 5 mil length is used which has a 90° bend.

Fig. 2 shows the *I–V* curves of a typical 2-μm junction measured at room temperature and at 16 K. From these curves a strong increase of the slope parameter η in the current–voltage equation $I = I_0[\exp(-qV/\eta kT) - 1]$ is evident ($\eta = 1.17$ at 300 K; $\eta = 8$ at 16 K). However, the dc resistance R_0 extrapolated from the high forward-current region does not seem to change noticeably with temperature ($R_0 = 7.5\ \Omega$ at 300 K and at 16 K). This indicates that the junctions are well suited for varactor applications at cryogenic temperatures. De Loach-type resonance measurements at room temperature around the midband signal frequency $f_s = 46$ GHz, and subsequent more precise reflection measurements at a fixed frequency of 46 GHz under varying bias voltage [3]–[5], indicated a cutoff frequency $f_c \geq 800$ GHz at zero bias voltage.

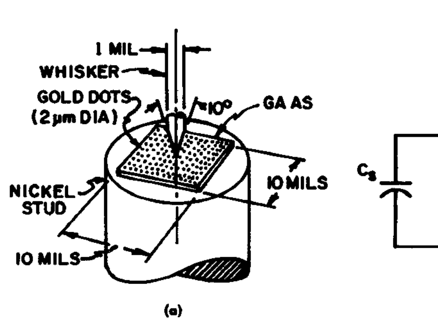

Fig. 1. (a) Physical diode structure close to junction. (b) Equivalent circuit of structure in (a).

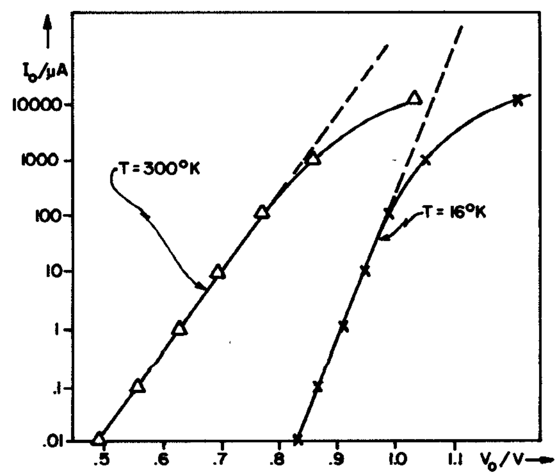

Fig. 2. *I–V* curves of Schottky-barrier diodes used as varactors (platinum–gallium arsenide). Epilayer donor concentration $N_D = 2 \times 10^{17}/cm^3$. *T* is the physical temperature.

Manuscript received May 14, 1973; revised December 14, 1973. Information upon which this publication is based was a result of a subcontract carried out under the Prime Contract NSF-C450 between Associated Universities, Inc. (National Radio Astronomy Observatory) and the National Science Foundation.
The author is with the Department of Electrical Engineering, University of Denver, Denver, Colo. 80210.

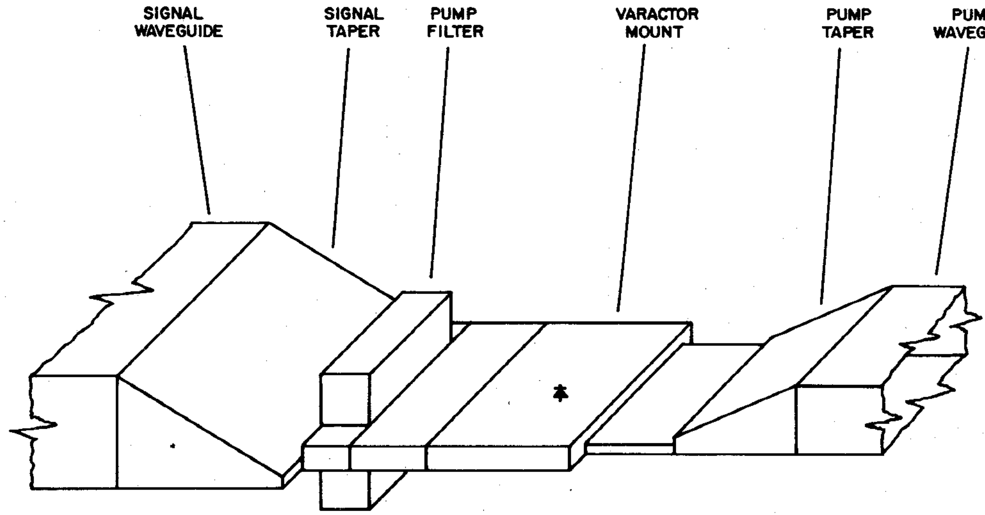

Fig. 3. Cutaway view of the amplifier mount.

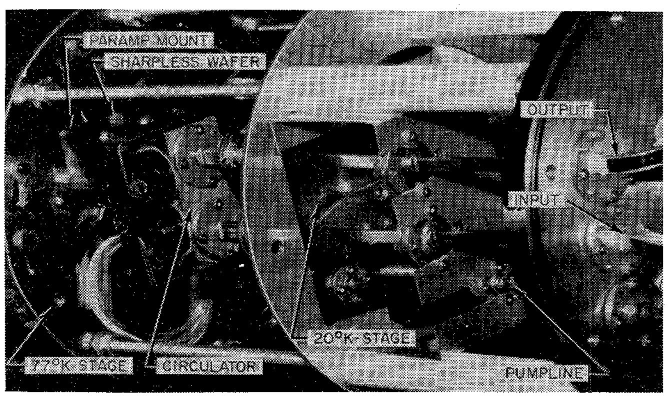

Fig. 4. 20-K-cooled parametric amplifier for 46 GHz. The dewar is removed.

III. AMPLIFIER DESCRIPTION

A modified and improved Sharpless wafer is used as the diode package [2], [6]–[10]. No tuning screws are employed in the amplifier mount in order to achieve a high degree of reproducibility and stability. Most of the tuning is done in the area close to the junction. As compared to the design described in [6], improvements have been made by using special $\lambda/4$-type filters in the bias and signal lines in order to better reject undesired frequency components without adversely affecting the power flow at desired frequencies. As a result of this method the leakage of signal and pump power through the bias line has been reduced to a negligibly small amount. Fig. 3 shows schematically the cross section of the amplifier mount. Fig. 4 is a photograph of the completed degenerate parametric amplifier for 46 GHz; it is attached, together with its coolable four-port circulator, to a closed-cycle helium refrigerator.

IV. PERFORMANCE AND DISCUSSION

Table I lists some important characteristics of the amplifier. Note the relatively low pump power of 12 mW, which is not too far away from the theoretical value of 8 mW. No special effort has been made yet to obtain a very wide bandwidth. It is therefore felt that the measured voltage-gain–bandwidth products of 3.4 GHz and 5.5 GHz at room temperature and at 20 K, respectively, could be improved by at least a factor of 2. Work is under way to accomplish this goal by optimizing the presently single-tuned signal circuit and subsequently double tuning it. The amplifier turned out to be mechanically very stable when cooled down to 20 K. A noise temperature of 40 K was measured using the "hot–cold" method. Table II lists the contributions of individual components. The calculated diode contribution is based on the RF-measured cutoff frequency f_c and is obtained from [11]:

$$T_{DSB} = T_A((f_s/\gamma f_c) + (f_s/\gamma f_c)^2 + 0.5(f_s/\gamma f_c)^3)$$

TABLE I
CHARACTERISTICS OF THE COOLABLE DEGENERATE PARAMETRIC AMPLIFIER FOR 46 GHz

	Uncooled Amplifier (T_A=300°K)	Cooled Amplifier (T_A=20°K)
Gain (Crystal Measurement)	18 db	23 db
Signal Frequency	45.8 GHz	45.8 GHz
Pump Frequency	91.6 GHz	91.6 GHz
3 db-Bandwidth	430 MHz	390 MHz
Bias Voltage	-1.8 V	-1.2 V
Bias Current	0.6 μA	0.1 μA
Theoretical Pump Power	8 mW	--
Measured Pump Power	12 mW	35 mW[1]
Theoretical Noise Temperature	187.6°K[2]	23°K[2]
Measured Noise Temperature	210 ± 30°K[2]	40 ± 20°K[2]

[1] At pump waveguide window, no matching devices at varactor mount.
[2] DSB value, referred to input window.

TABLE II
NOISE BUDGET OF THE COOLABLE DEGENERATE PARAMETRIC AMPLIFIER FOR 46 GHz

Origin of Noise Contribution (K°)	Uncooled Amplifier (T_A=300°K)	Cooled Amplifier T_A=20°K)
Diode, (f_c=850 GHz at V_{BIAS}=-1.5V; γ=0.2)	105.6°K	7.0°K
Amplifier Mount (Loss L=0.2 db at 300°K, L=0.02 db at 20°K)	19.1°K	0.13°K
Circulator (2 paths @ L=0.3 db at 300°K and @ L=0.7 db at 20°K)	62.9°K	10.3°K
Input Waveguide (10" long stainless steel, gold plated, used for cooled amplifier only).	0°K	5.5°K
Total Theoretical Noise Temperature (DSB, excluding second stage contributions)	187.6°K	22.9°K
Total Measured Noise Temperature (DSB, excluding second stage contributions)	210 ∓ 30°K	40 ∓ 20°K

assuming the values for γ and f_c given in Table II. The measured and theoretical values for the uncooled case disagree by only 12 percent. The larger discrepancy at 20 K is primarily due to the uncertainty in the exact temperature of the nitrogen cold-load used for the noise measurements, the relatively large second-stage contribution (30 K), and the neglect of other possible noise sources like the pump-heating effect [9].

This measured noise temperature of only 40 K constitutes an improvement of the noise performance by an order of magnitude as compared to previously reported uncooled amplifiers in this frequency range [6]. Based on these results it is felt that amplifiers with such low noise performance which are needed in many radiometry and millimeter-wave radio-astronomy applications can be developed up to frequencies of at least 90 GHz.

ACKNOWLEDGMENT

The author wishes to thank Dr. R. Mattauch of the University of Virginia for his support and for developing the junctions. He also wishes to thank L. Pizziconi, who computed the whisker stray capacitance.

REFERENCES

[1] H. L. Stover *et al.*, in *Digest 1973 Int. Solid-State Circuits Conf.*, Feb. 1973, pp. 80–81.
[2] J. Edrich, P. Hardee, and R. G. West, "Low loss 16°K-coolable junction circulators for the millimeter wave range," presented at the 1973 European Microwave Conf., Brussels, Belgium, Sept. 1973.
[3] N. Houlding, *Microwave J.*, vol. 3, pp. 40–45, Jan. 1960.
[4] R. Mavadat, *J. Electron. Contr.*, vol. 15, pp. 51–54, July 1963.
[5] E. W. Sard, "A new procedure for calculating varactor *Q* from impedance versus bias measurements," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 849–860, Oct. 1968.
[6] J. Edrich, "A parametric amplifier for 46 GHz," *Proc. IEEE* (Lett.), vol. 59, pp. 1125–1126, July 1971.
[7] M. W. Sharpless, *Bell Syst. Tech. J.*, vol. 35, pp. 1385–1420, Nov. 1956.
[8] T. P. Lee and C. A. Burrus, "A millimeter-wave quadrupler and an up-converter using planar-diffused gallium arsenide varactor diodes," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 287–296, May 1968.
[9] M. Cohn, L. E. Dickens, and J. W. Dozier, in *1969 Digest Int. Microwave Symp.*, pp. 225–231.
[10] J. Edrich, "Parametric amplification of millimeter waves using wafer diodes: Results, potentials, and limitations," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-18, pp. 1173–1175, Dec. 1970.
[11] L. A. Blackwell and K. L. Kotzebue, *Semiconductor-Diode Parametric Amplifiers.* Englewood Cliffs, N. J.: Prentice-Hall, 1961.
[12] K. Gardrecht, in *Digest Int. Conf. Solid-State Circuits*, 1965, pp. 22–23.

A Frequently Reinvented Circuit

R. W. BEATTY

***Abstract*—Attention is called to published work describing an impedance-measuring circuit that is frequently reinvented.**

A number of papers have appeared in which the VSWR or impedance is measured by sliding a short circuit in one side arm of a directional coupler and observing the response of a detector located in the other side arm. In addition, this idea has been reinvented on two different occasions of which the author is aware, and the inventors did not publish their independent work when informed of previous work.

Consequently, it appears worthwhile to call attention of microwave engineers to publications which deal with this topic. The following list may not be complete, but should be adequate for the intended purpose:

1) R. Musson-Genon and P. Brissoneau, "Sur un mesureur d'impedances a couplage directif en hyperfrequence," *C. R. Acad. Sci.*, vol. 230, pp. 1258–1259, Mar. 1950.
2) A. I. Zykov, "Impedance measurements by means of directional couplers," *Meas. Tech.*, vol. 3, pp. 211–215, Mar. 1959.
3) K. Chandra, R. Parshad, and R. C. Kumar, "Measurement of impedance at microwave frequencies using directional coupler and adjustable short circuit," *Proc. Inst. Elec. Eng.*, vol. 114, pp. 1653–1655, Nov. 1967.
4) R. K. Jha and V. K. Garg, "Voltage standing-wave ratio measurement by cross coupler," *Int. J. Electron.*, vol. 29, no. 2 pp. 179–183, 1970.

Manuscript received January 11, 1974.
The author is with the Electromagnetics Division, National Bureau of Standards, Boulder, Colo. 80302.

Generation of Acoustic Signals by Pulsed Microwave Energy

JOSEPH C. SHARP, H. MARK GROVE, AND OM P. GANDHI

***Abstract*—A discussion of the production of sound when short microwave pulses are directed at an absorber is presented. Possible mechanisms of the phenomenon are presented. These mechanisms may be important for a better understanding of the so-called microwave "hearing" effect.**

This letter is intended to describe a phenomenon first noticed in our laboratory during some preliminary experiments designed to further elucidate the mechanism(s) responsible for "hearing" pulsed microwave exposure (e.g., [1]–[3]). While attempting to shield portions of the head from RF radiation by using a carbon-impregnated polyurethane microwave absorber (Emerson and Cumming Eccosorb WG4 with a surface area of 3716 cm²), it was noticed that the apparent locus of the "sound" moved from the observer's head to the absorber. That is, the absorber acted as a transducer from microwave energy to an acoustic signal. This observation, to the best of our knowledge, has not been described in the literature and may serve as an important clue to the mechanism mediating the "hearing" of pulsed microwave signals.

That the signal from the absorber is acoustic is proven by the data presented in Fig. 1 where the ensemble sum of 50 epochs, each 25.6 ms long, is plotted. These data were collected with a General Radio model 1551C sound level meter fitted with a 1560-P5 microphone. The microphone was acoustically coupled to the absorber via one of two cone-shaped guides, 1.42 or 0.73 m long, respectively; these guides were made of construction paper. The recorder output of the sound meter was led through a Krohn-Hite model 3343R bandpass filter (set to pass 150–2500 Hz), to an HP Fourier analyzer model 5451A where the signals were digitized and the 50 epochs were summed at 512 equispaced sample points; the sampling interval was, therefore, 50 μs.

Fig. 1(a) represents one such ensemble sum when the microphone was 1.42 m from the absorber. The sound arrived at, and activated, the microphone approximately 4.68 ms after the trigger pulse was applied to the Applied Microwave Laboratories, Inc., model PG5KB pulse signal source. The output was radiated by a NARDA 646 horn which has a physical aperture of 53.3 $\times$ 39.6 cm. When the distance from the absorber to the microphone was 0.73 m, the sound arrived approximately 3.29 ms after the trigger signal [Fig. 1(b)].

Manuscript received October 29, 1973; revised January 11, 1974.
J. C. Sharp and H. M. Grove are with the Department of Microwave Research, Walter Reed Army Institute of Research, Washington, D. C. 20012.
O. P. Gandhi is with the Department of Electrical Engineering, University of Utah, Salt Lake City, Utah 84112.