Low Noise Receiving Downconverter

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Significant improvements in noise figure and band-width have been obtained in down conversion from frequencies in the 11 GHz range to frequencies of several hundred megacycles. An average noise figure of 5.6 dB and greater than 50 percent bandwidth have been obtained using a Schottky-barrier diode balanced mixer and a low noise transistor preamplifier. We discuss basic design criteria, and present a complete circuit description and measurements for one of the downconverters used in the short hop radio system experiment.

I. INTRODUCTION

In microwave radio relay systems the receiver thermal noise is one of the main contributors to the total noise of the radio line which is one of the fundamental limitations on many important system parameters, such as the number of voice circuits per radio frequency channel, repeater spacing, and system length. Since in heterodyne systems the receiver noise is essentially the noise of the receiving downconverter, the noise figure of the downconverter is one of the most important factors in setting the entire system performance. In radio systems such as those described by Tillotson, low noise figures and wide bandwidths are required in conversion from the higher microwave frequencies above 10 GHz to higher than normal intermediate frequencies in the range of several hundred MHz.[1] The system concept also places a premium on circuit and mechanical simplicity, low power consumption, and environmental stability. The downconverter described in this paper was designed to meet the requirements of such a system.

Before the Schottky-barrier diode, noise figures below about 7 dB could only be obtained by using tunnel diodes or parametric microwave amplifiers with atendant sacrifice in receiver simplicity, stability, and dynamic range. With the perfection of high quality GaAs Schottky-barrier diodes and low noise transistors, noise figures below 7 dB are possible without RF amplification. The 5.6 dB average noise figure and greater than 50 per cent 3 dB bandwidth achieved with the Schottky-barrier diode mixer and low noise preamplifier described here represent a significant improvement over those previously obtained in down conversion from frequencies in the 11 GHz range. Other important characteristics of the downconverter are the temperature stability, 19 dB RF to IF gain, low pump power, single dc supply, low dc power consumption, and circuit and mechanical simplicity. Table I summarizes the results achieved.

In the following sections, basic considerations in the design of a low noise Schottky-barrier diode mixer are discussed, followed by a description of the mixer and preamplifier circuitry, measurements, and performance.

II. BASIC DESIGN CONSIDERATIONS

2.1 *Noise Figure*

The basic consideration in the design of the mixer and preamplifier is the receiver noise figure. Friis has shown that the noise figure of a receiver can be expressed as a function of three parameters,[2]

$$n_R = l_x(t_x + n_{IF} - 1), \tag{1}$$

where n_R is the receiver noise figure, l_x is the overall conversion loss of the mixer, t_x is the equivalent output temperature of the mixer and source normalized to 290°K, and n_{IF} is the noise figure of the IF amplifier following the mixer. Equation (1) can be written in terms of the normalized equivalent diode temperature, t_{av},[3]

$$n_R = 1 + l_x\left[t_{av}\left(1 - \frac{1}{l_x}\right) + n_{IF} - 1\right]. \tag{2}$$

The equivalent diode temperature has the following meaning. The shot noise current produced by the diode, a function of the diode conduction current, is equated to the thermal noise from a conductance equal to the diode conductance. The temperature required to make the thermal noise equal the shot noise is the equivalent diode temperature. In a pumped diode the conduction current is a periodic function of time and thus the equivalent diode temperature is a periodic function of time; t_{av} is its average value. The conditions

TABLE I — SUMMARY OF PERFORMANCE

Radio frequency	10.760 GHz
Intermediate frequency	300 MHz
Pump power (total for 2 diodes)	10 mW
RF to IF gain at band center	18.6 dB
Frequency response	flat ±0.1 dB, 240 to 350 MHz 0.3 dB down at 230 and 360 MHz
Noise figure at 75°F	5.3 dB at band center 5.6 dB average 240 to 360 MHz
Temperature Range	−40 to +140°F

under which this representation is valid have been established rigorously by Dragone.[4] In a practical diode, because of its series resistance, R_s, t_{av} will be between 0.5 and 1.0. Equation (2) and the small range of values of t_{av} show that the receiver noise figure is primarily determined by the mixer conversion loss, especially when the loss is small. Therefore, to obtain the minimum receiver noise figure, the mixer should be designed for minimum conversion loss.

2.2 *Conversion Loss*

For a resistive mixer to have minimum conversion loss, the terminations at the image frequency and all pump harmonics must have zero admittance, that is, the diode is pumped with a sinusoidal current.[5] The conversion loss is then a function of the pumping voltage and the terminating resistances at the input and output frequencies. In general, the conversion loss decreases as the pump voltage increases, but the minimum loss values of the terminating resistances increase rapidly to impractical values. If the actual terminating resistances are smaller than the resistances required for minimum loss, the conversion loss, as derived by Dragone, is

$$l_z = 1 + \frac{2}{R}\left(R_s + \frac{KT}{qI_{co}}\right), \tag{3}$$

where R is the terminating resistance, R_s is the diode series resistance, and I_{co} is the dc component of the diode current. Equation (3) shows that minimum values of R_s and large values of I_{co} are required.

2.3 *Mixer Preamplifier Interface*

In addition to the conversion loss of the mixer diode, there are circuit losses in the filters, coupler, and impedance matching circuits which must be minimized. The IF output termination is a special problem in the case of a mixer followed by a low noise preamplifier because the noise figure of the input transistor depends on the source impedance and there is an optimum value for minimum noise. The interface between the mixer and preamplifier should be a lossless transformer to provide optimum terminations for both mixer and transistor. However, the loss of a nonideal broadband transformer can easily exceed the loss caused by nonoptimum terminating impedances.

In preliminary experiments, we found that the best performance was obtained with no impedance matching circuit at the mixer-preamplifier interface. A spot noise figure of 4.8 dB and an average noise figure of 5.4 dB over a 40 per cent bandwidth were obtained with 24 mW of local oscillator power and the diodes connected directly to the preamplifier. These results show that excellent performance can be obtained without the use of an impedance matching circuit at this interface; the downconverter reported here uses this technique.

III. DOWNCONVERTER CIRCUITRY

The downconverter consists of signal and local oscillator filters, a magic tee type of balanced mixer, and a two-transistor IF preamplifier connected as an integral part of the mixer. Figure 1 is a block diagram and Fig. 2 is a photograph of the completed unit.

3.1 *Filters*

The signal filter rejects input signals at the image frequency, reactively terminates the diode at the image frequency, and prevents leakage of local oscillator power to the antenna. The characteristics of the signal filter are important in an image rejection mixer because the filter loss at the signal frequency adds directly to the mixer conversion loss. Thus low insertion loss is required and at the same time good skirt selectivity is required to provide the image frequency termination. The signal filter is a three-section, 0.1 dB Tchebyscheff filter with a 120 MHz bandwidth and 0.2 dB midband insertion loss. Its insertion loss and return loss are shown in Fig. 3.

The local oscillator filter is a narrowband filter which attenuates undesired harmonics generated in the local oscillator multiplier chain which otherwise could enter the mixer at a higher level than the received signal. It is a three-section, 0.1 dB Tchebyscheff filter with a 30 MHz bandwidth and 1.0 dB midband insertion loss.

The electrical distance from the signal filter to the diode determines the admittance which terminates the diodes at the image frequency.

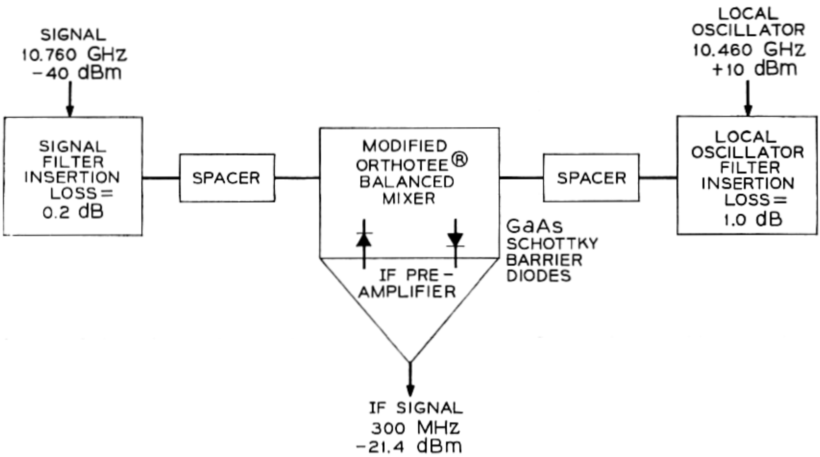

Fig. 1 — Block diagram of the receiving downconverter.

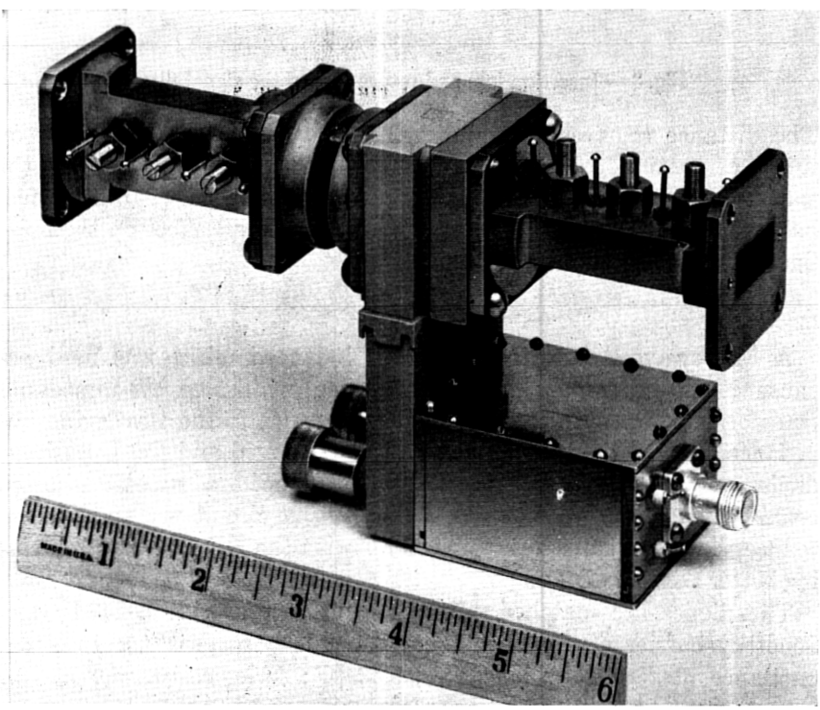

Fig. 2 — The downconverter.

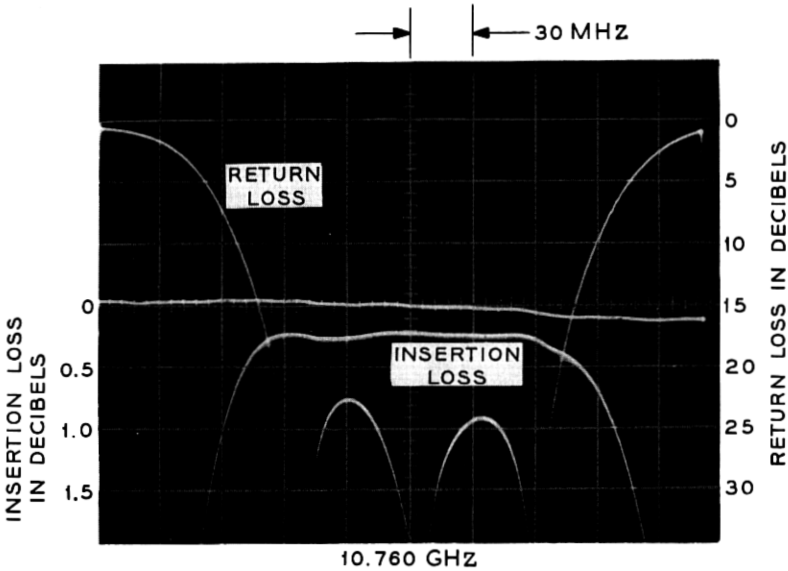

Fig. 3 — Insertion loss and return loss of the signal filter.

The distance required for minimum noise figure was determined by using a continuously adjustable waveguide line stretcher as the spacer between the signal filter and mixer. Because of imperfect balance the local oscillator filter spacer has a small effect on the noise figure and also requires adjustment.

3.2 *Mixer*

A Microwave Associates *Orthotee*® balanced mixer was used because it is a compact folded magic-tee with stepped impedance transformers for matching the diode impedance to the waveguide impedance. The original diode mounts were removed and the U package diodes were mounted across the waveguide in a tunable shorted coaxial line.* The RF choke in the IF output circuit was modified to reduce the shunt capacitance to 2.8 pF with the RF rejection remaining better than 25 dB.

The diodes are matched pairs of Bell Laboratories L-2486 GaAs Schottky-barrier diodes with these typical characteristics: total capacitance at zero volts bias, C_{To}, 0.42 pF; series resistance, R_s, 0.7

* The U package is described in Ref. 6.

ohms; cutoff frequency, 560 GHz; and breakdown voltage, 15 volts. Operating the diodes with self bias eliminates the need for an extra bias supply ordinarily required because of the reverse polarity of the two diodes. The diodes are connected in parallel directly to the IF preamplifier input transistor to avoid loss in a matching circuit or connecting line which would increase the noise figure.

3.3 *Preamplifier*

The preamplifier is a two stage stagger-tuned transformer coupled amplifier using low noise KMC Corporation 5002 and 5003 transistors in the common-emitter configuration. Noise figures at 450 MHz for these transistors are typically 1.7 and 2.2 dB, respectively, and the small signal power gain at 450 MHz is 22 dB. Figure 4 is a schematic diagram of the preamplifier. The bandwidth is obtained by stagger tuning the collector circuits of Q_1 and Q_2. Transformer T_1 is tuned by C_6 and the collector capacitance of Q_1; loading is provided by R_5. Transformer T_2 is similarly tuned by C_9 and Q_2, and loading is provided by the 50 ohm input to the main IF amplifier. The transformers are 4:1 bifilar transmission line transformers wound on a Rexolite core which provides good temperature stability.

In the circuit construction, a planar layout on a copper-clad epoxy-glass circuit board, and miniature components such as $\frac{1}{10}$-watt resistors and chip capacitors were used. In Fig. 5 the preamplifier is shown with a test connector (right side) replacing one of the normal inputs from the mixer.

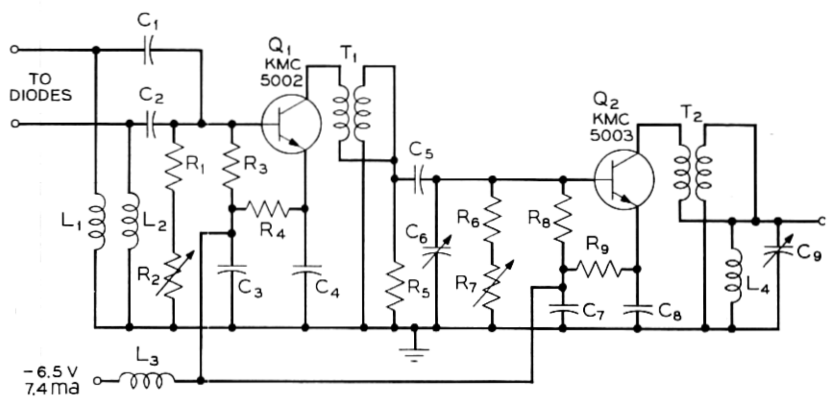

Fig. 4 — IF preamplifier schematic diagram.

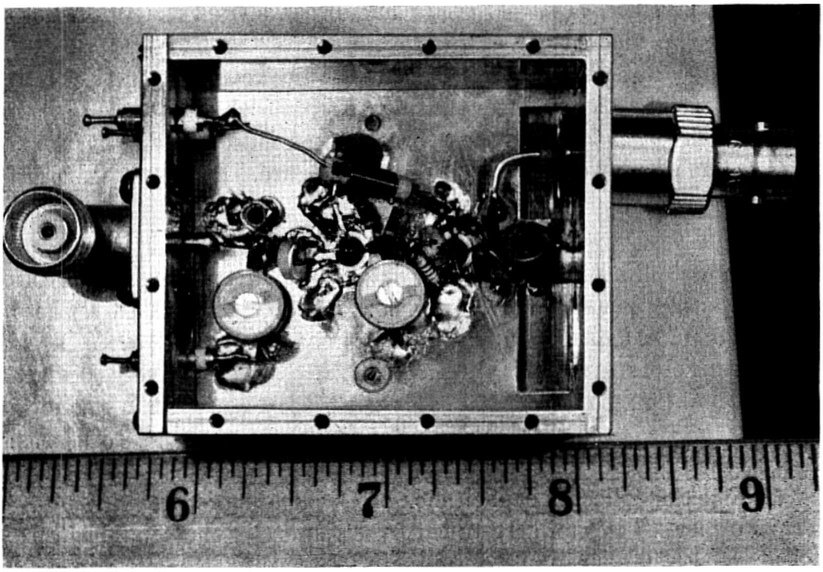

Fig. 5 — The IF preamplifier.

IV. MEASUREMENTS AND RESULTS

4.1 *Frequency Response*

4.1.1 *Preamplifier*

For initial tuning and measurements on the preamplifier, a BNC connector was connected directly to the input transistor in the same way the connection to the mixer would be made (see Figs. 2 and 5). Using a 50 ohm sweep frequency generator, an automatic noise measuring set, and a 50 ohm load, the preamplifier was adjusted for minimum noise figure and best band shape.

At 75°F and −22 dBm output power, the gain of the preamplifier alone when operating between a 50 ohm source and a 50 ohm load is 24 dB. The gain-frequency response, shown in Fig. 6, is flat to within 0.1 dB and the gain is down 0.3 dB at 240 and 370 MHz. At −40°F and +140°F the gain decreases by 0.4 dB and the gain-frequency response has a 0.1 dB positive slope across the 130 MHz band. The output power for which there is 0.2 dB gain compression is −14 dBm.

4.1.2 *Downconverter*

With the preamplifier attached to the mixer, the filter spacers, tuning screws, and diode mounts were adjusted for minimum overall

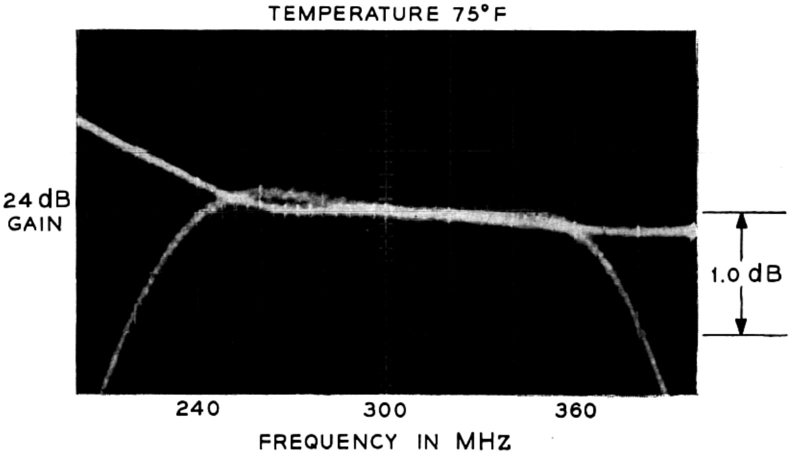

Fig. 6 — Gain-frequency response of the IF preamplifier.

noise figure and flat bandshape. Frequency response measurements were made with a leveled X-band backward wave oscillator sweep frequency generator and the IF output was displayed in dB on an Alfred sweep network analyzer. Except as noted, all measurements were made with a signal power of −40 dBm into the signal filter and a pump power of +10 dBm into the pump filter in accordance with system requirements.

At 75°F, the overall gain of the downconverter is 18.6 dB. The gain-frequency response, Fig. 7, is flat to within 0.1 dB and the gain is down 0.3 dB at 230 and 360 MHz. As shown in Fig. 8, the gain remains at 18.6 dB at −40°F but decreases to 17.7 dB at +140°F.

In system use, the pump power will change somewhat with temperature and from one pump source to another. The effect on the band shape is shown in Fig. 9. For a decrease in pump power from +10 dBm to +8 dBm there is a decrease in gain of 0.7 dB and a positive slope of 0.8 dB across the 120 MHz band. This slope can be corrected by minor retuning of the preamplifier.

The overload characteristics of the downconverter are shown in Fig. 10. The normal output power level with −40 dBm input is −21.4 dBm. At −16 dBm some slope is evident and at −14 dBm output the gain has decreased by 0.2 dB and there is considerable slope in the band shape. This compression primarily is due to the preamplifier since this is the same amount of compression measured for the preamplifier alone.

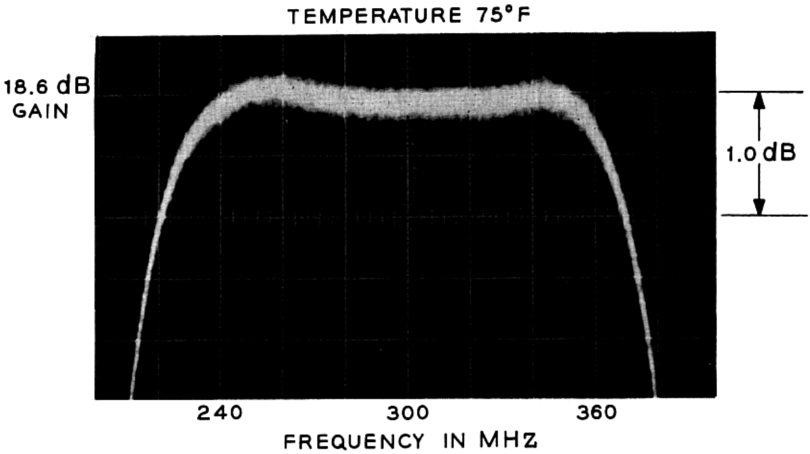

Fig. 7 — Gain-frequency response of the downconverter.

The input return loss at the input to the signal filter is more than 15 dB across the 120 MHz band. The return loss at the narrow band input to the pump filter at the pump frequency is more than 30 dB. The isolation from the pump port to the signal port of the hybrid, a measure of the mixer balance, is 13 dB.

4.2 *Noise Figure*

Noise figure measurements on the preamplifier were made using a Hewlett-Packard 343A temperature limited diode as the noise source.

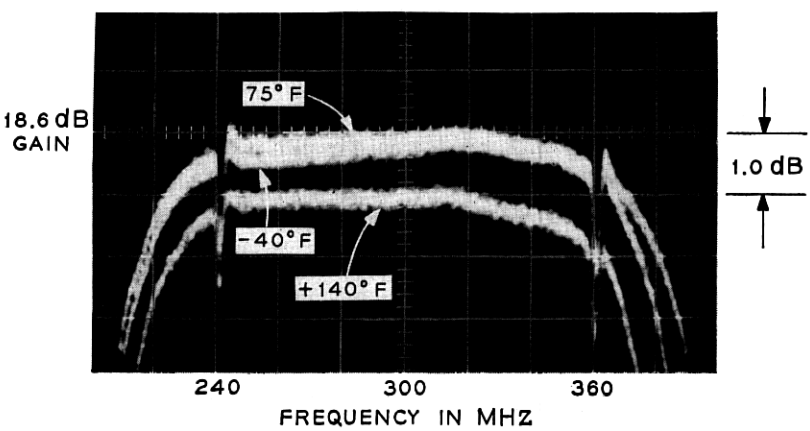

Fig. 8 — Downconverter frequency response at −40, +75, and +140°F.

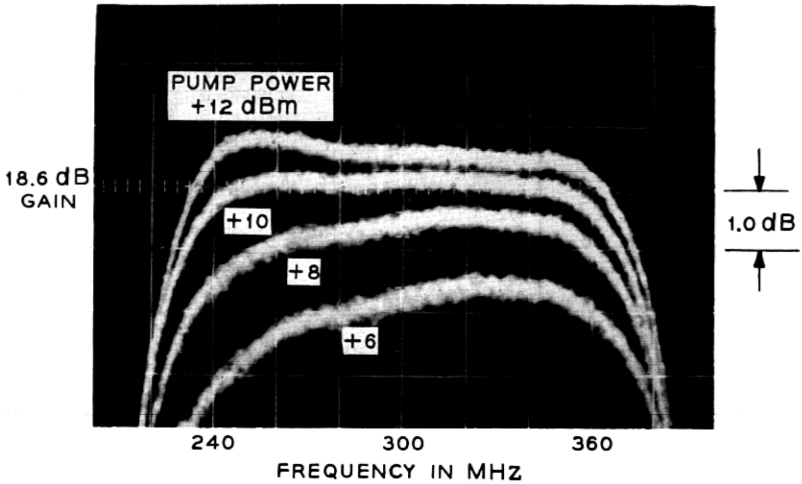

Fig. 9 — Downconverter frequency response as a function of pump power.

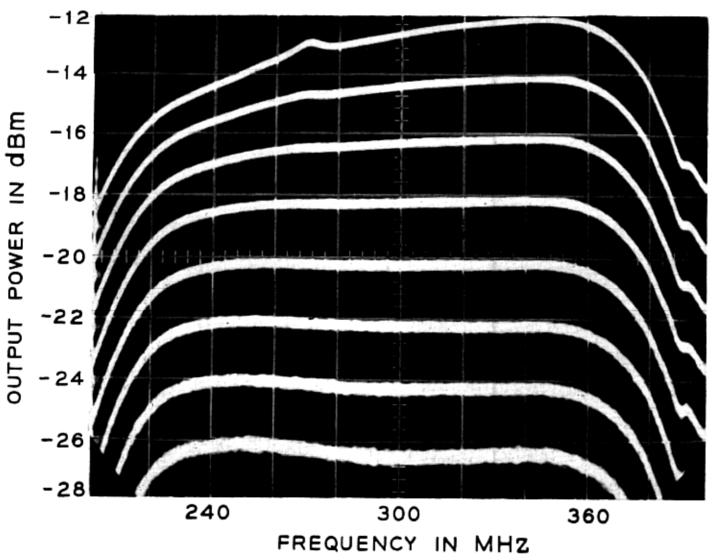

Fig. 10 — Downconverter frequency response as a function of IF output power.

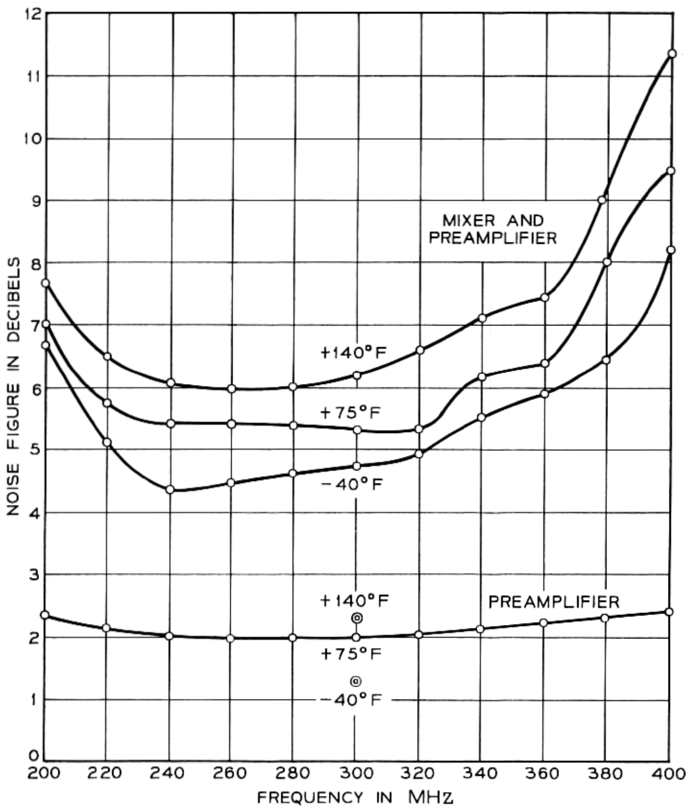

Fig. 11 — Preamplifier and downconverter noise figures as a function of frequency and temperature.

The preamplifier was followed by an Avantek amplifier, an AN/APR-4 radar receiver with 1 MHz bandwidth for converting the UHF signal to 30 MHz, and a Hewlett-Packard 342A noise figure meter. A Hewlett-Packard X347A argon gas discharge tube was used as a noise source for the downconverter. For both preamplifier and downconverter, the spot noise figure in a 1 MHz band was measured as a function of frequency from 200 to 400 MHz and at temperatures of −40, +75, and +140°F. The results are plotted in Fig. 11.

At 75°F, the preamplifier spot noise figure at 300 MHz is 1.98 dB and the preamplifier average noise figure for the 240 to 360 MHz band is 2.05 dB. The corresponding numbers for the downconverter are 5.3 and 5.6 dB. At −40°F the downconverter average noise figure decreases to 4.9 dB and at +140°F increases to 6.5 dB.

V. DISCUSSION

The noise figures obtained in the downconverter reported here are equal to or better than those obtainable with tunnel diode amplifiers and are approaching those obtainable with uncooled parametric amplifiers. However, Dragone's analysis shows that the noise figures reported here are still far above those theoretically possible with Schottky-barrier diode mixers. Theoretically the mixer conversion loss can be as small as a few tenths of a dB and, since noise figures of 1.5 dB have been obtained for transistor amplifiers, an overall noise figure under 2 dB is theoretically possible. The practical problems involved in achieving extremely low conversion loss center around the terminating impedances, particularly at the pump harmonics. In a waveguide circuit such as the magic tee, which has the advantage of low loss, control of harmonic terminations is difficult because of multimoding. On the other hand, in single mode TEM lines, line loss has prevented low conversion losses. Therefore, much lower conversion losses will require careful attention to the RF circuit construction.

When calculating the mixer conversion loss from equation (2) assuming $t_{av} = 1$, its largest value, the conversion loss is the difference between the overall noise figure and the preamplifier noise figure. Using 300 MHz spot noise figures gives $5.3 - 2.0 = 3.3$ dB.

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