Low-Noise Properties of Microwave Backward Diodes*

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Summary—**This paper describes, for what is believed to be the first time, the low-noise properties of backward tunnel diodes in microwave applications. The physics of the diodes are reviewed together with some of the characteristics and equivalent circuit parameters. The diodes are then considered as mixer diodes with IF in the audio range and also the standard 30-Mc IF. Another promising application considered is the use of the backward diodes in low-level detection.**

The results show that the noise figure at 13.5 kMc with a 1-kc IF is around 15 db better than any commercially available mixer diodes. Using 30-Mc IF, the noise figure of backward diode mixers is without special optimum design, comparable to the best mixer diodes on the market. Of great importance, especially in micro-miniaturization, is the fact that these diodes may be used with a very low local oscillator power (50 μw or less). The high nonlinearity of the I-V characteristic at the origin and the low 1/f noise properties of these diodes are also of benefit in crystal video receivers and other low-level detector applications.

I. Introduction

There are three basic types of noise which occur in semiconductor devices. Thermal noise is caused by random motion of electrons. When a drift velocity is superimposed by means of an electric field, we get shot noise. Then we have 1/f noise which is detected over and above thermal and shot noise, and which is distinguished by its spectral intensity.

The investigation reported in this paper is concerned with low 1/f noise (excess noise) and thermal noise in experimental samples of microwave backward diodes. The problem of noise reductions in mixer diodes is discussed in Section II, and the ideas which led to the fabrication of the backward diodes are also described.

Backward diodes made by diffusion or alloying techniques have not yet been accessible for microwave applications because of the large capacitances associated with the junctions. However, the pulse-bonding technique used in our experiments proves to be well adapted for microwave versions of these diodes. The physics of the diodes are also reviewed together with some of the characteristics and equivalent circuit parameters. These diodes have a nearly conventional diode forward I-V characteristic and the back characteristic of a tunnel diode.

A reduction of 1/f noise is of interest, for example, in Doppler radar systems where the IF is in the audio range. Since light weight, small size and simplicity are very important in this type of antenna-navigations radar, it does not seem desirable in some cases to increase the complexity of the system and go to higher IF (30 Mc) and thus possibly eliminate the 1/f noise problems. In some mixer diodes there is indication of a slight contribution of excess noise at 30 Mc. However, the main contribution to the noise at this frequency is shot and thermal noise. Because of the low spreading resistance in the semiconductor wafer, the thermal noise will be reduced somewhat compared with that of ordinary mixer diodes. Thus, an improvement of the sensitivity of systems using 30-Mc IF may also be expected. Present video crystal receivers and other low-level detector applications may also benefit in sensitivity from an 1/f noise reduction in diodes. All these application aspects of the backward diodes are described in the last part of this paper.

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II. Reduction of Diode Noise

Although the origin of the 1/f noise in semiconductors is not precisely known, a variety of experiments have indicated that the surface plays a significant part in connection with this noise. It has been observed that 1/f noise increases with higher density of slow surface states, and, for a given density of slow states, the 1/f noise will be higher for an inversion layer than for an accumulation layer [1].

One approach for decreasing the 1/f noise is a stabilization of the surface by etching, ambient gas control, or thermally grown oxide layers. These techniques for stabilization and evaluation have been successfully applied to conventional mixer diodes in our laboratory.

However, the author is suggesting another approach to the problem of 1/f noise reduction in mixer diodes. For nearly degenerate material the relative change in surface potential is much less pronounced than in the nearly intrinsic case. Thus, if nonlinearities in the I-V characteristics of diodes made of much lower resistivity material than conventional mixer diodes were utilized for mixing purposes, the surface contribution to the 1/f noise should be reduced. Also, since the resistivity of the semiconductor wafer is reduced, the thermal noise contribution from the spreading resistance may be smaller.

The backward diodes used in our experiment have doping levels one and two orders of magnitude higher than conventional mixer diodes. Another point of interest is that the 1/f noise decreases when the rectified current decreases [2]. Since the conversion loss can be preserved at very low local oscillator power when using the backward diodes as mixers, improvements in the over-all noise figure of systems using IF frequencies in the audio range should be obtained. The reduction of the spreading resistance may also be of value in decreasing the noise figure of receiver systems using 30-Mc IF.

III. The Backward Diode [3], [4]

Since electrons can be considered to have wave properties, they have the ability to penetrate potential barriers which would be impossible for particles according to classic theory. This effect is known as quantum-mechanical tunneling. A backward diode is a special case of a diode exhibiting quantum-mechanical tunneling phenomena. The most familiar example is the tunnel diode, where the impurity concentrations on both sides of the p-n junction are such that an increase in tunneling current is followed by a decrease, producing a negative resistance. The expression for the tunneling current is

$$J \propto \exp\left[-\frac{Am^{*1/2}Eg^{3/2}}{F}\right], \qquad (1)$$

where

A = numerical constant
m^* = reduced mass of holes and electrons
Eg = band gap of semiconductor
F = average electric field across the space-charge region.

F is inversely proportional to the width of the space-charge region of the p-n junction. A wide space-charge region means low tunneling current; a narrow one means high tunneling current. For a backward diode, it is necessary to reduce the tunneling current from the high levels of a tunnel diode to such levels that a negative resistance is either nonexistent or is so high that it can be disregarded. The expression for the width of the space-charge region of an abrupt junction is

$$W = \left[\frac{2K\,Ko(N_D + N_A)}{eN_DN_A}(V_D + V_A)\right]^{1/2}, \qquad (2)$$

where

N_D = donor concentration
N_A = acceptor concentration
V_D = built-in "diffusion" voltage
V_A = applied bias voltage
$K\,Ko$ = dielectric constant of semiconductor
e = electronic charge.

If, in fabrication, one doping level is kept constant at some high level, the space-charge region can be widened by simply decreasing the impurity level of the semiconductor wafer. This causes a decrease of the tunneling current, and enables the device designer to adjust it to the proper level.

It is theoretically possible to make backward diode junctions by diffusion techniques. However, it is very impractical to control a diffusion of only several hundred atomic layers into the wafer. The technological difficulties of making electrical connections to such a shallow diffused layer are also severe. In addition, diffused junctions are undesirable because the tunneling probability decreases exponentially with the width of the space-charge region.

Tunnel diodes and also backward diodes are generally made by alloying techniques. An appropriate alloy pellet is placed in contact with a semiconductor wafer and heated to such a temperature that wetting and dissolutions of some of the semiconductor into the alloy occurs.

The alloy contains the impurity that will give opposite conductivity type to that in the wafer. On cooling the dissolved semiconductor will epitaxially grow on the base semiconductor. This regrowth will now be doped to the opposite conductivity type. There will be an abrupt transition between the doping levels on the two sides of the junction. The capacitance of this type of junction may be too large for practical use in the microwave region. However, by subsequent etching, the junction diameter can be reduced. The main advantage of this technique is that fairly good control of the current-voltage characteristic can be obtained. The disadvantages are that capacitances in the 0.2 $\mu\mu$f range are difficult to reproduce and that the structure is mechanically weak.

The pulse-bonding technique seemed to be the best way of fabricating our diodes. A gallium-plated gold wire was brought into contact with an n-type germanium semiconductor wafer with a resistivity in the range of 0.001 to 0.004 ohm/cm, and the junction was formed by passing a pulse through it. The pulsing equipment has certain parameters to vary, such as the heights and lengths of the pulse. The I-V characteristic of the diode can be displayed on a scope so that the junction can be pulsed to the desirable current-voltage characteristic. The capacitances obtained are well below one picofarad. The capacitance-voltage relationship is that of a step junction.

Unlike tunnel diodes, the package is not too critical. A standard computer glass package supplemented with gold-plated brass adaptors and with over-all dimensions confirming with ordinary mixer diode packages was found to be satisfactory at 13.5 kMc.

The equivalent circuit of the diode used in the experiment is shown in Fig. 1. C_t is the space-charge capacitance, which was around 0.2–0.5 $\mu\mu$f at zero bias. The series wafer resistance R_S was found to be approximately 10 ohms when estimated from the shape of the I-V curve in the forward direction. The lead inductance L_S is mμh when measured at 1 kMc, and C is the stray capacitance of the package. The variable resistance R_b varies between 300 ohms and 80 ohms for local oscillator powers in the range from 10 μw to 1 mw.

The nonlinear barrier resistance is believed to be independent of frequency from dc to well beyond the microwave region and is also considerably less temperature dependent than that of a conventional mixer diode.

The backward diode I-V characteristics are shown in Fig. 2. As the reverse bias is increased, the supply of electrons which are able to tunnel increases without limit. At zero bias no current flows through the junction. At forward bias only a very small current is able to flow by the tunneling process. The excess current is, in some cases, fairly constant until carrier injection takes place giving rise to the normal forward characteristic of a *p-n* junction.

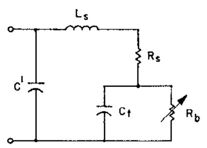

Fig. 1—The low-frequency diode equivalent circuit.

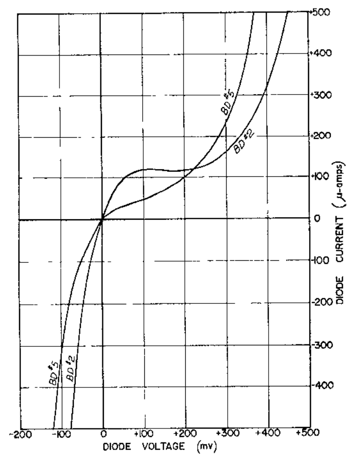

Fig. 2—The backward diodes' I-V characteristics.

IV. Application and Measurement

A. Mixer With IF in the Audio Range

Radars for navigation and moving target indications use the Doppler effect in one form or another. Since light weight, small size and simplicity are very important, it does not seem desirable in some cases to increase the complexity of the system by using 30-Mc IF to eliminate the 1/f noise problems. One simple arrangement is shown in Fig. 3. Power from the transmitter is mixed with the CW echo from a target. The beats between the two frequencies f and f' can be heard in phones or indicated on other types of indicators. The echo frequency is given by the well-known Doppler formula,

$$f' = \frac{c + v}{c - v} f. \tag{3}$$

The beat frequency is then

$$f_d = f' - f = \frac{2v}{c - v} \cdot f \simeq \frac{2v}{c} = \frac{2v}{\lambda}, \tag{4}$$

where v is the target velocity and λ is the wavelength of the transmitted signal. The beat frequency is usually in the kc range.

The operating noise figure of our Doppler system can be written as

$$F_{\text{op}} = (t_a - 1)\frac{B_t}{B_u} + L_m(t_m + F_{\text{IF}} - 1), \tag{5}$$

where

t_a = source temperature normalized with respect to room temperature
B_u = useful channel bandwidth
B_t = total channel bandwidth
L_m = mixer conversion loss
F_{IF} = IF amplifier noise figure.

The properties of the crystal diode itself are involved explicitly or implicitly in this equation. In our system the total bandwidth is approximately twice the useful bandwidth ($B_t/B_u \simeq 2$), since the signal is entering only one of the channels, while the antenna noise is appearing in the signal channel as well as the image channel.

Since 13.5 kMc is used in several types of navigation Doppler radar systems, the noise figures of the diodes were tested at this frequency in the experimental system shown in Fig. 4. In this way the noise figure can easily be measured with the so-called "signal generator

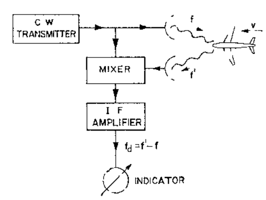

Fig. 3—Schematic diagram showing a simple Doppler radar system.

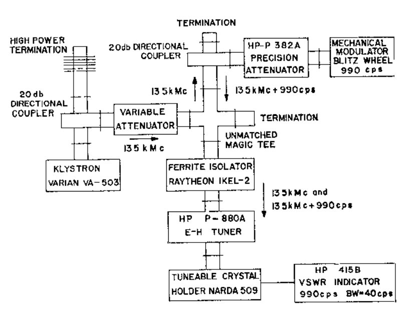

Fig. 4—The Doppler radar noise-figure measurement system.

method." The results obtained agree, within measurement errors, with calculated values of the noise figure obtained from separate measurement of the conversion loss and noise temperature. Microwave power at 13.5 kMc travels from the signal generator to the magic tee. One part of the power is delivered to the test diode and may be thought of as the local oscillator power of the mixer. Another part of the power travels through the precision attenuator to the "Blitz Wheel" mechanical modulator. The modulator reflects power at 13.5 kMc +990 cps, and part of this signal is available for delivery to the diode. This power may be considered the input signal, and it beats with the local oscillator signal in the test diode to produce the difference frequency of 990 cps, which is then amplified together with the audio noise generated by the diode. The calibration of the system is made by careful measurement of the individual insertion losses of the various microwave components and the response characteristic of the output meter. The signal amplitude is controlled by the precision attenuator in front of the modulator, and this input signal is adjusted so that the noise plus signal output power is double the output power obtained when the input signal is zero. Then the noise figure is obtained from the ratio of the input signal power used to the available thermal noise power from the source.

In order to properly evaluate the capabilities of the diodes, it was also found necessary to measure the conversion loss, noise temperature and the noise temperature spectrum of the experimental crystals [6].

The conversion loss L_m is defined as the ratio of the available RF input signal power to the measured IF output power at the mixer. In the "amplitude modulation method" used, the output of an oscillator at 13.5 kMc was amplitude modulated at 990 cps. The modulation envelope, after crystal detection, was developed across an output load. The conversion loss was then found from this voltage, since the percentage modulation and the power of the oscillator were known from careful calibration.

The mixer noise temperature t_m is defined as the ratio of available noise power output of the crystal to that of a resistor at room temperature. The "Y-factor method" [6] in which

$$t_m = F_{\mathrm{IF}}(Y - 1) + 1 \tag{6}$$

was used in our case. Y is the ratio of system noise output with the test diode in the crystal holder to the noise output when a resistor equal to the IF dynamic resistance of the crystal was substituted for the crystal in the holder. The input unmodulated signal was at 13.5 kMc, and the crystal was followed by a 990-cps VSWR (bandwidth 40 cps, $F_{\mathrm{IF}} \approx 6$ db) and a transistor post amplifier.

The noise temperature spectrum was measured under the same conditions as the noise temperature, except that the crystal was followed by a wide-band transistor amplifier and a spectrum analyzer.

In Fig. 5 the performance characteristics of a backward diode mixer with 990-cps IF are plotted. The noise figure of a commercially available low 1/f noise diode (1N1838) is also shown for comparison. First of all, it is indicated that the backward diode has a considerably lower noise figure which is caused by a reduction of 1/f noise (see Fig. 6). Another important consideration is that the diode is capable of operating with very low local oscillator powers without any dc bias. The reason is that the nonlinear region of the I-V characteristic is in the vicinity of the origin, while in ordinary mixer diodes the nonlinearity occurs around the contact voltage, which may be 0.3 to 0.6 volt in the forward direction. Thus, the backward diode may be used in a low-noise mixer using a tunnel diode or variable-capacitance diode harmonic generator as the local oscillator.

A more direct comparison of the two different diodes is made in Table I. Since the $R_S C_t$ product is higher in the BD No. 5 diode than in the 1N1838 diode, the conversion loss would be expected to be higher since the conversion loss is an increasing function of this product [6]. However, it should be pointed out that no real attempt has been made to optimize the fabrication technique.

Fig. 7 shows the noise temperature spectrums for the two diodes. It is interesting to note that the spectrums follow approximately the 1/f law. The turnover point from 1/f noise to shot and thermal noise is around 20 kc for the backward diode, and the noise temperature seems to be roughtly proportional to the square of the rectified current in the 1/f noise range. This current dependence of the noise temperature spectrum corresponds with results obtained for conventional point-contact mixer diodes [2].

It can be concluded that the real improvement in the noise figure obtained by the backward diode compared with that of a conventional mixer diode is caused by reduction in noise temperature. There is reason to believe that

1) 1/f noise is less pronounced in the backward diodes since they are made of lower resistivity material than ordinary mixer diodes.
2) 1/f noise is lower at the optimum noise figure because less local oscillator power (and thus rectified diode current) is needed for satisfactory operating performance.

B. Mixer with 30-Mc IF

In optimum receiver design it has been found that 30 Mc is a good choice for the intermediate frequency using present commercially available mixer diodes. This optimum IF is mainly determined by the noise figure of the IF amplifier and the mixer noise temperature. The

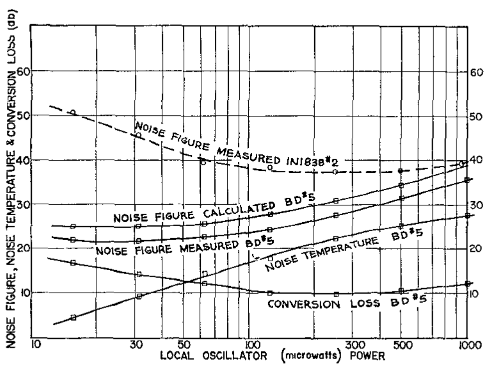

Fig. 5—Performance characteristics of a backward diode mixer with 990-cps IF. The noise figure of a 1N1838 diode (low 1/f noise) is also shown for comparison.

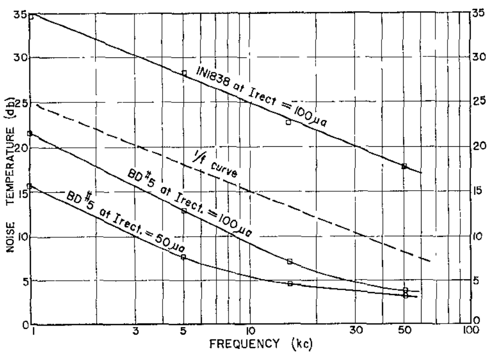

Fig. 6—The noise temperature spectrums for a backward diode and a 1N1838 low 1/f noise Doppler mixer diode.

TABLE I

Comparison of Mixer Characteristics
RF = 13.5 kMc, IF = 990 cps

Diode	R_S	C_t	30 μw Local Oscillator Power			250 μw Local Oscillator Power		
			F_{op}	L_m	t_m	F_{op}	L_m	t_m
	ohm	$\mu\mu$f	db	db	db	db	db	db
BD No. 5	10	0.3	21.5	14	9.8	27.5	10.0	21
1N1838	12	0.1	45.5	19.5	25	37.5	8	31.5

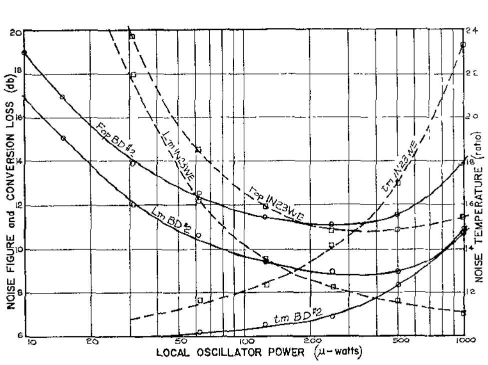

Fig. 7—Performance characteristics of a backward diode and a 1N23WE mixer diode with 30-Mc IF.

reduction of 1/f noise in mixer crystals may therefore influence receiver design.

At 30 Mc the main contribution to the noise temperature is shot and thermal noise. However, in some cases a very small excess noise contribution may be present. Nevertheless, since the backward diodes are made of lower resistivity material than conventional mixer diodes, a small improvement may be expected in the noise temperature since the thermal noise caused by the series bulk resistance will be reduced.

The experimental results are shown in Fig. 7. A comparison is made with the 1N23WE mixer diode. The noise figure was calculated according to (5) when $t_a = 1$, and the conversion loss was measured as outlined in Section IV-A. The noise temperature was measured with a 30-Mc IF amplifier ($F_{IF} = 1.7$ db) following the crystal.

In Table II the comparison is made at 300-μw local oscillator power, which seems to give the best noise figure for both diode types, and 30-μw, which may be of interest in lightweight systems since this small amount of power may be readily available from tunnel-diode oscillators or harmonic generators using variable-capacitance diodes.

TABLE II

Comparison of Mixer Characteristics
RF = 13.5 kMc, IF = 30 Mc

Diode	R_S	C_t	30-μw Local Oscillating Power			300-μw Local Oscillating Power		
			F_{op}	L_m	t_m	F_{op}	L_m	t_m
	ohm	$\mu\mu$f	db	db	ratio	db	db	ratio
BD No. 2	8	0.6	14.1	12.3	1	11.1	8.8	1.12
1N23WE	35	0.2	20	18	1.08	10.8	8	1.46

The backward diode is slightly higher in noise figure than the 1N23WE under conventional local oscillator power requirements. The difference is mainly caused by the conversion loss. This was expected, since the R_SC_t product is highest for the backward diode. However, the 1N23WE seems to have a lower nonlinearity coefficient for the barrier resistance than the backward diode (this can be verified by inspection of the I-V curves for the respective diodes). Also, since the backward-diode noise temperature is, indeed, lower, there may be reason to believe that, by optimizing the fabrication technique so that a lower value of capacitance can be obtained, the backward diode may be superior to the 1N23WE in this application with 300-μw local oscillator power.

At lower local oscillator powers the backward diode has much better noise figure than the 1N23WE diode. The main reason for this is that the 1N23WE diode does not have the same ability to rectify small powers as the backward diodes. Thus, the conversion loss will be substantially higher in the 1N23WE diode at low local oscillator powers.

C. Low-Level Detection

Another major application of the backward diode is in video detection. In a crystal video receiver, for example, the incoming modulated RF signal is detected immediately at the input from the antenna, and the resulting video signal is amplified by a high-gain video amplifier. The advantages of this type of receiver are simplicity, small size, low cost and broad RF bandwidth. The price paid for these attractive features is a large loss of sensitivity compared with that obtainable with a superheterodyne receiver. However, there are applications where the lower sensitivity is acceptable and where the small size or broad band is required (beacon radar receivers, square-law detectors in power measurement instruments, etc.).

The SNR of a detector crystal is proportional to a figure of merit [6] M, which combines the rectification properties and the noise generation of the crystal and the amplifier. A higher figure of merit indicates a greater sensitivity and thus a lower minimum detectable signal.

$$M = \frac{\beta R_b}{\sqrt{R_b + R_A}}, \tag{7}$$

where

β = short-circuit current sensitivity of the diode
R_b = video impedance of the diode
R_A = equivalent noise resistance of the video amplifier.

The current sensitivity β was measured at 13.5 and 6 kMc by observing the short-circuit rectified current i for a given input power P. Then $\beta = i/P$. The video resistance R_b is the dynamic dc resistance of the crystal at the operating point, and it was measured with a bridge at 100 kc.

The short-circuit current is plotted in Fig. 8 as a function of the absorbed input power at 13.5 and 6 kMc for a backward diode and a detector diode MA408B. The backward diode has a higher current sensitivity and a square-law response of a larger range than the conventional detector diode. A more direct comparison is made in Table III.

At 13.5 kMc the backward diodes seem more advantageous according to the figure of merit. The reason for the higher current sensitivity is partly due to the lower video impedance R_b compared with that of the MA408B diode. However, the product $R_S C_t$ is lower and the I-V nonlinearity is also higher for the backward diode. Both factors will result in higher current sensitivity. At 6 kMc the MA408B shows a higher figure of merit which may be contributed by the higher video resistance. There are good reasons for believing that the video resistance of the backward diode may be increased by suitable optimization of the shape of the I-V curve.

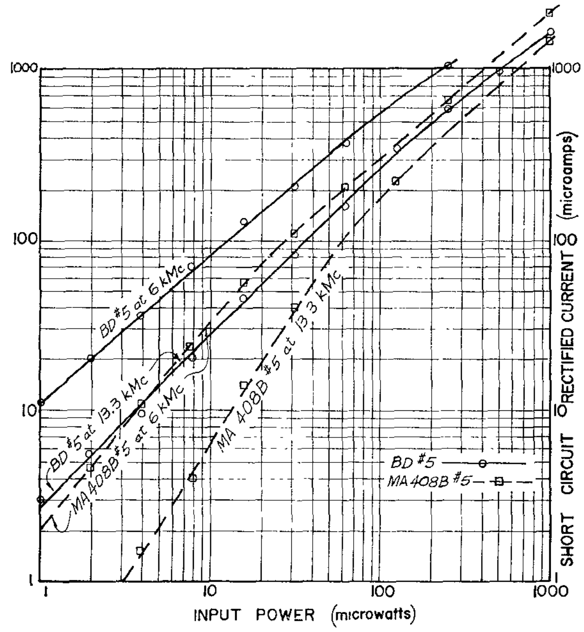

Fig. 8—The short-circuit current as a function of the absorbed input power for a backward diode and a detector diode MA408B.

TABLE III
COMPARISON OF VIDEO DETECTOR CHARACTERISTICS

Diode	R_S	C_t	R_b	13.5 kMc		6 kMc	
				β	M	β	M
	ohm	$\mu\mu$f	ohm	at 1 μw power	calculated	at 1 μw power	calculated
MA408B No. 5	42	0.23	35k	0.2	37	2	370
MA408B No. 6	32	0.32	20k	0.2	28	2	280
BD NO. 5	10	0.3	730	2.7	45	11	180
BD NO. 7	8	0.5	880	2.4	47	7.5	145

Other possible advantages of the backward detector diodes compared with conventional detector diodes may be the expected smaller variations in the performance characteristics with variations in temperature and nuclear radiation.

V. CONCLUSION

Experimental microwave backward diodes have been made, and the low-noise properties of these diodes investigated and compared with the best commercially available crystals. The performance characteristics show that backward diode mixers are of considerable advantage in receiver systems where the IF is in the audio range. The improvement is mainly caused by a reduction in 1/f noise. It should be noted that a backward diode mixer can be operated with an order of magnitude lower local oscillator power than mixer diodes used today. Very satisfactory performance was also obtained using 30-Mc IF and in low-level detection, in spite of the fact that no real attempt was made to optimize the diode fabrication technique. In fact, there are good theoretical reasons for believing that other wafer materials may well prove to be superior to germanium for the applications considered in the paper. Since the backward diodes are virtually independent of the lifetime of minority carriers or of the surface treatment, they can tolerate larger doses of nuclear radiation than conventional mixer diodes. The tunneling portion of the I-V curve is also expected to be substantially independent of temperature.

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Design Theory of Up-Converters for Use as Electronically-Tunable Filters*

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Summary—The up-converters discussed use a single diode, a wide-band impedance matching filter at their signal input, a moderately wide-band impedance matching filter at their pump input, and a narrow-band filter at their sideband output. With a narrow-band filter at the sideband output, the frequency which will be accepted by the amplifier can be controlled by varying the pump frequency. Analysis of the impedance matching problem involved shows that tuning ranges of the order of a half-octave to an octave are possible. Theory is presented for both the lower-sideband and upper-sideband types of tunable up-converters and for the design of the required impedance-matching networks. It is shown that, because of the pump input bandwidth required, it will generally be necessary to accept some mismatch at the pump input. But, by use of a properly designed impedance-matching filter, the reflection loss can be kept nearly constant across the pump band, and the incident pump power required is not unreasonable. It is seen that properly designed devices of this type using voltage-tunable pump oscillators should have wide tuning range, fast tuning capability, a useful amount of gain, no image response, and a low noise figure.

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I. INTRODUCTION

A. Description of the Proposed Devices

PREVIOUS work dealt with the application of filter theory to the design of wide-band parametric amplifiers and up-converters.[1] The present discussion applies a similar theoretical approach to a different but closely related problem. The objective will be to obtain an electronically controlled *wide tuning range* using up-converters having a wide-band input-impedance-matching filter, a narrow-band output-impedance-matching filter, and a voltage-tunable pump oscillator such as a backward-wave oscillator.

Defining f as the input frequency, f' as the sideband output frequency, and f^p as the pump frequency, for a lower-sideband up-converter the output is at the lower-

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