Wafer-Type Millimeter Wave Rectifiers*

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A wafer-type silicon point-contact rectifier and holder designed primarily for use as the first detector in millimeter wave receivers are described. Measurements made on a pilot production group of one hundred wafer rectifier units yielded the following average performance data at a wavelength of 5.4 millimeters: conversion loss, 7.2 db; noise ratio, 2.2; intermediate frequency output impedance 340 ohms. Methods of estimating the values of the circuit parameters of a point-contact rectifier are given in an Appendix.

INTRODUCTION

Point-contact rectifiers for millimeter waves have been in experimental use for several years. These units, for the most part, have been coaxial cartridges which were inserted in a fixed position, usually centered, in the waveguide. Impedance matching was accomplished by means of a series of matching screws preceding the rectifier and an adjustable waveguide piston following the rectifier. Tuning screws are generally undesirable because of the possibility of losses, narrow bandwidths and instability.

It is the purpose of this paper to describe a new type millimeter-wave rectifier and holder which were designed to eliminate the need for tuning screws and to provide a readily interchangeable rectifier of the flat wafer type. This wafer contains a short section of waveguide across which the point contact rectifier is mounted. The necessary low frequency output terminal (and the rectified current connection) together with the high-frequency bypass capacitor, are also contained within each wafer. The basic idea of the wafer-type rectifier is that the unit can be inserted in its holder and moved transversely to the waveguide to obtain a resistive match to the guide; the reactive component of the rectifier impedance is then tuned out by an adjustable waveguide plunger behind the rectifier.

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The wafer unit and holder were developed primarily for use as the first converter in double detection receivers operating in the 4- to 7-millimeter wavelength range. In order to check the practicability of the design and to supply rectifiers for laboratory use, a pilot production group of one hundred units was processed and measured. Performance data obtained with this group are presented. A balanced converter using wafer rectifiers is also described.

Methods of estimating the values of the various circuit parameters of a point-contact rectifier are outlined in an appendix. These calculations proved useful in the design of the wafer unit and in predicting the broadband performance of the converter.

DESCRIPTION OF WAFER UNIT AND HOLDER

Fig. 1 is a drawing of the wafer type rectifier. The unit is made from stock steel $\frac{1}{16}$-inch thick and is gold plated after the milling, drilling and soldering operations are completed. To allow for the transverse impedance matching adjustment, the section of waveguide contained in the wafer is made wider than the RG98U input guide to the holder. By making the wafer thin ($\frac{1}{16}$ inch), the short sections of unused guide on either side will remain "cut-off" over the operating range of the rectifiers. The silicon end of the rectifier consists of a copper pin on which the silicon is press mounted, the assembly held in place with Araldite cement which also serves as the insulating material for a quarter-wavelength long high frequency bypass capacitor. The pin serving as the intermediate frequency and direct current output lead is also cemented in place with Araldite cement. A soft solder connection is made between this pin and the pin holding the silicon wafer. A nickel pin with a conical end on which a pointed tungsten contact spring is welded is pressed into place from the opposite side of the guide at the time of final assembly.

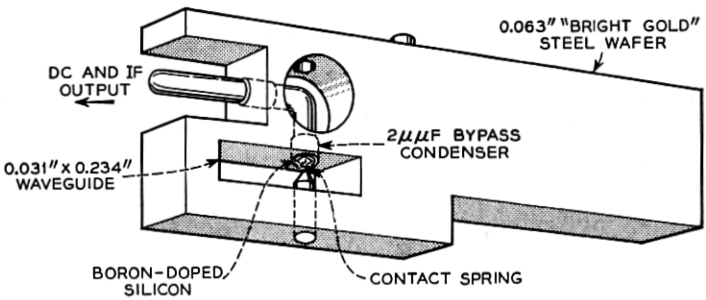

Fig. 1 — Millimeter-wave wafer unit.

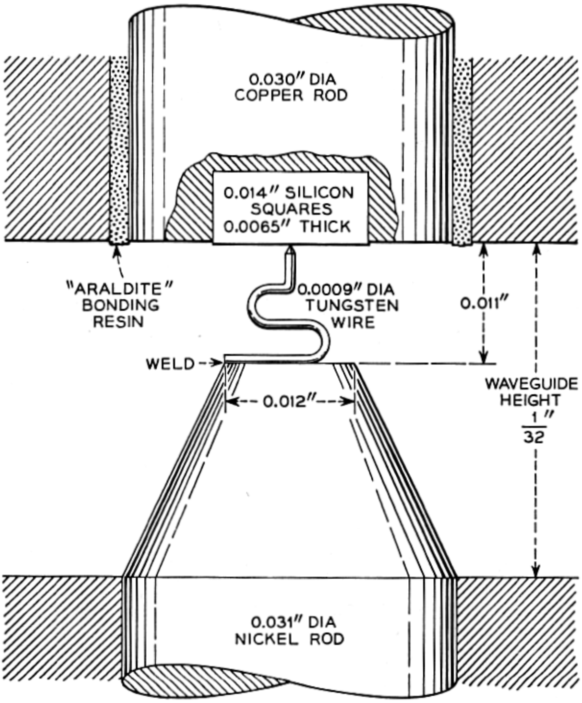

Fig. 2 — Millimeter-wave point-contact assembly.

The region of the wafer unit containing the silicon and point contact is shown in Fig. 2. The methods used in preparing the silicon wafer and the spring contact point are similar in many respects to the standard techniques used in the manufacture of rectifiers for longer wavelengths. Some modifications and refinements in technique are called for by a decrease in size and the increased frequency of operation.

A single-crystal ingot, grown from high purity DuPont silicon doped with 0.02 per cent boron, furnishes the material for the silicon squares used in the wafer unit. Slices cut from the ingot are polished and heat treated. Gold is evaporated on the back surface and the slices are diced into squares approximately 0.014-inch square and 0.0065-inch thick. These squares are pressed into indentations formed in the ends of the 0.030-inch copper pins which have previously been tin-plated. The rods are then cemented in place in the wafer. The spring contact points are made of pure tungsten wire that has been sized to 0.9 mil in diameter by an electrolytic etching process. A short length of this wire is spot welded on the conical end of the 0.031-inch nickel rod. The wire is then bent into

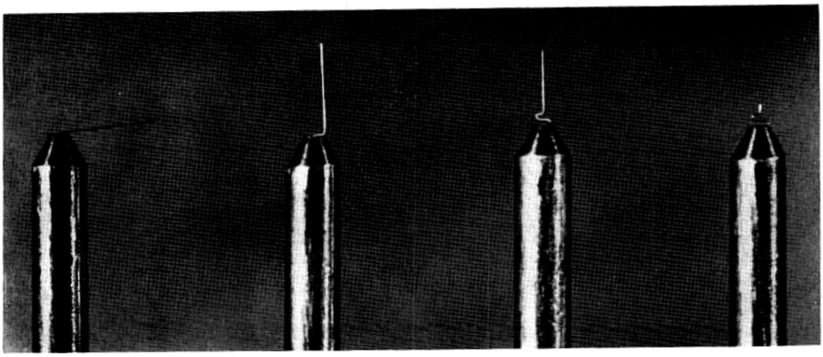

Fig. 3 — Micro-photograph showing successive stages in the formation of the contact spring. The posts are $\frac{1}{32}$ inch in diameter.

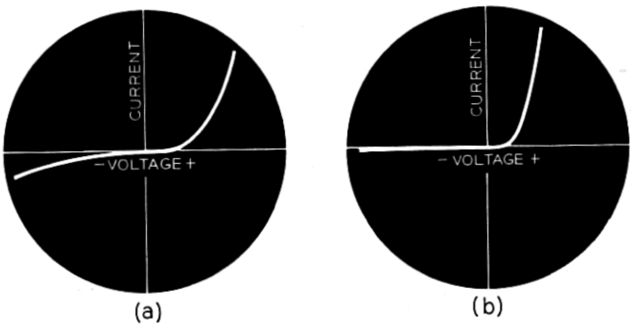

Fig. 4 — Cathode-ray oscilloscope display of wafer unit static characteristic: (a) before and (b) after tapping.

the "S" configuration in a forming jig. By an electrolytic process the spring is then cut to the proper length and pointed. The micro-photographs in Fig. 3 show successive stages in the formation of the contact spring.

In the final assembly of the unit the nickel rod with the contact spring is pressed into place until contact is made with the silicon. It is then advanced a half mil to obtain the proper contact pressure. The voltage-current characteristics as viewed at 60 cycles on a cathode-ray oscilloscope will then appear as shown in Fig. 4(a). The unit is "tapped" into final adjustment. This is done by clamping the unit in a holder and rapping it sharply on the top of a hard wood bench. This procedure requires experience as excessive "tapping" will impair the performance of the unit. Usually one vigorous "tap" is sufficient to produce the desired effect and the voltage-current characteristic will appear as shown in Fig. 4(b). The static characteristic of a typical unit is shown in Fig. 5.

The conversion loss of each unit is measured before the end of the nickel rod carrying the contact point is cut off flush with the wafer. In the event that this initial measurement shows that the conversion loss exceeds an arbitrarily chosen upper limit (8.5 db), it is possible at this stage to withdraw the point and replace it with a new one. This procedure, which was necessary on only a few of the units processed, always resulted in an acceptable unit. The final operation is to cut off the protruding end of the nickel rod flush with the wafer.

A holder designed to use the wafer units is shown in Figs. 6 and 7. At the input end of the converter block is a short waveguide taper section to match from standard RG98U waveguide to the $\frac{1}{32}$-inch high waveguide used in the wafer unit. As the wafer unit is moved in and out to match the conductance of the crystal to the waveguide, the output pin of the wafer unit slides in a chuck on the inner conductor of the coaxial

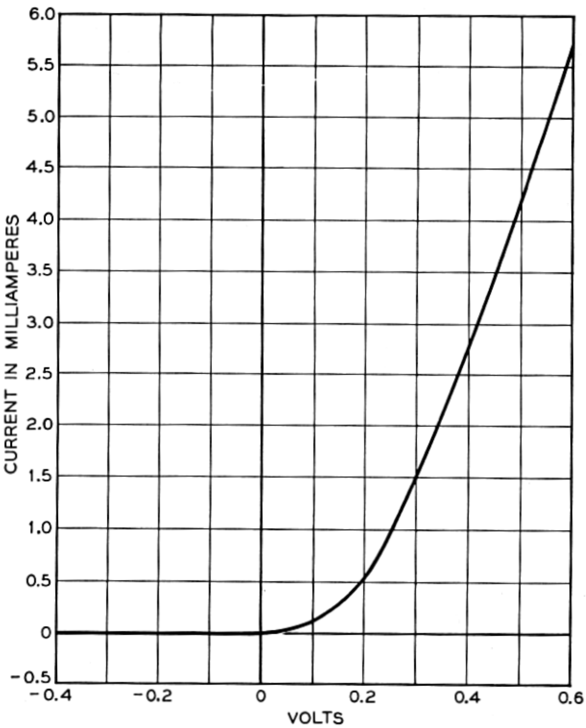

Fig. 5 — Static characteristic of typical millimeter-wave wafer unit.

output jack. The unit may be clamped in position after matching adjustments are made by tightening the knurled thumb screw which pushes a cylindrical slug containing an adjustable piston against the wafer unit. The piston is a short septum which slides in shallow grooves in the top and bottom of the $\frac{1}{32}$-inch high waveguide, thus dividing the waveguide into two guides which are beyond cut-off. This septum is made of two pieces of thin beryllium copper bowed in opposite directions so that good contact is made to the sides of the grooves in the top and bottom of the waveguide. Since the piston with its connecting rod is very light in weight and is held firmly in place by the spring action of the bowed septum, no additional locking mechanism need be provided. Since the rectifier is essentially broadband by design, the adjustment of the piston is not critical and is readily made by hand. The piston rod is protected by a cap which is snapped in place over the thumb screw when all tuning adjustments are completed.

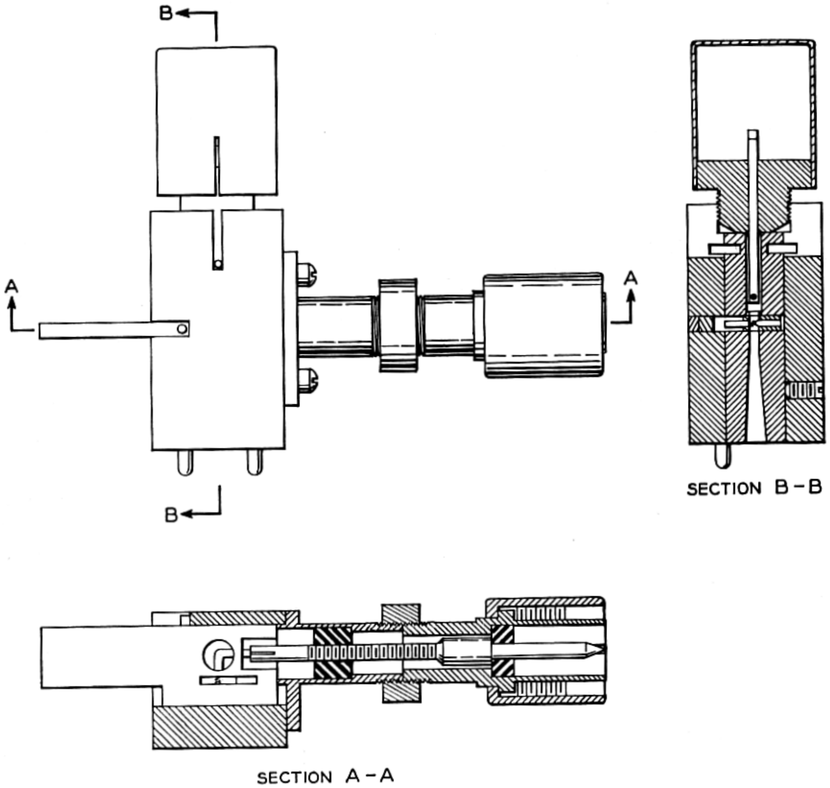

Fig. 6 — Assembly drawing of millimeter-wave converter.

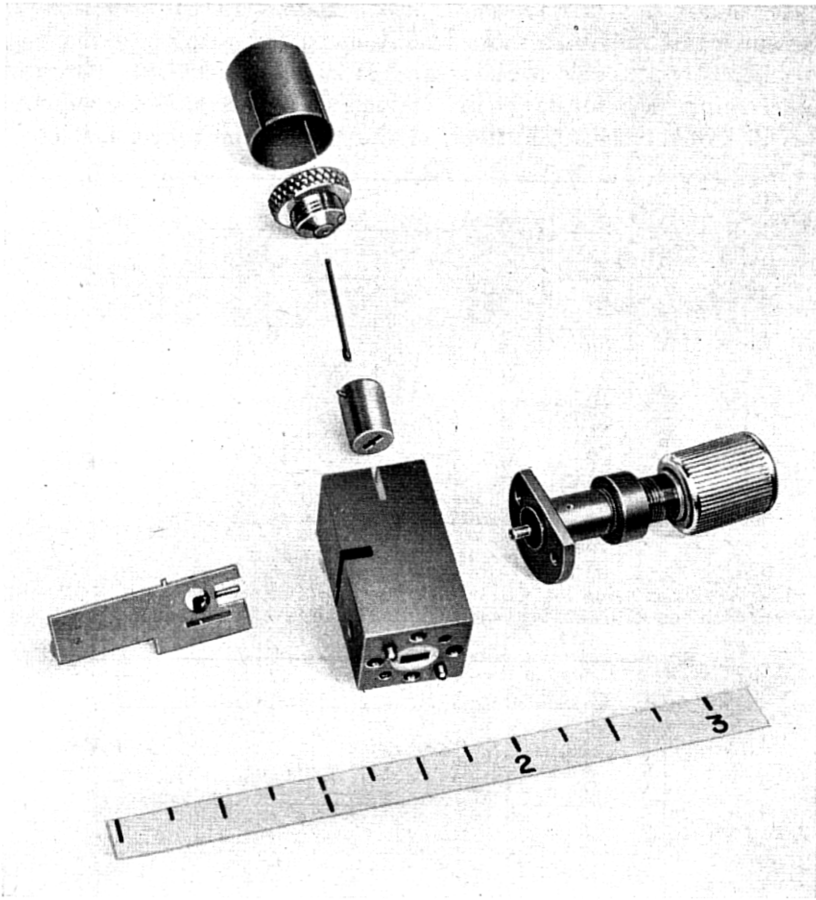

Fig. 7 — Explosed view of millimeter-wave converter.

With the converter fixed-tuned at 5.4 millimeters, a shift in wavelength to 6.3 millimeters (17 per cent change) produces a mismatch loss of from 1.6 to 4.0 db depending on the rectifier used.

PERFORMANCE DATA FOR WAFER-TYPE RECTIFIER UNIT

A pilot group of one hundred wafer units was processed and measured. Figs. 8, 9 and 10 are bar graphs of the distribution of the conversion loss L, and noise ratio N_R*, and the 60 megacycle intermediate frequency output impedance Z_{IF}, for the hundred rectifiers measured in the

* N_R is the ratio of the noise power available from the rectifier to the noise power available from an equivalent resistor at room temperature.

mixer of Fig. 7 at a wavelength of 5.4 millimeters. In order that the measurements might be more readily compared with those made on commercially available rectifiers used at longer wavelengths, the available beating oscillator power was maintained at a level of one milliwatt for all measurements.* Further, in the case of the conversion loss, a

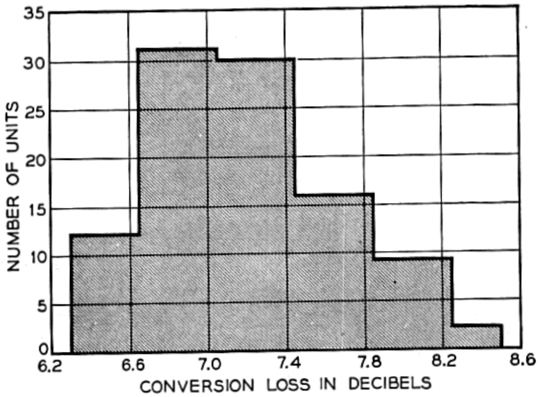

Fig. 8 — Conversion loss (L) of 100 wafer units at a wavelength of 5.4 millimeters with one-milliwatt beating oscillator drive (average 7.2 db).

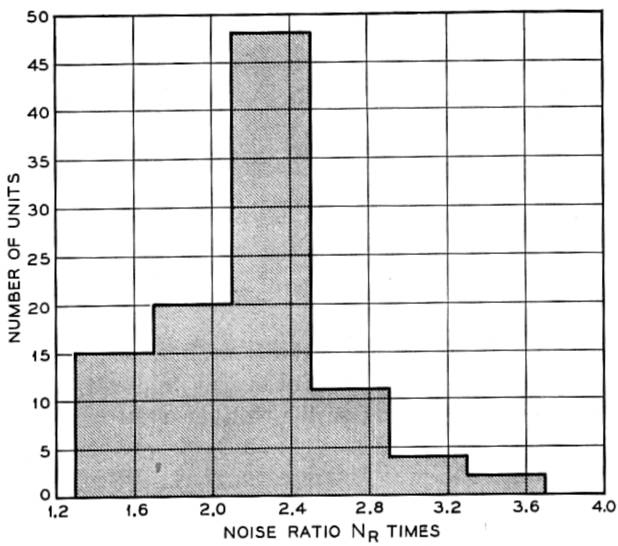

Fig. 9 — Noise Ratio (N_R) for 100 wafer units at a wavelength of 5.4 millimeters with a one-milliwatt beating oscillator drive (average 2.21 times).

* Power levels were determined by the use of a calorimeter. See, A Calorimeter for Power Measurements at Millimeter Wavelengths, I. R. E. Trans., MTT-2, pp. 45–47, Sept., 1954.

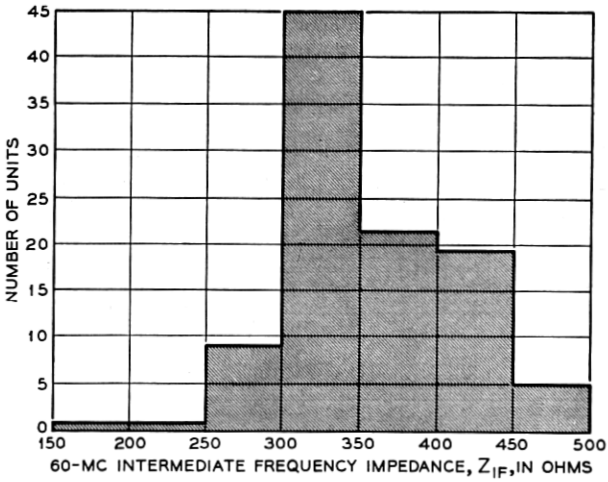

Fig. 10 — Sixty-megacycle intermediate-frequency output impedance (Z_{IF}) for 100 wafer units with one milliwatt beating oscillator drive (average 338 ohms)

limit of 8.5 db was arbitrarily adopted. This required the readjustment of eleven units, with a new point inserted in each case. No units were rejected because of high noise and none of the hundred units processed was lost.

From the bar graphs it may be seen that the wafer units have the average characteristics shown in the accompanying table at a wavelength of 5.4 millimeters.*

Conversion Loss L	7.2 db (5.3 times)
Noise Ratio N_R	2.2 times
IF Impedance (60 mc) Z_{IF}	338 ohms

Knowing the noise figure, N_{IF}, of the IF amplifier intended for use with the rectifiers, the overall receiver noise figure, N_{REC}, may be calculated by the following formula (using numerical ratios):

$$N_{REC} = L(N_R - 1 + N_{IF})$$

Assuming an IF amplifier noise figure of 4.0 db ($2\frac{1}{2}$ times) and the average values of "L" and "N_R" given above for the millimeter wafer units, we have for the case of a noiseless beating oscillator;

$$N_{REC} = 5.3\ (2.2 - 1 + 2.5) \approx 20\ (13\ \text{db})$$

* A few wafer units have also been measured at a wavelength of 4.16 millimeters. The conversion losses averaged about 1.6 db greater than those measured at a wavelength of 5.4 millimeters.

TABLE I — COMPARISON OF LOW-POWER CHARACTERISTICS OF CARTRIDGE-TYPE AND WAFER-TYPE RECTIFIERS

Test Conditions	JAN Specifications for Cartridge-Type Rectifiers		Performance of Wafer-Type Rectifiers
	IN26	IN53	
Frequency	23984 mc	34860 mc	55500 mc
Beating oscillator power level	1.0 milliwatts	1.0 milliwatts	1.0 milliwatts
Noise reference resistor	300 ohms	300 ohms	300 ohms
Conversion loss	8.5 db (max)	8.5 db (max)	8.5 db (max)*
Noise ratio	2.5 (max)	2.5 (max)	2.2 (average)†
Nominal IF impedance range	300 to 600 ohms	400 to 800 ohms	250 to 500 ohms

* Limit arbitrarily set on basis of 100 per cent yield as explained in the text.
† Limit not set. Actually in more recent production N_R has averaged 1.7 times.

In practice, the beating oscillator noise sidebands can be eliminated by the use of a matched pair of rectifiers in a balanced converter arrangement described later. The resulting overall noise figure of 13 db on an average compares quite favorably with the figures obtained at longer wavelengths.

In Table I it is seen that a high percentage of the group of one hundred units would be able to pass low-power JAN specifications similar to those set down for the commercially available IN26 and IN53 rectifiers used at longer wavelengths.

EFFECT OF VARYING THE BEATING OSCILLATOR POWER

When the optimum over-all receiver noise figure is desired, it may well turn out that a beating oscillator drive of one milliwatt (corresponding to a dc rectified current for different wafers of from $\frac{9}{10}$ to $1\frac{1}{4}$ milliamperes) is too large. Fig. 11 shows the effect on the performance of a typical unit as the beating oscillator drive is varied above and below the one milliwatt level as indicated by the change in the dc rectified current. It is seen that the value of N_R tends to increase rapidly for a beating oscillator drive much in excess of one milliwatt; with reduced drive, the over-all noise figure of the receiver, N_{REC} for the example taken, improves, reaching a minimum value near a rectified current of about $\frac{7}{10}$ milliampere corresponding to a drive of about $\frac{2}{3}$ of a milliwatt.

A BALANCED CONVERTER FOR WAFER UNITS

A broad-band balanced first converter has been developed which makes use of a pair of wafer-type millimeter-wave rectifiers. This converter

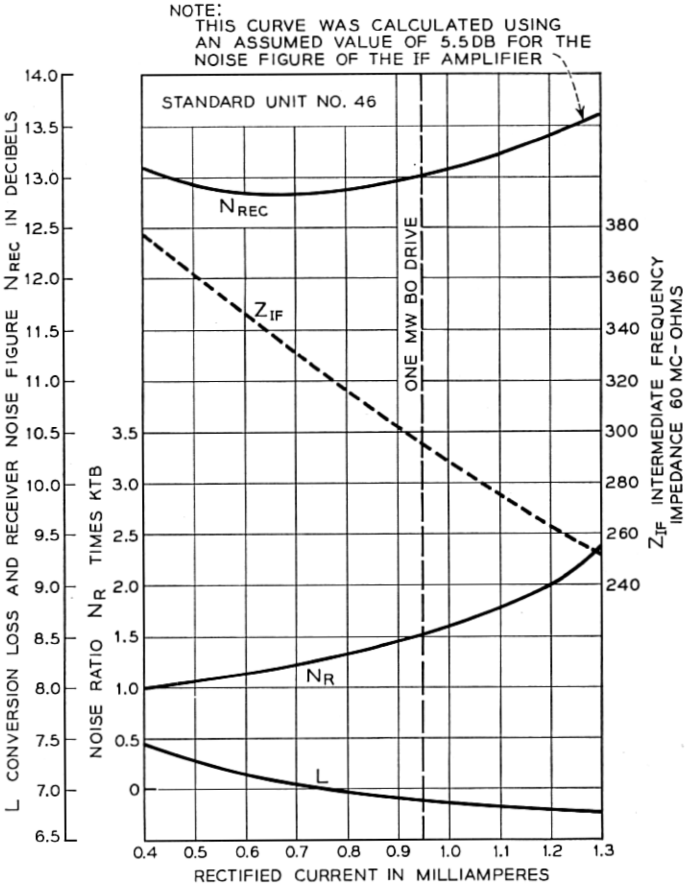

Fig. 11 — Typical performance curves for wafer-type rectifiers.

was designed to operate over the 4- to 7-millimeter band and is pictured in Fig. 12. A compact arrangement has been achieved which makes use of a waveguide finline-to-coaxial input circuit for the beating oscillator while the signal is introduced through a separate impedance-matched waveguide "Tee" section. Return loss measurements show that with a matched pair of wafer units, fixed-tuned in the center of the 5- to 6-millimeter band, an excess loss of about 1 db may be expected at the edges of a 15 per cent band. At midband, an improvement of 5 db in over-all receiver noise figure was obtained by substituting the balanced converter for an unbalanced one in a test receiver using an M1805 milli-

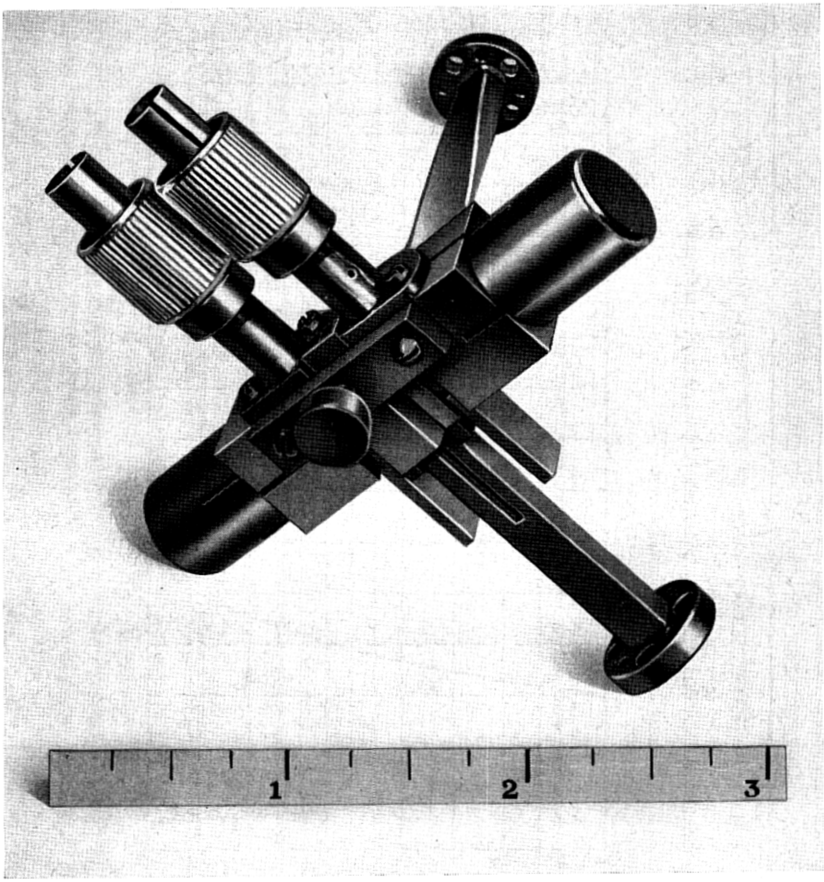

Fig. 12 — Balanced converter with wafer-type rectifiers.

meter-wave reflex klystron* as the beating oscillator and a 60-mc intermediate frequency amplifier with a 5-db noise figure.

REVERSED POLARITY WAFER UNIT

When using crystal rectifiers in a balanced converter arrangement, there is a distinct advantage, circuit-wise, in using two units of opposite polarity. For this reason, a reversed-polarity wafer type rectifier has also been developed. This was done by interchanging the silicon and the

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* E. D. Reed, A Tunable, Low-Voltage Reflex Klystron for Operation in the 50 to 60 kmc Band, B. S. T. J., **34,** pp. 563–599, May, 1955.

point contact spring in a standard unit. The standard and reverse-polarity wafer have the same outer physical dimensions and thus they may be used interchangeably in the holders as dictated by the specific problems at hand.

CONCLUDING REMARKS

Aside from their intended use as first detectors in double detection receivers, wafer units have been used for single detection measurements at frequencies as high as 107 kmc.

It is felt that the pilot production group of one hundred units is a sample of sufficient size to yield representative data and to demonstrate the practicability of the design. It should be pointed out that the units have not been filled with protective waxes and have not been subjected to temperature-humidity cycling tests. However, a few reference units have been in use in the laboratory for over a year and have shown no measurable deterioration. No attempt has been made to establish a burn-out rating for the rectifier, but units have withstood available cw input powers of the order of 15 milliwatts and narrow pulse discharges of the order of $\frac{1}{10}$ erg without causing noticeable changes in the conversion loss or noise ratio.

ACKNOWLEDGMENTS

The author wishes to express his gratitude to H. T. Friis and A. B. Crawford for their helpful suggestions and guidance during the course of this work. Extensive use has also been made of the experience and techniques of R. S. Ohl. E. F. Elbert participated in the development of the wafer unit, being particularly concerned with the techniques of fabrication. H. W. Anderson and S. E. Reed were most helpful in solving mechanical problems encountered in the production of wafer units and holders.

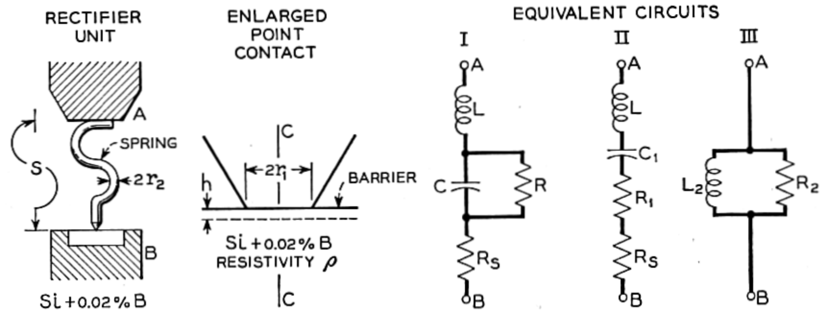
APPENDIX

This section describes some calculations that were made for the purpose of estimating the values of the various parameters involved in the design of a high frequency point contact rectifier. These parameters are the barrier resistance, the spreading resistance, the capacitance of the barrier layer and the inductance of the contact spring. Knowing the approximate values of these parameters one can, by an equivalent circuit analysis, arrive at a simple parallel circuit for the rectifier which may be used in designing an appropriate holder. Also, using this equivalent circuit, one may calculate the bandwidth expected for the converter.

Fig. 13 shows the point contact rectifiers under consideration and an enlarged view of the point contact region. On the right of the figure are shown equivalent circuits of the rectifier. Circuit I is the generally accepted circuit of a point contact rectifier. The true circuit for a rectifier operating at millimeter wavelengths is probably more complicated than that shown in the figure but, for an approximate analysis, the simplified circuit has been found to yield useful results. In the following paragraphs, values are derived for the parameters of this equivalent circuit. MKS units are used and values appropriate to the millimeter wave wafer unit are used as examples.

Spreading Resistance

The spreading resistance, R_s, may be calculated if we know the resistivity of the silicon used for the rectifier and the radius of the contact area formed when the units are assembled. For DuPont high-purity silicon, doped with 0.02 per cent boron by weight, W. Shockley* gives the resistivity, ρ, as 0.90×10^{-4} ohm meters. From numerous measurements on millimeter wave contact areas, R. S. Ohl finds the contact radius, r_1, to be about 1.25×10^{-6} meters. The spreading resistance,



$$\frac{1}{\omega C_1} = \frac{1}{\omega C\left(1 + \frac{1}{(\omega CR)^2}\right)} \qquad \omega L_2 = \omega L - \frac{1}{\omega C_1} + \frac{(R_S + R_1)^2}{\omega L - \frac{1}{\omega C_1}}$$

$$R_1 = \frac{R}{1 + (\omega CR)^2} \qquad R_2 = R_S + R_1 + \frac{\left(\omega L - \frac{1}{\omega C_1}\right)^2}{R_S + R_1}$$

Fig. 13 — Point contact rectifier and equivalent circuits.

* W. Shockley, Electrons and Holes in Semiconductors, New York: D. Van Nostrand Co., Inc., 1950, p. 284.

R_s, assuming a circular contact area, may be calculated from the formula, $R_s = \rho/4r_1$.* For the above example, $R_s = 18$ ohms.

Barrier Resistance

The approximate operating value of the barrier resistance, R, may be determined from a knowledge of the intermediate frequency impedance of a typical rectifier. A. B. Crawford has shown that the optimum intermediate frequency output impedance of a crystal mixer rectifier is a function of the exponent of the static characteristic of the rectifier and the impedance presented to the rectifier at the image and signal frequencies. This information is presented in Fig. 12.3–6 in G. C. Southworth's book.† In the millimeter wave case it is a good assumption that the impedances for the signal and image frequencies are equal; for this case and for matched conditions, the magnitude of the high frequency impedance is seen to be a simple multiple of the intermediate frequency impedance R_{IF}.

From numerous measurements on mixer rectifiers operating at different frequencies it is known that the intermediate frequency impedance of an average rectifier is very nearly 400 ohms. We also know from the DC static characteristics of our millimeter wave type rectifiers that the average exponent is about four. With this information, and the curves in Southworth's book, it is found that $R \approx R_{IF}/1.5$. Thus, the barrier resistance R is about 250 ohms.‡

Capacitance of Barrier Layer

From a knowledge of the point contact area, the barrier layer thickness, and the dielectric constant of the silicon, the capacitance of the point contact may be calculated. The radius of the contact point area is the same as that used for the calculation of the spreading resistance. The barrier layer thickness, h, for the heat treated silicon used for millimeter waves has been measured by R. S. Ohl to be about 10^{-8} meters. The dielectric constant of silicon is $\varepsilon_r = 13$. The capacitance is given by the following formula

$$C = \frac{r_1^2 \varepsilon_r}{3.6h \times 10^{10}} \text{ farads} \tag{1}$$

* J. H. Jeans, Mathematical Theory of Electricity and Magnetism, 5th Ed., Cambridge University Press, 1925.

† G. C. Southworth, Principles and Applications of Waveguide Transmission, New York: D. Van Nostrand Co., Inc., 1950.

‡ This resistance cannot be readily measured directly at millimeter waves.

For the above case $C = 5.7 \times 10^{-14}$ farads or $1/\omega C$ at 5.4 millimeters is about 50 ohms.

The accuracy of this capacitance calculation can be verified later when a completed rectifier is measured for its high frequency conversion loss. This is possible because we know the calculated low frequency conversion loss of the rectifier, for the case of zero spreading resistance from Southworth's book, Fig. 12.3–7. For an exponent of four this loss is given as 4.4 db. The additional loss at high frequency due to the capacitance, C, may be calculated (see Equivalent Circuit II) by the formula:

$$\text{Additional Loss} = 10 \log_{10} \frac{R_1 + R_s}{R_1} \text{ db} \tag{2}$$

From the text (Fig. 8), it is seen that the average wafer rectifier unit has a conversion loss at 5.4 millimeters of 7.2 db; thus, the difference between the low and high frequency conversion losses is very nearly 3 db. This means that about one-half the signal power is lost in the spreading resistance; hence R_1 and R_s are about equal. By transferring back to Equivalent Circuit I, the average value of the capacitance is found to be 4.1×10^{-14} farads, which is a reasonable check with the calculated value given by (1).

Inductance of the Contact Spring

The remaining parameter of the equivalent circuit to be determined is the inductance of the contact spring. The value of the equivalent parallel resistance, R_2, depends on the inductance L (the other parameters being fixed), or conversely, for a given value of R_2, the appropriate value for L may be calculated from the formula for Equivalent Circuit III. For an off-center match of the rectifier to the waveguide, R_2 must equal the guide impedance, Z_d, at the rectifier location. Also, for a match, the distance, ℓ, from the rectifier to the waveguide piston must

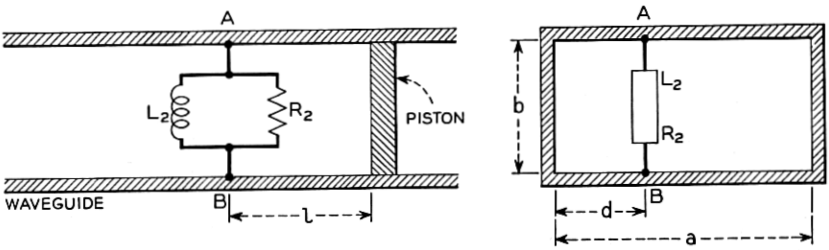


Fig. 14 — Matching circuit for rectifier offset in waveguide.

satisfy the relation, $Z_d \tan 2\pi\ell/\lambda_g = -\omega L_2$. (See Fig. 14.) The impedance of the guide as a function of d/a is given by,

$$Z_d = 240\pi \frac{b}{a} \frac{1}{\sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}} \sin^2 \frac{\pi d}{a} \tag{3}$$

As a compromise between electrical and mechanical requirements, a waveguide height, b, of $\frac{1}{32}$ inch was chosen for the wafer unit; the width of the guide was taken to be the same as *RG98U*. For $b = 7.88 \times 10^{-4}$, $a = 3.76 \times 10^{-3}$, $d/a = \frac{1}{4}$ and $\lambda = 5.4 \times 10^{-3}$, (3) gives a value of 113 ohms for Z_d (and R_2). The appropriate value for L then becomes 3.38×10^{-10} henries.

An estimate of the size of a contact spring having the inductance given above can be made from the formula below which gives the inductance of a straight thin wire of length S as a function of its sidewise position in the waveguide.* (See Fig. 15.)

$$L = 2S \log_e \frac{2a \sin \frac{\pi d}{a}}{\pi r_2} \times 10^{-7} \text{ henries} \tag{4}$$

$$r_2 \ll d$$

For $d/a = \frac{1}{4}$ and $2r_2 = 2.28 \times 10^{-5}$ (0.9×10^{-3} inches), the length, S, is found to be about 3.38×10^{-4} meters or about 0.013 inches.

Since the spring must be so very small, the circuit from the base of the spring to the waveguide wall is completed with a large low inductance conical post as shown in Fig. 2 of the text.

Bandwidth Calculation

Having assigned values to all the parameters of the equivalent circuit, it is now possible to calculate the mismatch loss of a fixed-tune

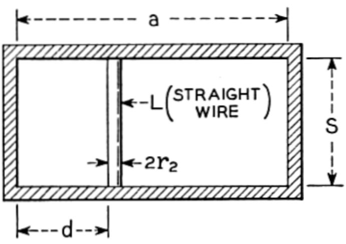


Fig. 15 — Thin wire in waveguide.

* Private communication from S. A. Schelkunoff.

converter for a given change in operating wavelength. This loss is given by the following formula:

Mismatch loss

$$= 10 \log_{10} \frac{4Z_d}{R_2\left[\left(1 + \frac{Z_d}{R_2}\right)^2 + \left(\frac{Z_d}{\omega L_2} + \frac{1}{\tan 2\pi\ell/\lambda_g}\right)^2\right]} db \qquad (5)$$

For the wafer unit, calculation shows that the rectifier is matched to the waveguide at a wavelength of 5.4×10^{-3} meters for $d/a = \frac{1}{4}$ and $\ell = 3.14 \times 10^{-3}$. If now the wavelength is changed to 6.3×10^{-3} meters, without retuning (17 per cent change) the mismatch loss calculated by (5) is 1.6 db. It was stated in the text that a number of wafer units gave measured mismatch losses of from 1.6 to 4.0 db for a 17 per cent change in wavelength without retuning. This is considered to be a reasonable correlation between calculations and measurements.