THE USE OF SILICON POINT-CONTACT RECTIFIERS FOR MODULATING MICROWAVE SIGNALS

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Abstract

Measurements have been made of the characteristics of silicon
point-contact rectifiers as microwave high-level mixers, or absorption
modulators. Conversion efficiency, linearity of modulation, r-f impedance,
(3000 Mc/sec) and modulating-frequency (5 Mc/sec) impedance were measured.
Crystal types tested were 1N21B, high-inverse-voltage silicon crystals,
and some special Bell Telephone Laboratories crystals.

Use of a pair of crystals in a balanced modulator gave 10 to 20 mw
of power in each sideband in the linear modulation region. Carrier suppression
of the order of 20 db below the first sidebands is easily maintained in such
a modulator.

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FOR MODULATING MICROWAVE SIGNALS

1. Introduction

A survey of the microwave art indicates that the techniques of modulation are rather primitive when one compares them to the techniques available at lower frequencies.

At present, various methods of pulse modulation of microwave oscillators (or amplifiers) are in common use. Frequency-modulated klystrons are fairly well developed, and electronically tuned magnetrons are in a more or less satisfactory state of development. Amplitude modulation is not very far advanced, particularly if one is concerned with large power levels. The lighthouse tubes and the recently announced close-spaced triodes of the Bell Telephone Laboratories may be amplitude-modulated through their control grids. The upper-frequency limit of the lighthouse tube series is about 2000 Mc/sec, and the new Bell Telephone Laboratory tube can be used up to about 6000 Mc/sec, but it is not generally available to the public.

In view of the considerations briefly outlined above, it was decided to make a study of the various techniques of modulating microwave signals, with the emphasis on means of "continuous" modulation (AM,FM,PM) as distinct from pulse modulation. As a first step in this program it was decided to make a detailed study of the characteristics of silicon point-contact rectifiers used as absorption modulators. Crystals have been employed as modulators by various people (1),(2),(3), but no detailed study of their performance has been previously published.

The data presented here are abstracted from a Master's thesis(4) by William N. Coffey.

2. Measurement Technique

All measurements were performed at a radio frequency of 3000 Mc/sec, and a modulating frequency of 5 Mc/sec. This particular radio frequency was chosen because oscillators and r-f components were easily available; the modulation frequency was chosen low enough so that both sidebands and the carrier could be seen simultaneously on a spectrum analyzer, and high enough so that it was possible to filter out any one of the components with cavities of reasonable Q. A number of spot checks confirmed our assumption that the modulation efficiency was the same at 30 Mc/sec and 60 Mc/sec as at 5 Mc/sec. No tests were made at higher radio frequencies, or with crystals such as the 1N23B or 1N26; all tests were made on 1N21B's, on some special 1N28 crystals used by the Bell Telephone System in their Boston-New York radio relay link, and on some crystals made with high-voltage silicon obtained from the University of Pennsylvania (5).

Figure 1(a) illustrates the basic measuring circuit. A coaxial hybrid junction was used, with the crystal and means for matching it on one arm, a matched load on the opposite arm, and the r-f input and output circuits on the remaining arms. It will be recalled that in an ideal magic T or hybrid junction, power coming to the junction from any arm divides between adjacent arms and none goes directly to the opposite arm.
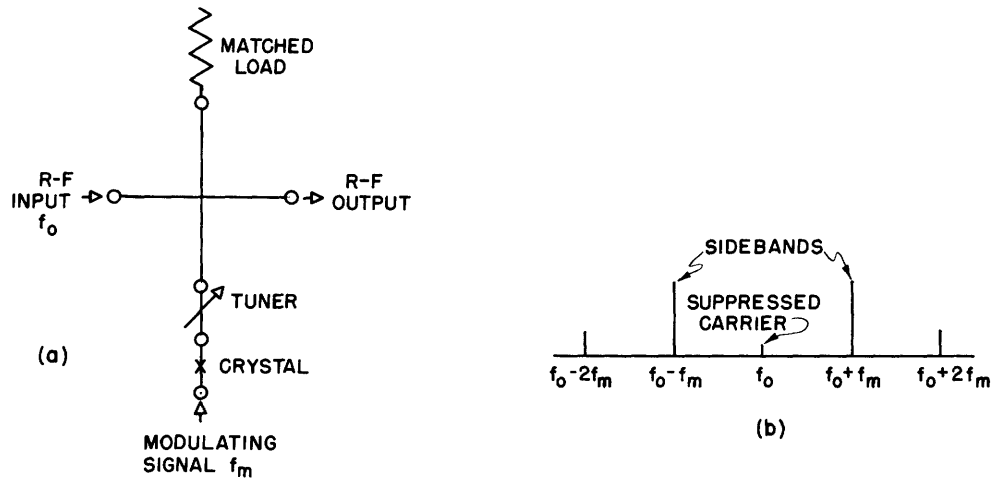

Figure 1(a),(b). Basic circuit used for measuring modulation
characteristics of crystals.

By proper adjustment of the matching device the crystal impedance at the zero of the modulating voltage can be made equal to the line impedance. Under these conditions no r-f carrier power will be reflected to the output, and a condition of two sidebands with a suppressed carrier will be obtained as shown in Figure 1(b). In this way it is possible to measure the absolute sideband power for quite low levels of modulation, without the use of elaborate filters to reject the carrier.
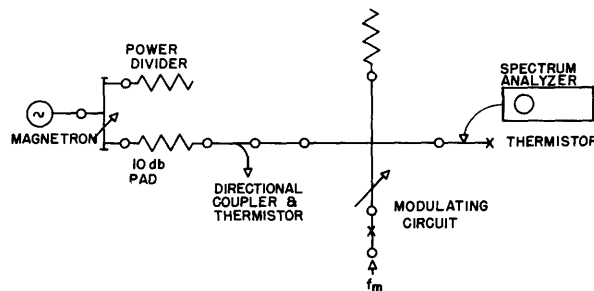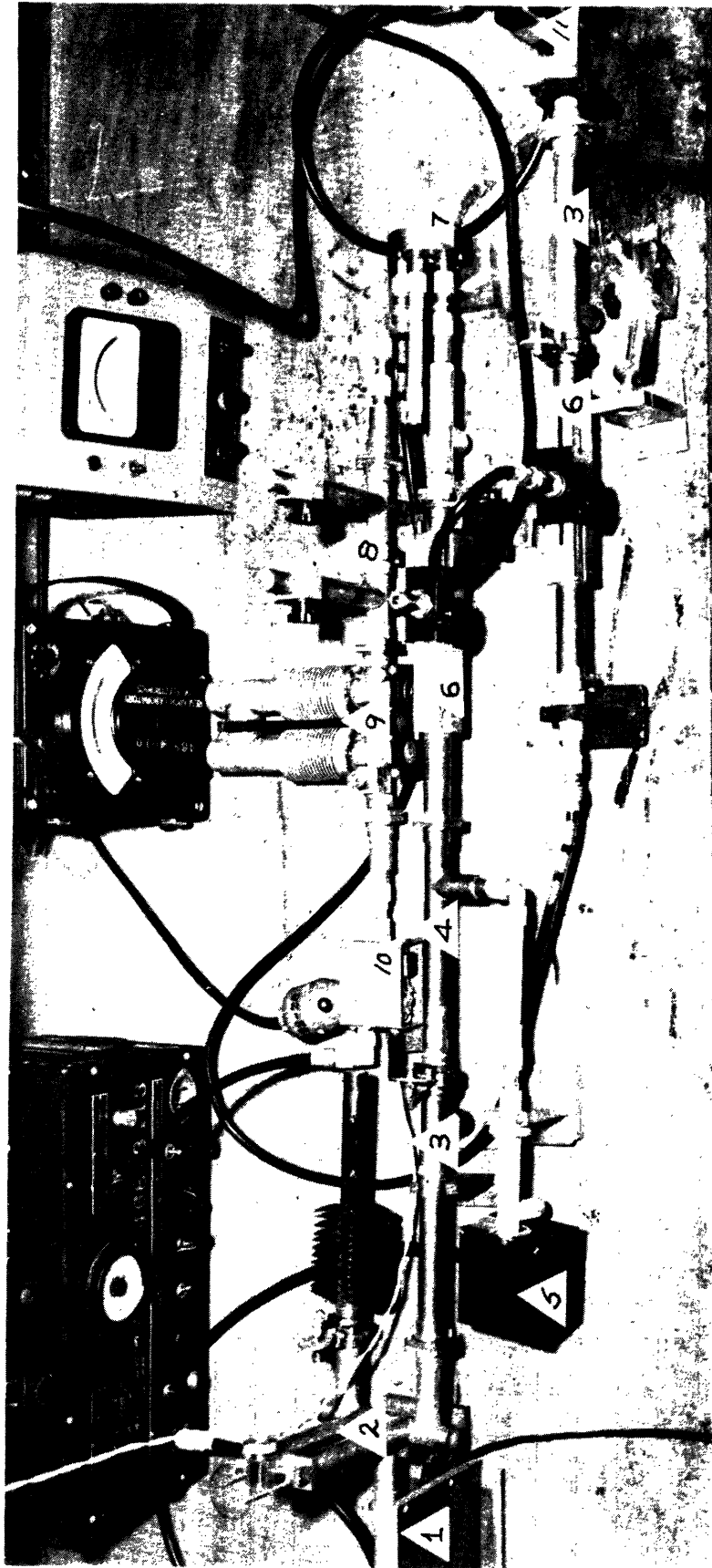

Figure 2. Block diagram of test setup.

Figure 2 is a block diagram of the test setup. A 50-watt c-w magnetron (QK61) with a power divider was used as the r-f power source. The incident power was monitored with a directional coupler and thermistor. The modulating signal was obtained from a 5-Mc/sec oscillator and it was measured with a conventional peak voltmeter.

1. Magnetron
2. Variable Attenuator
3. Fixed Attenuator
4. Directional Coupler
5. Thermistor (Input Power)
6. Slotted Section

7. Hybrid Ring
8. Double Stub Tuner
9. Line Stretcher
10. Crystal Junction Box
11. Thermistor (Sideband Power)

Figure 3. Photograph of microwave circuit.

Besides measurements of sideband power, measurements were also made of the impedance presented by the crystal to the modulating signal, and of the r-f impedance of the crystal. The modulation-frequency impedance was measured with a General Radio bridge, while the r-f impedance was measured in the usual manner with a coaxial slotted section.

3. Test Results

Single Crystal Modulator. Measurements were made on a number of 1N21B's all of which had closely similar modulation characteristics, as illustrated in Figure 4. Here we have plotted modulation voltage against sideband voltage (sideband power)$^{\frac{1}{2}}$, with the r-f power incident on the crystal as a parameter.
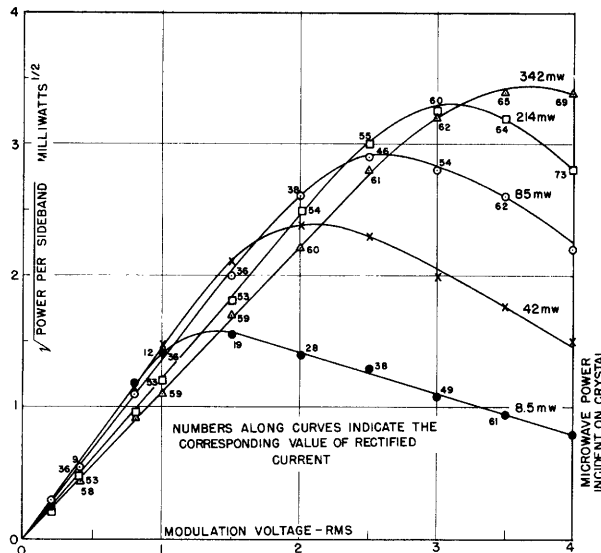
Figure 4. Modulation characteristics of 1N21B crystals.

It is evident that above an incident power level of 200 mw the increase in sideband power is very slow, and since there was some evidence of deterioration of the crystal at power levels above 350 mw, it was decided to call 200 mw a maximum useful value. Under these conditions a maximum power of about 10 mw/sideband, and a maximum power in the linear range of about 6 mw/sideband was available.

The actual measured power included both sidebands and their harmonics. None of the harmonics (second or higher order sidebands), however, was larger than about 1 per cent of the sidebands. The values plotted are the actual measured power in the output line, and are equal to the sum of the powers in the two sidebands. Alternatively, the data may be interpreted as giving the total power generated in each sideband, half of which is absorbed in the r-f generator impedance.

A number of crystals were made for us at the Sylvania Electric Products Company Inc. out of high-inverse-voltage silicon obtained from W. E. Stephens at the University of Pennsylvania(5). The crystals were

prepared just like 1N21B's, and were given no particular treatment. As a result, the properties of the various units were quite non-uniform. Figure 5 shows the modulation characteristics of one of the better units. The maximum useful driving power was 800 mw, and at this level 25 mw of maximum sideband power was available and the limit of the linear range was about 15 mw of sideband power. It will be observed that both the r-f driving power and the modulating voltage for a given sideband power are larger than for a 1N21B crystal, but that greater absolute values of sideband power can be obtained with these crystals.
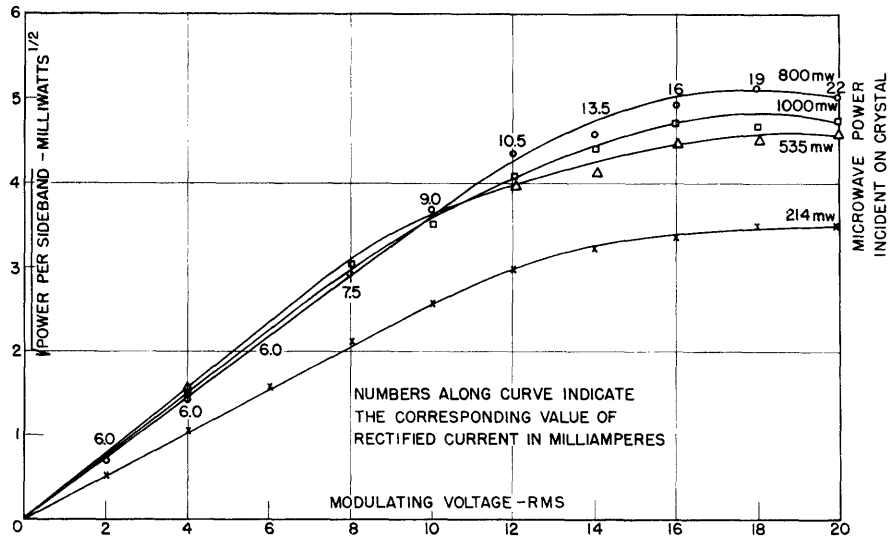

Figure 5. Modulation characteristics of high-inverse-voltage silicon crystals (No. H-1).

Two crystals were furnished by H. T. Friis of the Bell Telephone Laboratories. These were of the type used in the Boston-New York relay link, and are similar to the 1N28 crystal. Figure 6 shows their characteristics.
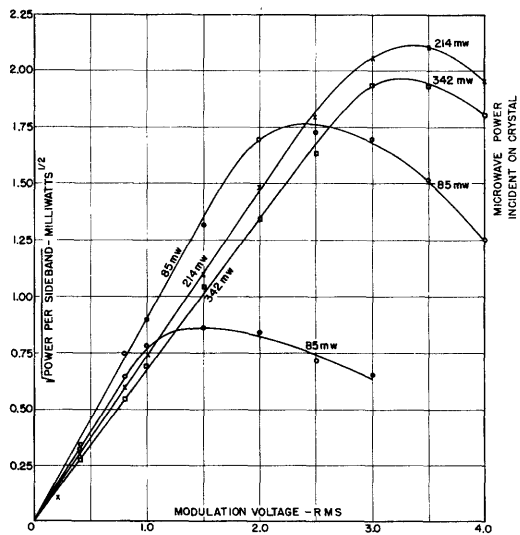

Figure 6. Modulation characteristics of special BTL crystal (No. K2950-45).

Both crystals were very closely alike, and were better matched than any pair of the 1N21B's tested. It will be noticed, however, that their sideband power output is definitely less than that of the 1N21B's.

In passing, it should be noted that a CV-58 microwave diode was tested as a modulator in the same circuit. Although its conversion efficiency was low, it had excellent linearity. With an exciting power of 214 mw, the power per sideband was linear up to the maximum available modulation voltage of 8, and was 9 mw at this point.

The effect of d-c bias on the modulation characteristics of 1N21B's was measured. Figure 7 summarizes the results obtained on one crystal.
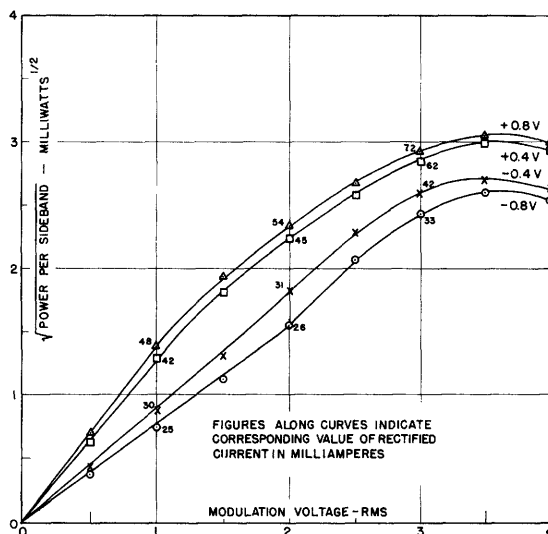

Figure 7. Effect of d-c bias on modulation characteristics of 1N21B crystal. 85 mw of microwave power incident on crystal.

The addition of positive bias increased the maximum available power, and negative bias reduced it. If we are concerned with the linear range only, then we see that the maximum power in the linear range is nearly independent of bias; but it can be obtained with a smaller modulating voltage if positive bias is used.

D-c bias may also be used as a fine control of the r-f impedance of a crystal. The magnitude of this effect is indicated in the section on r-f impedance characterics.

Two-Crystal Balanced Modulator. A balanced modulator may be devised by putting two crystals on opposite arms of a hybrid junction, at equal distances from the junction, and driving them push-pull with the modulating signal. If the crystals are exactly alike, the output will have only sideband energy, and the carrier will be suppressed. Moreover, all the sideband power will go out the arm away from the r-f exciting source, and is therefore all useful power.

A number of tests of such a circuit were made. The coaxial hybrid ring was terminated by a pair of "type-N" crystal holders. (A crystal in such a holder presents a mismatch of 3.0 or greater to a 50-ohm line.) Under these conditions, it was relatively easy to find a pair of 1N21B's which produced a carrier at least 20 db below the level of the first sidebands. Other crystals chosen at random would give a suppression of the order of 13 db. This could be improved, however, by adding a small amount of positive bias to one or the other of the crystals, and a suppression of 15 to 20 db was attainable for large values of the modulating voltage.

Tests on particular crystals resulted in very nearly twice the sideband power produced by one alone. The data in Figures 4, 5 and 6 give the total power in each sideband produced by one crystal; this is actually twice the measured power in the output arm. Thus, the balanced modulator produces four times as much available sideband power as a single-crystal modulator.

R-F Impedance Measurements. A number of static measurements of the r-f impedance of the crystal were made for various r-f power levels and d-c bias voltages. Figure 8 shows the crystal admittance in a 50-ohm coaxial, with the crystal matched at zero bias, and an incident r-f power of 42 mw.
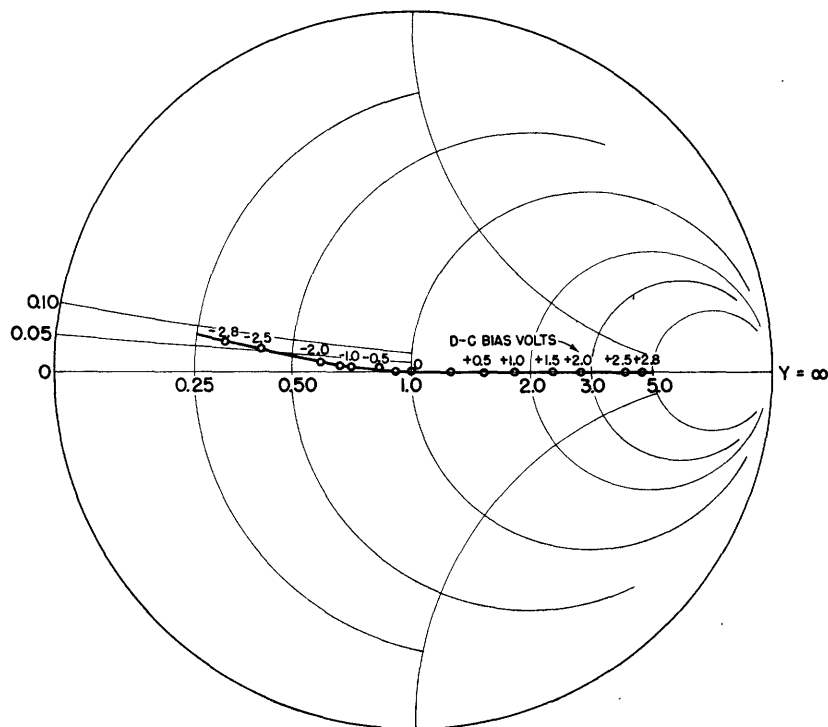

Figure 8. Microwave admittance of 1N21B crystal as a function of d-c bias. Crystal tuned to match a 50 Ω line with zero bias and 42 mw of incident r-f power.

Figure 9 shows the absolute value of the reflection coefficient $|\Gamma|$ and its angle φ, derived from Figure 8. In Figure 10 are plotted the instantaneous values of $|\Gamma|$ and φ for an assumed sinusoidal modulating signal with a peak voltage of 3.
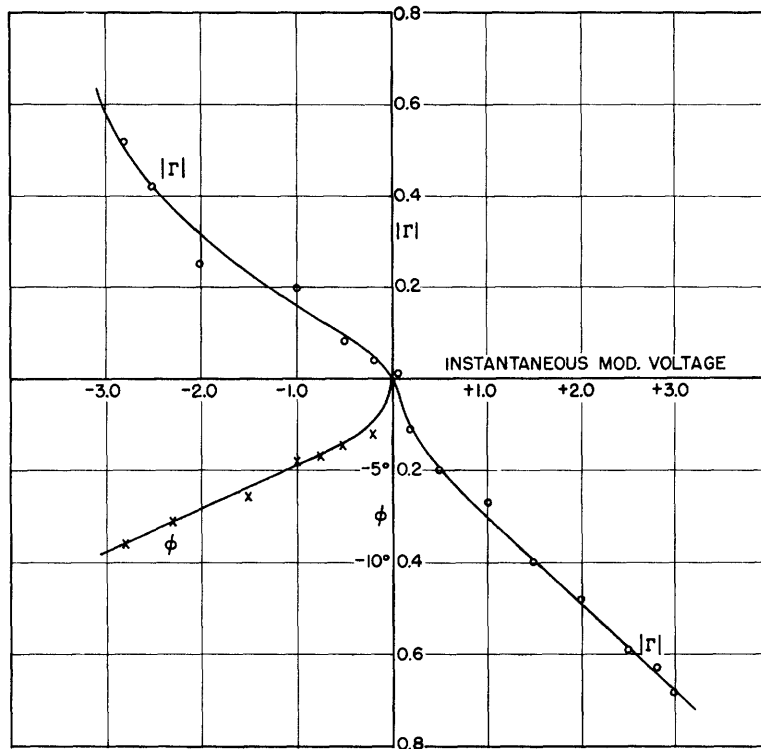
-7-

Figure 9. Absolute magnitude of $|\Gamma|$, and angle φ of reflection coefficient as a function of d-c bias. Plotted from Figure 8.
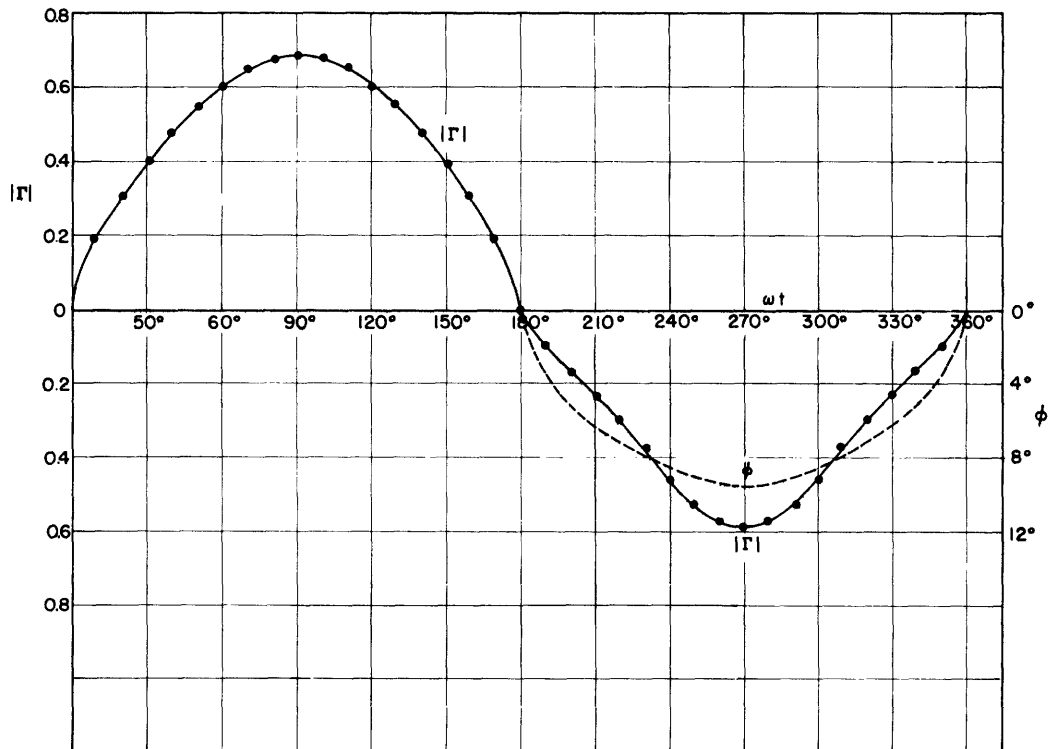

Figure 10. Instantaneous values of $|\Gamma|$ and φ for an assumed sinusoidal modulation signal with an amplitude of 3 volts. Computed from Figures 8 and 9.

We see from Figure 10 that the crystal actually produces a combination of amplitude and phase modulation. The expression for the amplitude of the first-order sidebands is

$$V_1 = \sqrt{\left[a_o J_1(\varphi_1)\right]^2 + \left[\frac{k_1}{2}\left\{J_o(\varphi_1) - J_2(\varphi_1)\right\}\right]^2} \qquad (1)$$

where the J's are Bessel functions, a_o and k_1 are defined by

$$|\Gamma| = a_o + k_1 \sin pt + k_2 \sin 2pt + \ldots \qquad (2)$$

and φ_1 is the index of phase modulation in the expression for an amplitude- and phase-modulated voltage.

$$V = \left[a_o + k \sin pt\right] \sin\left[\omega t + \varphi_o + \varphi_1 \sin pt\right] \qquad (3)$$

and is given by

$$\varphi = \varphi_o + \varphi_1 \sin pt + \varphi_2 \sin 2pt + \ldots \qquad (4)$$

Thus, the effect of φ_1 is to produce an amplitude distortion in the first-order sidebands. The value of φ_1, obtained by Fourier analysis of Figure 10, is only 5°, and its effect turns out to be negligible.

A complete Fourier analysis of Figure 10 was made, and the predicted and measured values of the carrier and the first and second sidebands are compared in the table below.

	Calculated	Measured
Carrier	-13 db	-14 db
First sideband	0	0
Second sideband	-24 db	-20 db

Note that the carrier, which was balanced out with no modulation, rose to a level of 13 db below the sideband power. It can, of course, be returned for balance at any level of modulating signal.
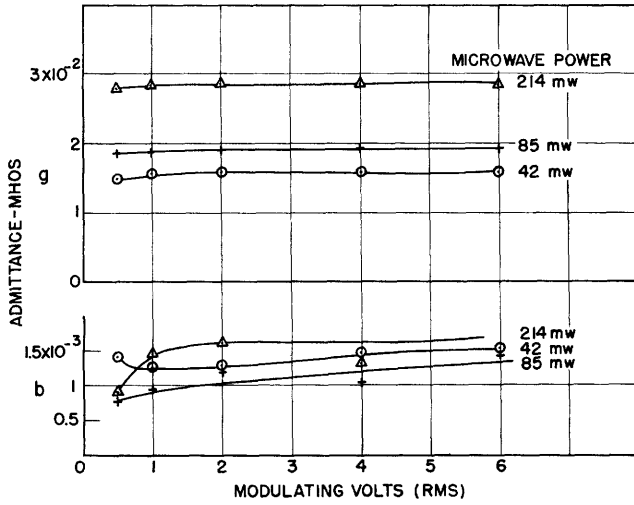
Fig. 12. Modulation-terminal admittance of 1N21B crystal, f_m=5Mc/sec.
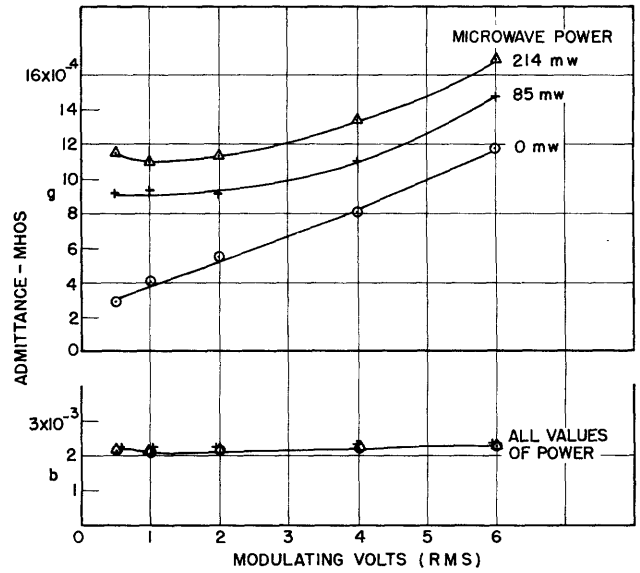
Fig. 13. Modulation-terminal admittance of high-inverse-voltage silicon crystal, f_m = 5 Mc/sec.
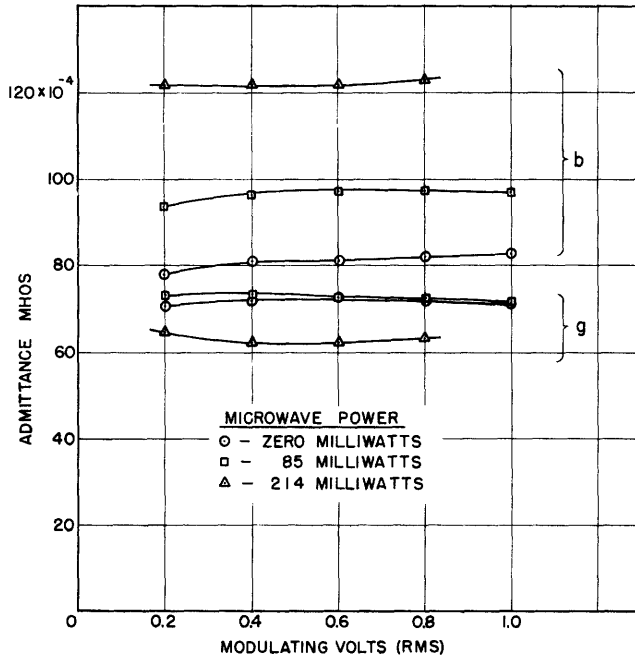
Fig. 14. Modulation-frequency admittance (terminal A) of 1N21B crystal.
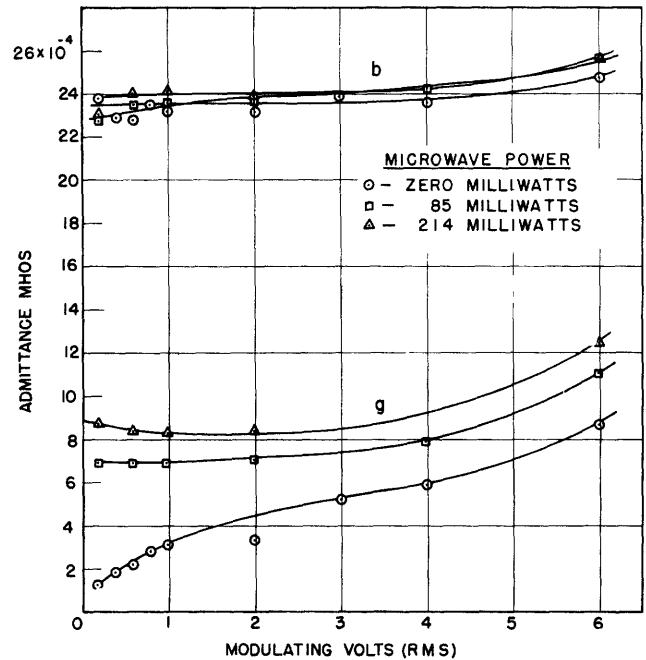
Fig. 15. Modulation-frequency admittance (terminal A) of high-inverse-voltage silicon crystal.

Modulation Frequency Impedance. For all measurements the crystal was mounted in the circuit shown in Figure 11.
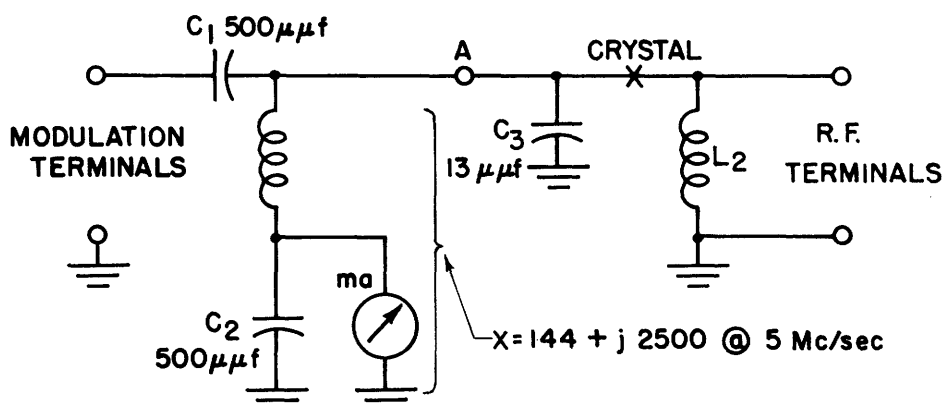

Figure 11. Modulating-frequency bypass and blocking circuit.

L_1, C_1, and C_2 serve as a d-c blocking circuit to permit measurement of the rectified crystal current; C_3 is the r-f bypass condenser in the crystal holder; and L_2 is a 10-cm, quarter-wave stub in the coaxial line. The impedance measurements discussed here were all made at the "Modulation Terminals", and were made with a General Radio Model 916A R-F Impedance Bridge. Figures 12 and 13 show the measured values of the assumed parallel RC circuit at the modulation terminals for a 1N21B and a high-inverse-voltage crystal, while Figures 14 and 15 show the admittance at the terminal A, computed from the data in Figures 12 and 13. It will be observed that the susceptance at A is considerably larger than can be accounted for by the condenser C_3 ($\omega C_3 = 4 \times 10^{-4}$ mhos), and that it is not a constant, but is dependent upon both the r-f and modulating levels.

4. Conclusions

The high-level modulation characteristics of several crystal types have been measured at a radio frequency of 3000 Mc/sec. Their characteristics are summarized in the following table. Although all the data were obtained with a modulation frequency of 5 Mc/sec, a few tests indicated that the performance at 30 and 60 Mc/sec was substantially the same: i.e., a given modulating voltage at the crystal terminals produced the same amount of sideband power. No measurements were made, however, of the modulation impedance at these higher frequencies.

Since the performance of low-level crystal converters is substantially the same in the various microwave bands for which they are designed, we believe that the same general magnitude of sideband power should be available at frequencies at least as high as 10,000 Mc/sec.

TABLE I

SUMMARY OF OPERATION DATA

Crystal Type and Number Tested	Safe Incident Power				Overload Incident Power		
	Maximum Sideband Power*	Correspond. Incident Power	Maximum Sideband Power+*	Correspond. Incident Power	Maximum Sideband Power*	Maximum Sideband Power+*	Incident Power
1N21B	10 (3.0)	214 mw	5 mw (1.7)	85 to 214 mw	11 mw (3.4)	8 mw (2.2)	342 mw
BTL 2	4 (3.3)	214	3 (2.2)	214	4 (3.3)	2 (2.2)	342
High-Inverse-Voltage	19 (19.0)	800	10 (9.8)	800	19 (19.0)	7 (8.6)	1000

+ Without deviation from linearity
* Subscripts indicate corresponding modulating voltage

The performance of the high-inverse-voltage crystals is encouraging enough to warrant a more careful study of their characteristics with a view towards developing a unit that will be capable of generating large amounts of sideband power. The importance of this can be estimated by recalling that the transmitted power from a microwave relay station ought to lie between 100 mw and 2 watts. Thus, a balanced modulator, generating 10 to 20 mw of sideband power, must be followed by 10 to 20 db of relatively wide-band r-f amplification. Any substantial increase in the output of the modulator allows either a simplification in the following amplifier or a corresponding increase in the final output power.

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