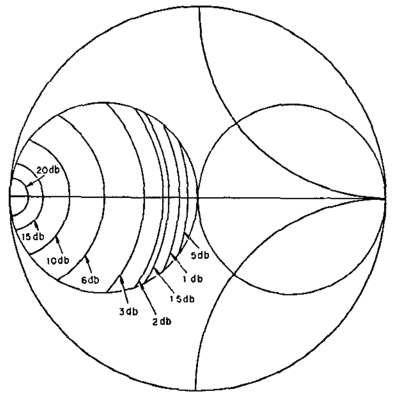

Fig. 4—Attenuation from a planar impedance in a transmission line.

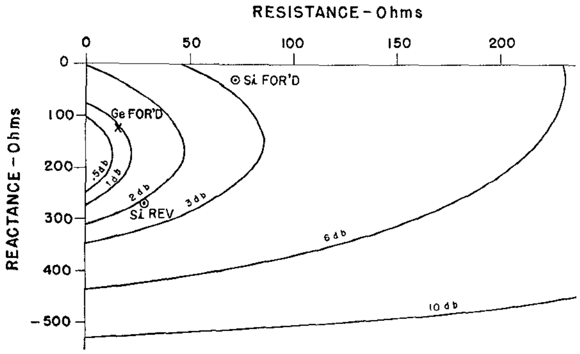

Fig. 5—Attenuation as a function of diode contact impedance for the 1N23 type cartridge at 9300 mc in full size standard X-band waveguide. The contact impedances of silicon and germanium are shown to demonstrate their switching behavior.

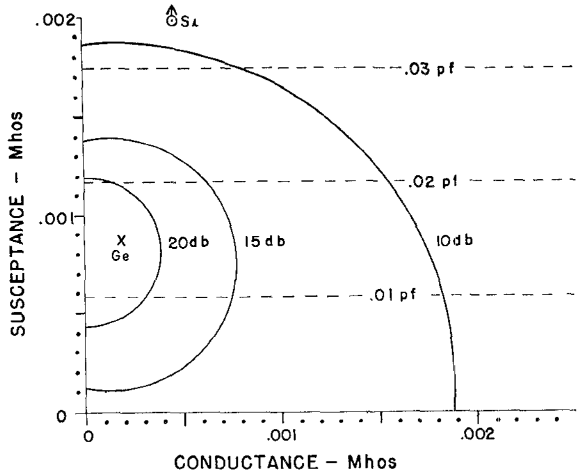

Fig. 6—Attenuation as a function of diode contact admittance for the 1N23 type cartridge at 9300 mc in full size standard X-band waveguide. The contact admittance of germanium at reverse bias is shown to demonstrate its good switching behavior.

Lawson's theory. Silicon, on the other hand, appears to follow the minority carrier theory of Shockley. Thus, the observed difference between the microwave switching capabilities of germanium and silicon is provided with a theoretical foundation.

ACKNOWLEDGMENT

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Improvement in the Square Law Operation of 1N23B Crystals From 2 to 11 kmc*

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Summary—Crystal rectifiers have been used for many years as video detectors in microwave measurements. In most of the applications the detection characteristic at low level is assumed to be square law. It is well known that, in general, this assumption is not justified, particularly if reasonable accuracy is desired. The conditions required to increase the dynamic range over which square law response may be achieved have been investigated experimentally. Results obtained in this laboratory have indicated that a forward bias current of 100 microamperes or more with a low video load resistance made the operation of the crystal closer to the ideal square law over a larger dynamic range.

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INTRODUCTION

CRYSTAL diodes have been used for many years as low-level video detectors of radio-frequency energy both in microwave receivers and in laboratory measuring equipment. The superior low-level performance of the crystal as opposed to a bolometer, together with its small size and short-term stability, make it useful in such applications despite variations between crystals. The crystal rectifier is not limited to the measurement of average power or to low modulation frequencies as are bolometers and thermistors. In its square law region, the crystal is well suited to the comparative measurements of peak power with either pulse or square-wave modulation.

It had previously been observed in this laboratory that the rectification characteristics of crystal diodes could be improved and the dynamic range of their response extended by the application of a forward bias current. Recently, a more complete investigation was carried out to determine the effect of such factors as dc load resistance, ac load resistance and bias currents on the law of video response of crystal rectifiers in several different types of crystal mounts.

The operation of a crystal diode in the microwave region is the result of a large number of interrelated factors which it is difficult to separate. The RF power applied to the crystal has a marked effect on its RF impedance[1] and also on its video impedance.[2] The values of the ac and dc load resistances into which the crystal feeds will also affect the operation. The application of a forward dc bias current has been found to affect the RF and video impedances and also the rectification efficiency[3,4,5] Some results obtained in this laboratory had also indicated that a forward bias current made the operation of crystal diodes closer to the ideal square law over a larger dynamic range and an investigation was set up to assess the effect of several variable factors on the law of crystal response.

Experimental Measurements

To carry out the required measurements of crystal law the equipment was set up as in Fig. 1. The output of the signal generator fed through a calibrated RF attenuator and a fixed pad to the crystal mount being used. The output of the crystal was connected through the bias unit and a calibrated video attenuator to the video amplifier and thence to the oscilloscope. Broadband untuned crystal mounts were used, most of the measurements being made on an NRC Mark V mount shown in Fig. 2. This mount has a bypass capacitance of approximately 30 $\mu\mu$f.

After adjustment of the variable being investigated (dc or ac load, biasing or change of crystal), the video attenuator was set to zero and the RF attenuator adjusted to give a certain convenient fixed deflection on the oscilloscope. The video attenuation was then increased in 5-db steps. At each step, the calibrated RF attenuator was adjusted to bring the output up to the original level and the setting recorded. For a perfect square law response, each step should require 2.5 db of RF attenuation to be removed for every 5 db of video attenuation inserted. By operating in this manner, the video amplifier signals remained at a constant level and the accuracy of the results depended mainly on the precision of the attenuators. The exponent of crystal law calculated from these readings is probably within the limits ± 0.02. The complete circuit of the crystal biasing unit is shown in Fig. 3. This provides dc loads of 1, 10 and 100 kilohms and ac loads of 50, 200 and 1050 ohms when a 50-ohm load is connected to each of the output terminals in turn.

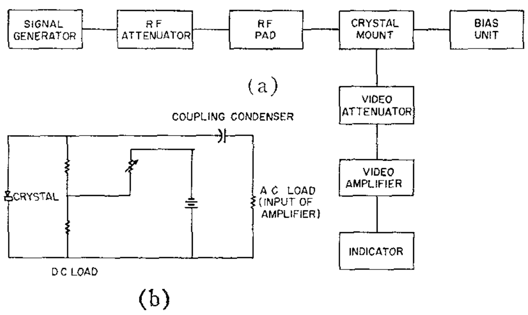

Fig. 1—(a) Block diagram of experimental setup. (b) Simplified crystal bias and coupling circuit.

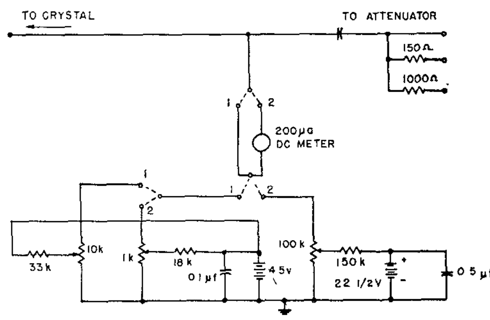

Fig. 2—Bias unit circuit.

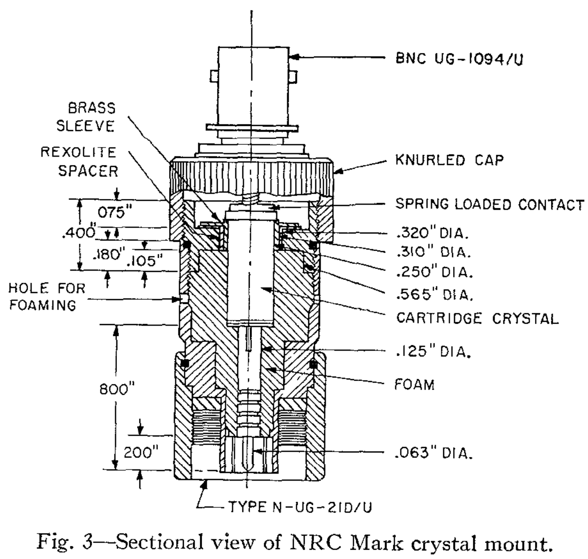

Fig. 3—Sectional view of NRC Mark crystal mount.

[1] H. N. Dawirs and E. K. Damon, "Measurements of crysta impedance at low levels," IRE Trans. on Microwave Theory and Techniques, vol. 4, pp. 94–97; April, 1956.

[2] E. R. Beringer, "Crystal Detectors and the Crystal Video Receiver," Rad. Labs., Mass. Inst. Tech., Cambridge, Mass., Rept. No. 638; November 16, 1944.

[3] W. E. Meyerhof, B. Serin, and R. H. Vought, "X-Band Crystal Performance with Bias," University of Pennsylvania, Philadelphia, Rept. No. NDRC 14-505; July 6, 1945.

[4] E. F. Gallaher and R. L. Crosby, "A transistorized crystal video receiver, *Proc. Natl. Elec. Conf.*, vol. 11, pp. 455–463; 1955.

[5] D. J. Grace, "Some applications of crystal rectifiers in broadbeam microwave circuits," *Microwave Crystal Rectifier Symp. Rec.*, Signal Corps Engrg. Labs., Ft. Monmouth, N. J.; February, 1956.

To facilitate the plotting of such a large number of response curves, the readings were plotted directly on graph paper with the aid of an X-Y plotter.

Effect of Bias and dc Load

After some preliminary measurements in which the characteristics of crystal rectifiers were investigated in rather general terms, experiments were set up to cover more specific conditions of operation. A series oJ measurements was made to determine the effect of various values of bias current and dc load resistance on the crystal characteristics with an ac load resistance of 50 ohms. The first measurements were made to determine the effect of bias on the crystal sensitivity. With equipment as in Fig. 1, the RF input required to produce a certain fixed video output was measured for different values of bias current and it was found that there was a broad maximum in the rectification efficiency with the peak at approximately 100 μa bias. For this set of measurements, the RF power level at the crystal input was about -25 dbm at 100 μa bias.

Further tests were then carried out to investigate the effects of both bias and dc load resistance. Typical results are shown in Figs. 4, 5 and 6. The curves have been normalized to the 0-db video attenuation level which occurred for 140-μa bias condition at about -35 dbm. The measurements of Fig. 4 were made with a pulse modulated input, an ac load of 50 ohms and a dc load of 100 kilohms. It can be seen that at zero bias the slope of the curve is approximately 2 at the lower end but approaches 3 at higher input levels. For small values of bias current, the slope of the curve becomes less than 2 with progressively lower slopes as the RF input is increased. For larger bias currents, the same general trend is seen but as the bias is increased the approach to the 2.00 slope becomes much closer. How-

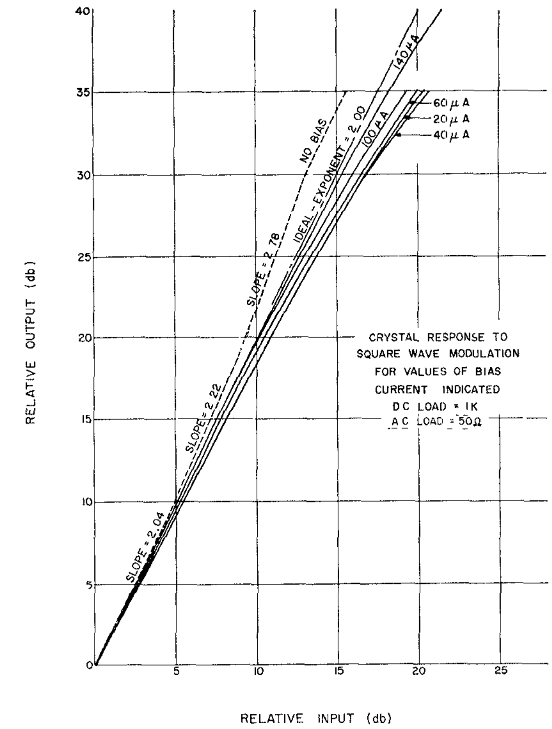

Fig. 5—Effect of bias on law of crystal response—square-wave modulation—1000 ohms dc load.

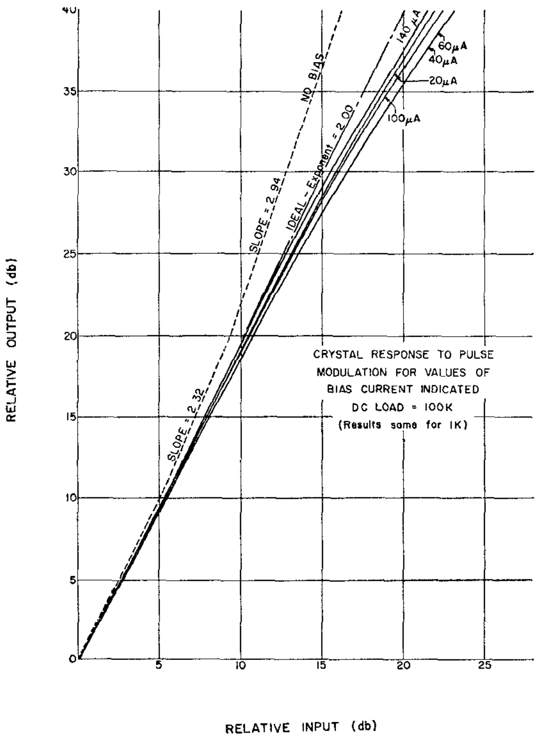

Fig. 4—Effect of bias on law of crystal response—pulse modulation—100 kilohms dc load (1000-ohm dc load similar).

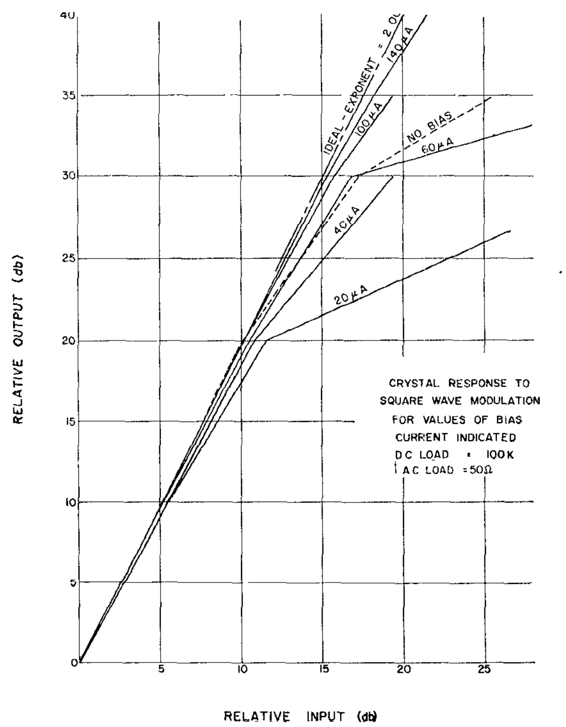

Fig. 6—Effect of bias on law of crystal response—square-wave modulation—100 kilohms dc load.

ever, above 140 μa the change of exponent is very small. Measurements made with a 1000-ohm dc load showed no significant difference.

Measurements on the same crystal with square-wave modulation and 1000-ohm dc load are shown in Fig. 5. The results are very nearly the same as those in Fig. 2. However, when the dc load was increased to 100 kilohms with square-wave modulation a very significant change occurred (see Fig. 6).

For zero bias, the slope of the curve was practically 2 for a good range of signals but at higher levels the slope approached 1, indicating linear rather than square law response. With the application of forward bias, the curve shows a more violent departure from square law for low values of bias but for values above 100 μa the slopes are essentially the same as those shown in Figs. 4 and 5.

It can be seen that for values of bias above 100 μa the exponent of the response law approaches the ideal value of 2.00 over the range measured, with the approach being nearer for larger bias currents. At large bias currents the response becomes practically independent of dc load conditions. The difference between the results for square-wave modulation with the 100-kilohm load and the results for other conditions arises from back biasing which is more pronounced for high-duty cycle and long-time constant conditions.

This back biasing is clearly indicated by the rapid increase of video resistance at higher power levels with square-wave modulation. A comparison of the video resistance for pulse and square-wave modulation with 140 μa forward bias for a typical crystal is shown in Fig. 7. This value of bias was chosen as being a reasonable compromise between the good square law obtained at higher bias and the maximum rectification efficiency obtained at lower bias.

From an examination of the zero bias curves of Figs. 4 and 5, it would appear that there is some value of dc load between 1000 and 100,000 ohms which would produce an exponent close to 2.00 for square-wave modulation. This is true, but the resistance value required to produce the desired result is rather critical and is sensitive to the particular crystal used and the PRF of the square-wave modulation. In particular cases, this method of obtaining good square law response might be justified but at the expense of being of very limited application. Some isolated crystals will give a good square law response with zero bias but will require a lot of measurement and selection to obtain.

With a bias current of 140 μa, the range over which the response of the crystal was nearly square law did not depend to an appreciable extent on the value of the dc load resistance. However, with a low value of dc resistance there was a gradual transition to linear response with increasing power levels, while with the higher values of dc load resistance the response changed abruptly from square law to a limited level due to back biasing (See Fig. 8).

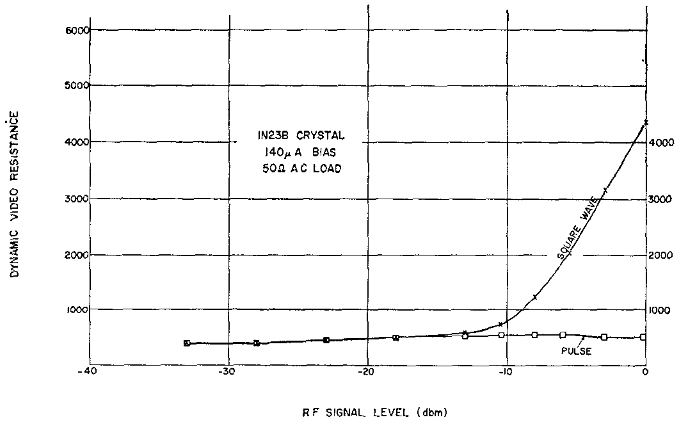

Fig. 7—Dynamic video resistance for pulse and square-wave modulation.

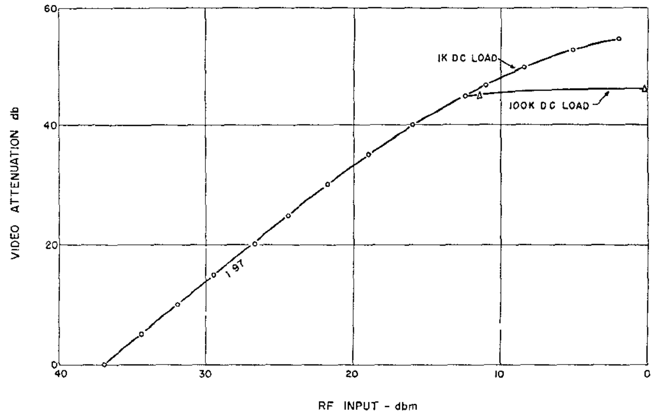

Fig. 8—Effect of dc load on crystal response.

Effect of ac Resistance

With a bias current of 140 μa, an assessment was made of the effect of the law of rectification with a change in the value of the ac load. Measurements were made on a group of crystals with ac loads of 50 and 1000 ohms with both pulse and square-wave modulation. The values of the exponents obtained for the four conditions are shown in Fig. 9. With square-wave modulation, there is decided difference between the two conditions. With the 50-ohm load, the exponents are more closely grouped and the average value is closer to the ideal 2.00. With pulse modulation, the effect is not quite so obvious but the 50-ohm load appears to give a slightly better exponent.

A much larger group of crystals (50) was measured at zero bias, 10-K ac load, and compared with measurements of the same crystals at 140 μa bias and 50-ohm ac load to obtain a quantitative comparison of the improvement obtained with combined bias and low ac load. For zero bias, the slope measured between input powers of -28 and -18 dbm, gave a value of 2.25 ± 0.20 for square wave and 2.30 ± 0.20 for pulse conditions. For 140 μa bias and 50-ohm ac load, the corresponding results were 1.98 ± 0.04 for square-wave and 1.98 ± 0.03 for pulse. A smaller number of crystals measured with

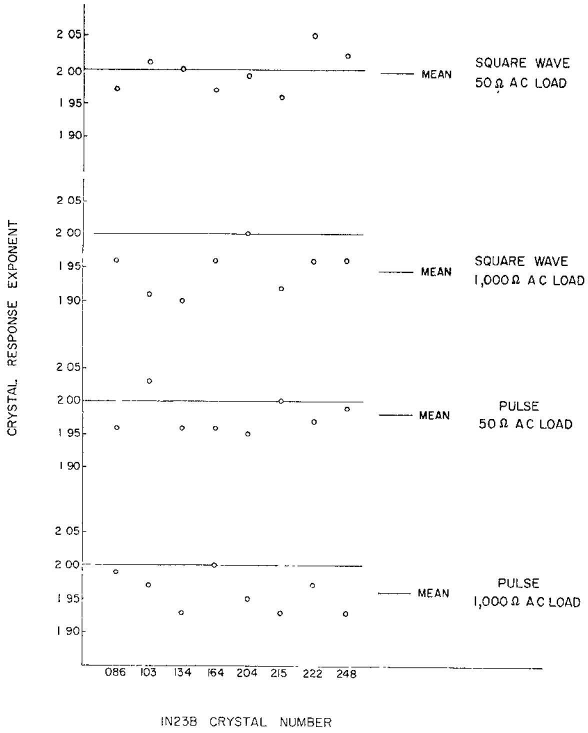

Fig. 9—Effect of ac load on crystal response.

no bias, pulse modulation, and a 1-K ac load gave a value of 2.22 ± 0.21 indicating no appreciable improvement for a change of ac load under zero bias conditions.

Effect of Crystal Mount

The effect of the crystal mount on the law of the crystal was investigated by measuring the same crystal in several mounts under various conditions of bias and ac load. Typical results are shown in Fig. 10. With 140 μa bias and 50-ohm ac load, the crystal law was practically independent of the crystal mount used within the designed frequency range of the mount and remained close to the ideal 2.00 exponent. All mounts used were of the broad-band untuned type, with both coaxial and waveguide inputs.

Effect of Crystal Type

Although most of the measurements reported here were made on 1N23B type crystals, a number of runs were made with various other types to confim that the results were of general application. The measured exponents of several different crystals in an NRC Mark V mount are shown in Fig. 11. The exponents remain within the limits 1.98 ± 0.05 for the frequency range of the mount (2.0–5.5 kmc).

Conclusion

If it is desired to have a crystal rectifier of the 1N23B or similar type operate as near to the ideal square law as possible over a large dynamic range, it should be operated with a forward bias current of approximately 140 μa and the signal should be developed across a low resistance ac load (50 to 200 ohms). These conditions of operation will give satisfactory results with both square-wave and pulse modulation. These conditions appear to give a response with an exponent of 2.00 ± 0.05 with a wide variety of crystals, mounts and frequencies of operation provided the mounts are used within their design frequency limits.

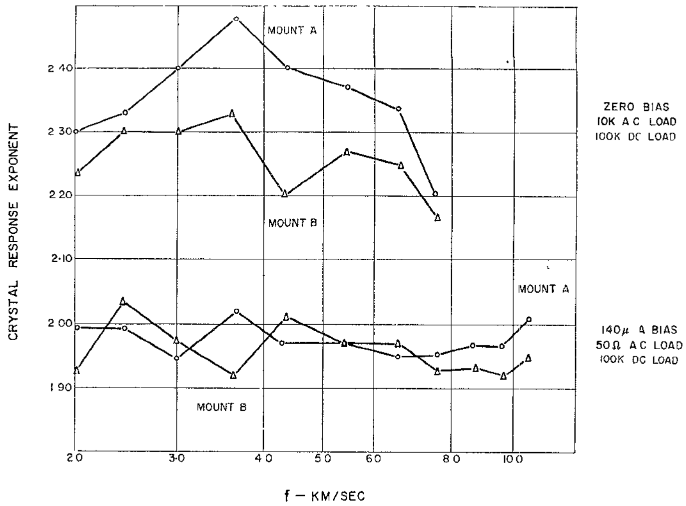

Fig. 10—Effect of bias with other crystal mounts (mounts A and B are commercially available broad-band crystal mounts).

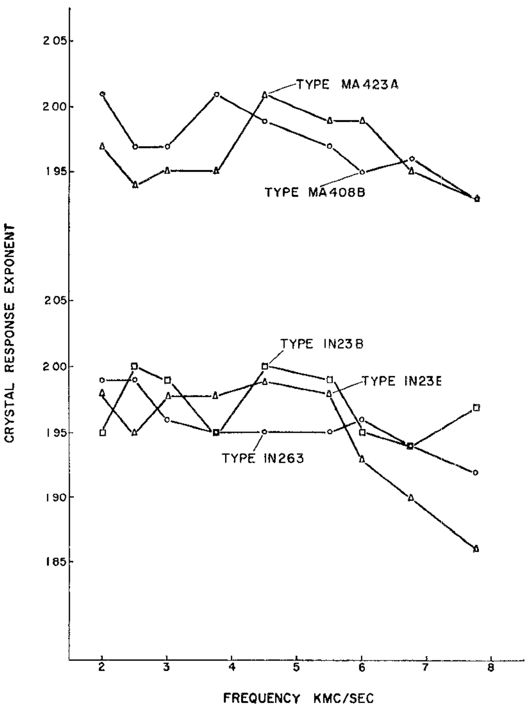

Fig. 11—Effect of crystal type on law of response (measured in NRC Mark V mount).

Acknowledgment

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