SUPERHETERODYNE RECEIVER FOR THE 100 TO 150 kMc REGION

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Introduction

In our work in the region from 100 to 300 kMc we are continually searching for more sensitive receiving systems and have recently been investigating superheterodyne detection in this region.

At lower microwave frequencies a superheterodyne receiver is usually about 100,000 times more sensitive than a crystal video receiver. At 100 or 150 kMc it appears that approximately the same increase in sensitivity can be obtained if sufficient local oscillator power were available. However, to obtain enough local-oscillator power is our big problem. The only available sources of power in this region are harmonic generators that furnish about 10 or 20 microwatts at 100 kMc. This amount is about two orders of magnitude below the usual optimum local-oscillator level, and, hence, the conversion loss in the mixer is excessively high. With our best obtainable L-O power we obtained a conversion loss of 45 db in mixing two 100 kMc signals, and the superheterodyne system was only slightly more sensitive than the crystal video system.

In order to reduce this prohibitive conversion loss due to insufficient L-O power we resorted to a harmonic mixing process and achieved a tremendous improvement over fundamental mixing. Instead of a 45 db conversion loss we obtained values as low as 11 db. Harmonic mixing has been used at lower frequencies[1] before, but in the usual superheterodyne receiver it is a mixing action one tries to suppress.

Measurements

Figure 1 shows a block diagram of our 100 kMc system. The transmitter tube is operating at say 25,000 Mc and drives a harmonic generator which converts a small amount of the input power to the fourth harmonic at 100 kMc. The lower frequencies are filtered out by beyond cut-off waveguide, and the 100 kMc signal is transmitted through the loss path to the receiving horn and mixer. The local oscillator is operating at 25,015 Mc, and its energy feeds directly into the other arm of the mixer. The two signals combine in the crystal rectifier element to produce among other combinations an output at 60 Mc which is amplified and detected by the receiver.

That a 60 Mc intermediate frequency is produced by this mixing process can be seen at least qualitatively by expressing the output crystal current, i, as a power series of the impressed voltage, e. If

$$e = E_R \cos \omega_R t + E_L \cos \omega_L t \tag{1}$$

where E_R and E_L are the peak amplitudes of the received and L-O signals, respectively, and ω_R and ω_L their angular frequencies, then it can easily be shown that output terms of the form

$$i_{IF} = a E_R E_L^n \cos(\omega_R - n\omega_L)t \tag{2}$$

are produced along with the usual terms in $\cos(\omega_R - \omega_L)t$ and $\cos(\omega_R + \omega_L)t$. Thus for the case we are considering Eq. (2) would become

$$i_{IF} = aE_R E_L^4 \cos 2\pi(100{,}000 - 4 \cdot 25{,}015)t \tag{3}$$

which is the desired 60 Mc IF term. All the microwave frequency terms (i.e. $\cos(\omega_R - \omega_L)t$, etc.) are by-passed at the mixer.

In order to verify that the IF output is a linear function of the received signal voltage, the 100 kMc energy was transmitted through space for various path lengths. We found that, to the accuracy we could measure, the detector system was operating linearly even up to our maximum obtainable harmonic signals of 25 microwatts. This result is, of course, not surprising since the L-O power was at least several milliwatts, which is many times greater than the received signal.

The transmitter and local-oscillator tubes were reflex klystrons (Types 2K33 and QK290) with an available power output of 30 to 60 milliwatts. The fundamental output of these tubes was measured with a commercial bolometer. However, at present we do not have bolometers that will measure power in the 100 to 150 kMc region, and, therefore, absolute power measurements could not be made on the harmonics generated by the crystal multiplier. Thus, in these tests the only means of estimating the amount of harmonic power is by comparing the modulation output from a crystal detector operating at 100 or 150 kMc with the output of a crystal detector operating at 25 kMc. In the results given subsequently it has been assumed that the detection efficiency at the harmonic frequencies is the same as at the fundamental frequency. No doubt some correction should be made, but it is somewhat dubious at the moment as to just how much.

The IF output of the mixer was measured by comparison with the output of a calibrated VHF generator. From measurements of this IF power, the power of the fundamental oscillator, the loss in generating the harmonic energy and the transmission path loss, if any, the conversion loss in the mixer was readily determined.

Figure 2 shows a photograph of the mixer, and Figure 3 gives a cross-sectional view of the device. It is an unbalanced type with the mixing element located at the intersection of the crossed waveguides. The L-O signal at 25 kMc enters through the large-size waveguide and the received signal at 100 kMc enters through the small-size guide. Each arm contains a tuning plunger.

The silicon wafer is flush with the inside of the waveguide and the whisker, a 1.5 mil tungsten wire with an extremely sharp point, is directly across the small guide. With no L-O power, this mixer unit is only about 1 or 2 db worse as a video detector than our regular detector units, indicating that we are not losing a great amount of our received signal into the L-O channel.

Figure 4 is a photograph of the complete test system showing the klystron oscillators, harmonic generator, mixer, and accessory devices.

For these measurements the transmitter oscillator was swept through several megacycles and the local oscillator was operated CW. In this manner the beat frequency outputs at several harmonics could be observed simultaneously on an oscilloscope as shown in Figure 5. The beats occur at different places along the trace because to produce beats at a fixed IF, the frequency separation of the fundamental oscillators is, of course, different for successive harmonics. With the adjustable shorting plungers, any particular harmonic can be maximized at the expense of detuning some of the others.

In Figure 5 the large response on the end of the group is due to a fourth harmonic transmitted signal at 96 kMc. All lower harmonics are filtered out of the transmitted signal by the small-size waveguide on the output of the harmonic generator. The next three beats shown are due to the fifth, sixth and seventh harmonics at 120, 144 and 168 kMc. However, beyond this point the IF outputs are no longer due solely to terms of the form of Eq. (2). Other possibilities arise such as the second and third harmonics of the beat frequencies themselves, i.e.,

$$i_{IF} = b\, E_R^{\,m}\, E_L^{\,n} \cos 2(\omega_R - 4\omega_L)t \qquad (4)$$

giving responses that fall at the same place on the trace as the beats due to the higher rf components. By inserting smaller-size filter sections in the output of the multiplier to remove the fourth and fifth harmonics we also removed these spurious responses masking the beats due to higher rf frequencies. In this manner we were able to detect energy up to 240 kMc, the tenth harmonic of 24 kMc.

Results

Quantitative data were taken on the third, fourth, and fifth harmonics of 31 kMc and the fourth, fifth, and sixth harmonics of 24 kMc. Figures 6, 7 and 8 are some of the typical plots of conversion loss and noise figure as a function of mixer crystal current at intermediate frequencies of 65 and 210 Mc.

Since the mixer was unbalanced and no other means was used to reduce L-O noise, the total crystal noise factor, t', is made up of the regular crystal noise temperature plus a term due to L-O noise.[2]

The overall noise figure of the receiver N_F in decibels is given by

$$N_F = L + 10 \log_{10}(F^*_{IF} + t' - 1) \qquad (5)$$

where L is the conversion loss in the mixer in decibels and F^*_{IF} is the effective noise figure of the IF amplifier.

The curves show that the conversion loss decreases quite rapidly in the region from .05 ma up to about 1.0 ma of rectified mixer current and then decreases slowly over quite a range usually up to the maximum obtainable current. The crystal noise increases, of course, for increased L-O drive and thus the curve for overall noise figure decreases quite rapidly up to about 1 ma of current and then decreases very slowly for higher drives.

The crystal noise temperature even allowing for the L-O noise seems extremely high and it is probably due to the very sharp pointed cat-whiskers. We hope to achieve some improvement in noise figure by using a different shaped point. An external bias current and decreased L-O drive on the mixer gave very little improvement in noise figure.

Table I gives a comparison of video and superheterodyne detection for several frequencies. All of the data at a particular fundamental frequency were taken during the same run with the tuning plungers optimized at each harmonic. For video detection the mixer was replaced with a detector mount tuned for the particular harmonic to be measured.

With the bandwidths given in Table I the superheterodyne system using third harmonic mixing is 29 db more sensitive than the video system at 93 kMc. If, as mentioned above, it is assumed that the detection efficiency is the same at 93 kMc as at 31 kMc then the absolute sensitivity for the crystal video system is -57 dbm and for the superheterodyne system -86 dbm. As the harmonic number is increased the gain in sensitivity of superheterodyne over video detection decreases so that harmonic mixing appears to have very little advantage above the fifth or sixth harmonic.

Applications

With an absorption cell inserted between the multiplier and the mixer the sweep system using harmonic mixing forms an interesting microwave spectrometer. Since the IF bandwidth is 4 Mc and the width of the absorption line is about 0.5 Mc at the pressures usually used, the line will appear as a sharp pip in the beat frequency response when the transmitted signal is swept through the absorption frequency. Figure 9 shows the absorption pip in the sixth harmonic IF response due to the $J = 11 \rightarrow 12$ rotational transition of $O^{16}C^{12}S^{34}$ at 145.95 kMc. The scale along the scope trace is expanded much more than in Figure 5.

Frequency measurements can be made with a wavemeter and frequency standard in the same manner as with a simple video system. Since very small-size waveguide filter sections are usually somewhat lossy at these high frequencies, it has become the practice to permit energy at all harmonics above say the third or fourth to propagate simultaneously through the absorption cell. With video detection we do not know when we have attained maximum energy at the particular harmonic frequency we desire until we can observe a known absorption line at this frequency. With the superheterodyne system we can peak up on any harmonic directly. Also, by this method the particular harmonic at which an unknown absorption line occurs is unambiguously determined. The absorption frequencies of most linear and symmetric top molecules can usually be calculated much closer than the frequency difference between harmonics, but this is not true in the case of many asymmetric top molecules.

Since a molecule such as OCS has multiple absorption frequencies which are almost but not quite harmonics of the lowest frequency absorbed, it furnishes a convenient means of testing whether our harmonic beats displayed on the oscilloscope are due to terms of the form of Eq. (2) or due to spurious terms like those of Eq. (4). If the higher absorption frequencies were exact harmonics of the lowest frequency, all the pips would occur at the same spot on the oscilloscope trace. However, the case is that each higher absorption is displaced slightly more than the preceding one toward the lower frequency side of the trace. (See following paper by W. C. King) Hence, by manually tuning the local oscillator the absorption pip shown in Figure 9 could be made to appear in any of the harmonic beats but always displaced slightly more toward lower frequency for each higher harmonic. When this displacement failed to occur, or occurs at two different places, we know the beat term is not purely Eq. (2). This condition occurred for what we at first thought was the beat due to the eighth harmonic of 24.3 kMc. This beat, however, gave a pip where that due to fourth harmonic energy should have occurred. It was only after inserting a filter that removed the fourth harmonic energy from the transmitted signal that we could get an unambiguous pip at the eighth harmonic. A similar condition existed for the higher harmonics.

With the klystron oscillators frequency stabilized and the transmitter amplitude modulated so that a narrow-band audio amplifier can be used after the second detector, it should not be difficult to obtain sensitivities of -120 dbm or a dynamic range of 100 db at 100 kMc. A system of this type should be useful in making radiation scattering measurements from models and perhaps also as a radiometer for detecting atmospheric absorptions.

Acknowledgement

I am indebted to Mr. S. P. Schlesinger for making many of the above measurements.

References

1. D. L. Falkoff, Rad. Lab. Report quoted by H. C. Torrey and C. A. Whitmer, Crystal Rectifiers, McGraw-Hill Book Co., Inc., New York, pp 170-172; 1948.
2. R. V. Pound, Microwave Mixers, McGraw-Hill Book Co., Inc., New York, pp 237-241; 1948.

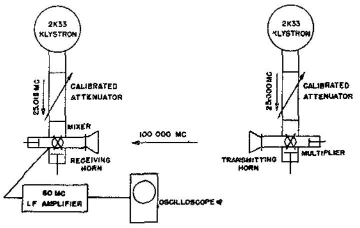


DIAGRAM OF 100 KMC SUPERHETERODYNE SYSTEM

Fig. 1

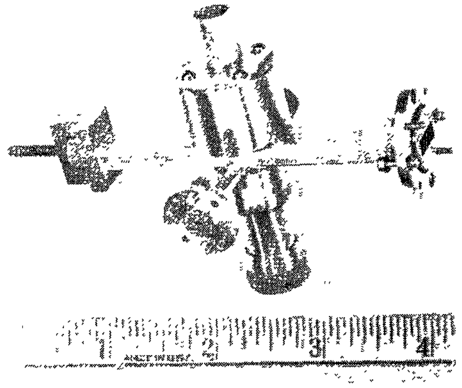


Fig. 2 - Photograph of mixer unit.

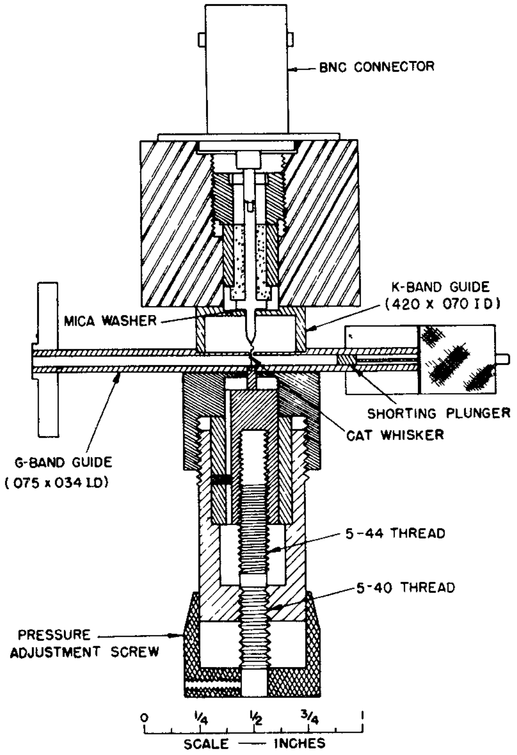


Fig. 3 - Cross-sectional view of mixer unit.

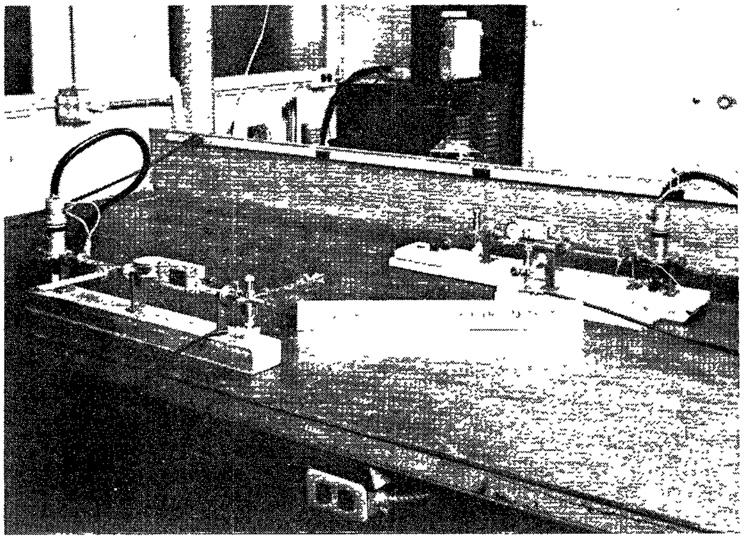


Fig. 4 - Photograph of test system used for the harmonic mixing experiments.

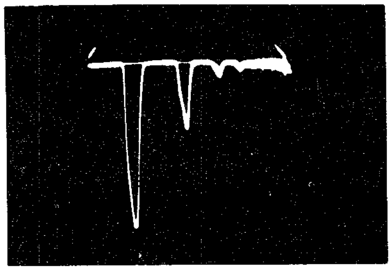


Fig. 5 - Oscilloscope picture of harmonic responses obtained by mixing the output from a frequency-swept transmitter with a C-W local oscillator.

Fig. 6

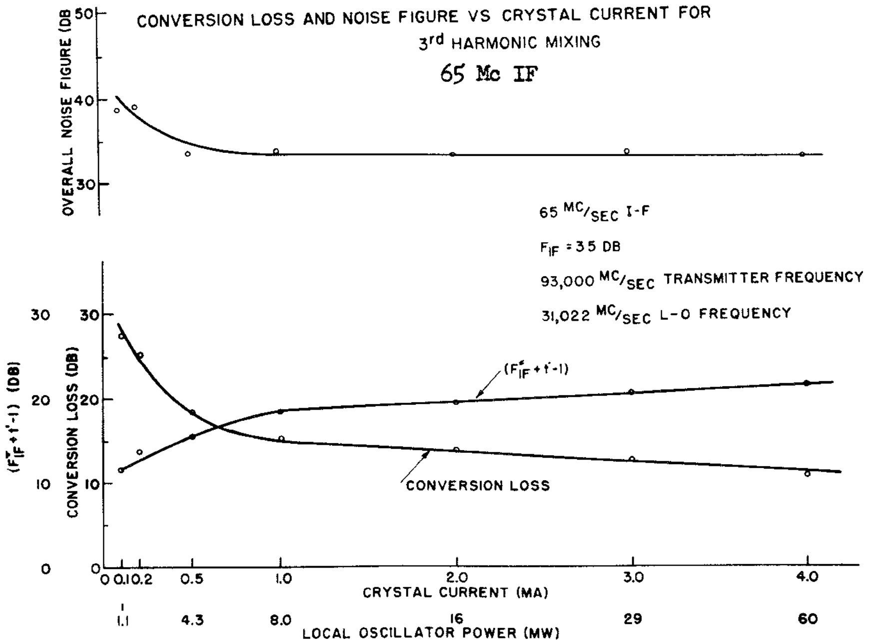


Fig. 7

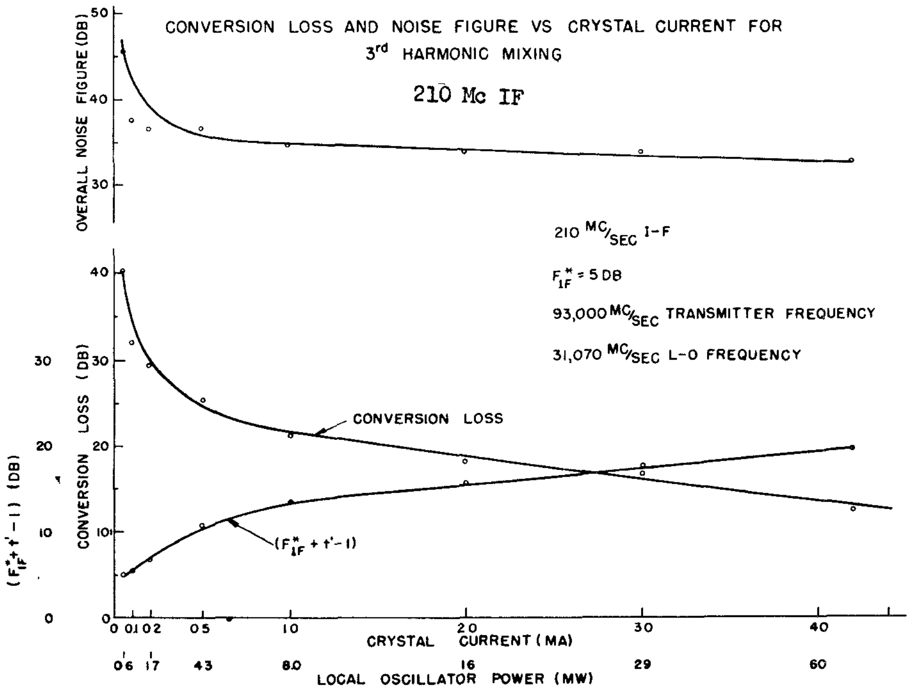
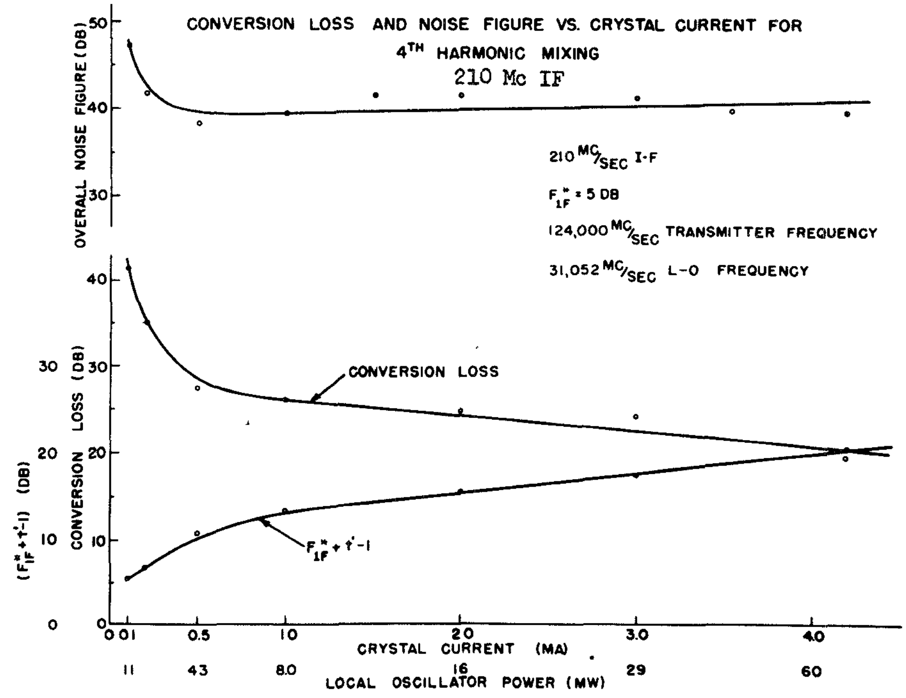

CONVERSION LOSS AND NOISE FIGURE VS CRYSTAL CURRENT FOR
3rd HARMONIC MIXING
210 Mc IF
OVERALL NOISE FIGURE (DB)
50
40
30
210 MC/SEC I-F
F*1F = 5 DB
93,000 MC/SEC TRANSMITTER FREQUENCY
31,070 MC/SEC L-O FREQUENCY
CONVERSION LOSS (DB)
(F*1F + t' - 1) (DB)
40
30
20
10
0
CONVERSION LOSS
(F*1F + t' - 1)
0 0.1 0.2 0.5 1.0 2.0 3.0 4.0
CRYSTAL CURRENT (MA)
0.6 1.7 4.3 8.0 16 29 60
LOCAL OSCILLATOR POWER (MW)

Fig. 8


CONVERSION LOSS AND NOISE FIGURE VS. CRYSTAL CURRENT FOR
4TH HARMONIC MIXING
210 Mc IF
OVERALL NOISE FIGURE (DB)
50
40
30
210 MC/SEC I-F
F*1F = 5 DB
124,000 MC/SEC TRANSMITTER FREQUENCY
31,052 MC/SEC L-O FREQUENCY
CONVERSION LOSS (DB)
(F*1F + t' - 1) (DB)
40
30
20
10
0
CONVERSION LOSS
F*1F + t' - 1
0 0.1 0.5 1.0 2.0 3.0 4.0
CRYSTAL CURRENT (MA)
1.1 4.3 8.0 16 29 60
LOCAL OSCILLATOR POWER (MW)

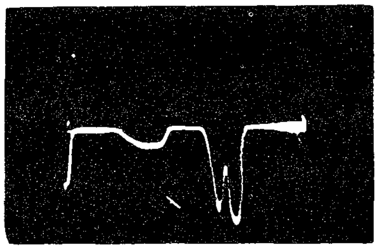


Fig. 9 - Oscilloscope picture of the absorption line line due to the $J = 11 \rightarrow 12$ rotational transition of OCS as detected by harmonic mixing. The frequency of the absorption is 145.95 kMc.

TABLE I

COMPARISON OF CRYSTAL VIDEO DETECTION WITH SUPERHETERODYNE DETECTION USING HARMONIC MIXING †

Fundamental Oscillators	Harmonic	Multiplication Loss (db)	Dynamic Range Video Detection* (db)	Conversion Loss for Minimum N_F (db)	Dynamic Range of Superheterodyne Detection** (db)
QK 290	3	34	40	12	69
54 mw	4	37	37	19	59
at 31 kMc	5	51	23	22	44
2K 33	4	38	36	21	55
35 mw	5	41	33	25	44
at 24 kMc	6	52	22	26	33

* Video detection - 200 kc bandwidth amplifier

** Superheterodyne detection - 210 Mc IF amplifier with 4 Mc bandwidth followed by an audio amplifier of 200 kc bandwidth

† Local-oscillator signal entering mixer at approximately the fundamental frequency