TECHNICAL REPORT NUMBER 7

A COMPARATIVE STUDY OF THE BALANCED AND SINGLE-ENDED MIXERS IN THE PRESENCE OF LOCAL-OSCILLATOR NOISE

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PREFACE

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The ability of the balanced mixer to reduce local-oscillator noise is investigated by comparing the outputs of a balanced and a single-ended mixer when the local-oscillator signal is summed with and modulated by a simulated noise signal. This comparison is made analytically as well as experimentally. In addition, the outputs of the single-ended and balanced mixers are compared experimentally for the cases where the local-oscillator signal is summed with and modulated by band-limited random noise. It is shown in all cases that the balanced mixer significantly reduces the amount of noise in the mixer output for the two types of local-oscillator noise studied.

Author

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I. INTRODUCTION

G. E. Clausen and M. A. Honnell

It has been known for many years that noise limits the reception of weak radio signals. In the early days of radio when the majority of the broadcasting frequencies in use were below 30 megacycles per second, most radio noise came from atmospheric and man-made sources. Since there was little that could be done to reduce the noise from these sources, the radio designer adapted his standards to accept it.

As broadcast frequencies progressed above 30 megacycles per second it was discovered that atmospheric and man-made noise were almost non-existant in the higher regions of the radio spectrum.[1] However, it was found that reception was still limited by noise, but from a different source. It was found that noise generated by the receiver itself limited the reception of weak signals. Unlike atmospheric and man-made noises the radio designer could do something about this source of noise.

Receiver noise comes from many sources since all elements within a receiver generate some degree of noise. However, since nearly every stage of a receiver amplifies the output of the preceding stage, those sources of noise closest to the input terminals are the most important.

Of the various stages that are sometimes found at the input of a receiver, the mixer or converter stage is one of the noisiest. Mixer noise comes primarily from two sources: (1) random fluctuations of electron currents within the mixer and the local-oscillator circuitry which cause the local-oscillator signal to be amplitude modulated with noise, and (2) thermal agitation of electrons in the local-oscillator output circuit which adds noise to the local-oscillator signal. Either of these noise sources can cause a considerable amount of noise in the mixer output. This is particularly true when these noise components are such that they are separated from the local-oscillator signal by an amount equal to plus or minus the intermediate frequency of the receiver, since they beat with the local-oscillator signal in the mixer to give a noise output at the desired intermediate frequency. Many complex and costly techniques are employed in an effort to reduce this noise. However, much of this noise can be reduced by using a rather simple circuit known as the balanced mixer.

The balanced mixer consists fundamentally of two non-linear elements arranged in a balanced or push-pull arrangement as shown in Figure 1. Although many other configurations can be found in the literature, the principle of operation is still basically the same. The two non-linear elements are arranged so that the local-oscillator voltages applied to each of the elements are in phase while the signal voltages applied to each of the elements differ in phase by 180 degrees. The local-oscillator noise arrives at the two elements through the same circuit as the local-oscillator signal and is therefore of the same phase as the local-oscillator signal. Since the local-oscillator output is applied to each element in phase, it produces output currents from each element that are likewise in phase. If it is assumed that

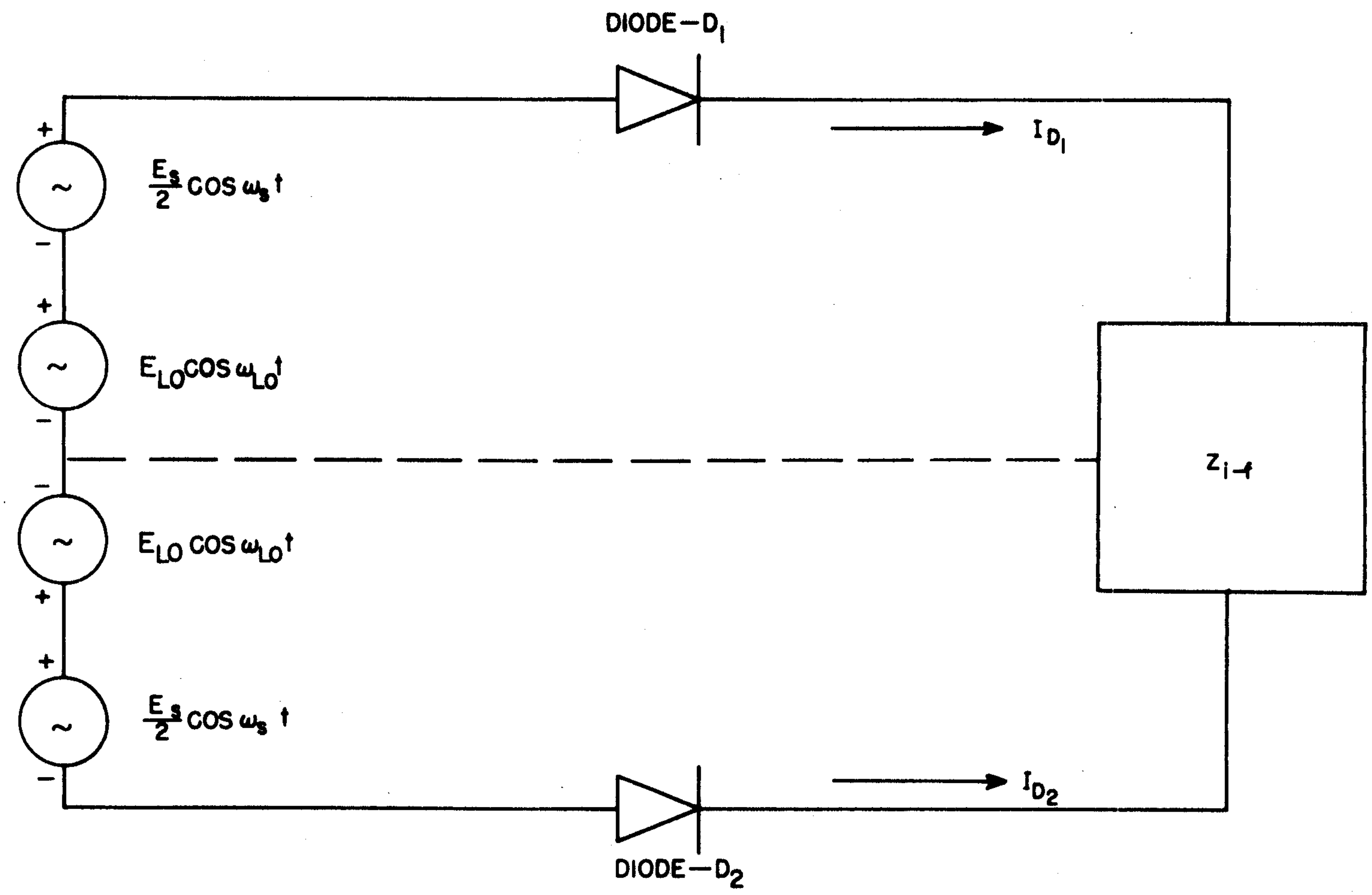

FIGURE 1. AN EQUIVALENT CIRCUIT OF A BALANCED DIODE MIXER

the elements are perfectly matched, the currents will also be of the same magnitude. It is seen from Figure 1 that the current presented to the intermediate-frequency load is proportional to the difference between these two currents. Thus, the currents produced by the local-oscillator and the noise components subtract and produce no output. Since the signal voltages applied to each element are 180 degrees out of phase, the output currents from each element are also out of phase by 180 degrees. Thus, the modulation products due to the local-oscillator and signal currents add, producing an output at the desired intermediate frequency. The degree to which the local-oscillator noise is suppressed depends generally on how well the two non-linear elements are matched, although in some configurations such as the "Magic Tee" and the "Short Slot Hybrid" this is not a critical factor.[2,3]

Although much is said about the advantages of the balanced mixer for reducing local-oscillator noise, little proof is given to support these claims.[4,5,6,2] It is the purpose of this study to show analytically as well as experimentally that the balanced mixer will substantially reduce the afore-mentioned types of local-oscillator noise.

II. ANALYSIS OF THE SINGLE-ENDED DIODE MIXER IN THE PRESENCE OF LOCAL-OSCILLATOR NOISE

The process by which mixing is accomplished depends fundamentally on the use of some device whose output impedance varies in a non-linear way with the applied voltage such as a vacuum tube or a crystal diode.

If two sinusoidal voltages of frequencies f_s and f_{Lo} are applied to a single-ended diode mixer as shown in Figure 2, the resultant diode current contains the new frequencies $nf_s \pm mf_{Lo}$ where n and m are positive integers, including zero. Likewise if there are any additional frequencies accompanying the local-oscillator frequency, f_{Lo}, the resultant diode current contains still additional frequencies as will be shown.

If it is assumed that the non-linear characteristic of the diode can be reasonably expressed by the equation

$$i_D = a_o e_{in} + a_1 e_{in}^2 \tag{1}$$

where a_o and a_1 are constants of the particular diode, and

$$e_{in} = E_s \cos\omega_s t + E_{Lo} \cos\omega_{Lo} t \quad ,$$

where ω_s is the signal frequency and ω_{Lo} is the local oscillator frequency, then the local-oscillator frequency is equal to ω_s plus the intermediate frequency. The resultant diode current is given by

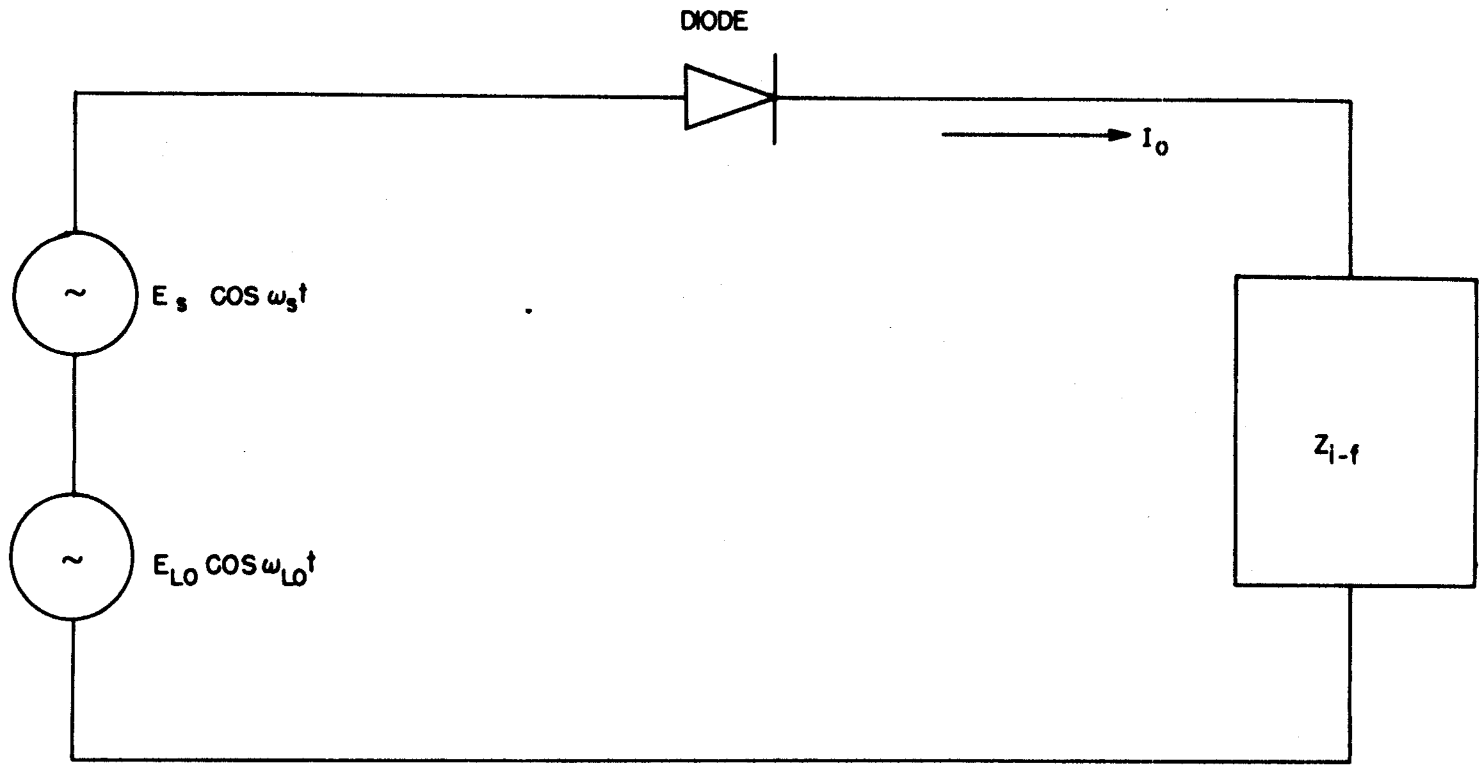

FIGURE 2. AN EQUIVALENT CIRCUIT OF A SINGLE-ENDED DIODE MIXER

$$i_D = a_o(E_s\cos\omega_s t + E_{Lo}\cos\omega_{Lo} t) + a_1(E_s\cos\omega_s t + E_{Lo}\cos\omega_{Lo} t)^2 \ . \tag{2}$$

If this is expanded and the following triogonometric identity is applied

$$\cos A\cos B = 1/2\left[\cos(A + B) + \cos(A - B)\right]$$

equation (2) becomes

$$i_D = a_o(E_s\cos\omega_s t + E_{Lo}\cos\omega_{Lo} t) + a_1\left[\frac{E_s^2}{2}\cos 2\omega_s t + \frac{E_s^2}{2}\right.$$

$$+ E_sE_{Lo}\cos(\omega_s + \omega_{Lo})t + E_sE_{Lo}\cos(\omega_s - \omega_{Lo})t \tag{3}$$

$$\left. + \frac{E_{Lo}^2}{2}\cos 2\omega_{Lo} t + \frac{E_{Lo}^2}{2}\right]$$

which is seen to contain the new frequencies $2f_s$, $2f_{Lo}$ and $f_s \pm f_{Lo}$. If it is assumed that the tuned output circuit filters out all but the difference frequency, then the desired output current supplied to the intermediate-frequency load is

$$i_o = a_1 k E_s E_{Lo}\cos(\omega_s - \omega_{Lo})t \tag{4}$$

where k is a constant of the output transformer.

Suppose, however, that the local-oscillator signal has some noise component superimposed upon it such that the instantaneous local-oscillator output voltage is given by

$$e_{Lo} = E_{Lo}\cos\omega_{Lo}t + E_n\cos\omega_n t \quad ,$$

where ω_n represents one frequency component of the interfering, or noise, signal. (The noise may consist of a single frequency, a harmonically-related spectrum of frequencies, or random noise.) Then equation (1) can be written as

$$\begin{aligned} i_D &= a_o(E_s\cos\omega_s t + E_{Lo}\cos\omega_{Lo}t + E_n\cos\omega_n t) \\ &\quad + a_1(E_s\cos\omega_s t + E_{Lo}\cos\omega_{Lo}t + E_n\cos\omega_n t)^2 \quad . \end{aligned} \tag{5}$$

If equation (5) is expanded, the output diode current is given by

$$\begin{aligned} i_D &= a_1(E_s\cos\omega_s t + E_{Lo}\cos\omega_{Lo}t + E_n\cos\omega_n t) + a_1\left[\frac{E_s^2}{2}\cos 2\omega_s t\right. \\ &\quad + \frac{E_s^2}{2} + E_sE_{Lo}\cos(\omega_s + \omega_{Lo})t + E_sE_{Lo}\cos(\omega_s - \omega_{Lo})t \\ &\quad + E_sE_n\cos(\omega_s + \omega_n)t + E_sE_n\cos(\omega_s - \omega_n)t + E_{Lo}E_n\cos(\omega_{Lo} + \omega_n)t \\ &\quad \left. + E_{Lo}E_n\cos(\omega_{Lo} - \omega_n)t + \frac{E_{Lo}^2}{2}\cos 2\omega_{Lo}t + \frac{E_{Lo}^2}{2} + \frac{E_n^2}{2}\cos 2\omega_n t + \frac{E_n^2}{2}\right] \end{aligned} \tag{6}$$

It is seen from this equation that the output current from the diode contains many new frequencies due to the presence of the noise; however, the output current presented to the intermediate frequency load contains only the difference frequencies as before and is given by

$$i_o = a_1 K \left[E_s E_{Lo} \cos(\omega_s - \omega_{Lo})t + E_s E_n \cos(\omega_s - \omega_n)t + E_{Lo} E_n \cos(\omega_{Lo} - \omega_n)t \right]. \tag{7}$$

Consider now the case where the local-oscillator signal is modulated by some noise voltage such that the output voltage from the local-oscillator is $e_{Lo} = E_{Lo}(1 + \frac{E_n}{E_{Lo}} \cos\omega_n t)\cos\omega_{Lo} t$; then equation (1) can be written as

$$i_D = a_o \left[E_s \cos\omega_s t + E_{Lo} \cos\omega_{Lo} t + \frac{E_n}{2} \cos(\omega_{Lo} - \omega_n)t + \frac{E_n}{2} \cos(\omega_{Lo} + \omega_n)t \right] + a_1 \left[E_s \cos\omega_s t + E_{Lo} \cos\omega_{Lo} t + \frac{E_n}{2} \cos(\omega_{Lo} - \omega_n)t + \frac{E_n}{2} \cos(\omega_{Lo} + \omega_n)t \right]^2. \tag{8}$$

If this equation is expanded and filtered as in the two previous cases, the output current supplied to the intermediate-frequency load is

$$i_o = Ka_o \frac{E_n E_{Lo}}{2} \cos(\omega_{Lo} - \omega_n)t + a_1 K \left[E_s E_{Lo} \cos(\omega_s - \omega_{Lo})t \right.$$

$$\left. + \frac{E_s E_n}{2} \cos(\omega_s - \omega_{Lo} + \omega_n)t + \frac{E_s E_n}{2} \cos(\omega_s - \omega_{Lo} - \omega_n)t \right] . \qquad (9)$$

It is seen by comparing equations (4), (7) and (9) that when the local-oscillator output contains spurious frequencies in addition to the desired frequency, the output of the single-ended mixer also contains spurious frequencies in addition to the desired intermediate-frequency.

As is generally the case with all mixers, the local-oscillator voltage is much, much greater than either the signal or the accompanying noise voltages. Thus, the largest noise producing terms in equations (7) and (9) are those containing $E_{Lo}E_n\cos(\omega_{Lo} - \omega_n)t$. This is not to say that there are never exceptions when the noise voltage is larger than the local-oscillator voltage; however, in most cases the noise voltage is small compared to the local-oscillator voltage. It may also be noted that equations (7) and (9) contain additional noise terms besides $E_{Lo}E_n\cos(\omega_{Lo} - \omega_n)t$. However, in general these terms are not present in the mixer output unless the noise is a frequency less than BW/2, where BW = Bandwidth of the mixer output circuits. Thus, if the noise frequencies are such that they are separated from the local-oscillator by a frequency equal to the intermediate-frequency, the single-ended mixer contains a large noise output due to the previously mentioned term, $E_{Lo}E_n\cos(\omega_{Lo} - \omega_n)t$. Therefore, if some way could be found to reduce or eliminate this term, the signal-to-noise ratio at the mixer output would be greatly enhanced. It will be shown in the following chapter that the balanced mixer will give such an improvement.

III. ANALYSIS OF THE BALANCED MIXER IN THE PRESENCE OF LOCAL-OSCILLATOR NOISE

In Chapter II it is shown that the output of the single-ended mixer contains a considerable amount of noise when the output of the local-oscillator contains noise sidebands about the desired local-oscillator signal. It is also shown that this noise is greatest when these noise sidebands are separated from the local-oscillator signal by an amount equal to plus or minus the intermediate frequency of the receiver. It will be shown in this chapter that the balanced mixer significantly reduces this noise.

If it is assumed as in Chapter II that the transfer function of the diode used in the mixer can be expressed by

$$i_D = a_o e_{in} + a_1 e_{in}^2$$

then the output current from diode D_1 in Figure 1 is given by

$$\begin{aligned} i_{D_1} = a_o \left[\frac{E_s}{2}\cos\omega_s t + E_{Lo}\cos\omega_{Lo} t\right] + a_1 \Bigg[\frac{E_s^2}{8}\cos 2\omega_s t \\ + \frac{E_s^2}{8} + \frac{E_s E_{Lo}}{2}\cos(\omega_s + \omega_{Lo})t + \frac{E_s E_{Lo}}{2}\cos(\omega_s - \omega_{Lo})t \\ + \frac{E_{Lo}^2}{2}\cos 2\omega_{Lo} t + \frac{E_{Lo}^2}{2}\Bigg] . \end{aligned} \tag{10}$$

In a similar manner the output current from diode D_2 is shown to be

$$i_{D_2} = a_o \left[- \frac{E_s}{2} \cos\omega_s t + E_{Lo}\cos\omega_{Lo} t \right] + a_1 \left[\frac{E_s^2}{8} \cos 2\omega_s t \right.$$

$$+ \frac{E_s^2}{8} - \frac{E_s E_{Lo}}{2} \cos(\omega_s - \omega_{Lo})t - \frac{E_s E_{Lo}}{2} \cos(\omega_s + \omega_{Lo})t \tag{11}$$

$$\left. + \frac{E_{Lo}^2}{2} \cos 2\omega_{Lo} t + \frac{E_{Lo}^2}{2} \right] .$$

From Figure 1 it is seen that the output current presented to the intermediate-frequency load is proportional to the difference between the current from diode D_1 and the current from diode D_2; thus

$i_o = b(i_{D1} - i_{D2})$ where b is a constant of proportionality. (12)

If equations (10) and (11) are substituted into equation (12) the output current seen by the intermediate-frequency load becomes

$$i_o = a_o b(E_s \cos\omega_s t) + a_1 b \left[E_s E_{Lo} \cos(\omega_s - \omega_{Lo})t \right.$$
$$\left. + E_s E_{Lo} \cos(\omega_s + \omega_{Lo})t \right] \tag{13}$$

which after filtering is further reduced to

$$i_o = a_1 b E_s E_{Lo} \cos(\omega_s - \omega_{Lo})t \quad . \tag{14}$$

If, however, it is assumed that there is additive noise accompanying the local-oscillator signal, the output current presented to the intermediate-frequency load is found to be

$$i_o = a_1 b E_s E_{Lo} \cos(\omega_s - \omega_{Lo})t + a_1 b E_s E_n \cos(\omega_s - \omega_n)t \quad . \tag{15}$$

Likewise, for the case where the local-oscillator is modulated by noise, the output current is found to be

$$i_o = a_1 b E_s E_{Lo} \cos(\omega_s - \omega_{Lo})t + a_1 b \frac{E_n E_s}{2} \cos(\omega_s - \omega_{Lo} - \omega_n)t$$
$$+ a_1 b \frac{E_n E_s}{2} \cos(\omega_s - \omega_{Lo} + \omega_n)t \quad . \tag{16}$$

If equations (15) and (16) are compared with equations (7) and (9), it is seen that the balanced mixer output does not contain any term containing $E_n E_{Lo} \cos(\omega_{Lo} - \omega_n)t$ which is shown in the previous chapter to be the major noise producing term. Thus, the balanced mixer significantly reduces the amount of noise present in the mixer output when the local-oscillator output contains noise sidebands, and as a result provides a higher output signal-to-noise ratio compared to the single-ended mixer.

IV. EXPERIMENTAL RESULTS

In order to demonstrate the reduction in mixer noise that is obtained with the balanced mixer, two separate measurement techniques are employed using the mixer circuits shown in Figures 3 and 4. The measurement systems used are shown in the block diagrams of Figures 5 and 6.

In the first technique the signal input to each mixer is a 35 kilocycles per second continuous-wave (C-W) signal. The local-oscillator input is composed of a 50 kilocycles per second C-W signal which is alternately summed with, or modulated by, a simulated noise signal of 63 kilocycles per second which produced a beat signal at 13 kilocycles per second. The frequency of 63 kilocycles per second is chosen so that the beat between the noise and the local-oscillator signal differs slightly from the intermediate frequency of 15 kilocycles per second, thus allowing a comparison to be made. The output from the mixer being tested is observed on a Hewlett-Packard 302A Wave Analyzer at the frequencies determined from equations (7), (9), (15) and (16).

The amplitude of the simulated noise is varied from a value near the amplitude of the input signal to a value near the amplitude of the local-oscillator signal. This is done to show the response of both the single-ended and the balanced mixer to various noise levels.

In all cases the input signal is held constant at 30 millivolts while the local-oscillator signal is held constant at 3 volts.

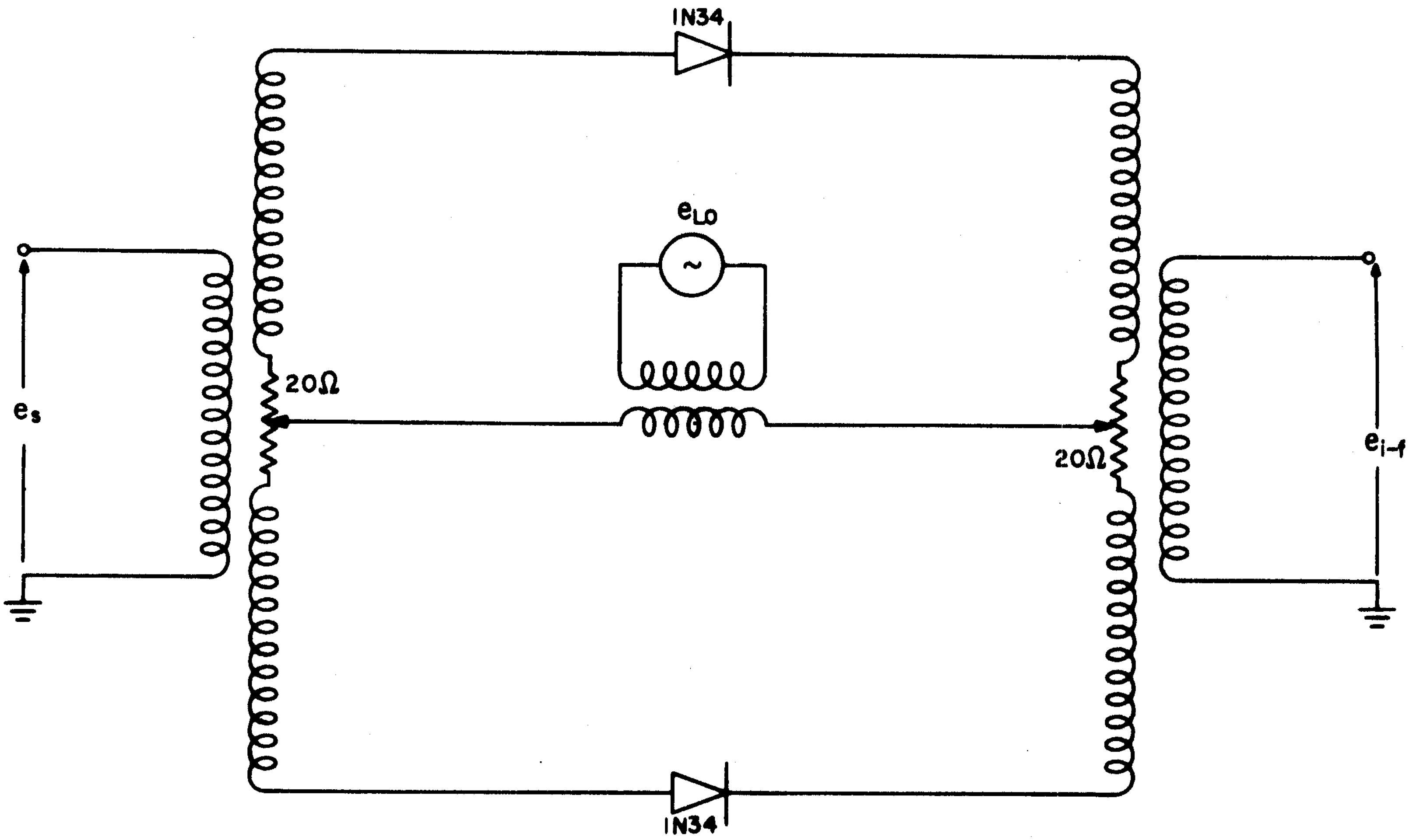

FIGURE 3 . CIRCUIT DIAGRAM OF THE BALANCED MIXER

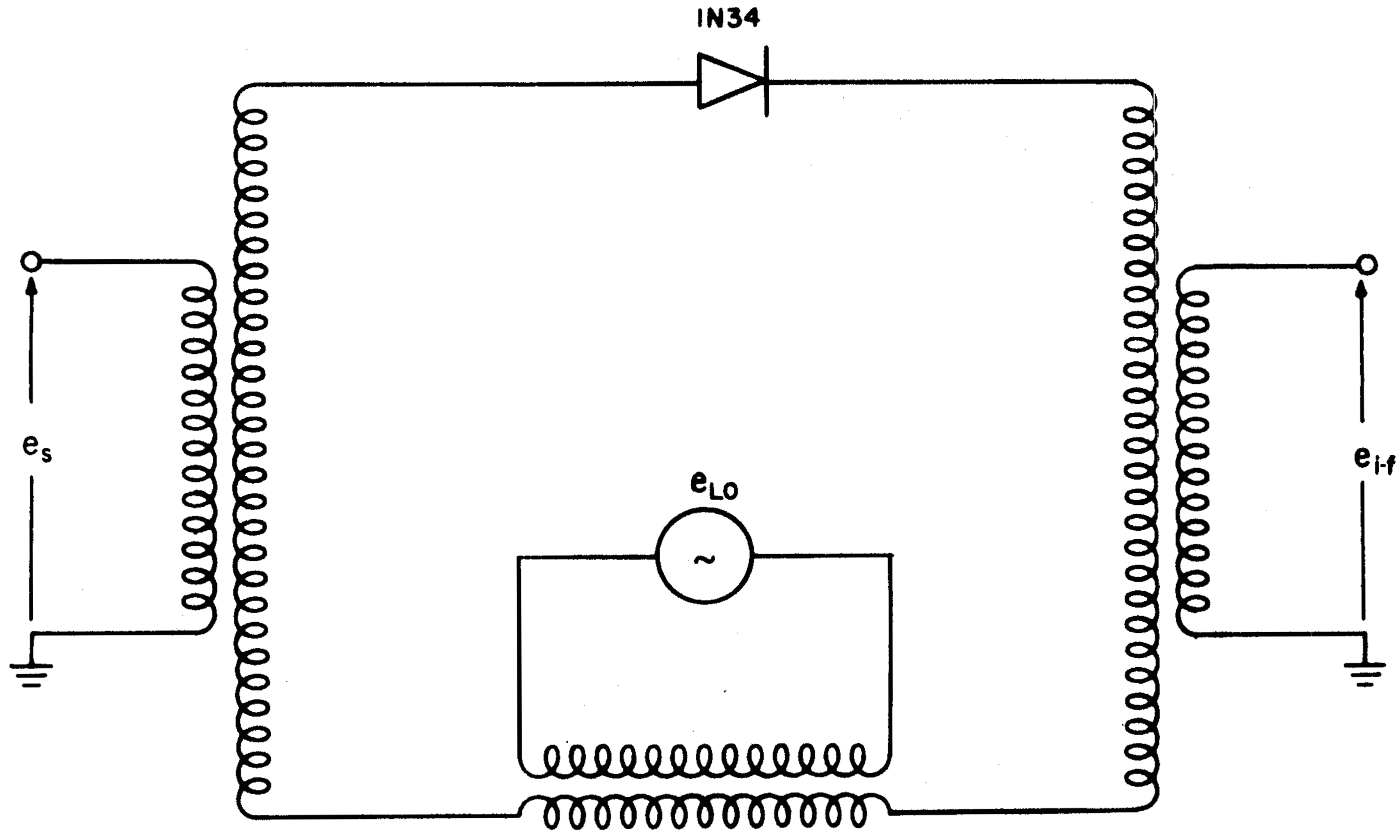

FIGURE 4. CIRCUIT DIAGRAM OF THE SINGLE-ENDED MIXER

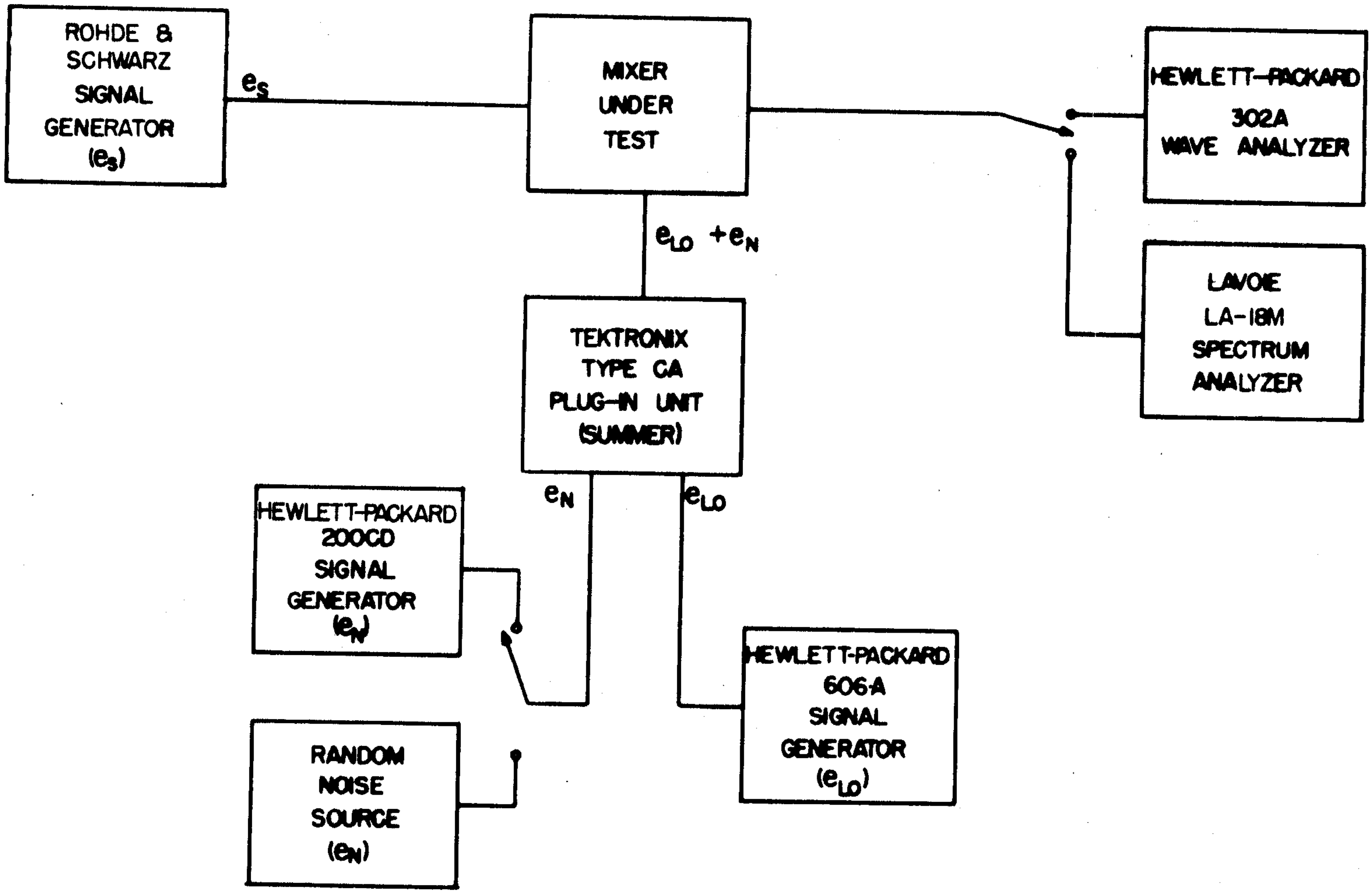

FIGURE 5 . BLOCK DIAGRAM OF MEASUREMENT SYSTEM USED WHEN NOISE IS ADDED TO LOCAL OSCILLATOR SIGNAL

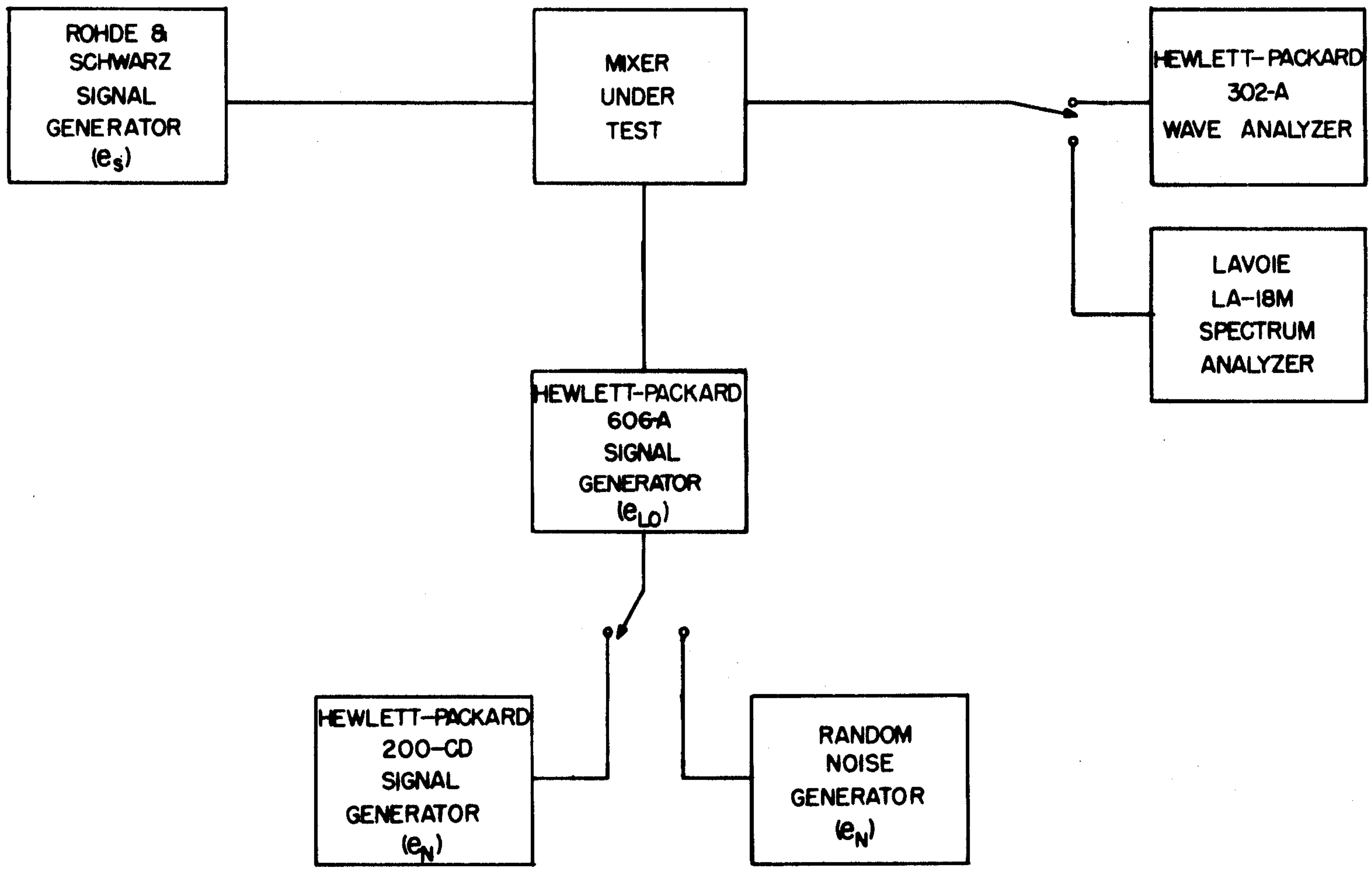

FIGURE 6 . BLOCK DIAGRAM OF MEASUREMENT SYSTEM USED WHEN LOCAL OSCILLATOR SIGNAL IS MODULATED BY NOISE

The data obtained from these measurements are shown in Tables I and II. These data are also plotted in Appendices A and B. The measured output voltages are all normalized to the output voltage at the intermediate-frequency in order that a valid comparison can be made between the outputs of the single-ended and balanced mixers. It is seen for each noise level that the balanced mixer gives a significant reduction in the noise output at 13 kilocycles per second compared to the single-ended mixer. It is also seen that the noise output at the other frequencies indicated in equations (7), (9), (15) and (16) are in each case small compared to the other signals present in the output.

It was also desired to show the reduction in mixer noise when the noise signal consists of band-limited random noise centered about a frequency displaced from the local-oscillator signal by the intermediate-frequency. However, the output reading on the wave analyzer voltmeter fluctuated quite rapidly making it difficult to obtain a valid reading. Thus, a second technique is employed in which the input to the mixer consists of a 65 Megacycle per second C-W signal while the local-oscillator signal is composed of a 35 Megacycle per second C-W signal summed with and modulated by band-limited random noise centered about 5 Megacycle per second. The output spectrum is observed on a Lavoie 18M Spectrum Analyzer.

The results obtained using this technique are shown in Figures 7 through 10. It is seen again that the balanced mixer gives a significant reduction in the amount of noise present in the mixer output.

TABLE I

MIXER OUTPUT VS. FREQUENCY WITH NOISE ADDED TO THE LOCAL-OSCILLATOR SIGNAL

SINGLE-ENDED MIXER					
Magnitude of Added Noise, E_n	50 mv	100 mv	0.5 v	1.0 v	2.0 v
E_{out} @ 28 kc	---	---	68 uv	105 uv	180 uv
E_{out} @ 15 kc	1.0 mv	1.05 mv	1.0 mv	1.0 mv	1.2 mv
E_{out} @ 13 kc	1.0 mv	2.2 mv	10 mv	20 mv	62 mv
BALANCED MIXER					
Magnitude of Added Noise, E_n	50 mv	100 mv	0.5 v	1.0 v	2.0 v
E_{out} @ 28 kc	72 uv	140 uv	0.72 mv	1.45 mv	4.0 mv
E_{out} @ 15 kc	7.9 mv	7.9 mv	7.9 mv	7.4 mv	5.6 mv
E_{out} @ 13 kc	56 uv	112 uv	0.53 mv	1.15 mv	6.8 mv

NOTE: E_s = 30 mv and, E_{Lo} = 3.0 v for all measurements.

TABLE II

MIXER OUTPUT VS. FREQUENCY WITH THE LOCAL-OSCILLATOR SIGNAL MODULATED BY NOISE

SINGLE-ENDED MIXER					
Magnitude of Modulating Noise, E_n	60 mv	0.5 v	1.0 v	3.0 v	> 3.0 v
E_{out} @ 15 kc	1.75 mv	1.8 mv	1.85 mv	1.7 mv	1.8 mv
E_{out} @ 13 kc	110 uv	265 uv	1.7 mv	4.6 mv	6.7 mv
BALANCED MIXER					
Magnitude of Modulating Noise, E_n	60 mv	0.5 v	1.0 v	3.0 v	> 3.0 v
E_{out} @ 15 kc	8.7 mv	8.7 mv	8.8 mv	8.7 mv	8.7 mv
E_{out} @ 13 kc	13 uv	34 uv	215 uv	0.6 mv	0.89 mv

NOTE: E_s = 30 mv and, E_{Lo} = 3.0 v for all measurements.

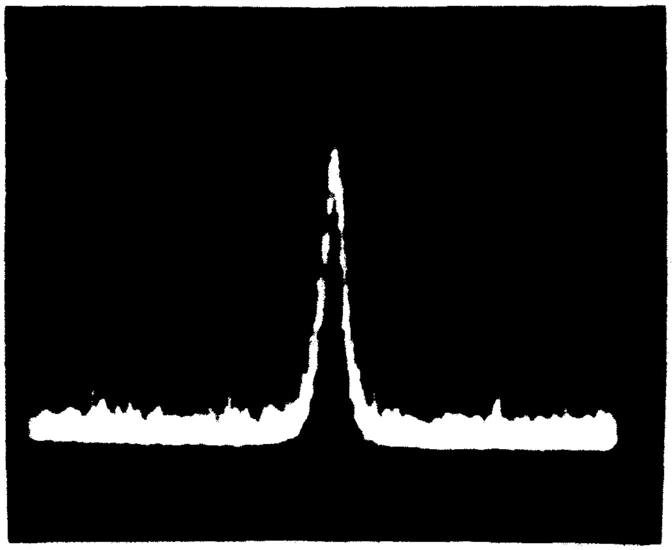

FIGURE 7. OUTPUT FROM THE SINGLE-ENDED MIXER WITH RANDOM NOISE ADDED TO THE LOCAL-OSCILLATOR SIGNAL

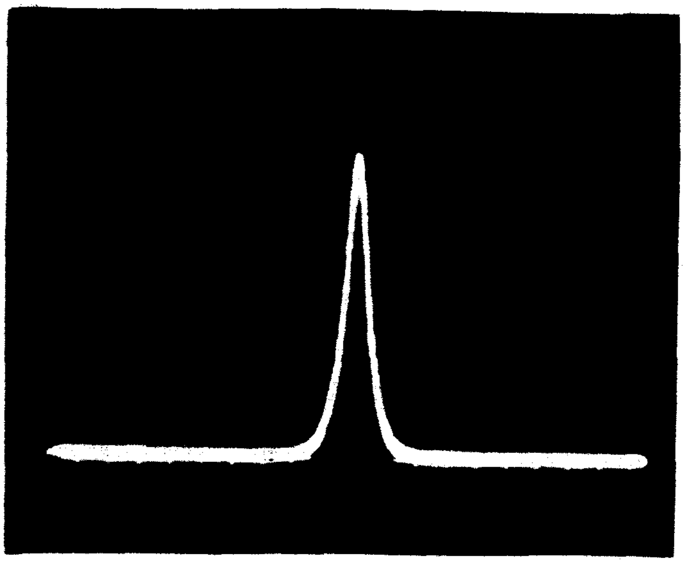

FIGURE 8. OUTPUT FROM THE BALANCED MIXER WITH RANDOM NOISE ADDED TO THE LOCAL-OSCILLATOR SIGNAL

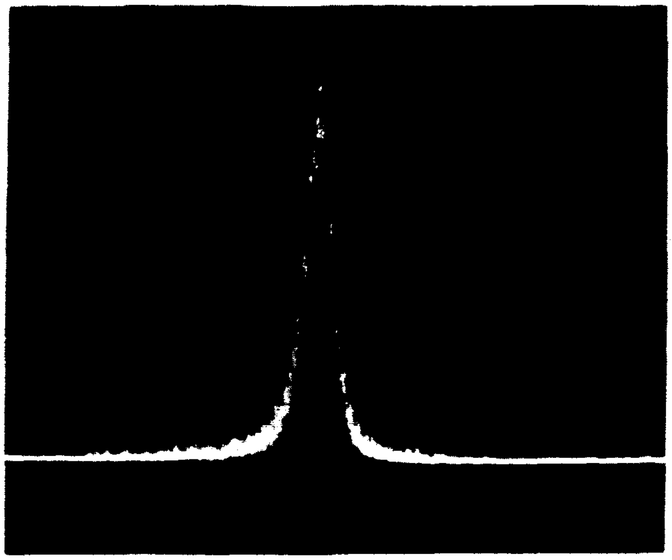

FIGURE 9. OUTPUT FROM SINGLE-ENDED MIXER WITH LOCAL-OSCILLATOR SIGNAL MODULATED BY RANDOM NOISE

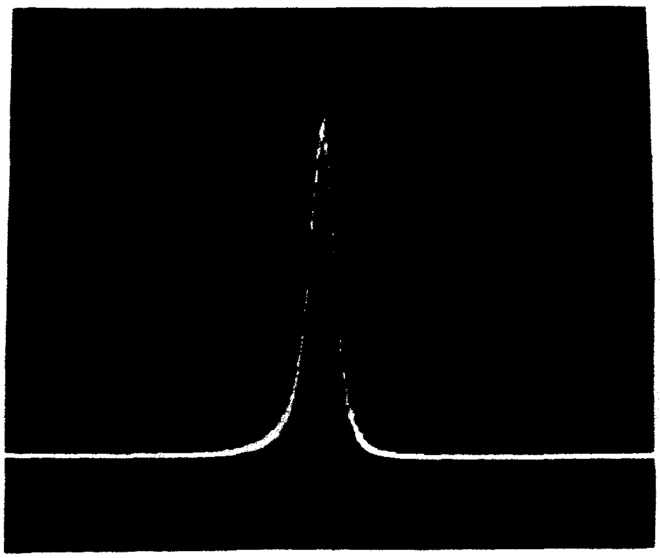

FIGURE 10. OUTPUT FROM BALANCED MIXER WITH LOCAL-OSCILLATOR SIGNAL MODULATED BY RANDOM NOISE

V. CONCLUSION

It is shown in Chapter III that in theory the balanced mixer eliminates those terms containing $E_n E_{Lo} \cos(\omega_{Lo} - \omega_n)t$ from the mixer output. It is also shown that these terms are the major noise producing terms when the frequency of the noise accompanying the local-oscillator is such that it is separated from the local-oscillator signal by an amount equal to the intermediate frequency. Experimentally it is shown in the data of Figures 7 through 10 and A1 through B10 that in reality these terms are not completely eliminated as was predicted, but are instead reduced to a relatively low value in most cases when compared to the desired intermediate frequency. This is due to the fact that even though matched diodes are used in the mixers slight unbalances still exist in the other circuitry. However, small unbalances will not seriously affect the mixer performance since the noise is still reduced to a relatively insignificant level as seen from the plotted data.

Thus, it is shown both analytically and experimentally that the balanced mixer provides a significant reduction in local-oscillator noise compared to the single-ended mixer for the two cases studied: namely, for the case where the local-oscillator signal is modulated by noise and the case where noise is added to the local-oscillator signal.

The mixers used in this study are diode mixers and the analytical work is therefore based on the use of diode mixers. However, using techniques similar to the ones presented here it can be shown that in general the overall results of this study will apply to any balanced mixer configuration (i.e., triodes, pentodes, etc.).

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APPENDIX A

NORMALIZED OUTPUT VS. FREQUENCY CURVES FOR CASE WHERE SIMULATED 63 KILOCYCLES PER SECOND NOISE IS ADDED TO LOCAL-OSCILLATOR SIGNAL

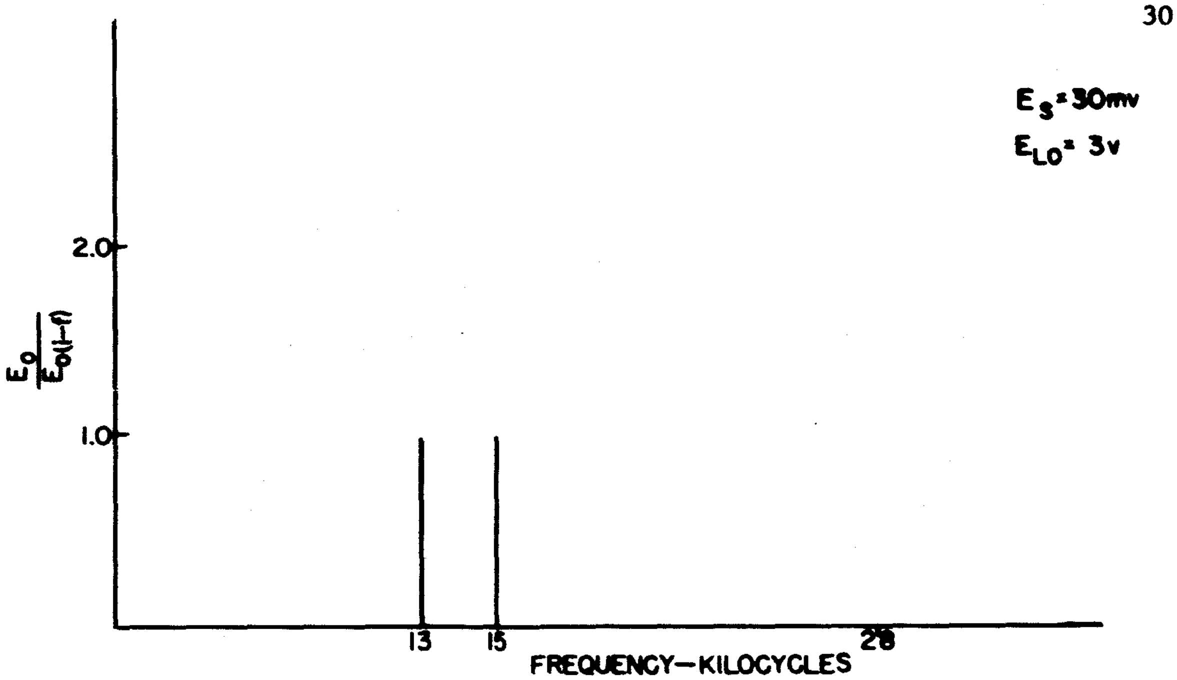

FIGURE A1. OUTPUT FROM SINGLE-ENDED MIXER WITH E_N =50 millivolts
(E_N ADDED TO LOCAL-OSCILLATOR SIGNAL)

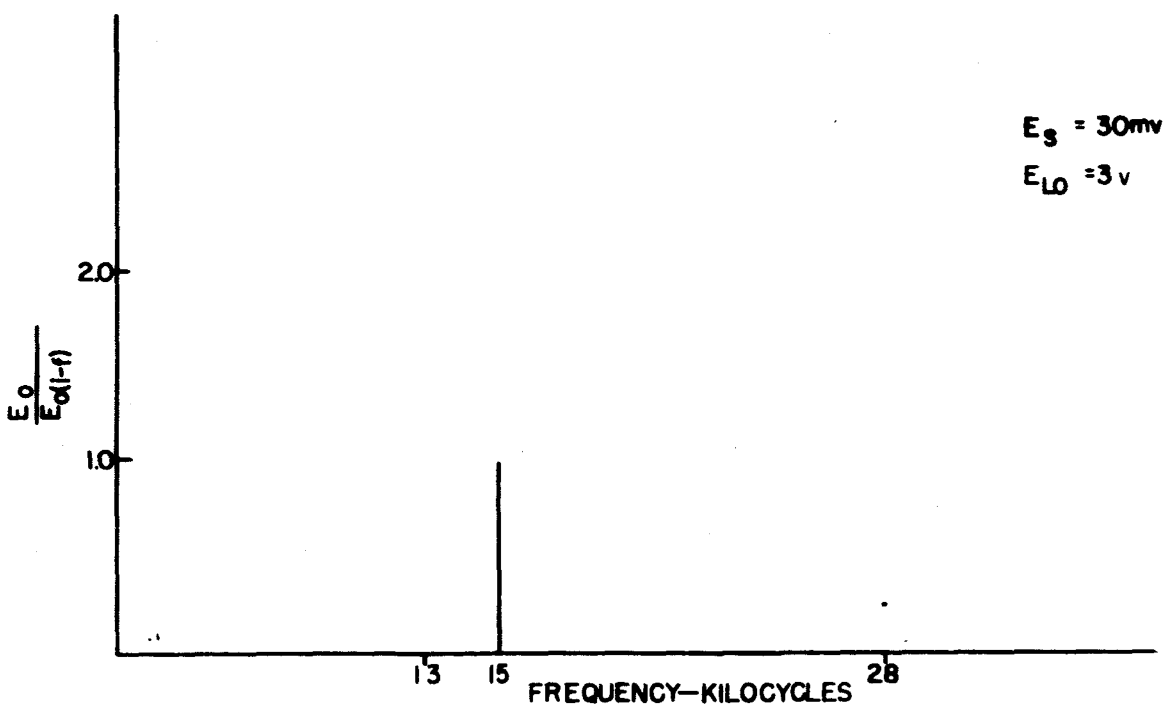

FIGURE A2. OUTPUT FROM BALANCED MIXER WITH E_N = 50 millivolts
(E_N ADDED TO LOCAL-OSCILLATOR SIGNAL)

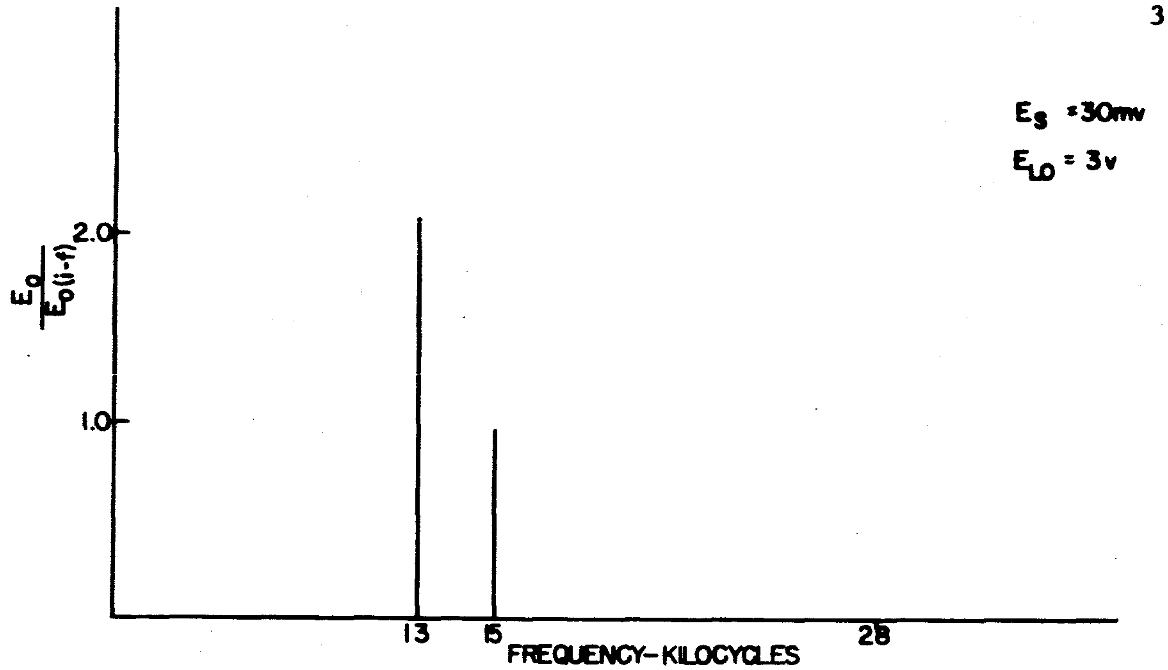

FIGURE A3. OUTPUT FROM SINGLE-ENDED MIXER WITH E_N=100 millivolts (E_N ADDED TO LOCAL-- OSCILLATOR OUTPUT)

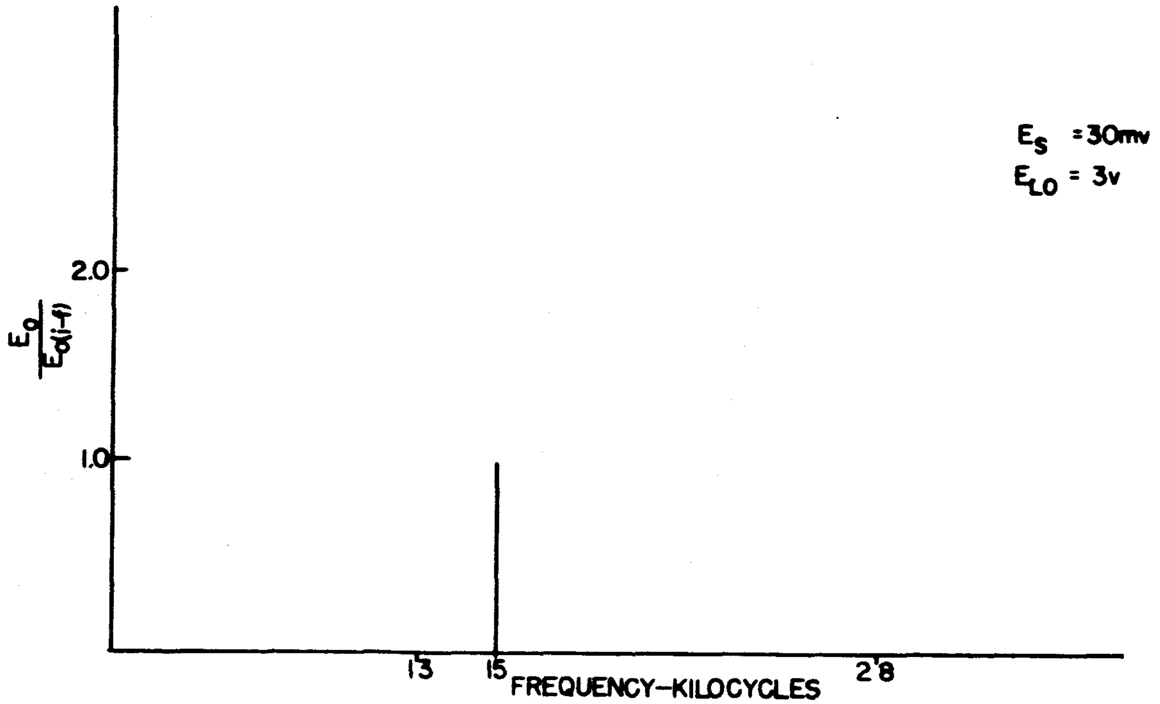

FIGURE A4. OUTPUT FROM BALANCED MIXER WITH E_N =100millivolts (E_N ADDED TO LOCAL OSCILLATOR OUTPUT)

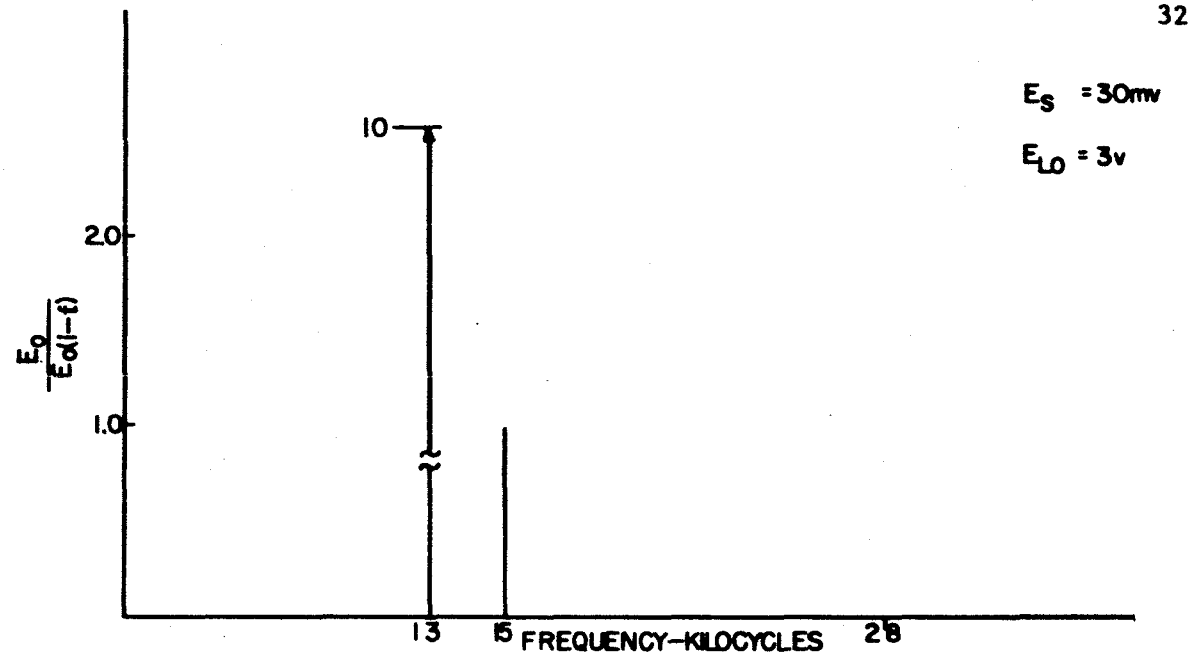

FIGURE A5. OUTPUT FROM SINGLE-ENDED MIXER WITH E = 0.5volts
(E_N ADDED TO LOCAL-OSCILLATOR OUTPUT)

FIGURE A6. OUTPUT FROM BALANCED MIXER WITH E_N = 0.5 volts
(E_N ADDED TO LOCAL-OSCILLATOR OUTPUT)

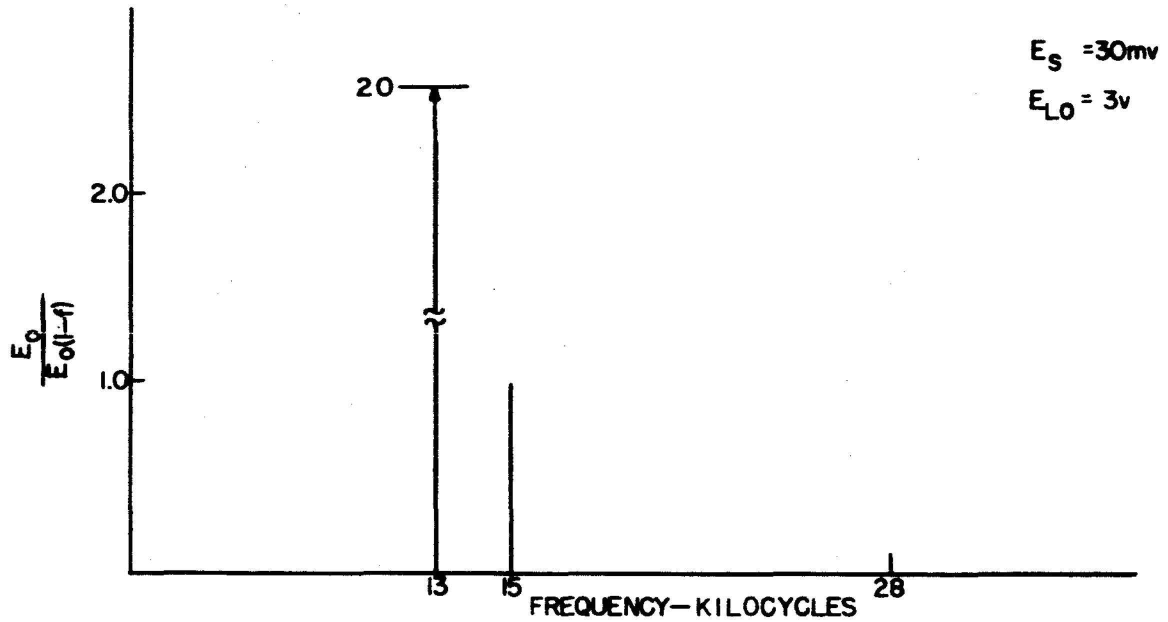

FIGURE A7. OUTPUT FROM SINGLE-ENDED MIXER WITH E_N = 1.0volt (E_N ADDED TO LOCAL OSCILLATOR OUTPUT)

FIGURE A8. OUTPUT FROM BALANCED MIXER WITH E_N =1.0volt (E_N ADDED TO LOCAL OSCILLATOR OUTPUT)

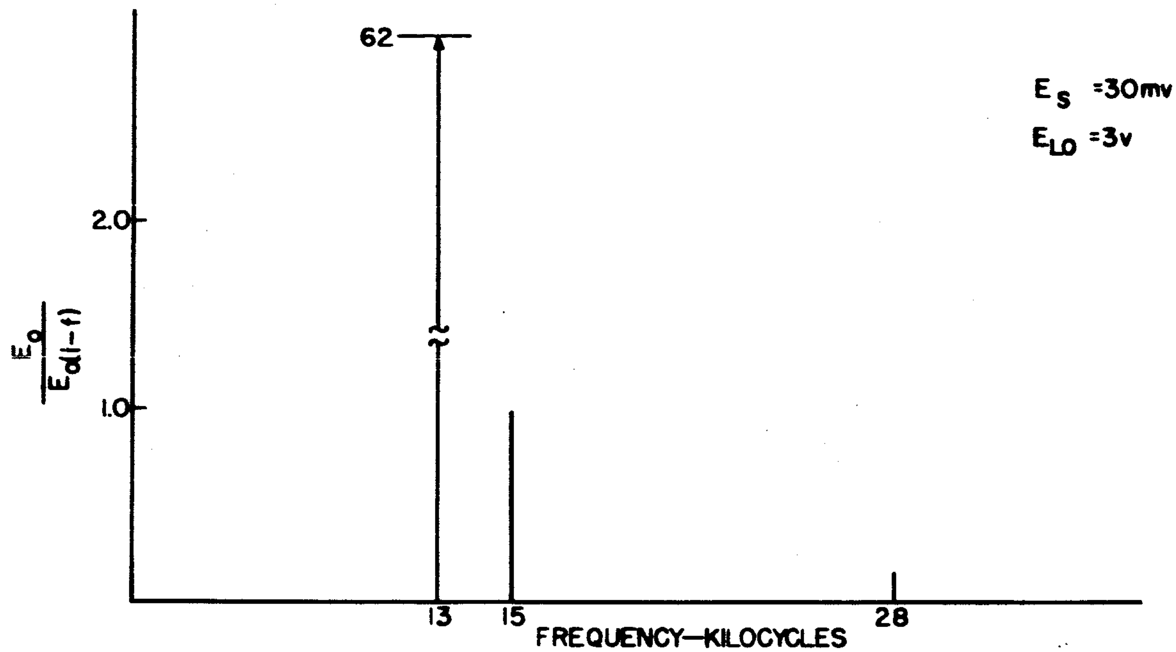

FIGURE A9. OUTPUT FROM SINGLE-ENDED MIXER WITH E_N=2.0volts
(E_N ADDED TO LOCAL-OSCILLATOR OUTPUT)

FIGURE A10. OUTPUT FROM BALANCED MIXER WITH E_N=2.0 volts
(E_N ADDED TO LOCAL-OSCILLATOR OUTPUT)

APPENDIX B

NORMALIZED OUTPUT VS. FREQUENCY CURVES FOR CASE WHERE SIMULATED 63 KILOCYCLES PER SECOND NOISE MODULATES LOCAL-OSCILLATOR SIGNAL

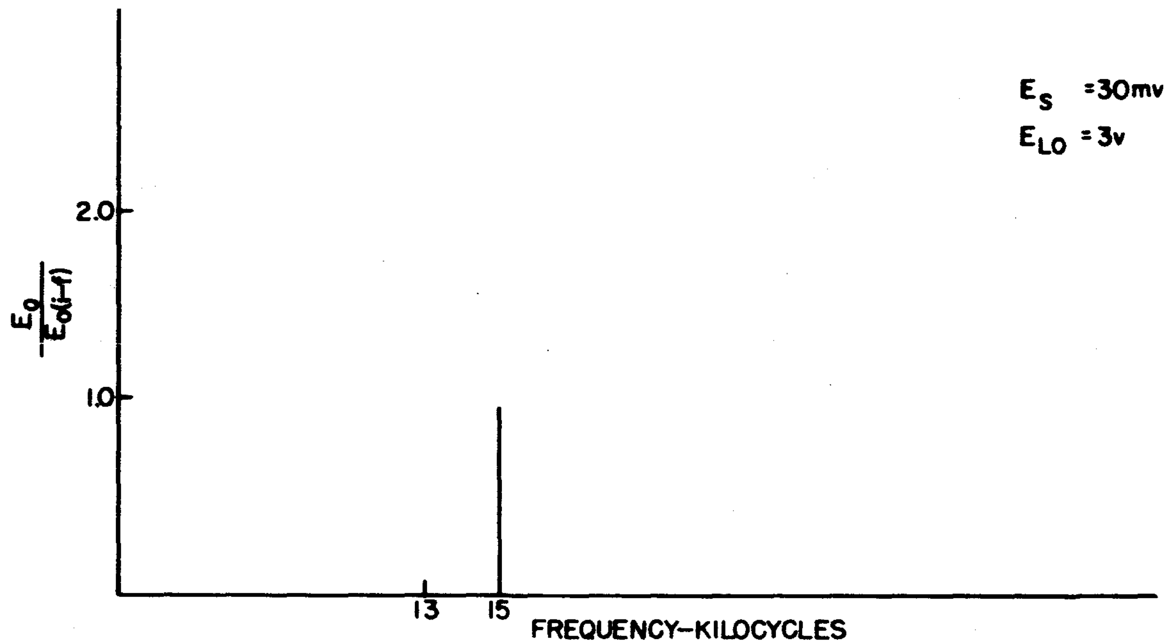

FIGURE B1. OUTPUT FROM SINGLE-ENDED MIXER WITH E_N =60millivolts (LOCAL OSCILLATOR MODULATED LESS THAN 5% BY E_N)

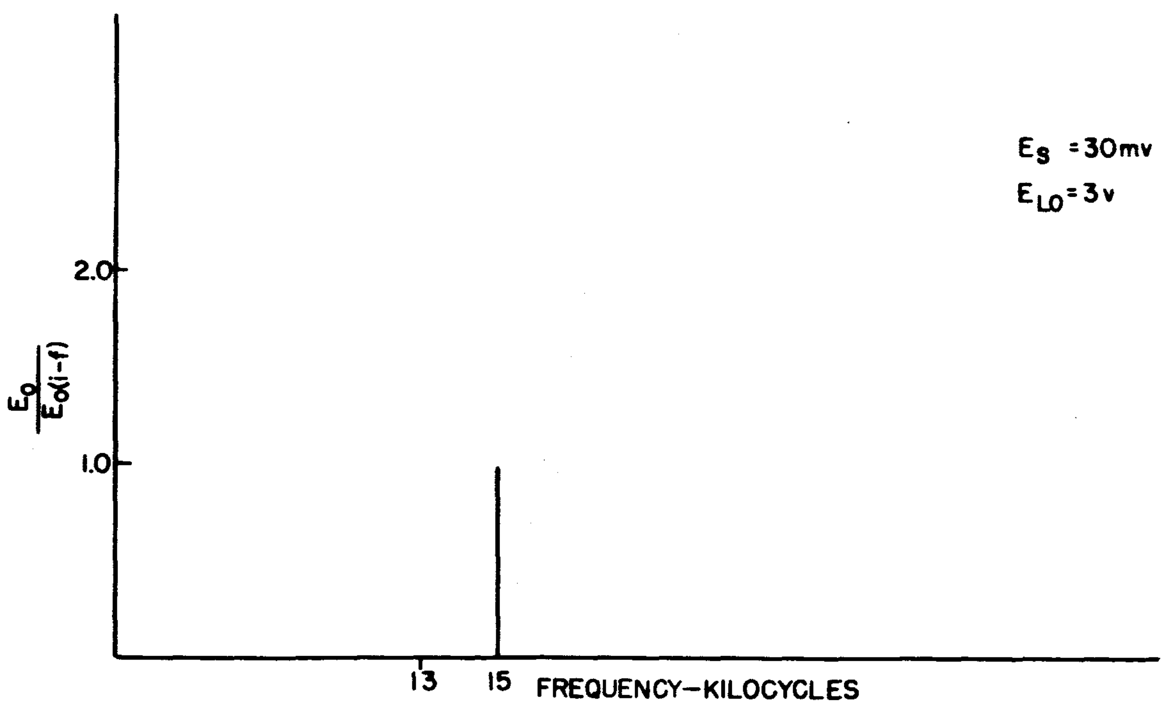

FIGURE B2. OUTPUT FROM BALANCED MIXER WITH E_N =60millivolts (LOCAL OSCILLATOR MODULATED LESS THAN 5% BY E_N)

FIGURE B3. OUTPUT FROM SINGLE-ENDED MIXER WITH E_N = 0.5 volts (LOCAL OSCILLATOR MODULATED 10% BY E_N)

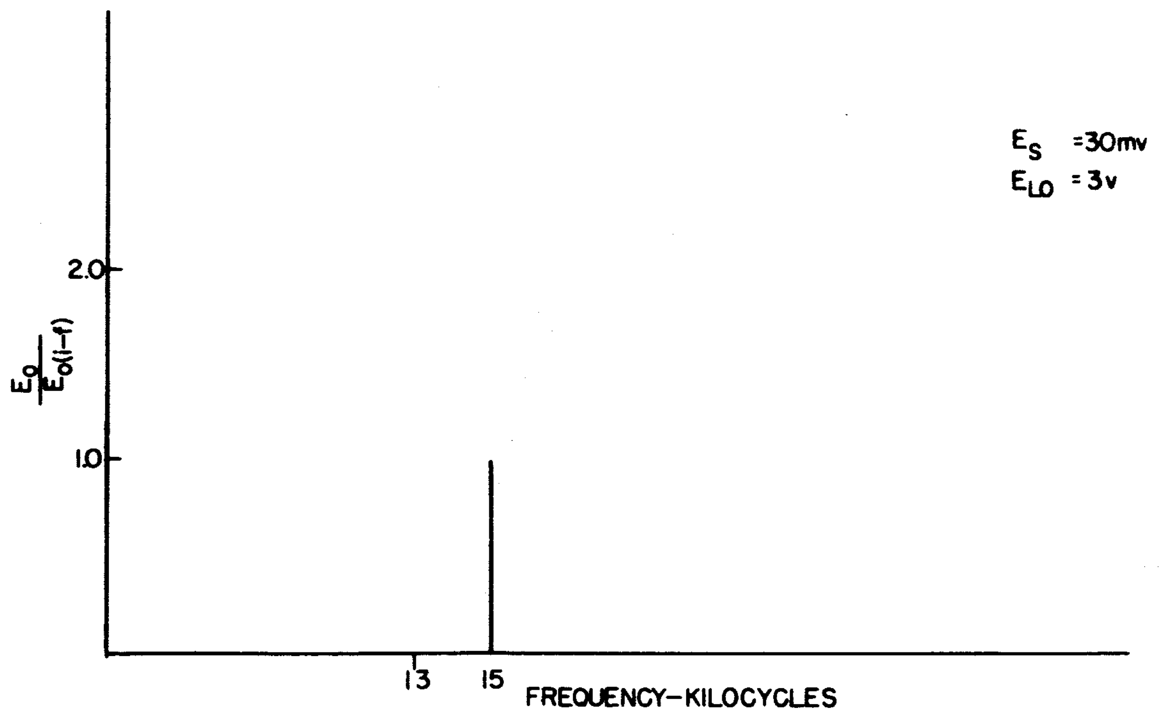

FIGURE B4. OUTPUT FROM BALANCED MIXER WITH E_N = 0.5 volts (LOCAL OSCILLATOR MODULATED 10% BY E_N)

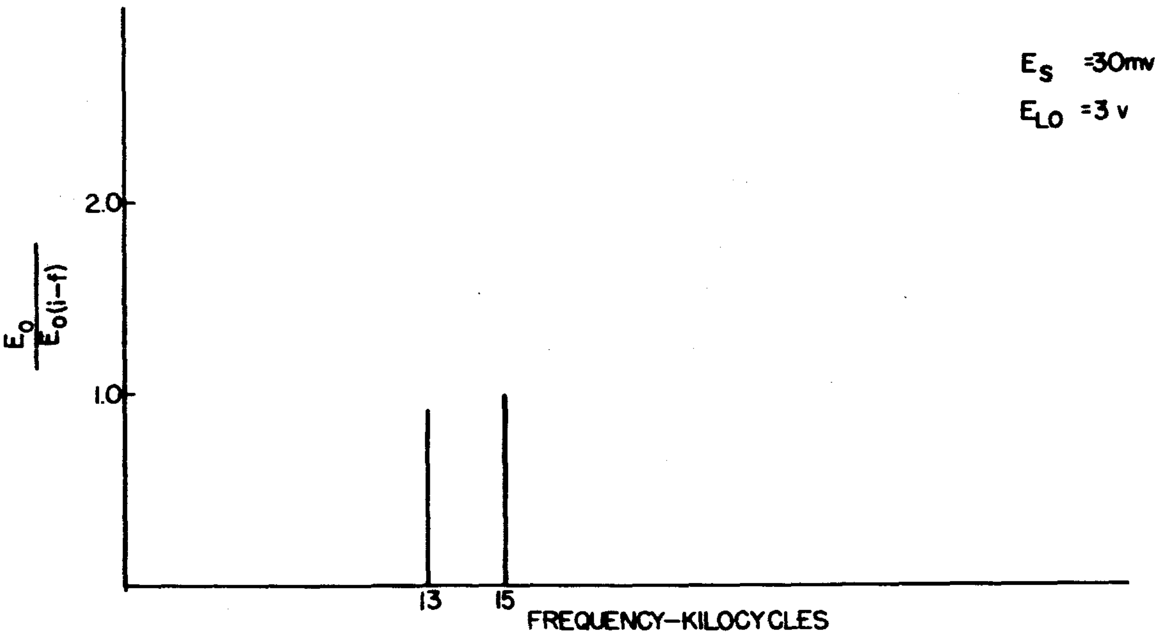

FIGURE B5. OUTPUT FROM SINGLE-ENDED MIXER WITH E_N=1.0 volt
(LOCAL OSCILLATOR MODULATED 20% BY E_N)

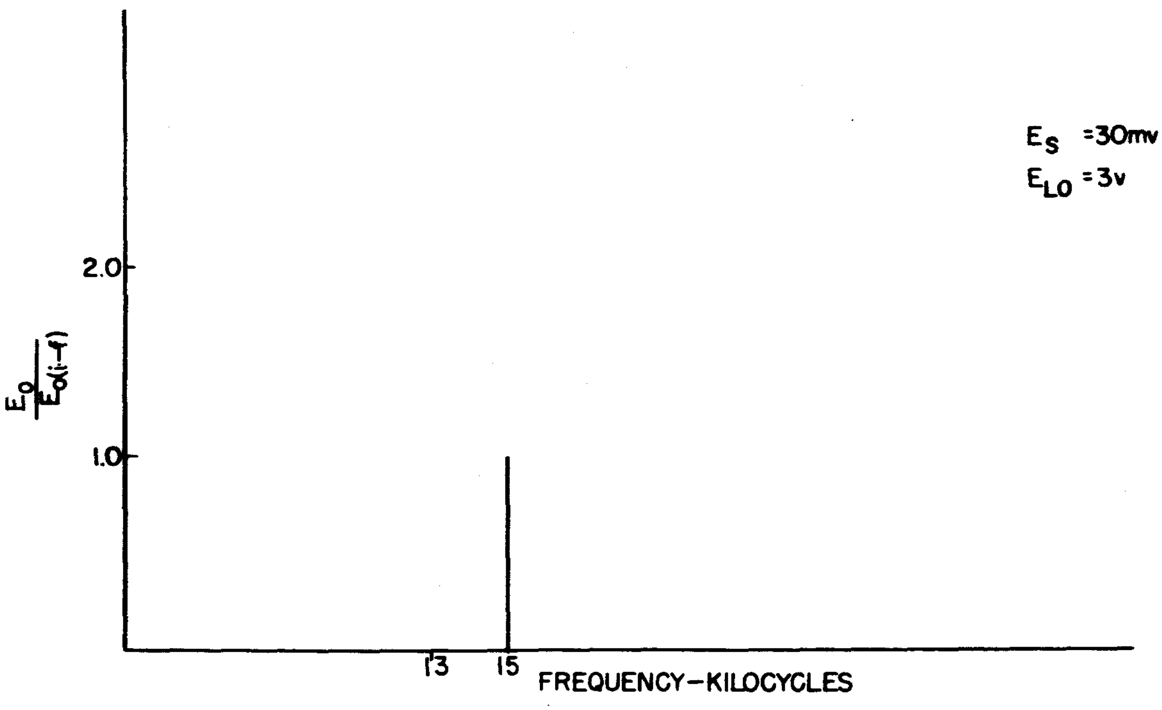

FIGURE B6. OUTPUT FROM BALANCED MIXER WITH E_N=1.0volt
(LOCAL OSCILLATOR MODULATED 20% BY E_N)

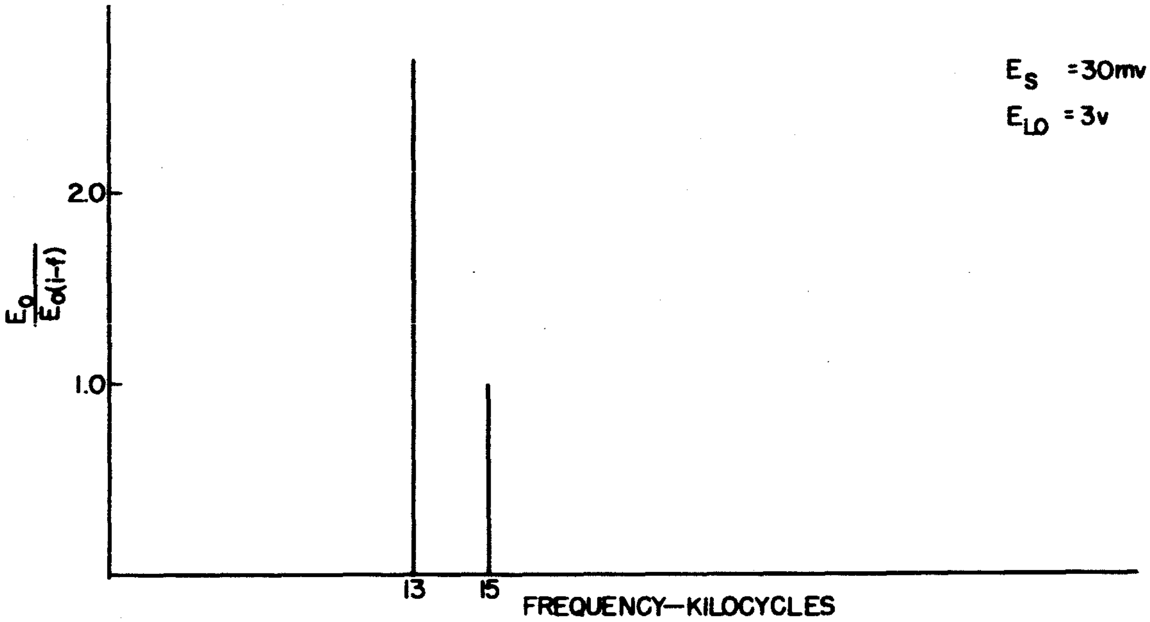

FIGURE B7. OUTPUT FROM SINGLE-ENDED MIXER WITH E_N=3.0 volts (LOCAL OSCILLATOR MODULATED 60% BY E_N)

FIGURE B8. OUTPUT FROM BALANCED MIXER WITH E_N=3.0 volts (LOCAL OSCILLATOR MODULATED 60% BY E_N)

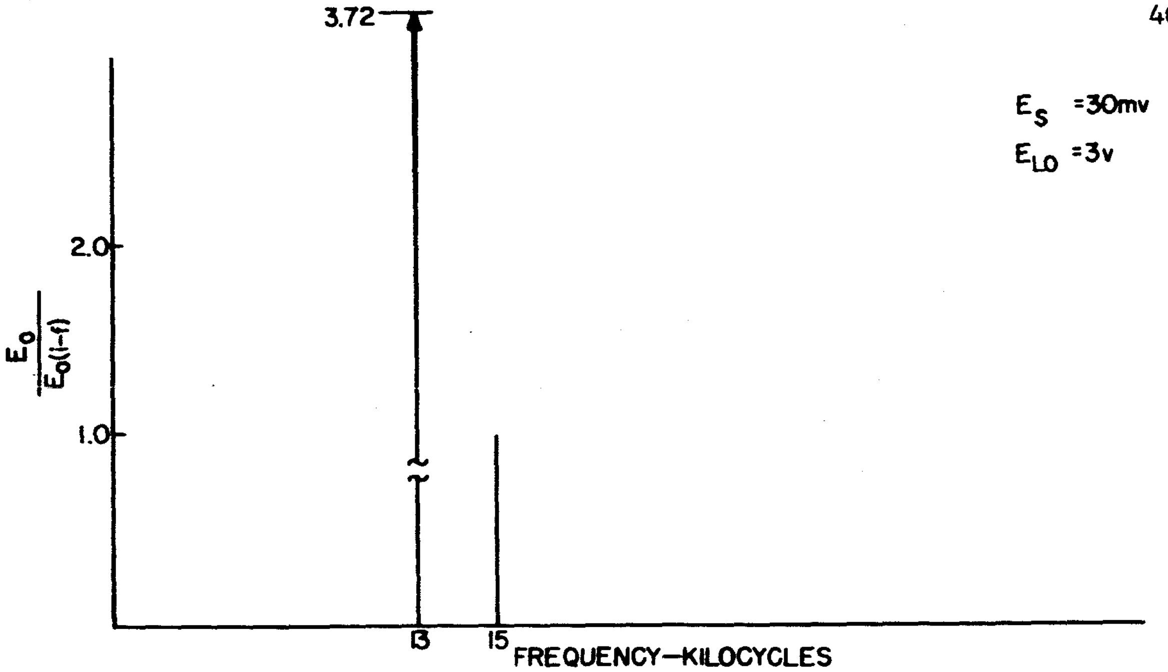

FIGURE B9. OUTPUT FROM SINGLE-ENDED MIXER WITH E_N=5.3 volts (LOCAL OSCILLATOR MODULATED 100% BY E_N)

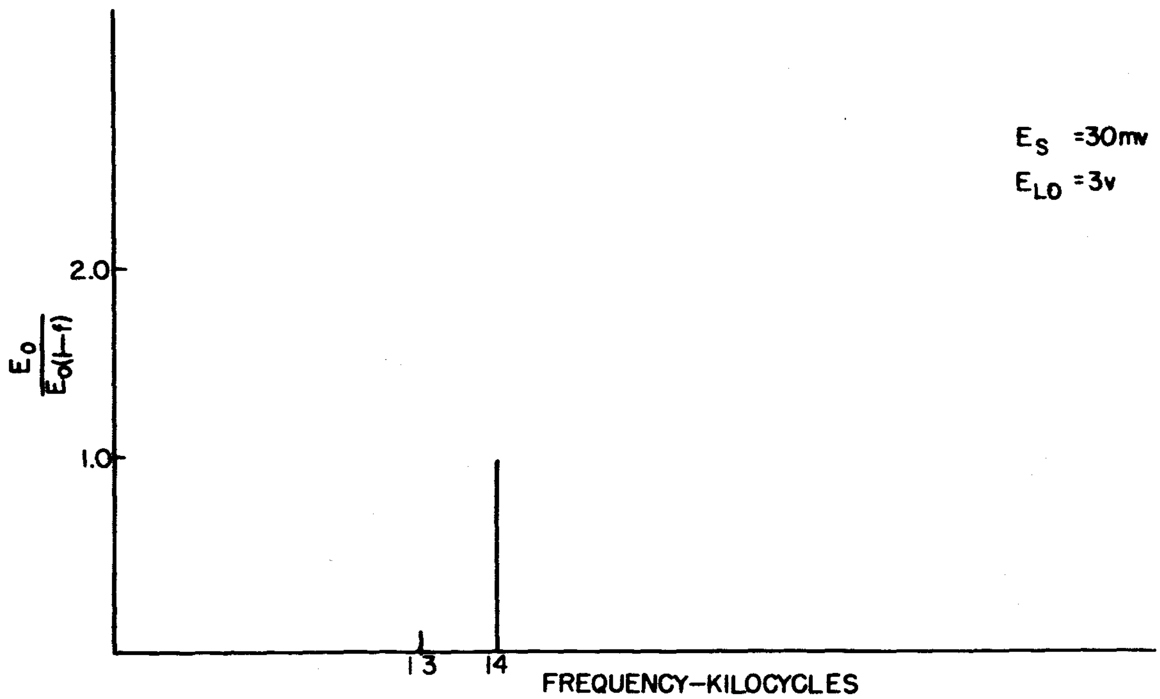

FIGURE B10. OUTPUT FROM BALANCED MIXER WITH E_N=5.3 volts (LOCAL OSCILLATOR MODULATED 100% BY E_N)