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INTEGRATED CIRCUITS SYNCHRODYNE RECEIVER RESEARCH

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FM Receivers

The design of an integrated circuit FM receiver has been accomplished by Camenzind and Grebene of Signetics Corporation. Their technique^[1,2] uses a phase-locked loop to demodulate the FM signal. The circuit replaces the i.f. amplifier and demodulator used in FM receivers. Performance of the circuit is claimed to be equal to that of a high quality commercial FM tuner. The front end of an FM receiver is the only section that has not yet been incorporated into an integrated circuit form. That is, there is not yet a way of eliminating the tuned circuits (inductor) of the front end. Nonetheless, the FM integrated circuit receiver problem has been pretty much solved.

AM Receivers

Amperex is marketing a single integrated circuit package that contains all the active components of a complete AM radio. The TAD100 integrated circuit has performance similar to that of a quality AM receiver made from discrete components. The disadvantage of the circuit is that the non-integrable expensive items, tuned-circuits, are still required for the receiver. The ultimate AM receiver goal is to do away with these elements.

Synchrodyne

The Synchrodyne approach to AM receivers represents an attempt to eliminate at least the i.f. transformers of a conventional AM receiver. This would leave only the front end remaining to be integrated in some form.

Simulation Phase

Although the original grant proposal included simulating proposed receiver systems on a hybrid computer, this phase of the project was

partially by-passed since sufficient information was found in the literature (see References). If, in the future, one wished to use computational techniques to assist in optimizing a particular design (e.g., with regard to noise rejection, pulling behavior, etc.), then certainly hybrid simulation studies could prove useful. A 10 KHz phase-lock loop was set up on the Locust high-speed hybrid computer to prove the feasibility of simulating with carrier frequencies this high; the simulation was found to work quite well.

From our review of the literature several conclusions may be drawn, including the following:

1. Phase-lock loops drive the local oscillator to match the frequency of the incoming signal but to have a 90-degree phase difference with respect to the incoming signal. Consequently, a second product demodulator operating from the output of the loop shifted 90 degrees is required to perform the actual demodulation of the AM information in the incoming signal.

2. For the application considered here, the loop filter transfer function can be simply a first-order low-pass filter that blocks the high-frequency cross products at the output of the product detector and provides the required low-frequency gain. This is because we wish primarily to achieve frequency lock, but can tolerate a small steady-state phase error.

3. Injection-locked oscillators have the same capability to acquire and track a carrier as a phase-lock loop^[8,9]; however, they provide a local carrier that is in phase with the incoming carrier. This fact makes the use of injection-locked oscillators attractive.

Synchrodyne Circuits

Several types of synchrodyne circuits were designed and built. Each offered its own advantages and disadvantages. A description of each type follows.

Crystal Filter Synchrodyne

A method that was first tried is that shown in Fig. 1. The carrier is selected out by a crystal filter and then sent to a multiplier. Here the product of the signal and carrier yields several components. The desired audio signal is obtained by passing the multiplier's signal through a low pass filter.

While this scheme can give satisfactory results, it has drawbacks. The crystal requires very close tolerances if it is to select the incoming carrier. This presents an economic problem since accurately ground crystals are relatively expensive. Not only does the resonant frequency need to be precise, but the Q of the crystal must be very high or else low frequency audio signals can cause interference. This is evident from the mathematical considerations of the signal processing.

Notice that some form of front end tuning is still required. Otherwise, a strong interfering signal would pass through the preamp and saturate it (or the multiplier). The AVC (Automatic Volume Control) would not cut down the preamp's gain since AVC level is a function only of the desired signal of frequency f_0 .

Math Analysis of Crystal Filter Synchrodyne

Assume that the input signal $x_1(t)$ is of the following form

$$x_1(t) = \left[1 + \sum_{i=1}^N a_i \cos \omega_i t \right] \cos \omega_c t \quad (1)$$

where ω_c is the carrier frequency, and ω_i is the frequency of the modulating signal of amplitude a_i ($a_i = 1$, maximum). Eq. (1) can be rewritten as

$$x_1(t) = \cos \omega_c t + \sum_{i=1}^N \frac{a_i}{2} [\cos(\omega_c + \omega_i)t + \cos(\omega_c - \omega_i)t]. \quad (2)$$

Because the crystal is not perfect, it passes each frequency but with a reduction factor of β_i . Ideally, β_i would be zero, but in reality, it is a function of frequency. Thus, the signal that reaches the multiplier is

$$x_2(t) = \cos \omega_c t + \sum_{i=1}^N \frac{a_i}{2} [\beta_i \cos(\omega_c + \omega_i)t + \beta'_i \cos(\omega_c - \omega_i)t]. \quad (3)$$

This assumes that the crystal filter is tuned to the carrier frequency ω_c , and that the carrier passes through the crystal filter unattenuated. If the crystal filter has a symmetric frequency response about the frequency ω_c , then the attenuation factors β_i and β'_i are equal. The output signal from the multiplier is

$$\begin{aligned} x_1(t)x_2(t) &= \cos^2 \omega_c t \left(1 + \sum_{i=1}^N a_i \cos \omega_i t \right) \\ &+ \sum_{i=1}^N \frac{a_i \beta_i}{4} [\cos(2\omega_c + \omega_i)t + \cos \omega_i t] + \frac{a_i \beta'_i}{4} [\cos(2\omega_c - \omega_i)t + \cos \omega_i t] \\ &+ \sum_{i=1}^N \sum_{j=1}^N \frac{a_i a_j}{4} \left\{ \frac{\beta_j + \beta'_j}{2} [\cos(2\omega_c + \omega_j + \omega_i)t + \cos(2\omega_c + \omega_j - \omega_i)t \right. \\ &\left. + \cos(\omega_j - \omega_i)t + \cos(\omega_j + \omega_i)t] \right\}. \quad (4) \end{aligned}$$

The high frequency components are removed by the low pass filter, and a blocking capacitor removes d.c. components. This results in an output signal

$$\begin{aligned}
 x_o(t) = & \frac{1}{2} \sum_{i=1}^N a_i \cos \omega_i t + \sum_{i=1}^N a_i \left(\frac{\beta_i + \beta'_i}{8} \right) \cos \omega_i t + \sum_{i=1}^N \frac{a_i^2}{8} (\beta_i + \beta'_i) \cos 2\omega_i t \\
 & + \sum_{i=1}^N \sum_{\substack{j=1 \\ j \neq i}}^N \frac{a_i a_j}{8} (\beta_i + \beta'_j) [\cos(\omega_i + \omega_j)t + \cos(\omega_i - \omega_j)t]
 \end{aligned}
 \tag{5}$$

The first term of Eq. (5) represents the original modulating signal. The second term represents a nonlinear distortion due to the fact that the β_i 's vary with frequency. The third term represents harmonic distortion while the fourth term represents intermodulation distortion. It is immediately obvious from Eq. (5) that all the distortion terms disappear if the β_i 's are all zero. This would be the case with a crystal of infinite Q.

Standard Synchrony Approach

A way of overcoming the crystal limitations is by replacing the crystal with a local oscillator tuned to the desired frequency f_o .

If the oscillator is synchronized with the incoming signal (see Fig. 2), it will be phase locked. The advantages of the oscillator scheme is that its output frequency is pure (i.e., does not contain the modulation signal). But this is only true when the synchronizing signal is small in amplitude. If it is too strong, the sync signal will overpower the

oscillator's feedback input and the unit will begin to act like a bandpass filter, and that is not what is wanted. If the sync signal is sufficiently weak, the oscillator will effectively lock into the signal's strongest component, i.e., the carrier. For weak input signals the output amplitude of the oscillator is virtually constant and independent of the input signal strength. If this is the case, intermodulation and harmonic distortion are low.

A circuit that was built to simulate the block diagram of Fig. 2 is shown in Fig. 3. AVC was not incorporated in the design, though. The receiver had a tuned input stage consisting of an LC circuit, tuned to about 535 KHz.

Although this tuned circuit could have been replaced by an active filter, it was felt that this was unnecessary since most a-m receivers use an inductor for an antenna, and it might as well serve as part of a tuned circuit also.

Circuit Details of Figure 3 .

Transistors Q1, Q2, and Q3 comprise a simple multiplying circuit (Fig. 3) which forms the product of the incoming signal and the local oscillator. Q4 and Q5 form a differential amplifier which amplifies the low frequency differential output components of the multiplier signal. (A low pass filter is formed by components R_1 , C_1 and R_2 , C_2 .) The differential amplifier then drives a simple audio amplifier circuit (Q6).

Transistors Q9 and Q10 are used to form an R-C oscillator circuit. Figure 4 shows the basic circuit operation. The transfer function for the circuit is

$$\frac{V_{OUT}}{V_{IN}} = \frac{K_p}{p^2 + (2 + \frac{1}{RC} + \frac{1}{R} - K)p + \frac{2}{RC}}$$

If we let $K = 3$, $R = 2$, and $C = 1$, then the transfer function becomes

$$\frac{V_{OUT}}{V_{IN}} = \frac{3p}{p^2 + 1},$$

which places the poles of the system on the $j\omega$ axis. This makes the circuit an oscillator with the capability of being synchronized by the injected voltage signal, V_{IN} . Transistors Q9 and Q10 form an amplifier with a gain of approximately + 3.

The oscillator is driven by a two stage amplifier (Q7 and Q8). Q7 provides a high input impedance to prevent loading of the tuned LC circuit, and it also provides a small voltage gain of about 3. Q8 is an emitter follower and provides a low output impedance which is required if the oscillator is to be driven by a voltage source.

The multiplier circuit that is used in the synchrodyne is shown in Fig. 5. The FET, Q1, acts like a variable resistor $r(V_{IN_1})$ and thus controls the gain $\frac{V_{OUT}}{V_{IN_2}}$. Q1 also passes a signal proportional to V_{IN_1} . The total output is

$$V_{OUT} \approx - \left(\frac{R_L}{R} - \frac{R_L}{r(V_{IN_1})} \right) V_{IN_2} - g_m R_L V_{IN_1}$$

Assuming $r(V_{IN_1})$ is approximately $(1 - \alpha V_{IN_1})R$, where $\alpha \ll 1$, then

$$V_{OUT} \approx \frac{\alpha R_L}{R} V_{IN_1} V_{IN_2} - g_m R_L V_{IN_1}$$

The first term represents the product of V_{IN_1} and V_{IN_2} , and α is approximately g_m/I_{DSS} . Therefore

$$V_{OUT} = \frac{g_m R_L}{I_{DSS} R} V_{IN_1} V_{IN_2} - g_m R_L V_{IN_1}$$

It is immediately obvious that the circuit is not a perfect multiplier since one of the output signals, $-g_m R_L V_{IN_1}$, is a linear function of V_{IN_1} . However, in the particular circuit application the multiplier is immediately followed by a low pass filter which removes the $-g_m R_L V_{IN_1}$ signal along with any high frequency components of

$$\frac{g_m R_L}{I_{DSS} R} V_{IN_1} V_{IN_2} .$$

Thus, the multiplier circuit in conjunction with the low pass filter gives the desired result and it assures that no output proportional to V_{IN_2} alone is present.

In the constructed circuit the E101 used for Q1 was found to have a resistance of about 800 ohms with $V_{GS} = 0$. The voltage drop across the FET was .25 volts and the level of V_{IN_2} was about 50 mV(RMS).

Figure 6 shows the selectivity of the synchrodyne receiver of Fig. 3. Notice that for small input signals (below 30 mV) the capture range is small and hence the effective selectivity is high. One problem is immediately obvious. A strong signal at, say 600 KHz, can capture the oscillator. Thus, this circuit is not very good at rejecting nearby strong interfering signals. One method of improving the basic receiver circuit is to place an active filter before the oscillator as shown in Fig. 7. Note that the active filter has the same circuit configuration as the oscillator. Only the feedback gains are different.

It was found that the oscillator's feedback gain could be reduced a fair amount because parasitic feedback coupling effects were greatly enhanced by the addition of the high Q (about 100) active filter. Figure 8 shows the performance of the synchrodyne of Fig. 7. Notice that although the capture range has been improved by a factor of about 2 to 3, much is left to be desired. This is perhaps the greatest weakness in the standard synchrodyne approach. The selectivity is determined by the capture characteristics of the synchronized oscillator, and these characteristics are not good at rejecting nearby strong signals. This places the burden of selectivity on the front end circuitry. But this is what one is trying to avoid, i.e., the superhetrodyne receiver became the standard of the day because it did not require an ultra-selective front end like the tuned radio frequency (TRF) receiver.

Synchronized Modulated Oscillator (SMO) Receiver

The disadvantage of the standard synchrodyne circuit, a required highly selective front end, is overcome by a synchronized modulated oscillator scheme. Figure 9 shows a block diagram of the receiver. Inherent in the circuitry is an oscillator which is formed by the input tuned circuit, the r.f. amplifier, the saturating amplifier and the controlled level feedback path. The result is that oscillation is sustained at a fixed amplitude and at a frequency determined by the LC circuit. The r.f. signal going into the r.f. amplifier is typically about 30 mV RMS. The selection of this low operating level is not arbitrary, but is chosen such that the level will be larger than most incoming signals. But the oscillator signal cannot be too large or else it will saturate the r.f. amplifier.

The idea behind the operation of the SMO receiver is that the oscillator locks onto the strongest signal coming out of the r.f. linear amplifier which is, by design, the signal due to the oscillator. Now if the oscillator is tuned to an incoming signal, that signal will sync the oscillator if the two frequencies are the same. Suppose, now, that there is a strong, adjacent, interfering signal. Even though the interfering signal is much stronger than the desired signal, it is probably weaker than the feedback signal from the oscillator. Consequently, the oscillator remains synchronized with the desired signal. The interfering signal will get through the r.f. amplifier, but it will be eliminated by the product detector and low pass filter. Although the SMO receiver has only one tuned circuit with a Q of typically 100, it exhibits an effective Q many times higher (approx. 1000).

Figure 10 shows the circuit that was constructed to test the SMO receiver theory. Although the circuitry is extremely simple -- the product detector is just a chopping circuit -- the receiver performed amazingly well. It picked up all twelve commercial AM stations in the Tucson area (where research on this receiver was conducted) and showed fairly good selectivity. The only interference that was noticeable was that between KOPO, a relatively weak station at 1450 KHz and KTUC at 1400 KHz, which happened to be the most powerful incoming signal. Even here KTUC was only faintly heard in the background. A good product detector in the SMO receiver would probably have eliminated the interference altogether.

Circuit Details of the SMO Receiver

The eight transistors of the SMO receiver perform the following functions. Transistor Q_1 , Q_2 , and Q_3 comprise the r.f. amplifier. Q_1 , an

N channel FET provides a high input impedance and therefore does not load down the tuned circuit formed by L, C₁, C₂. (The inductor L also serves as antenna for the receiver.) Transistor Q₂ provides a voltage gain of around 50 for the r.f. amplifier and Q₃ provides a low output impedance driving circuit. Transistors Q₄ and Q₅ comprise the saturating amplifier. The output signals from their collectors are about 0.8 volts peak-to-peak. Q₅ provides the oscillator feedback signal to the LC circuit. This signal is reduced to present about a 30 mV signal to the r.f. amplifier. Q₄ drives Q₆ which forms a very crude but simple product detector (in reality Q₆ is just a chopping circuit). The output of the detector drives Q₈, which makes up the audio amplifier driving a set of earphones. A low pass filter, formed by R₁, C₃ bypasses the high frequency signals going into Q₈. Resistors R₂, R₃, R₄ and capacitor C₄ form a low pass filter and biasing circuit for Q₇ which controls the feedback to the LC tuned circuit. Q₇ behaves like a variable resistor and thus adjusts the feedback level so that a relatively constant output level comes out of the r.f. amplifier.

As was mentioned earlier, this simple receiver performed remarkably well, all things considered. It certainly outperformed the crystal filter synchrodyne receiver and the conventional synchrodyne receiver as well. It should be pointed out that the SMO receiver is a form of synchrodyne receiver since it utilizes a synchronized oscillator.

There is one disadvantage inherent in the SMO receiver. Namely, tuning is a bit of a problem due to the very narrow capture range of the receiver. Figure 11 shows this capture range as a function of input signal level. (The input level is a relative value and does not represent the true signal level coupled into the antenna coil.) The curve displays the

typical capture ratio form, but the significant point is that most incoming signal levels occur in the narrow capture range region. A strong AM station must be tuned to within a couple KHz for synchronization to occur. A weak signal may have to be tuned to within a few hundred cycles for synchronization. This all means that a practical receiver would probably need a fine tune control or a vernier tuning drive. (C_2 was used as a fine tune control.)

Once a station is tuned, the SMO receiver remains locked on it; that is, the receiver is relatively stable frequency-wise. It was observed that if the SMO receiver was tuned to a particular station, and then power was removed from the circuit, the receiver would still be tuned (synchronized) with the AM signal when power was applied to the receiver a day later.

Summary of the SMO Receiver

The SMO receiver has much to offer:

1. It is tunable by a single element (variable capacitor).
(The inductor is assumed to serve as an antenna along with a tuning element.)
2. No tracking problem exists such as in the case of a super-heterodyne receiver which needs two tracking tuned circuits.
3. The circuit exhibits good selectivity. An interfering signal 30 KHz away from a 800 KHz signal has to be typically about 30 times stronger than the desired signal to cause an equal level of interference between the two signals.)
4. The SMO lends itself to integrated circuit fabrication since it has no inductors. A number of the capacitors shown in the circuit of Fig. 10 could be omitted if the circuit were redesigned for integration. The few remaining capacitors would be inexpensive

bypass and filtering capacitors. None of the values of the capacitors would be critical as would be the case if integrated active RC filter circuits were needed.

Synchronous AM Detector

A fair amount of time was spent investigating synchronous AM detectors. Figure 12 shows the block layout of the detector. A relatively constant amplitude signal is fed into the first amplifier whose output is non-saturated. (The signal level into the first amplifier is held relatively constant by the AVC.) The second amplifier consists of a saturated amplifier which provides a square wave for the chopper. Demodulation is accomplished by chopping the linear signal and feeding the result through a low pass filter.

Figure 13 shows one of the test circuits used. In this specific circuit there is no AVC or first amplifier. The second amplifier consists of a high gain amplifier preceding a Schmitt trigger. The idea behind the Schmitt trigger is to make the square wave output somewhat immune to noise variations at the input. The Schmitt trigger will operate satisfactorily with input signals as low as 1 mV RMS.

An FET serves as the chopper. It modulates the incoming signal by varying its drain to source resistance. The low pass filter is of fairly straight-forward design as is the audio amplifier following it.

Figure 14 shows the gain of the system of Fig. 13 as a function of input signal level. For high level input signals, the detector saturates, resulting in decreased gain. From 20 mV to 300 mV, the gain is relatively constant. The surprising result is that the gain reaches an unusually high value for low level signals (between 1 and 2 mV). This is

a result of a nonlinear waveshape distortion effect due to modulation of the Schmitt trigger by a weak signal. The fidelity of the incoming signal is, of course, very poor due to the distortion effect.

An interesting side point ought to be mentioned here. The circuit of Fig. 13, when connected to a wire antenna, would pick up the strongest local station. No preamplifiers were necessary.

The synchronous AM detector of Fig. 13 displayed an interesting selectivity feature; that is, it would detect the strongest incoming signal while it would suppress weaker signals (of different frequency). This is basically a feature of product detectors when followed by low pass filters.

Figure 15 shows the result of adding an interfering, non-modulated signal, V_I , to a low level input signal, V_S . The signal V_I has no effect until it is roughly 1/3 the amplitude of V_S . V_I then gradually suppresses V_S until there is no output signal at all when V_I is approximately seven times the level of V_S . If the interfering signal, V_I , is AM modulated, we get the result of Fig. 16. Again, at low levels, V_I has no effect on V_S . As V_I increases in amplitude, it gradually suppresses V_S , and the output signal, V_O , locks in on V_I . The reason for the dip in V_O for V_I/V_S in the range of 10 to 30 is due to the fact that the gain of this detector decreases rapidly as signal level increases (see Fig. 14). As V_I becomes large, the detector reaches its linear region of operation, and this results in a voltage V_O proportional to V_I .

For high level interactions (V_S and V_I in the linear detector region) we get the results of Fig. 17 and 18 which show the difference between an unmodulated and a modulated interfering signal. In both cases the desired signal V_S is suppressed when the amplitude of V_I exceeds that of V_S .

This, as before in the low level case, is because the Schmitt trigger locks into the strongest signal. The product detector and low pass filter eliminate the weaker signal. Note, however, that interfering signals of a harmonic frequency can have a serious effect on the output (Fig. 17). This is because the product detector used is actually a chopper and therefore not a true multiplier. This tends to let odd harmonics through the detector.

Conclusions

The following can be said about the three types of receivers previously discussed.

1. The crystal filter synchrodyne offers very good selectivity, but it requires a very high Q crystal if distortion levels are to be kept low. The receiver is inherently fixed frequency unless crystal switching is allowed. The crystal filter receiver would probably be the most expensive to fabricate due to the cost of making precision crystals. Aside from the crystal, the rest of the components could be integrated.

2. The conventional synchrodyne receiver requires a highly selective front end design. The receiver could be built in integrated circuit form but would probably require external tuning capacitors and gain controls as these component values are usually very critical in high Q active R-C circuits. The conventional synchrodyne receiver is basically a fixed frequency receiver.

3. The synchronized modulated oscillator (SMO) receiver offers good selectivity and wide band reception. Since it only has one tuned circuit, the SMO receiver readily lends itself to integrated circuit fabrication. Tuning weak signals is a bit difficult, though,

and some means of fine tuning the receiver should be made available. If the SMO receiver is designed for a single frequency, the front end tuning can easily be accomplished by using a small, relatively inexpensive, trimmer capacitor in parallel with the antenna coil.

4. All synchrodyne receivers ultimately derive much of their selectivity from use of a product or a synchronous detector. While a true product detector is desired, a synchronous detector (chopper) can often perform the job, and it is generally of simpler design than a multiplier circuit.

5. Future research might try fabricating an SMO receiver in integrated form since it appears to be the best of the three types of synchrodyne circuits examined. Another possibility would be the design of a super-regenerative integrated circuit receiver. Super-regenerative receivers, like the SMO receiver, only require one tuned circuit.

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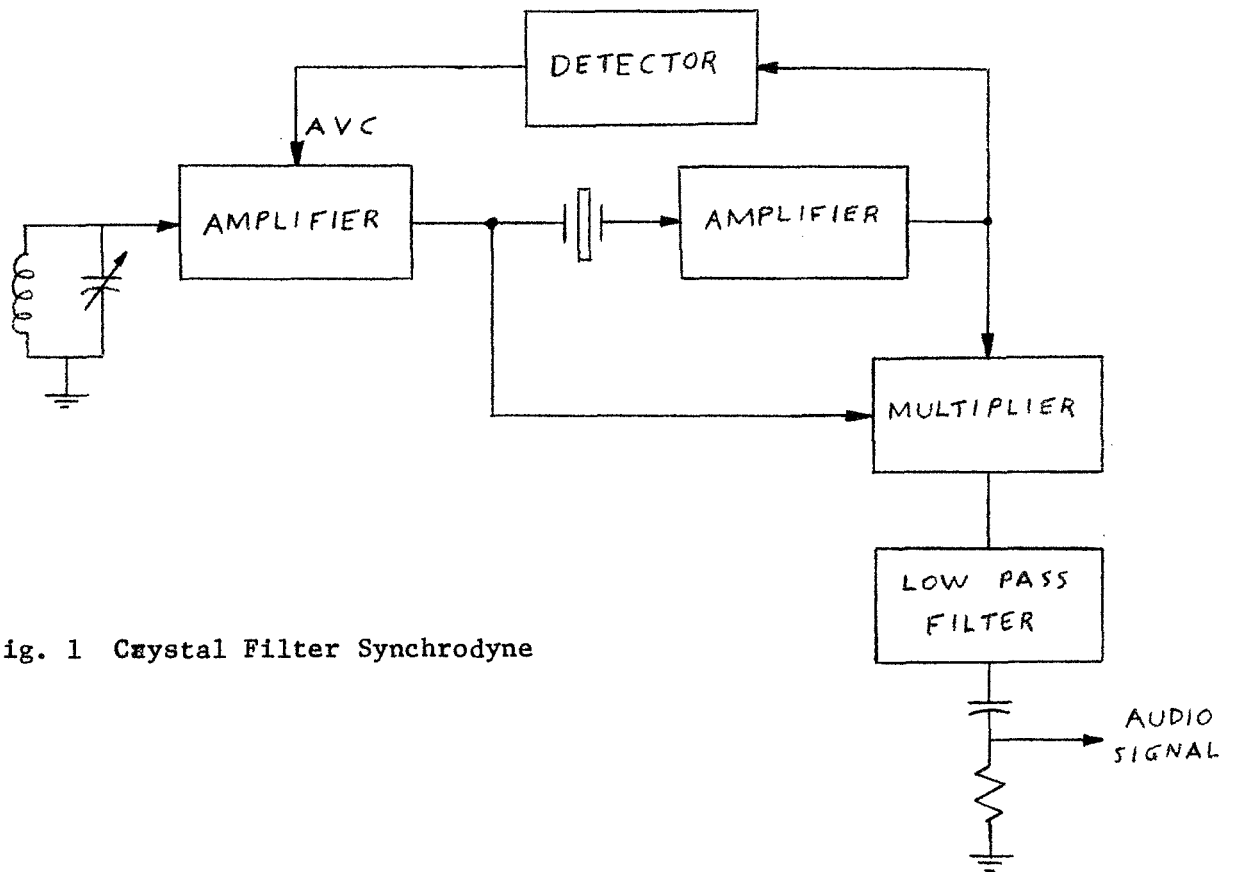


Fig. 1 Crystal Filter Synchronodyne

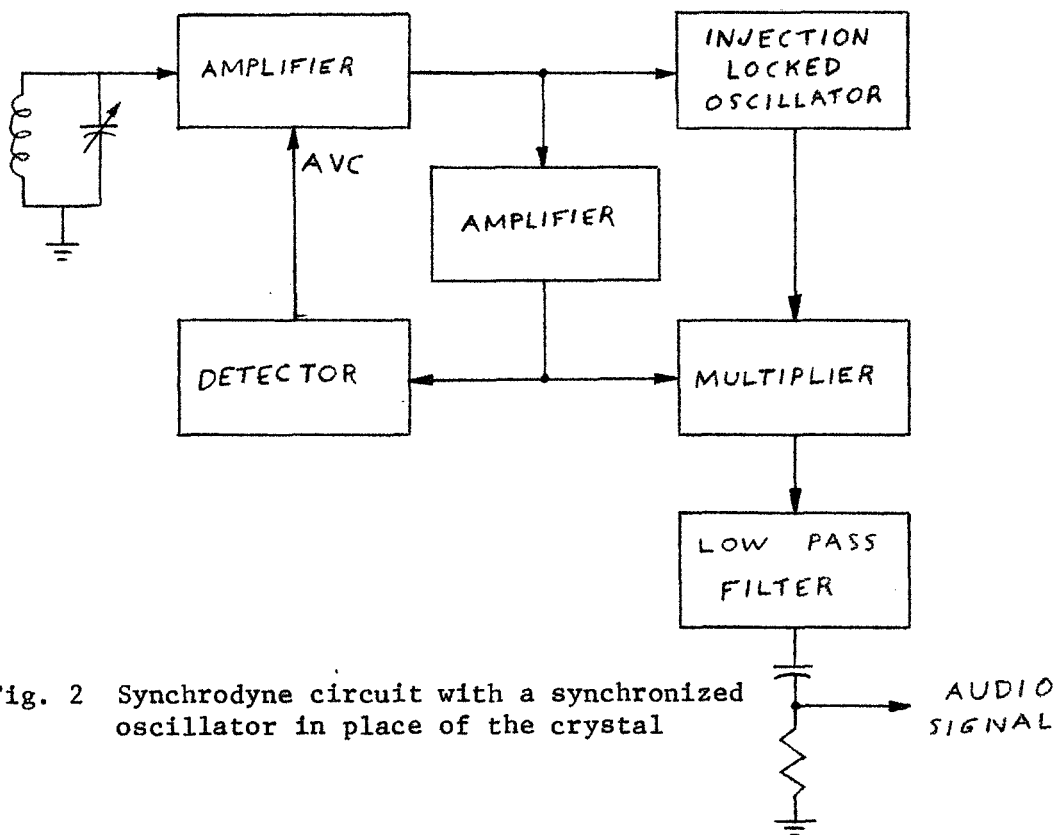


Fig. 2 Synchronodyne circuit with a synchronized oscillator in place of the crystal

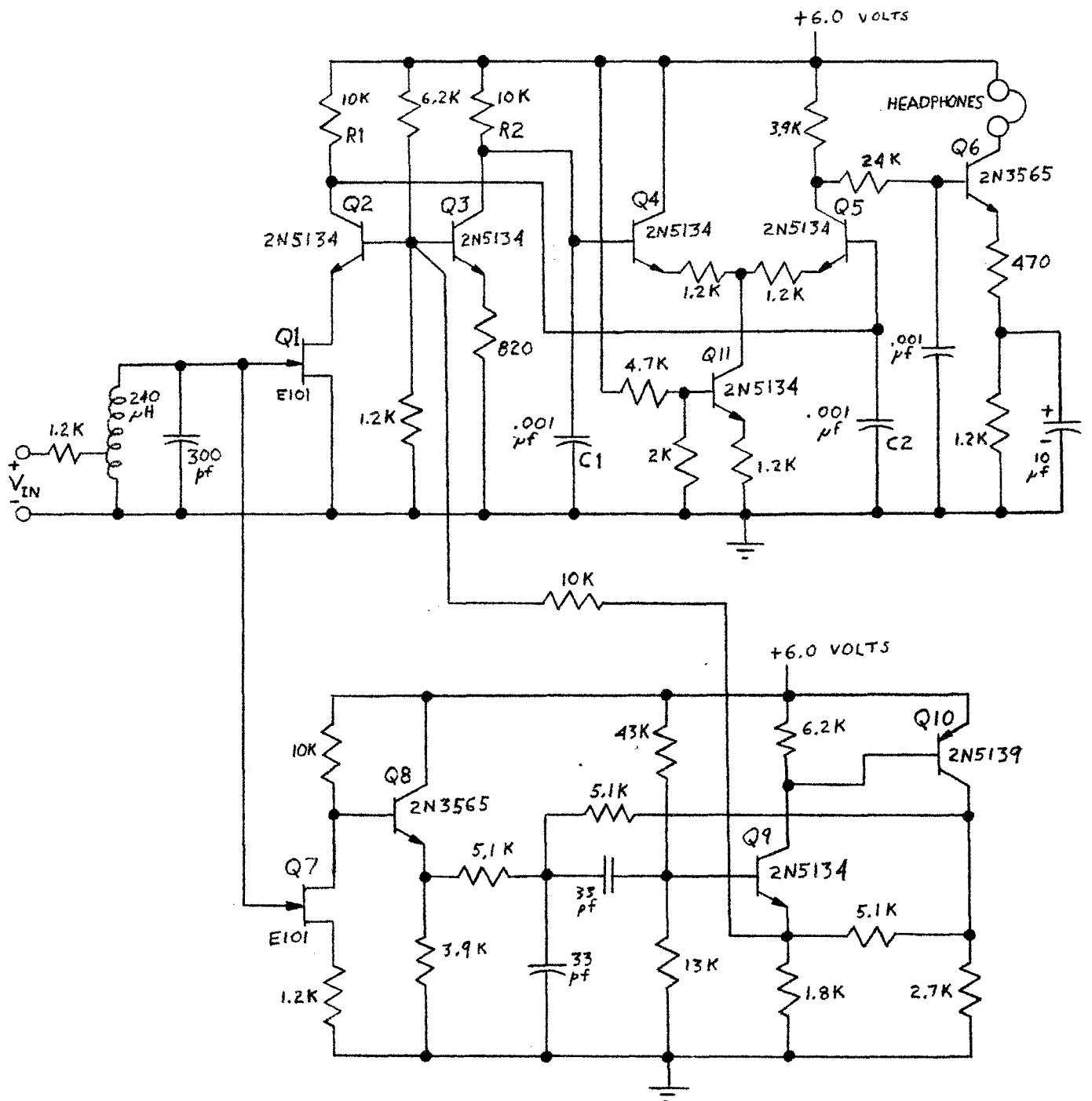


Fig. 3 Circuit details of a conventional synchrodyne circuit

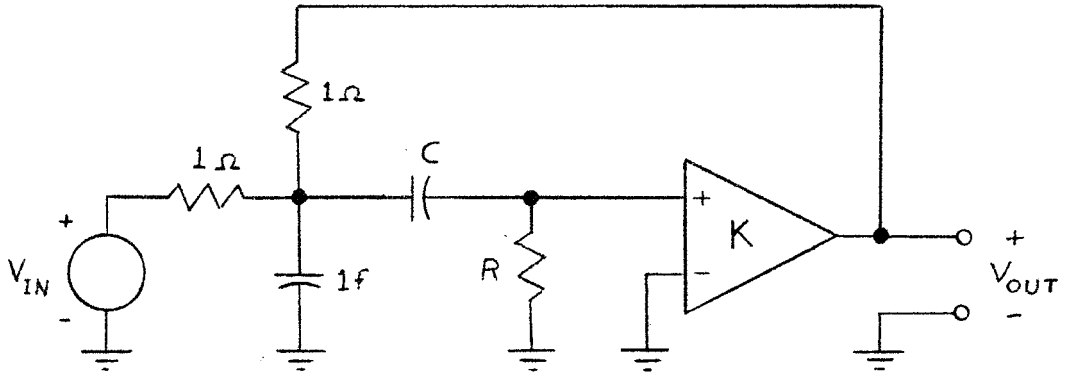


Fig. 4 Basic R-C oscillator circuit used in the synchrodyne

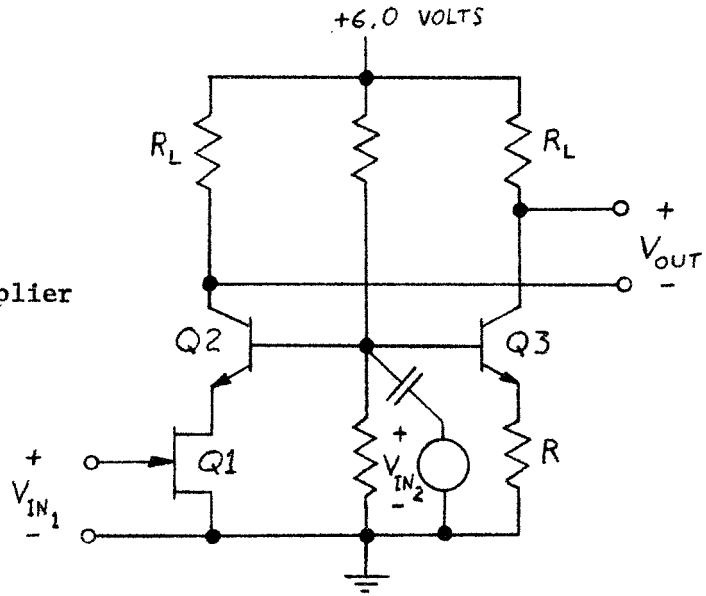


Fig. 5 Synchrodyne multiplier

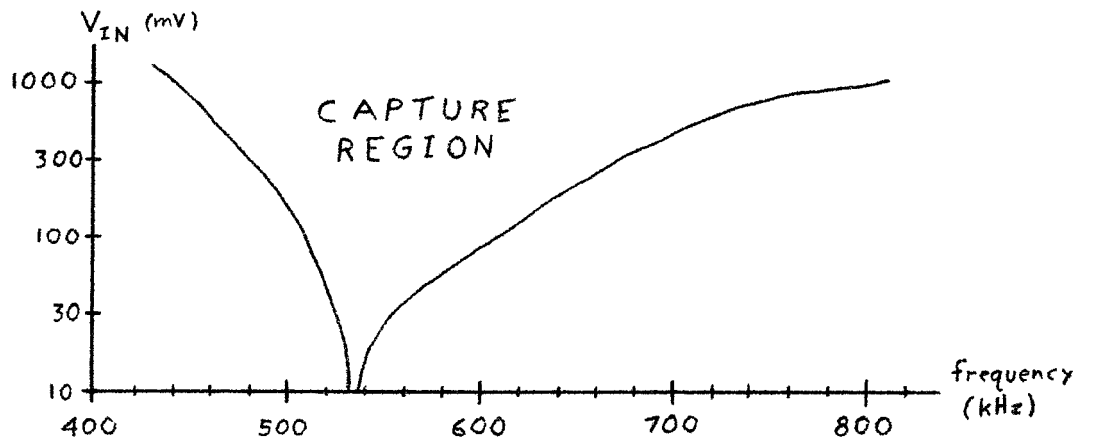


Fig. 6 Selectivity of the synchrodyne receiver of Fig. 3

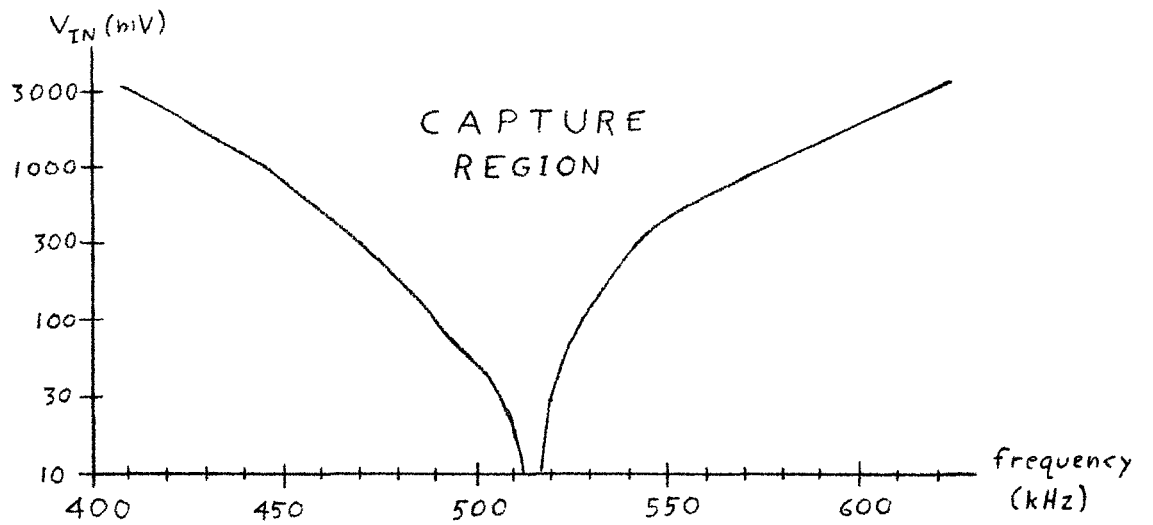


Fig. 8 Improved selectivity of synchronodyne

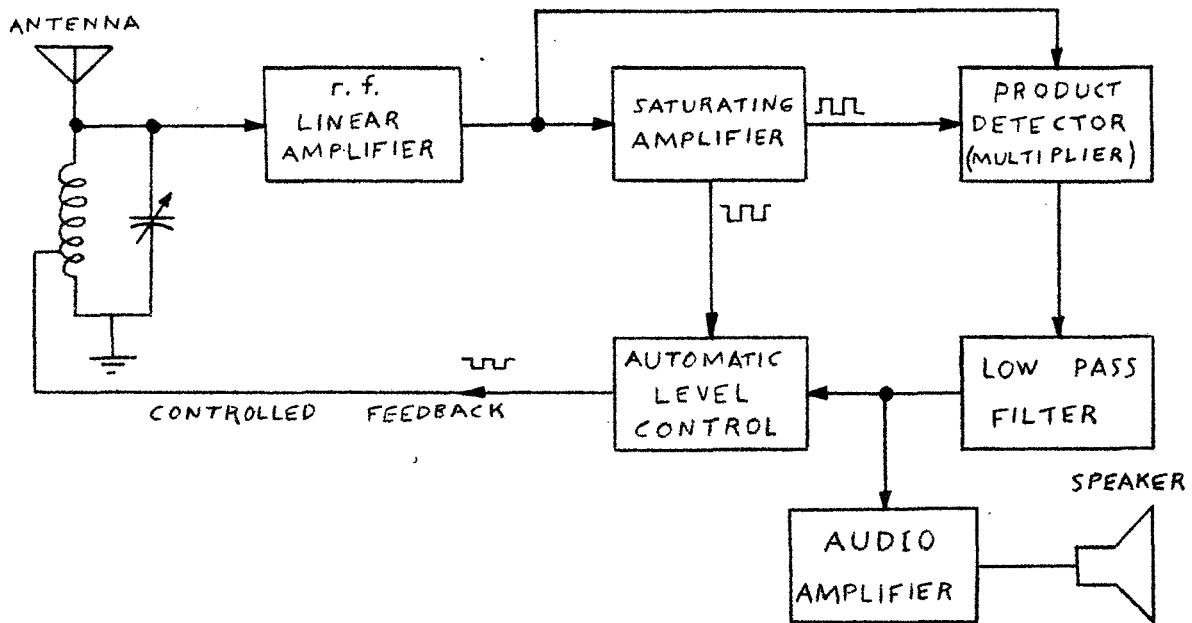


Fig. 9 Block diagram of the synchronized modulated oscillator (SMO) receiver

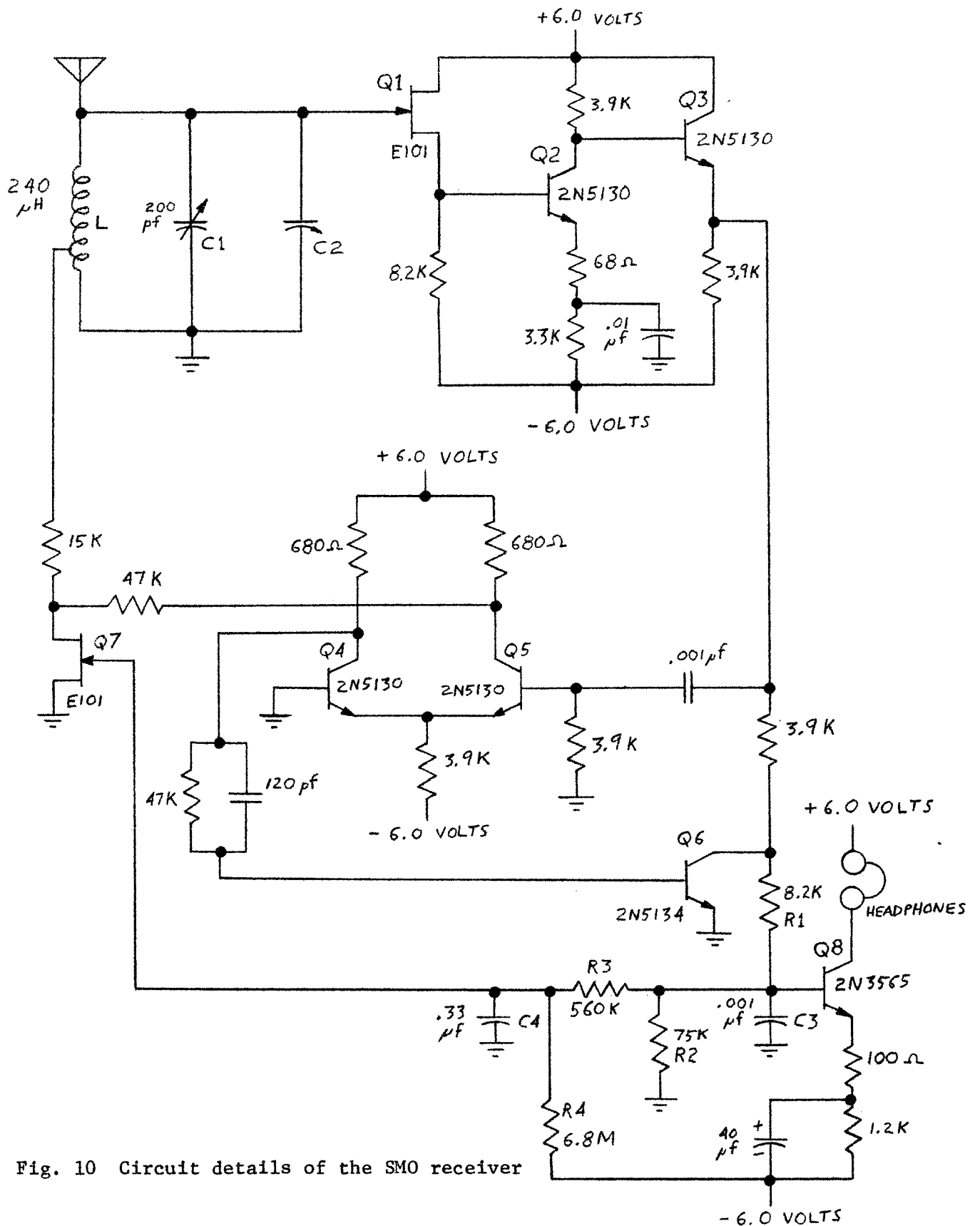


Fig. 10 Circuit details of the SMO receiver

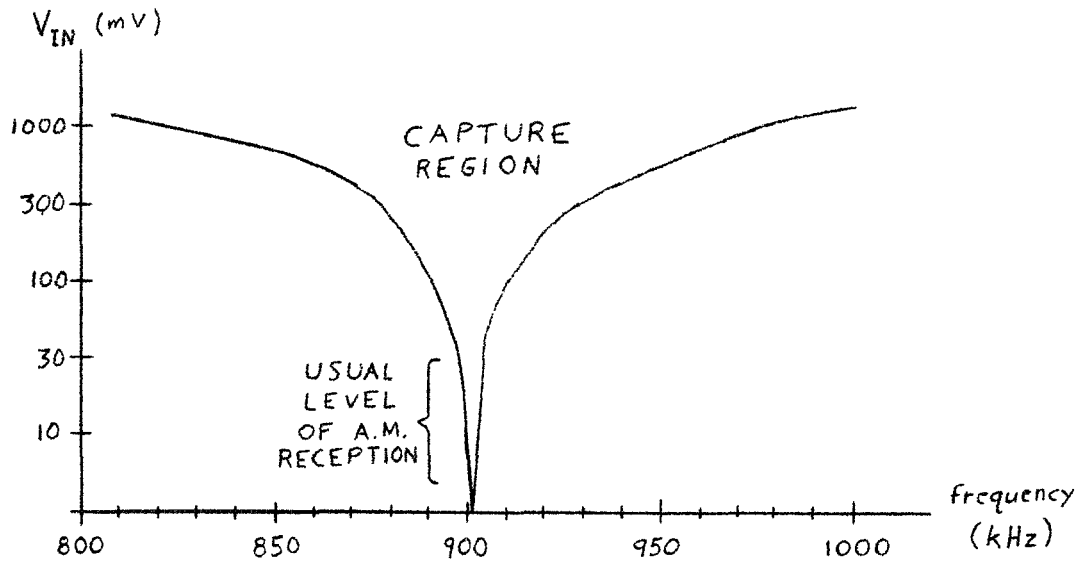


Fig. 11 Selectivity curve for the SMO receiver

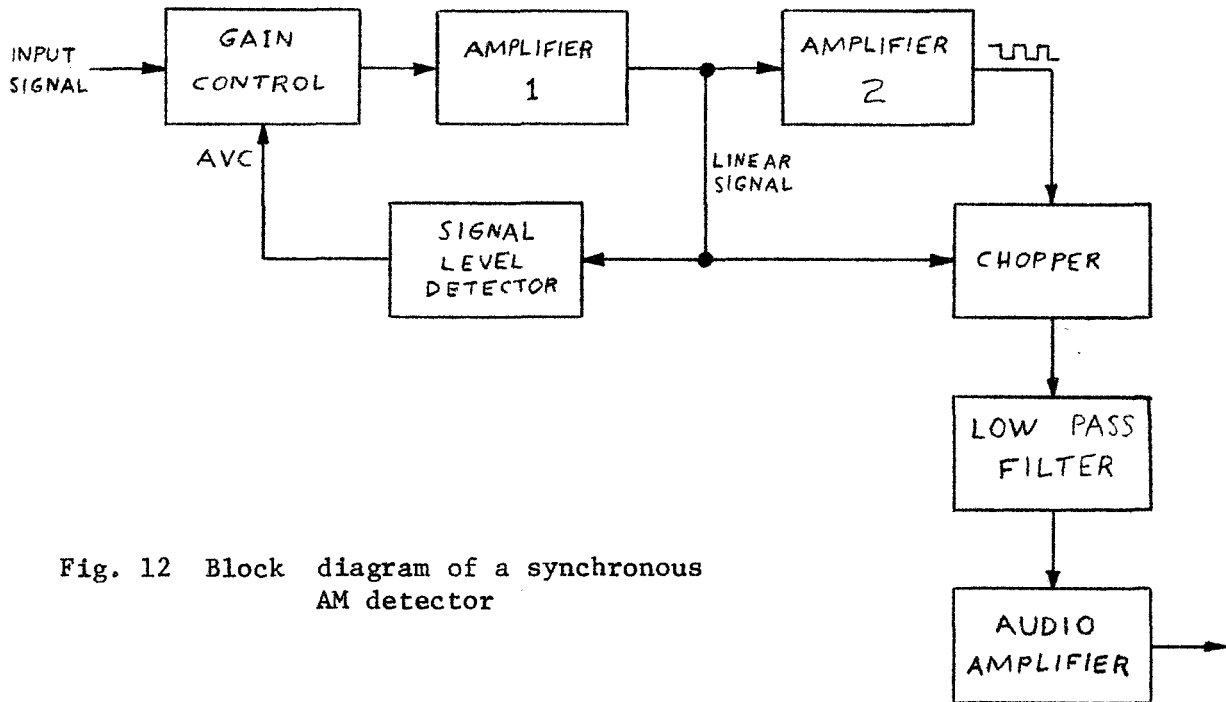


Fig. 12 Block diagram of a synchronous AM detector

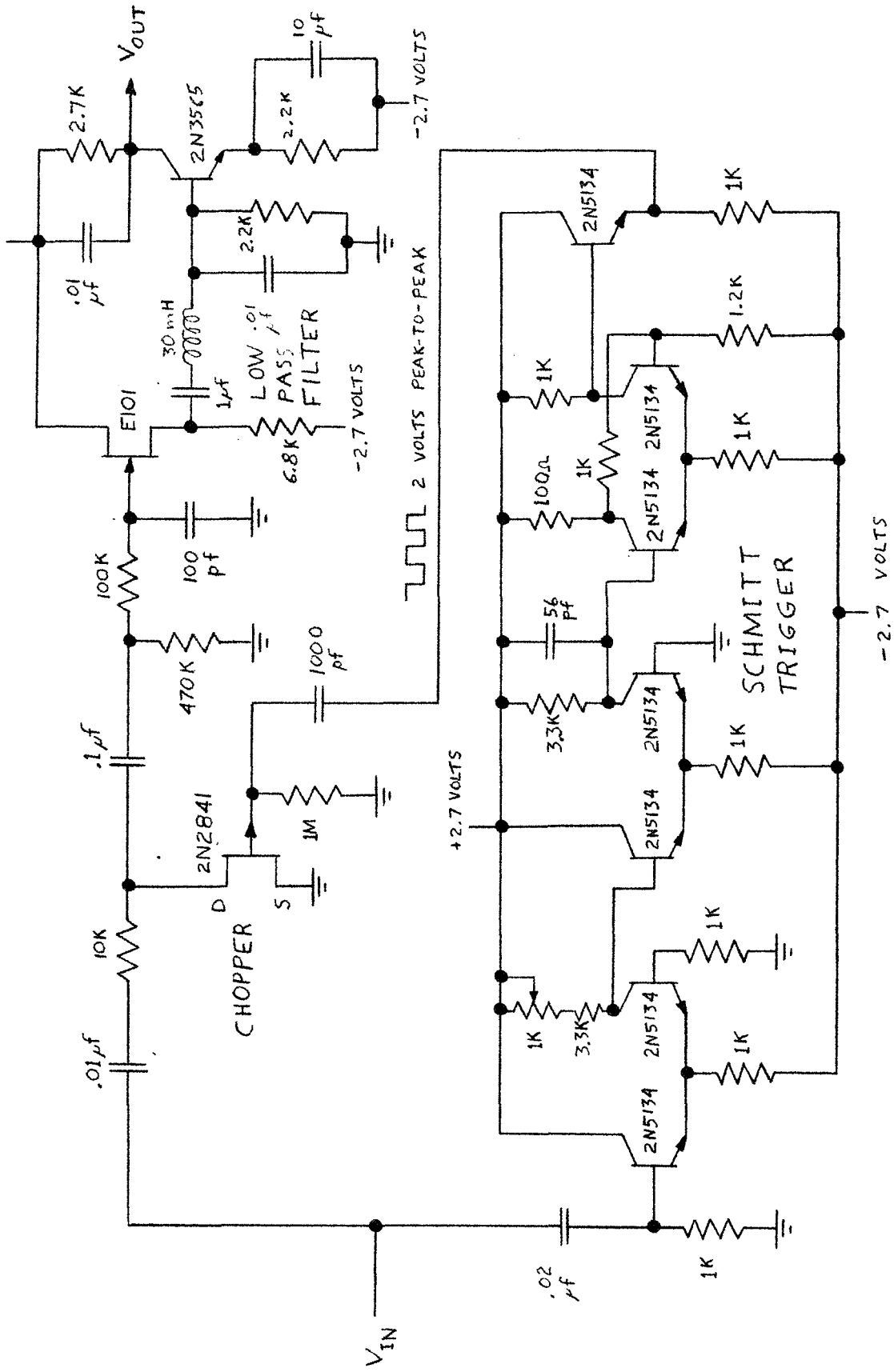


Fig. 13 Circuit details of a synchronous AM detector

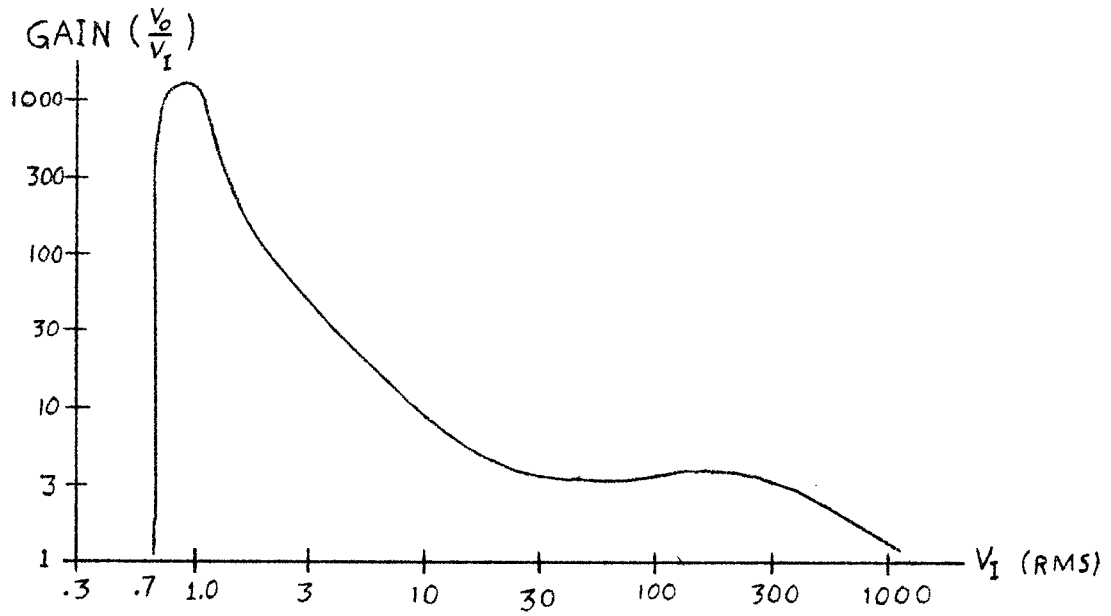


Fig. 14 Response of synchronous AM detector to an AM signal. V_I is the RMS amplitude of a 1 Mhz, 30% amplitude modulated signal. V_O is the peak-to-peak detected modulating signal.

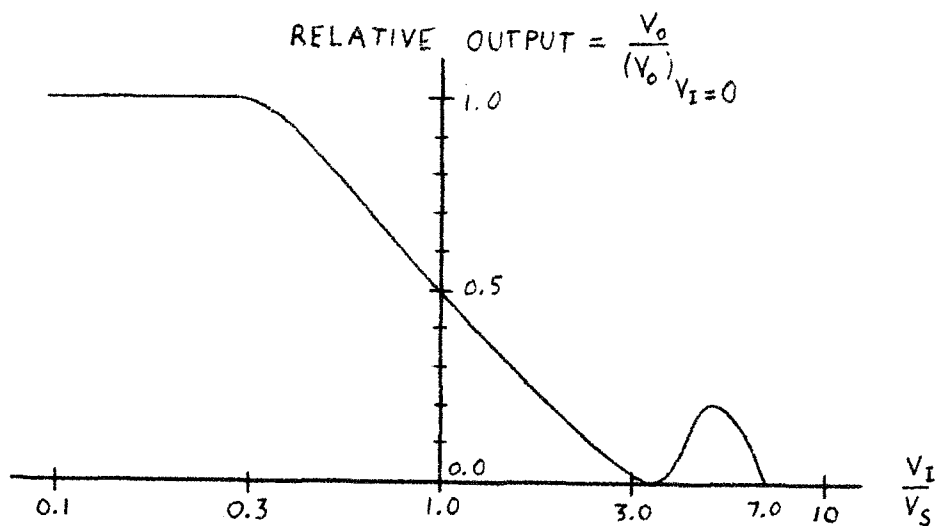


Fig. 15 Low level response of synchronous AM detector. V_S is the desired input signal and has an amplitude of 2 mV(RMS) at 1.02 Mhz. It is 30% amplitude modulated by a 600 Hz signal. V_I is an unmodulated interfering signal at a frequency of 1.1 Mhz. V_O is the output signal from the detector.

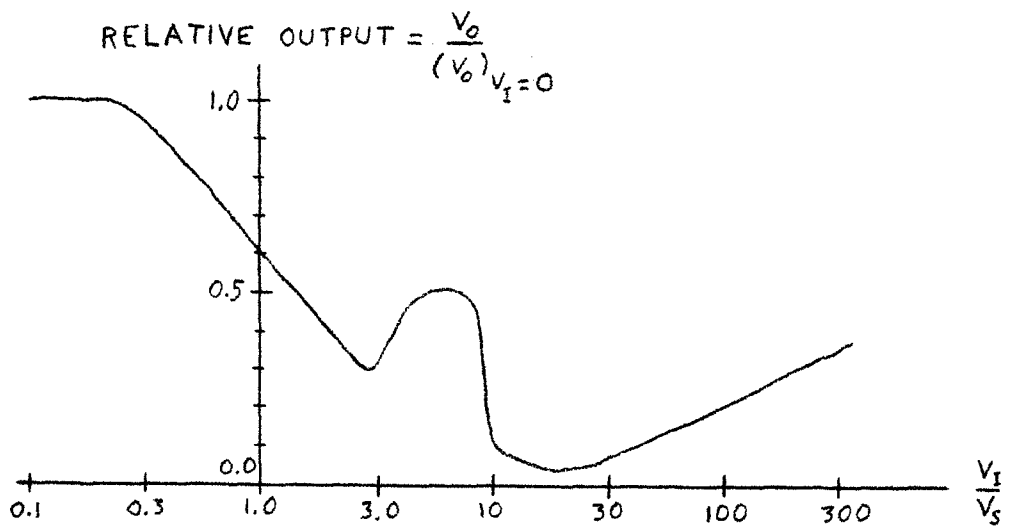


Fig. 16 Low level response of synchronous AM detector. The conditions here are the same as in Fig. 15 except that the interfering signal is 30% amplitude modulated by a 1 KHz signal.

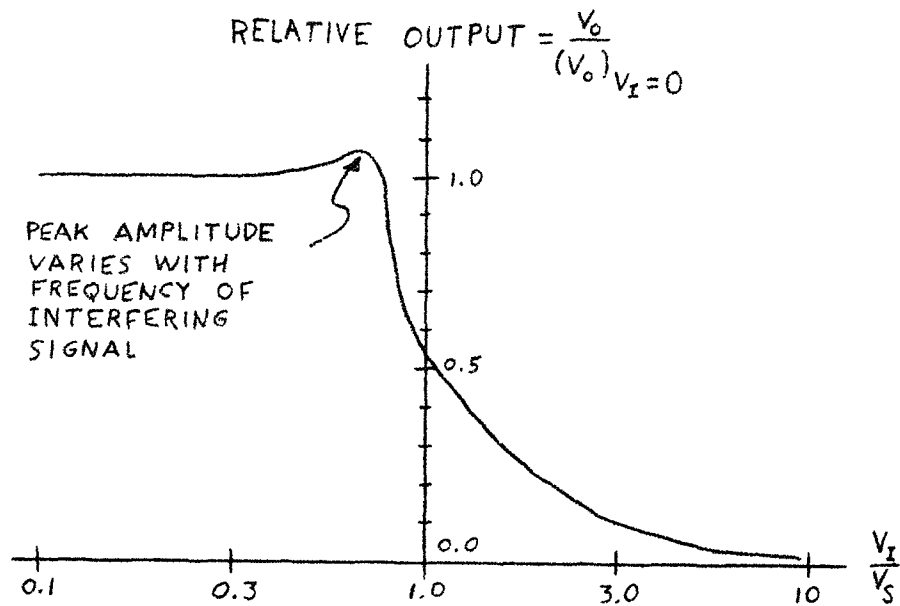


Fig. 17 High level response of synchronous AM detector. V_S , the desired signal, is a 100 mV(RMS) 1.02 Mhz signal with 30% amplitude modulation at 600 Hz. V_I is an unmodulated signal at 1.1 Mhz. V_o is the detector output signal.

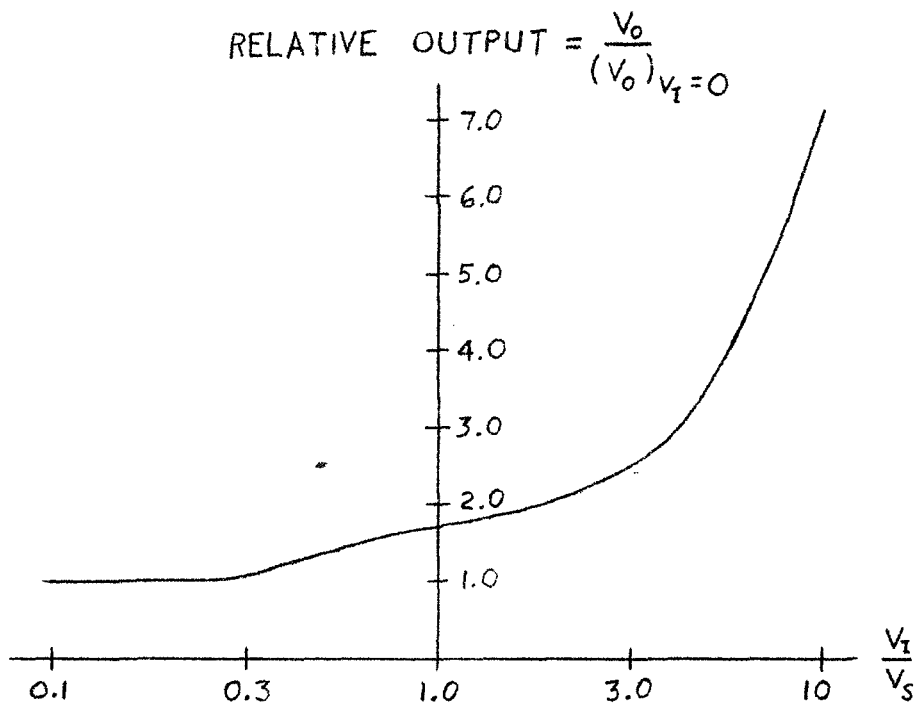


Fig. 18 High level response of synchronous AM detector. The conditions are the same as in Fig. 17 except that the interfering signal is 30% amplitude modulated by a 1 KHz signal.