

## X. TRANSISTORS

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### A. I-F AMPLIFIER DESIGN STUDIES

A Butterworth characteristic of order three was realized in a three-stage amplifier, with an over-all  $Q$  of 20 and a center frequency of 200 kc/sec, using the design method outlined in the Quarterly Progress Report, October 15, 1952. A power gain of 36 db was obtained from point-contact transistors. Variations of the collector bias on all three transistor stages did not affect the frequency response to a noticeable degree, although the power gain decreased to 17 db.

In connection with the receiver study previously reported (see also sec. D of this report), the same design procedure was next applied to a more elaborate i-f amplifier, with the following prescribed characteristics:\*

- a. Center frequency: 455 kc/sec
- b. Three bandwidths as follows:
  - 2 kc/sec between 6-db points; 10 kc/sec between 70-db points
  - 4 kc/sec between 6-db points; 14 kc/sec between 70-db points
  - 8 kc/sec between 6-db points; 26 kc/sec between 70-db points
- c. Power gain: 60 db (using point-contact transistors)
- d. Maximum  $Q$  of the coils: 150.

As is evident from Fig. X-1, the design uses multiple-order poles, staggered in such a way as to give a flat-top frequency response. The amount of staggering is varied by the capacitors to give the three required bands. Seven stages are used, and the values given for one stage in the figure are typical. The interstage transformers are all physically realizable and all alike. The amplifier has not been built; the design was carried out for comparison with that employed in connection with electromechanical filters (see sec. D).

As a convenient means of studying the interaction present (in the grounded-base connection) when complementary impedances are not used to isolate tuned stages, the iterative method of analysis has been applied to the i-f amplifier problem. Using a derivation and notation similar to that of E. A. Guillemin (Communication Networks, Vol. 2, John Wiley, New York, 1935, pp. 163-65), we obtain for the  $k$ th unit in a cascade of identical stages of active devices (each with parameters  $z_{11}$ ,  $z_{12}$ ,  $z_{21}$ ,  $z_{22}$ ):

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\*An asterisk denotes work that has been undertaken in cooperation with members of Lincoln Laboratory under Contract AF19(122)-458. This report is therefore duplicated in the Lincoln Laboratory Quarterly Progress Report.

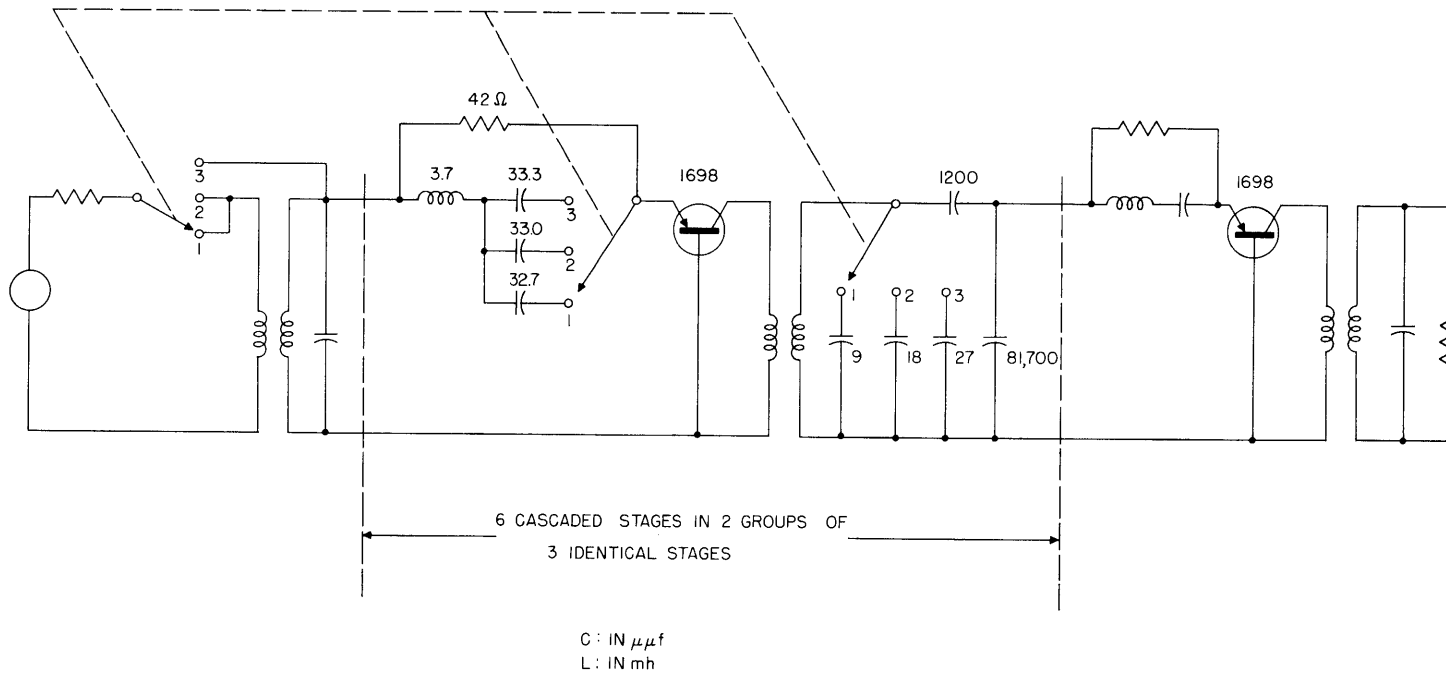


Fig. X-1

Representative stages for three-band i-f amplifier (power supply not shown).

$$E_k = (A_1 e^{-\gamma k} + A_2 e^{\gamma k}) e^{rk}$$

$$I_k = (B_1 e^{-\gamma k} + B_2 e^{\gamma k}) e^{rk}$$

$$\gamma = \cosh^{-1} \left[ \frac{z_{11} + z_{22}}{(z_{12} z_{21})^{1/2}} \right], \quad Z_{01} = z_{21} e^{\gamma - r} - z_{22}$$

$$r = \frac{1}{2} \log_e \left[ \frac{z_{21}}{z_{12}} \right], \quad Z_{02} = z_{22} - z_{21} e^{-\gamma - r}.$$

As an example, we may consider a shunt-tuned circuit in the collector of a resistive transistor with an ideal transformer of turns ratio  $(r_{22}/r_{11})^{1/2}$ .

Letting

$$\frac{1}{c\lambda + \frac{1}{L\lambda}} = \frac{r_{22}}{jx}$$

and

$$\tau = \frac{z_{12} z_{21}}{z_{11} z_{22}}$$

we find

$$\gamma = \cosh^{-1} \left[ \frac{2 + jx(1-\tau)}{2\tau^{1/2}} \right]$$

$$Z_{01} = \frac{r_{11}}{1 + jx} (1 - \tau^{1/2} e^{-\gamma})$$

$$Z_{02} = \frac{r_{11}}{1 + jx} (\tau^{1/2} e^{\gamma} - 1).$$

Some work is now under way for wide-band i-f amplifiers using series-tuned circuits as interstage networks. It seems, from an iterative analysis similar to that exemplified above, that they may be especially suitable for wide-band applications.

M. Boisvert

## B. BROAD-BAND I-F AMPLIFIERS

Two additional studies pertinent to i-f amplifier design have been expanded since the Quarterly Progress Report, October 15, 1952: (a) experimental verification of the amount of attenuation necessary to isolate cascaded tuned stages; (b) theoretical study of the over-all power-gain bandwidth product for different methods of cascading in a multistage i-f amplifier.

In connection with the first study (a), four separate pairs of transistors were coupled

Table I

Gain-Bandwidth Comparison

Matched Flat-Staggered Doubles Compared to Synchronous Stages Mismatched to Give Same Over-all Bandwidth.

Number of Stages "n"	Matched Synchronous Stages or Pentodes* $\left(\frac{GB}{G_m^n B_m}\right)$	Doubles			Mismatched Synchronous			Comparison $\left[\frac{GB(n/2 \text{ doubles})}{GB(n \text{ mismatched synch.})}\right]$
		$\left(\frac{B}{B_m}\right)$	$\left(\frac{GB}{G_m^n B_m}\right)$	$\left(\frac{G^{1/n}B}{G_m B_m}\right)$	$\left(\frac{B}{B_m}\right)$	$\left(\frac{GB}{G_m^n B_m}\right)$	$\left(\frac{G^{1/n}B}{G_m B_m}\right)$	
1	1.00							
2	0.64	1.41	0.35	0.707	2.2	0.81	1.07	0.66 (1.56)*
3	0.51							
4	0.44	1.14	0.071	0.57	2.61	0.239	0.77	0.74 (1.84)*
5	0.39							
6	0.35	1.01	0.016	0.505	2.88	0.064	0.64	0.79 (2.04)*
7	0.32							
8	0.30	0.93	0.0036	0.465	3.11	0.0154	0.56	0.835 (2.19)*

Matched Flat-Staggered Triples Compared to Synchronous Stages Mismatched to Give Same Over-all Bandwidth.

Number of Stages "n"	Matched Synchronous Stages or Pentodes* $\left(\frac{GB}{G_m^n B_m}\right)$	Triples			Mismatched Synchronous			Comparison $\left[\frac{GB(n/3 \text{ triples})}{GB(n \text{ mismatched synch.})}\right]$
		$\left(\frac{B}{B_m}\right)$	$\left(\frac{GB}{G_m^n B_m}\right)$	$\left(\frac{G^{1/n}B}{G_m B_m}\right)$	$\left(\frac{B}{B_m}\right)$	$\left(\frac{GB}{G_m^n B_m}\right)$	$\left(\frac{G^{1/n}B}{G_m B_m}\right)$	
1	1.00							
2	0.64							
3	0.51	2.0	0.10	0.74	3.9	0.25	1.0	0.74 (1.96)*
4	0.44							
5	0.39							
6	0.35	1.73	0.0043	0.636	4.9	0.0086	0.711	0.89 (2.47)*
7	0.32							
8	0.30							

\*Gain-bandwidth figures for pentodes are shown in parentheses.

through variable attenuators, and the frequency response measured in each case as a function of the amount of isolating attenuation. Apparently, 3 db of isolation is sufficient to prevent coupling between synchronously tuned stages, while 5 db is necessary to isolate stagger-tuned stages. Smaller amounts of attenuation sometimes produce undesired peaks in the response.

The second study (b) has been made subject to the following assumptions: (a) Bandwidth is limited by the capacitance of the coupling transformers. (b) Transistor parameters are real and independent of frequency. (c) Stages are isolated, but the loss differences associated with such isolation in various cases are neglected (see sec. A). (d) All transistors employed have been made short-circuit stable (by padding, if necessary). (e) The power gain is computed at band center.

The results are shown in Table I, where  $G_m$  and  $B_m$  refer respectively to power gain and bandwidth of a single stage under matched conditions, while  $G$  and  $B$  refer to the over-all power gain and bandwidth for the number of stages considered. Because power gain and bandwidth in these circumstances cannot be traded (maintaining a fixed product), the following points must be noted in connection with Table I: (a) In columns comparing doubles and triples to mismatched synchronous stages, the over-all bandwidth of each type of connection has been made the same. (b) Comparisons of doubles and triples to matched synchronous stages have not been listed explicitly because of the bandwidth differences, but comparisons may be made by inspection if desired.

Table I indicates that (when the number of stages is less than nine) synchronous cascading is always preferable. Thus, whenever the bandwidth of  $n$  matched synchronous stages is at least as large as that desired, the highest over-all power-gain bandwidth product is obtained by matched synchronous tuning. In the case of six synchronous stages, for example, the over-all power-gain bandwidth product is 22 times larger than that for three doubles, and 81 times larger than that for two triples. Similarly, if bandwidths wider than those obtainable from matched synchronous cascades are needed, mismatched synchronous tuning is better than stagger tuning.

J. W. Vorndran

### C. PHASE MODULATOR

The 164 kc/sec crystal-controlled oscillator has been redesigned to operate from a 22.5-volt supply. As before, transistors having a current gain greater than 2.3 and a collector resistance higher than 15,000 ohms function satisfactorily in the circuit. The efficiency of operation is approximately 23 percent. The amplifiers in the phase modulator have been redesigned to ensure stable operation for all Western Electric 1698 transistors that satisfy their tentative specifications. A padding resistor is placed in series with the emitter lead to accomplish this result. Of course, the gain of the

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amplifier varies with different transistors, but it is maintained above an acceptable minimum if the transistors remain within the specifications.

The dynamic range of this phase modulator, as well as that of other diode modulators which have been studied, is still limited by the temperature stability of the diodes employed. A large variety of point-contact germanium diodes, p-n diodes, and selenium diodes has been tested, but in no case is the dynamic range satisfactory unless the temperature is held within  $\pm 10^\circ\text{C}$  or less.

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### D. RECEIVER STUDY\*

The design of transistor circuits for the developmental Signal Corps receiver has been continued. A Collins Radio Company electromechanical filter having a 3-kc/sec bandwidth between 6-db points has proved quite satisfactory for the i-f selectivity. If these filters become available in 2-kc/sec and 4-kc/sec bandwidths, it is probable that the remaining 8-kc/sec bandwidth can be obtained from the interstage networks of the rest of the i-f amplifier. This conclusion is supported in part by the design study outlined in section A, although that study was made for point-contact transistors which create some power-supply problems in this particular mobile receiver application.

Principally because of the aforementioned power-supply problems, junction transistors have been investigated for the i-f stages of the receiver. At 455 kc/sec, a p-n-p junction stage in the grounded-base connection has a power gain of 18 db. To achieve this gain, some conjugate-matching must be employed. Such a stage consumes about 15 mw of supply power, and has a bandwidth between 3-db points of 20 kc/sec. It should be possible to reduce this bandwidth to approximately 10 kc/sec by employing special i-f coils, ordered from the F. W. Sickles Company. These coils should have a Q of 200 at 455 kc/sec. While two electromechanical filters, combined with a junction-transistor i-f strip, offer promise of providing both the gain and the three bandwidths required for this receiver, it should be kept in mind that filters with the correct responses for the 2-kc/sec and 4-kc/sec bands are not yet available. Moreover, the insertion loss of the present 3-kc/sec filter is 26 db at band center. Even if this loss were reduced to 10 or 15 db, as suggested by the Collins Radio Company, it implies at least one extra i-f stage. For these reasons, the possibility of using crystal filters is being surveyed. It is almost certain that quartz crystals would be unsatisfactory for these large bandwidths, but EDT, DKT, and ADP crystals offer greater electrical possibilities (correct bandwidth and insertion loss of about 5 db or less). Unfortunately, the mechanical, thermal, and hygroscopic properties of these crystals will probably make them unsuitable for this particular application, but in the general matter of transistor circuit applications they cannot be overlooked.

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A conventional detector employing a 1N34 crystal diode has been built to drive a single p-n-p junction-transistor audio amplifier. The audio amplifier had a power gain of 26 db, delivered 16 mw, and operated at an efficiency of 20 percent (including transformer loss). Since the audio-power stage of the receiver is required to deliver 200 mw into a speaker load, it now appears that it will probably be necessary to employ special p-n-p junction power-transistors. These may be available in the near future.

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### E. FREQUENCY MULTIPLIERS

Further study has been given to the problem of frequency multiplication, using a diode full-wave rectifier to produce the harmonics and a succeeding transistor as amplifier. To conserve components in the long run, a biased-diode quadrupler (instead of a doubler) was built and tested. An over-all loss of 12 db was sustained between the input to the diode circuit and the output of the single-transistor amplifier stage. This loss is much greater than was expected. The excess appears to reside principally in the diodes and the interstage transformer. It may be possible to reduce this loss by transferring the diodes to the high-level side of the transformer.

Since the auxiliary losses due to transformers and diodes are of the same order of magnitude as that which would be produced merely by generation of the fourth harmonic with ideal elements, a high-ratio multiplier chain may operate most efficiently if each stage multiplies by more than four to one.

C. R. Hurtig

### F. STUDY OF P-N-P TRANSISTORS

An investigation has been undertaken of the effects of space-charge widening upon the small-signal characteristics of p-n-p junction transistors of the alloy type. The phenomena in question were first reported for grown n-p-n transistors by J. M. Early (Proc. I.R.E. 40, 1401-1406, 1952), but no published work on p-n-p alloy units is available.

Preliminary data indicate the presence of the effects to a major extent. Further work will cover: (a) quantitative evaluation of the effects in the form of Early's modified equivalent circuit; (b) significance of the modified equivalent circuit in connection with the design of lowpass and bandpass amplifiers.

S. R. Blom

### G. LOW-FREQUENCY OSCILLATOR

The 2000-cps oscillator has been redesigned using two p-n-p junction transistors.

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Grounded-collector and grounded-emitter stages are used. One coil has been eliminated by combining it with a transformer in the frequency-determining network. The power drain is now reduced to 180 mw, the output signal power increased to 27 mw, and the over-all efficiency is 15 percent. A study is currently being made of the temperature stability of the oscillator frequency. As far as the tuned circuit alone is concerned, the inductance is the major problem; a toroid inductor varies approximately 200 ppm per degree centigrade. This cannot be balanced by a capacitor with negative temperature coefficient, because the temperature coefficient of the inductance is not sufficiently constant. The effect of temperature on the rest of the oscillator components remains to be determined.

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