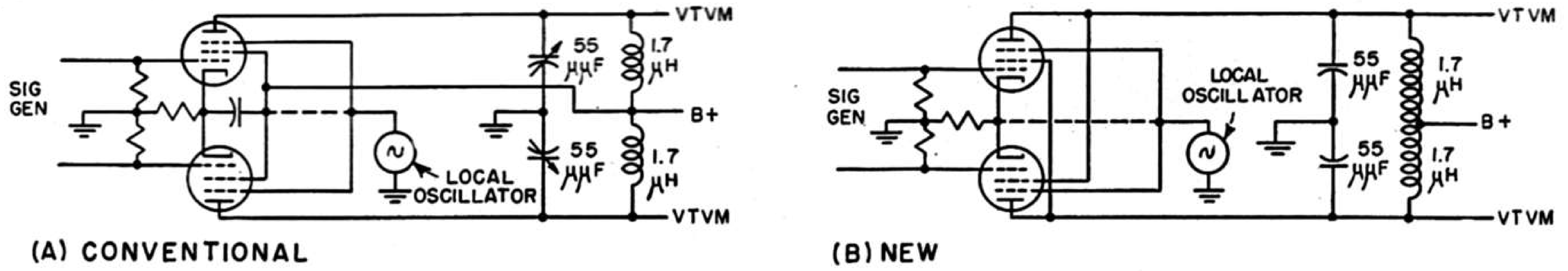


(A) CONVENTIONAL

(B) NEW

E_{osc} RMS VOLTS	I-F VALUE		GAIN A_1	$A_1 \Delta f_1$
	f_1 MC	Δf_1 MC		
2.5	16.1	0.126	14.0	1.76
5.0	16.1	0.192	15.0	2.88
7.5	16.1	0.238	13.0	3.10
10.0	16.1	0.232	13.5	3.13

E_{osc} RMS VOLTS	I-F VALUE		GAIN A_2	$A_2 \Delta f_2$	$\frac{A_2 \Delta f_2}{A_1 \Delta f_1}$
	f_2 MC	Δf_2 MC			
2.5	16.1	0.128	26.5	3.39	1.93
5.0	16.1	0.190	28.0	5.32	1.85
7.5	16.1	0.226	26.5	6.00	1.93
10.0	16.1	0.241	25.5	6.15	1.96

FIG. 1—Comparison of conventional balanced push-pull pentode mixer with improved method that places tuned circuit between screen and plate of each tube. Values of components are not necessarily the most desirable for the frequency and bandwidth used

GAIN-DOUBLING

Theory and experimental results for a method of obtaining twice the normal conversion transconductance from pentode mixers. Signal is applied to an inner grid, and No. 3 grid is used in an outer space-current local oscillator. Practical converter circuits for narrow-band broadcast receivers and wide-band f-m receivers are given

IN THE USUAL frequency mixer tube the conversion transconductance is approximately g_m/π, where g_m is the maximum signal grid-to-plate transconductance during the excursion of an oscillator cycle. The possibility of obtaining a conversion transconductance equal to $2g_m/\pi$ was first pointed out by E. W. Herold[1]. In effect, his method involves changing the phase of the signal current 180 deg at the local oscillator frequency rate, using a beam-deflection tube or one having multihumped characteristics. The method to be described here achieves the same gain-doubling result more simply with a pentode mixer.

Analysis

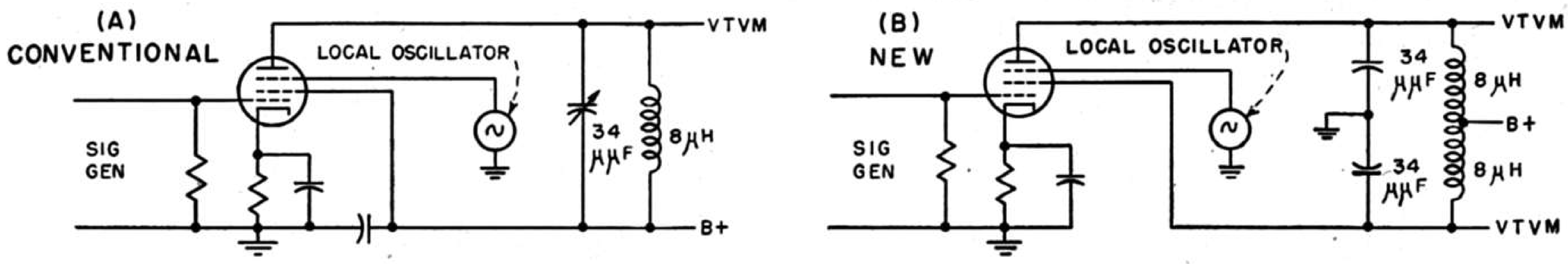
The conversion transconductance g_c of a mixer tube, when considering a small signal modulating a relatively large local oscillator signal of radian frequency ω, is

$$g_c = \frac{1}{2\pi}\int_{-\pi}^{+\pi} g_m \cos \omega t \, d(\omega t) \qquad (1)$$

Solution of this equation does not give maximum conversion transconductance because the negative portion of the cycle subtracts from the positive portion. However, if the integral is observed from $\pi/2$ to $-\pi/2$ only, we obtain g_m/π as the maximum positive limit for conversion transconductance with conventional mixing. These limits are achieved in a triode mixer by imposing sufficient oscillator voltage on the No. 1 grid to cut off the tube during the negative portion of the oscillator cycle. In conventional pentode mixing with the oscillator signal on an outer grid, the same limits are obtained by diverting the space current to an inner grid of the tube during the negative portion of the local oscillator cycle. The goal, however, is to double this transconductance value.

With conventional triode and pentode mixing, the i-f signal is obtained from a tube element that is cut off for half of the tube-operating period. If by some means the sign of the integral of Eq. 1 could be changed for this cutoff half of the oscillator cycle, then the conversion transconductance would be doubled.

Consider a pentode mixer in which the incoming carrier signal is applied to the No. 1 grid and the local oscillator to the suppressor (No. 3) grid. Since a pentode maintains essentially constant current in the screen-plate region, each increase in plate current due to oscillator modulation of the suppressor must be offset by an equal decrease in screen current. As a



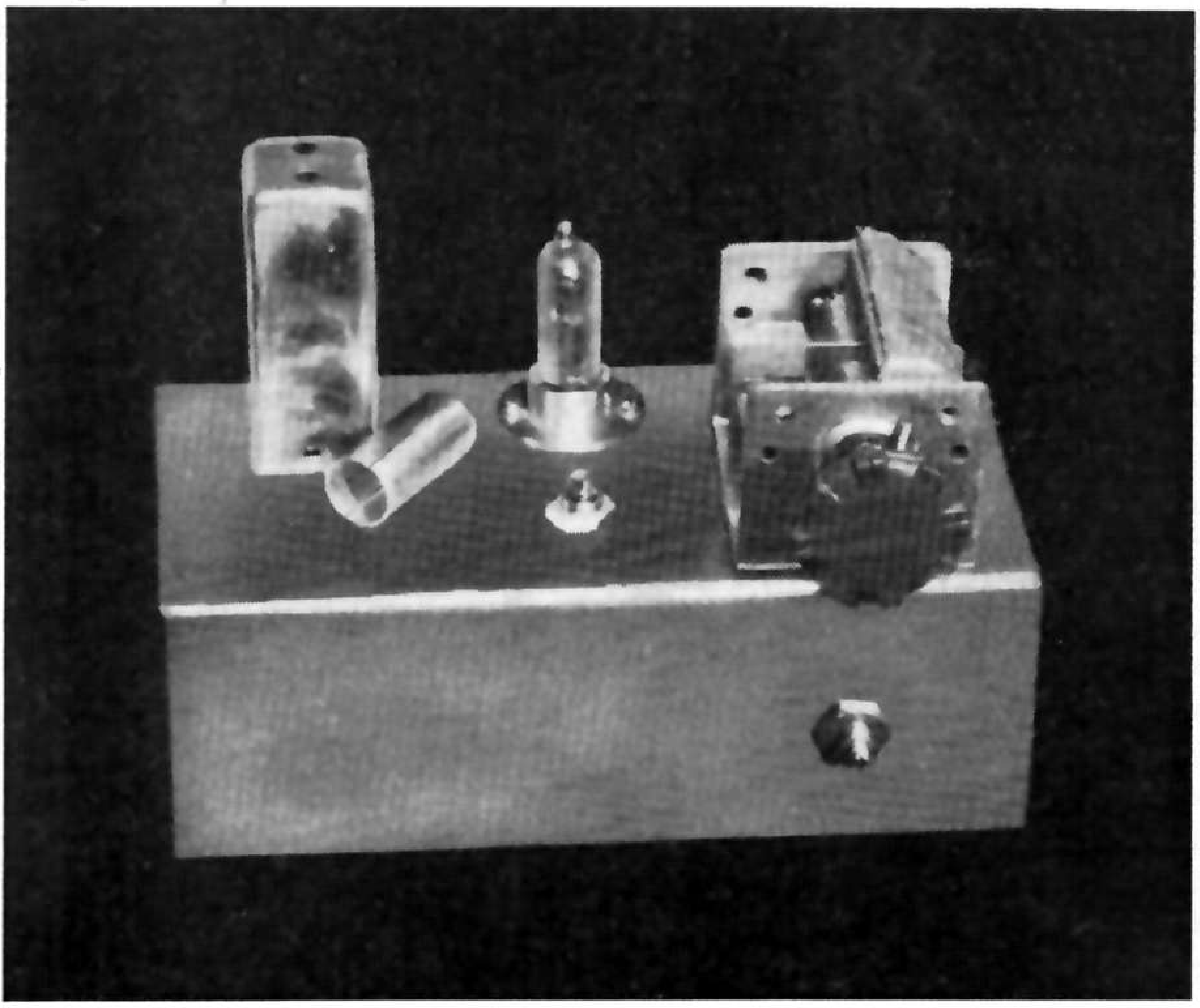
E_{osc} RMS VOLTS	I-F VALUE		GAIN A_3	$A_3 \Delta f_3$
	f_3 MC	Δf_3 MC		
2.5	9.5	0.440	10.5	4.60
5.0	9.5	0.383	11.5	4.40
7.5	9.5	0.348	12.4	4.32
10.0	9.5	0.340	12.6	4.29

E_{osc} RMS VOLTS	I-F VALUE		GAIN A_4	$A_4 \Delta f_4$	$\frac{A_4 \Delta f_4}{A_3 \Delta f_3}$
	f_4 MC	Δf_4 MC			
2.5	9.5	0.460	19.5	8.96	1.95
5.0	9.5	0.440	20.5	9.03	2.05
7.5	9.5	0.413	21.4	8.85	2.04
10.0	9.5	0.410	21.5	8.83	2.05

FIG. 2—Comparison of conventional single-tube pentode mixer circuit with improved method that eliminates screen bypass capacitor so tuned circuit is between screen and plate. Values of corresponding inductances and capacitances should be equal as indicated

Frequency Converters

By VERNON H. ASKE
Application Laboratory
Sylvania Electric Products Inc.
Kew Gardens, N. Y.



Subminiature pentode converter for broadcast band use, employing improved circuit of FIG. 5 to achieve more than twice the gain of a conventional 6BE6 circuit

result, the i-f components of plate and screen currents are 180 deg out of phase and can be added in a conventional push-pull manner to get twice the gain from the tube. Actually, the mere placing of a tuned circuit between the plate and screen changes the sign of the integral in Eq. 1 for half of each cycle to give the desired doubling of conversion transconductance.

Verification

Experimental verification of gain doubling with this frequency-mixing process is given in Fig. 1 and 2. Performance of a conventional balanced type mixer is presented in Fig. 1A and results for the new circuit, using the same tubes under the same d-c operating conditions, are in Fig. 1B. The tubes were developmental types with many-turns-per-inch suppressor grids. The oscillator voltage is used as a variable.

Since the voltage gain is inversely proportional to Δf and the two vary with oscillator voltage, the product of these two terms serves as a convenient means of comparison between the two systems. The last column of the tabulation in Fig. 1B indicates the ratio of $A_2 \Delta f_2$ for the new system to $A_1 \Delta f_1$ for the conventional system. These values center about a ratio of 2 to 1, which is predicted from the theory.

As a further check and comparison, the new frequency-conversion method was compared with the conventional method when using a single tube. Data for a conventional single-ended mixer circuit is given in Fig. 2A, and corresponding data for the new circuit in Fig. 2B. The ratios are again approximately 2 to 1.

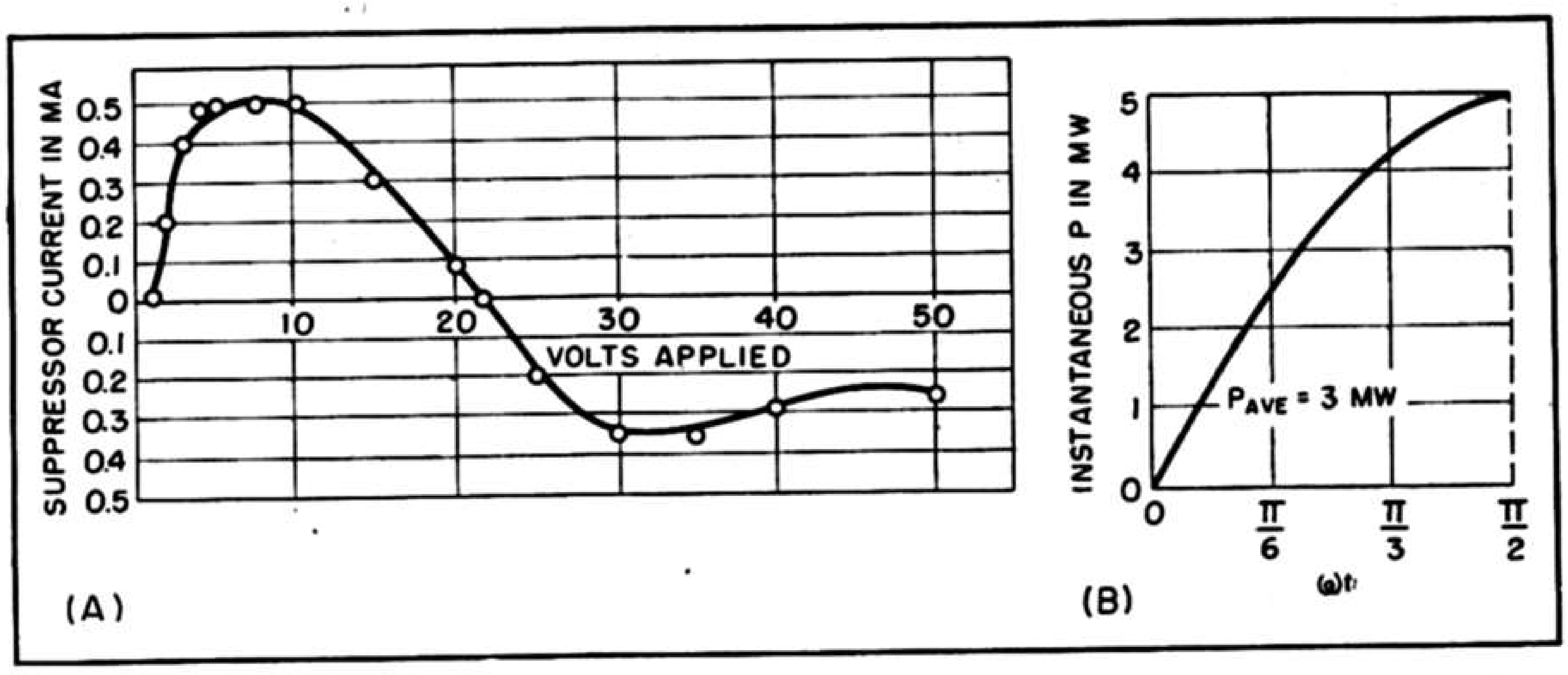


FIG. 4—Characteristic curves for No. 3 grid of typical experimental pentode

The foregoing data were obtained with the suppressor grid operating at zero d-c bias rather than the grid-leak bias that is usually employed. Operating the grid at zero bias results in a much greater peak g_m and thereby increases conversion transconductance. If sufficient oscillator voltage is impressed, the plate current is swung into saturation and g_c approaches the ideal value of approximately 32 percent of the peak g_m.

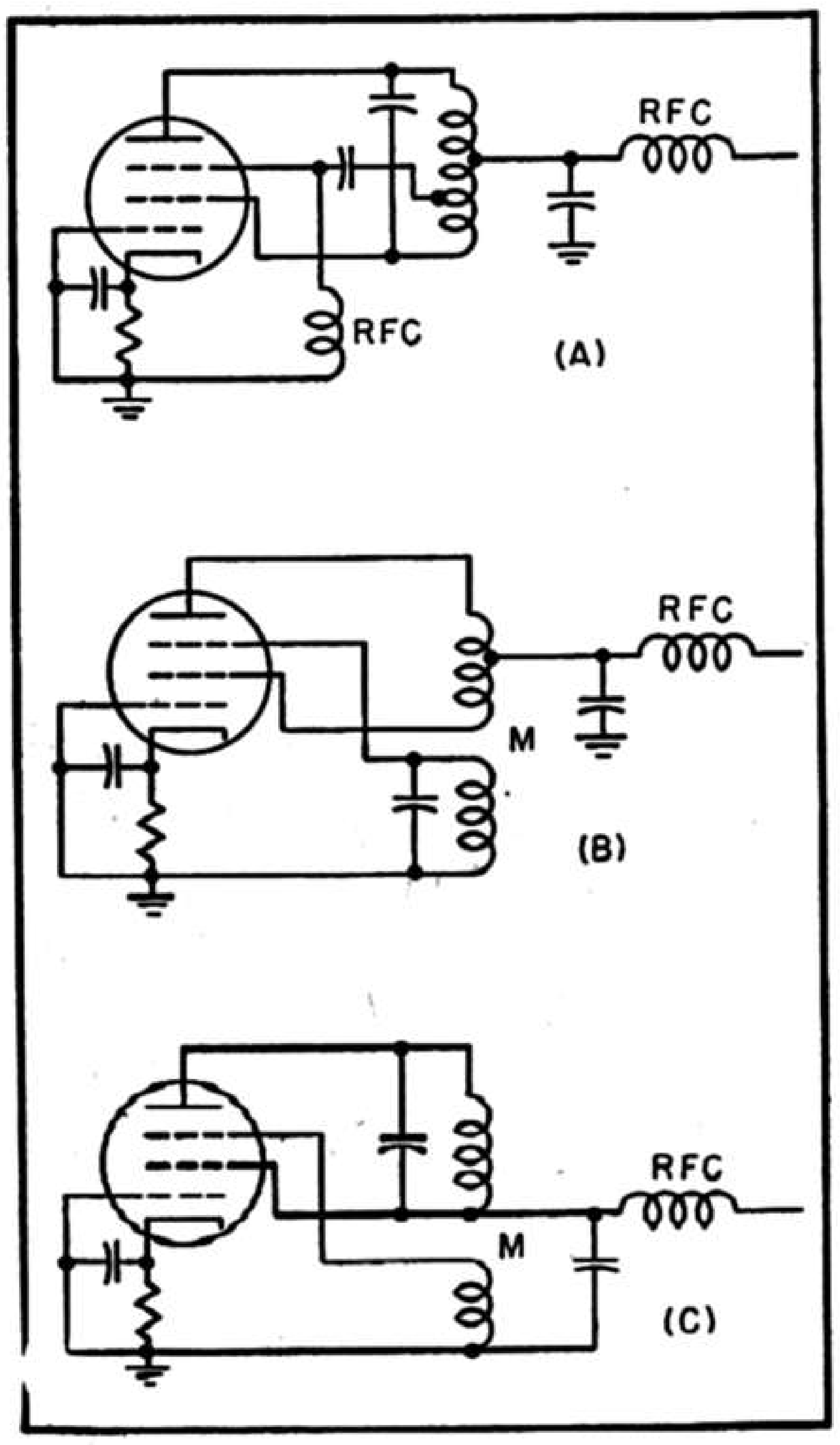


FIG. 3—Balanced and unbalanced oscillator circuits employing new gain-doubling technique

Isolation

Another interesting aspect of the circuit is the isolation it offers to signals that tend to pass through the mixer tube at the intermediate frequency. Isolation exists, since any signal on the No. 1 grid produces modulation of the same phase on the screen and plate currents, and will cancel out in the push-pull i-f transformer. This action makes it somewhat difficult to align the i-f by the usual manner of placing the i-f signal on the signal grid of the mixer tube. In this case the signal can better be placed on the oscillator grid. The degree of isolation is determined by the degree of balance in the primary of the i-f transformer and by the transconductance from signal grid-to-plate relative to the transconductance of signal grid-to-screen.

In a pentode we are mainly concerned with shot-effect noise and partition noise. The former is due to time-varying emission from the cathode, and the latter is due to random distribution of cathode current to the positive electrodes in the tube.

Noise Suppression

Assume an ideal pentode in which partition noise does not exist. Assume also that there is a push-pull connection between plate and screen, and that the screen and plate currents are precisely equal. The noise in the plate and screen would then be of equal magnitude and identical phase, disregarding transit-time effects. With a perfect output transformer, there would be no noise output from the tube, because of cancellation within this transformer.

Now, imagine another ideal pentode in which no shot-effect noise exists, but in which partition noise does exist. In this tube any noise variation that takes place in the plate circuit must be accompanied by an equal and opposite noise variation in the screen circuit, since space current is perfectly constant. Thus, if this push-pull connection has in some way doubled the effective transconductance, the equivalent noise resistance of the tube has not changed since the effective noise has also been doubled.

The pentode mixer circuit presented here is actually the combination of these two ideal cases. It therefore has somewhat smaller equivalent noise resistance in the circuit than does a conventional mixer, since the shot-effect noise has decreased while the affect of partition noise remains unchanged.

Converter Tube

In conjunction with this work on the mixer circuit, a program was also carried out to combine this circuit into a converter tube that performs the functions of mixer and local oscillator. In this converter, the outer space current oscillations that exist between the outer elements of a multigrid tube are utilized. The resulting converter circuit gives four times the voltage gain with 30 percent less cathode current relative to the 6BE6 converter. The equivalent noise resistance of this converter was below 18,000 ohms, which is less than one-tenth that of the 6BE6.

The tube characteristics most desirable for the oscillator are those of a pentode whose No. 3 grid-to-plate transconductance is relatively high. This No. 3 grid is used as the control grid, and the plate or screen as the oscillator anode.

The oscillator may be either the balanced or unbalanced type. In the balanced oscillator, shown in Fig. 3A and 3B, the plate-screen coil is center-tapped to r-f ground. This oscillator is suited to a balanced-type circuit since the current variations, as caused by No. 3 grid modulation, are 180 deg out of phase in the plate and screen. The plate voltage holds the same phase relationship to the controlling grid voltage as it does in a conventional oscillator.

For unbalanced operation, either plate or screen may be grounded to r-f as in Fig. 3C. Since the screen-plate current is nearly constant, the oscillations are confined to the outer space of the tube.

The No. 3 grid characteristics for a typical experimental pentode are shown in Fig. 4A. The negative resistance characteristic encountered above 10 volts tends to enhance oscillations. To find the required grid-driving power, a sine wave can be impressed on the suppressor grid and a time plot of current obtained from the grid characteristics. The product of instantaneous voltage and grid current is shown in Fig. 4B. A peak swing of 10 volts is used because this value produces plate current cutoff and is in accordance with characteristics that follow. The average power may be obtained by integrating the instantaneous power curve. The resulting average power is three milliwatts, which is very low and normally will be less than the associated circuit losses.

Converter Design

It is possible to calculate the tickler coil impedance required for a particular application. Suppose an oscillator is to be built at 20 mc in which a tickler coil is placed in the plate circuit to excite a tuned circuit connected to the No. 3 grid, and a total driving power of 15 milliwatts is required. The available exciting power is proportional to the external voltage drop, or in this case the reactive drop across the tickler coil. Then $P_{\text{exciting}} = I_{\text{eff}}^2\, \omega L = 15 \times 10^{-3}$. The effective plate current for the development tubes used is approximately 4 ma. The required tickler coil impedance is then $\omega L = 15 \times 10^{-3}/(4 \times 10^{-3})^2 = 938$ ohms.

These outer space current oscillations may readily be obtained from a pentode as used in Fig. 5 and 6, and the application of a signal to the No. 1 grid will result in a simplified converter. In each circuit, a tickler coil is placed in series with the i-f transformer primary to provide feedback to the No. 3 grid, which is tuned to the local oscillator frequency. In Fig. 5 the screen is grounded for r-f. Figure 6 represents a similar circuit in which the i-f is connected in push-pull between the screen and plate, and results in increased conversion transconductance.[1] The circuit of Fig. 5 is most useful in narrow-band applications, since the plate resistance in converter use is much larger than the effective plate-screen resistance. Conversely, Fig. 6 is more applicable to wide-band circuits.

The above circuits are operated with zero d-c bias on the suppressor grid. This type of operation is desirable since greater conversion transconductance will result owing to the larger peak plate current. A grid-leak bias on the grid of the oscillator is not necessary with the outer space current oscillator, as it would have little effect on the average current.

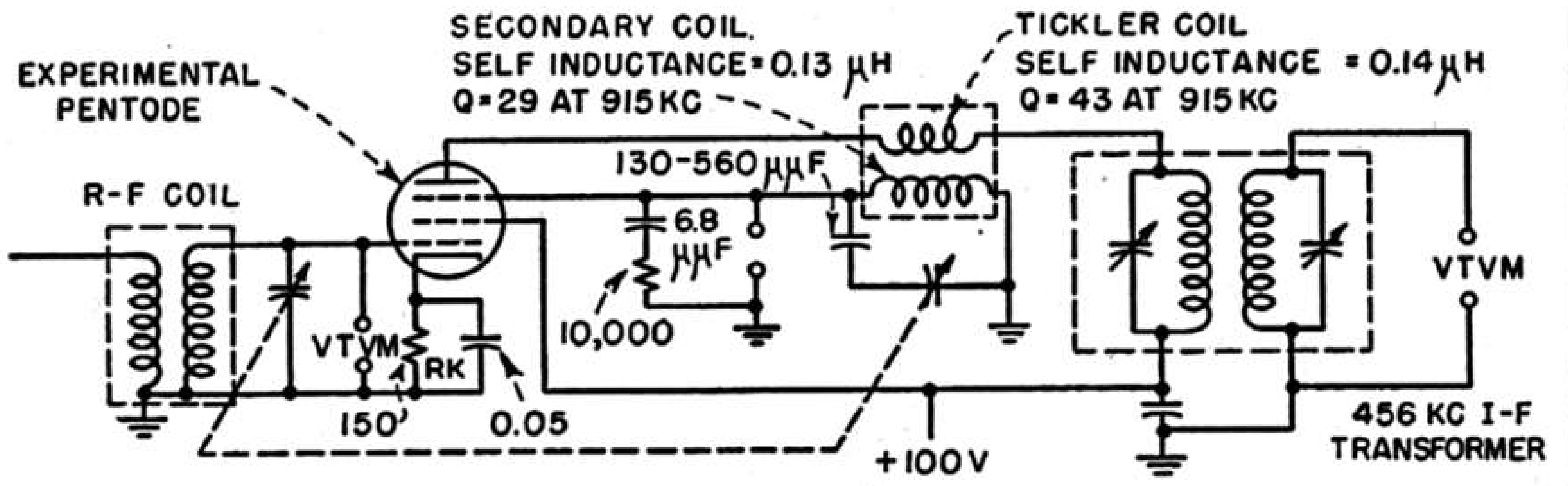
It is desirable that the peak swing be sufficient to produce plate-current saturation during the positive excursion of the local-oscillator cycle, and plate-current cutoff during most of its negative excursion, since these are the desired characteristics for maximum conversion transconductance.

Comparisons

The most important characteristics of a converter-type tube are probably (1) conversion transconductance, (2) plate resistance, (3) noise, (4) isolation between signal and oscillator circuits, which is indicative of antenna radiation, (5) voltage gain as a function of wide-range tuning, and (6) automatic volume control, which indicates the cutoff characteristics of a particular tube and any undesirable detuning effects. These characteristics will be discussed in connection with a comparison of the new high-gain pentode converter circuit of **Fig. 5** and a conventional 6BE6 frequency converter for the same narrow-band application (550 to 1,600 kc).

Before making comparative measurements, the oscillator voltage on the No. 3 grid was measured as a function of tuning. The oscillator voltage varied from 19 volts at 1,006 kc (the low end of the oscillator range) to 66 volts rms at the top frequency of 2,056 kc. This wide range of oscillator voltage is undesirable from the viewpoint of oscillator radiation, hence a series R-C circuit was used to load the oscillator. Values of 10,000 ohms and 6.8 $\mu\mu$f discriminate against the higher frequencies as desired to keep the range of oscillator voltage between 11 to 19 volts rms, which is within the practical limits of most converters.

Comparative sensitivity values are given in Fig. 5. With the experimental type pentode, the components were tuned for each individual measurement. The voltage gain was measured from the signal-generator terminals to the secondary of the i-f transformer. The i-f transformer used was designed as an output transformer, and consequently had closer coupling than that usually found in input i-f transformers. With the conven-



NEW CIRCUIT (ABOVE)			
f_{SIG} IN KC	GAIN	I_K IN MA	Δf IN KC
550	580	7.3	10.6
1,000	780	7.3	12.0
1,550	680	7.4	12.0

CONVENTIONAL 6BE6 CIRCUIT			
f_{SIG} IN KC	GAIN	I_K IN MA	Δf IN KC
550	140	11.0	11.8
1,000	320	10.5	11.8
1,550	300	10.5	12.1

FIG. 5—Narrow-band version of new converter circuit, suitable for broadcast band, and comparative performance data on conventional circuit

tional circuit, plate and screen voltages were 100 volts, and the signal grid was biased to −1.5 volts. The circuit was optimized for voltage gain.

The comparative data shows that greater than twice the voltage gain can be obtained with the pentode with 30 percent less cathode current. The increased voltage gain results from the increased conversion transconductance.

The conversion transconductance of the experimental pentode was approximately 1,200 μmhos. This conversion transconductance is easily determined for this type of operation by measuring the g_m of the signal grid with +10 volts on the suppressor grid, and taking 30 percent of this g_m value as the conversion transconductance. This is accurate to within a few percent.

The effective mixer plate resistance for the new type of operation is approximately three times the value measured for the tube as an amplifier. This value was 350,000 ohms for the development tubes used, as contrasted with 1 megohm for the 6BE6. The conversion transconductance of the 6BE6 is 475 μmhos.

Oscillator Radiation

Radiation back to the antenna from a converter tube depends on the capacitance and space charge coupling between the oscillator grid and the signal grid. In the circuit of Fig. 5, oscillator currents are confined to the outer space of the tube so there is little or no space-charge coupling. The capacitance from the signal grid to oscillator grid of the tube under these conditions is approximately 0.10 μμf, while the corresponding capacitance for the 6BE6 is 0.15 μμf. The relative coupling values from the oscillator to the signal grid at signal frequencies of 550, 1,000 and 1,550 kc are 0.01, 0.07 and 0.13 respectively for the 6BE6 and 0.01, 0.05 and 0.21 for the pentode.

The space-charge coupling within the tube acts with a 180-deg phase shift relative to the direct capacitive coupling voltage. In most converters, these effects are controlled so that they are approximately equal on the broadcast band. This is the reason that the coupled voltage is slightly less with the type 6BE6 in spite of the fact that its capacitance and space-charge coupling are greater.

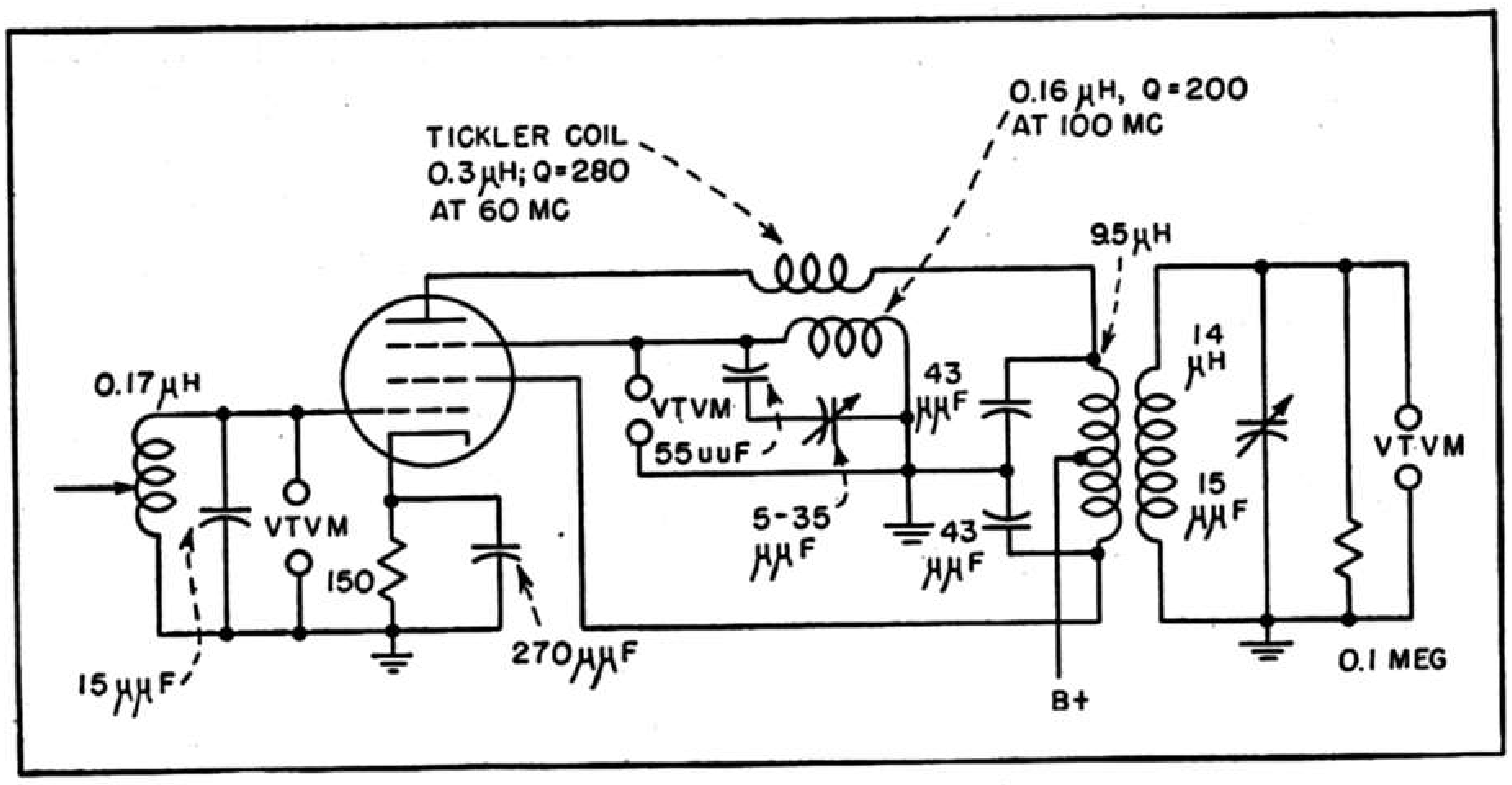


FIG. 6—Wide-band version of new converter circuit

AVC Action

The action of an avc voltage on the signal grid of the experimental pentode changes the oscillator amplitude as well as the signal-grid g_m. This gives accentuated avc action, and may require a very remote cutoff characteristic for proper operation. Since extensive bias will ultimately result in a reduction of oscillator grid g_m to the point where oscillations will cease, extended avc application (1,000 to 1 reduction of gain) is not possible in this new converter.

In conjunction with avc, it is important to consider the amount of frequency shift that results from its application. To obtain this relative measurement, the gain of the two systems was decreased by the same ratio, and the frequency shift of the oscillator section was measured. The results indicated that the frequency shift was comparable in the two systems, but in opposite directions; the frequency of the 6BE6 converter decreased with decreasing gain and the frequency of the new converter increased with decreasing gain.

F-M Converter Circuit

Modifications needed in the new converter circuit to meet the requirements of the f-m band are given in Fig. 6. The relatively wide bandwidth permits the use of a push-pull i-f and derives increased gain. At 100 mc the voltage gain from the grid through a double-tuned i-f transformer is 27.5. (The calculated gain of the 6BE6 under similar conditions is one-fourth this value.) The center of the i-f band is 10.7 mc and the bandwidth at the half-power points is 350 kc. The frequency drift of this oscillator circuit was compared with that of a triode in a Hartley circuit and found to be nearly equal. The converter had less frequency shift as a function of filament voltage, but more as a function of supply voltage.

Conclusions

Increased gain can be obtained by using a pentode tube as a converter, with the signal applied to an inner grid and the No. 3 grid used as an outer space current local oscillator. Four times the gain of the type 6BE6 may be obtained by using this less complicated tube, with 30 percent less cathode current. Simple tube construction, high conversion transconductance and low noise characterize this converter. The Sylvania type 5636 and SN1007B tubes are suitable for this application.

The author acknowledges the valuable assistance of B. F. Tyson and James Cooper who supplied measurements that confirmed the theory outlined here and John B. Grund of Sylvania's Emporium division, whose measurements in practical circuits contributed greatly to this project.

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