

July 3, 1945.

C. B. FISHER

2,379,513

ELECTRONIC AMPLIFICATION

Filed June 10, 1942

4 Sheets-Sheet 1

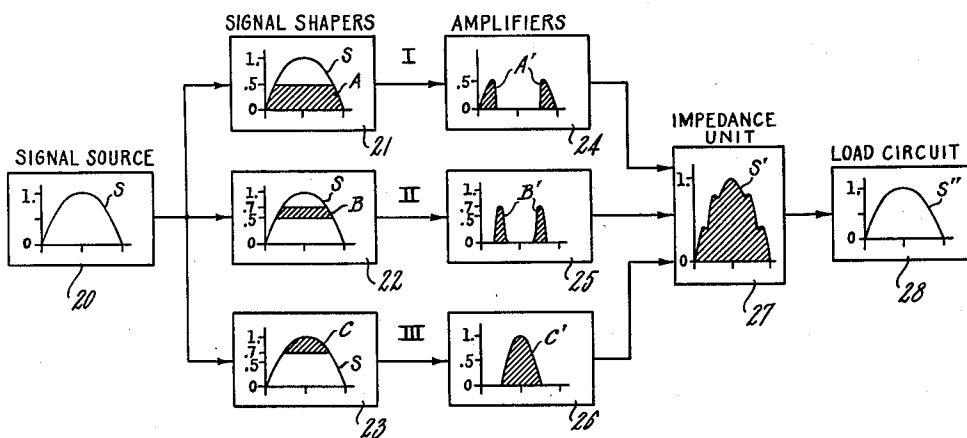


Fig. 1

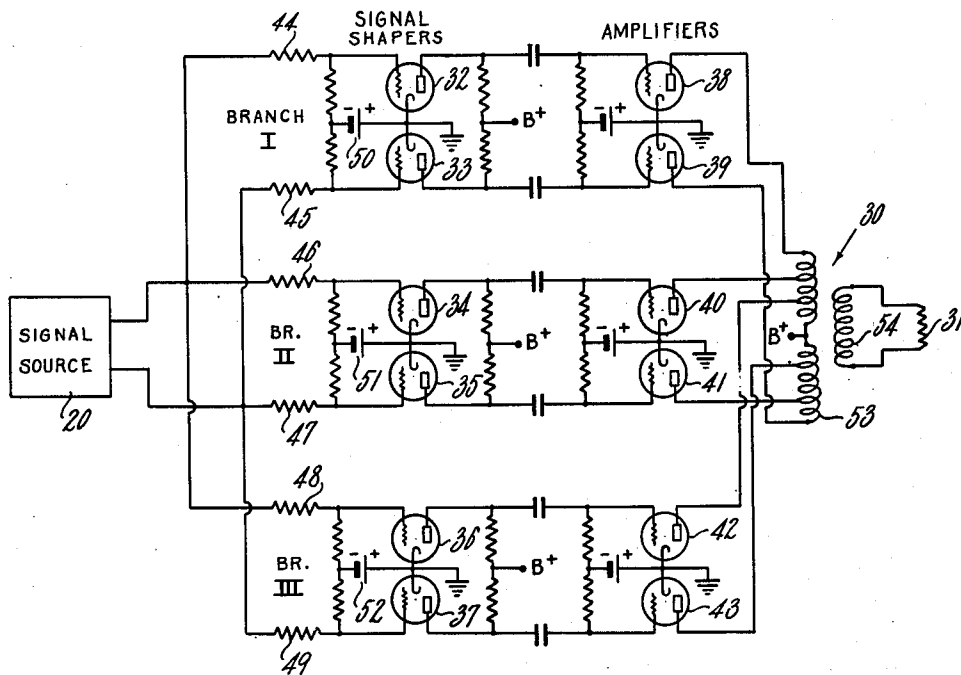


Fig. 2

INVENTOR.
Charles B. Fisher

BY

Sam A. Rosenthal

ATTORNEY

July 3, 1945.

C. B. FISHER

2,379,513

ELECTRONIC AMPLIFICATION

Filed June 10, 1942

4 Sheets-Sheet 2

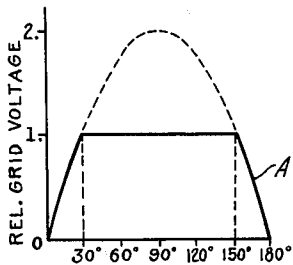


Fig. 3

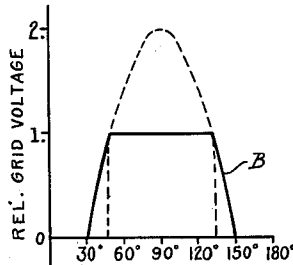


Fig. 4

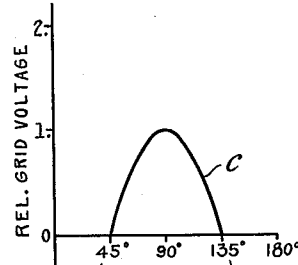


Fig. 5

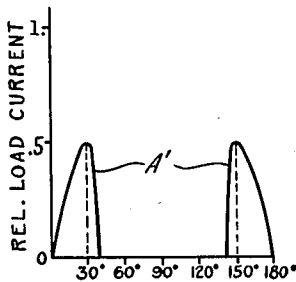


Fig. 6

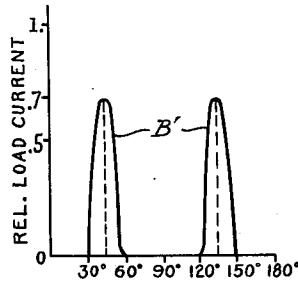


Fig. 7

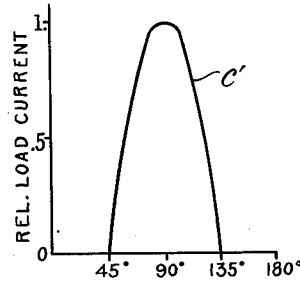


Fig. 8

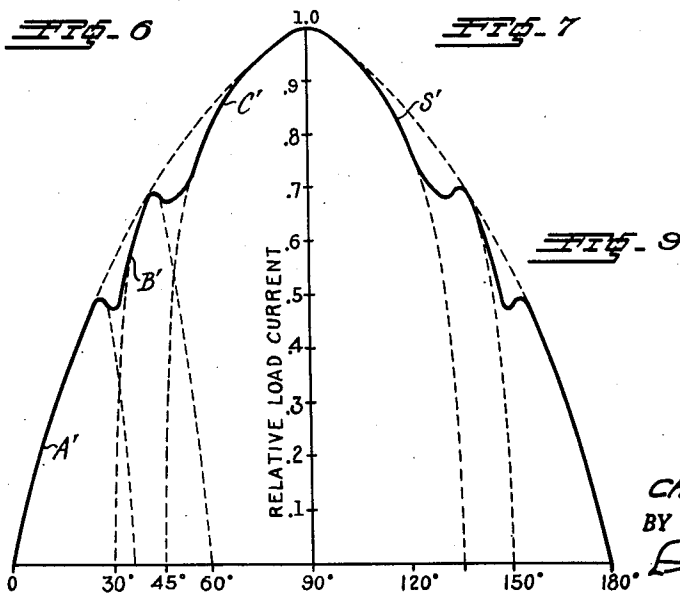


Fig. 9

INVENTOR.
Charles B. Fisher

BY
Dan A. Brantley

ATTORNEY

July 3, 1945.

C. B. FISHER

2,379,513

ELECTRONIC AMPLIFICATION

Filed June 10, 1942

4 Sheets-Sheet 3

FIG. 10

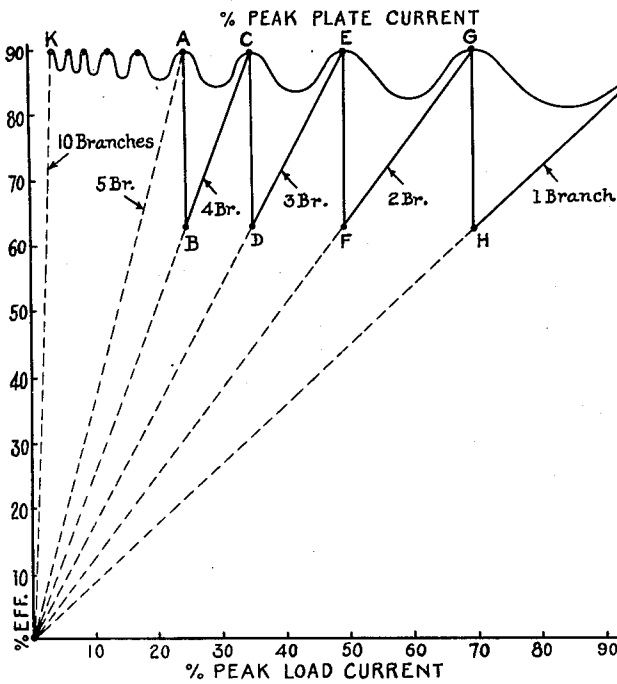


FIG. 11

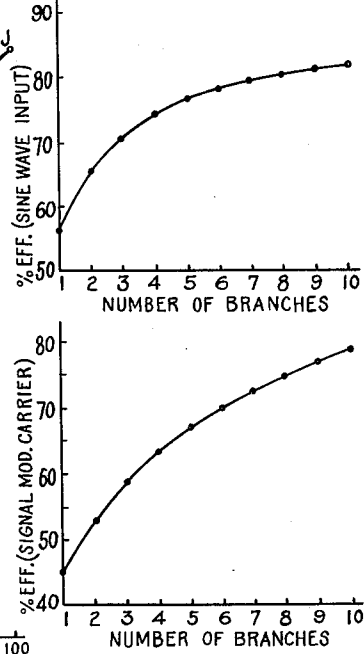


FIG. 12

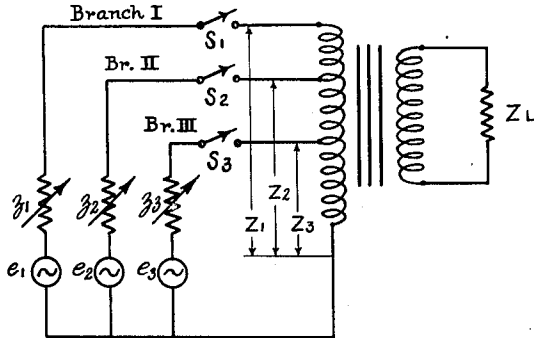


FIG. 13

FIG. 14

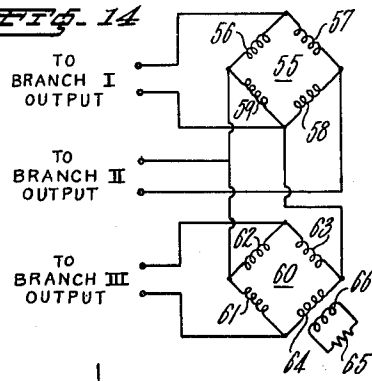


FIG. 17

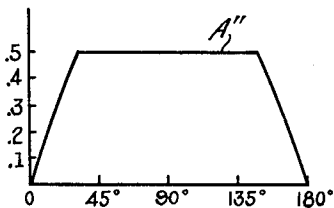


FIG. 15

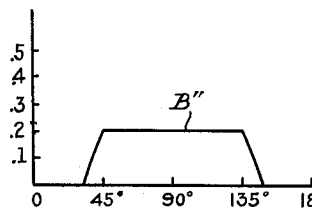
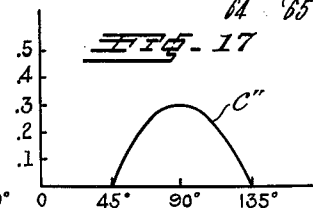


FIG. 16



INVENTOR.
Charles B. Fisher

BY

Don A. Penhall

ATTORNEY

July 3, 1945.

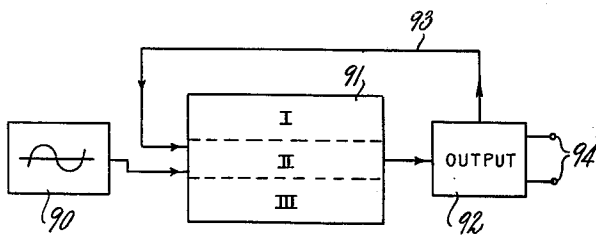
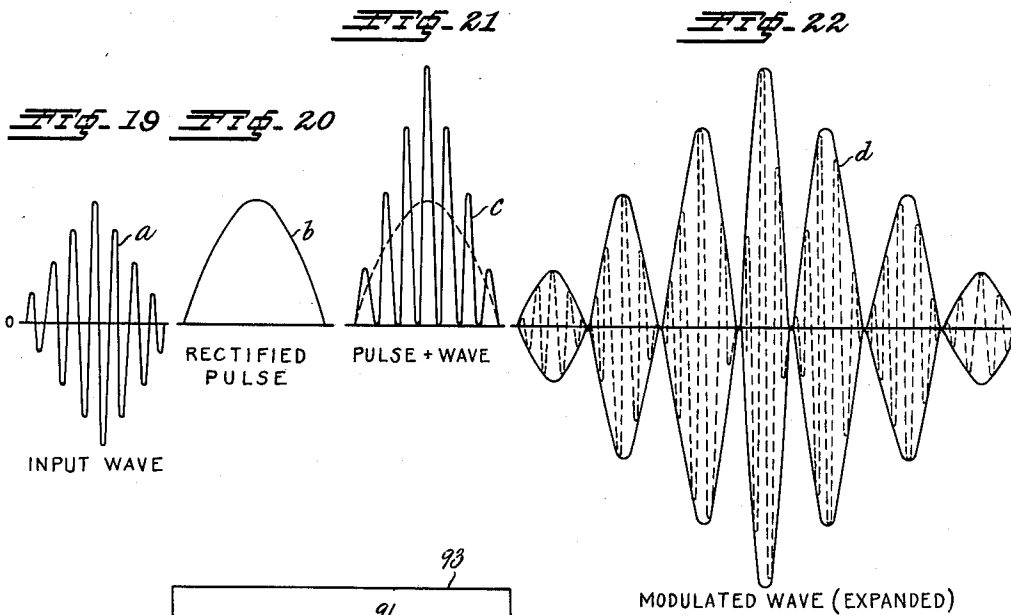
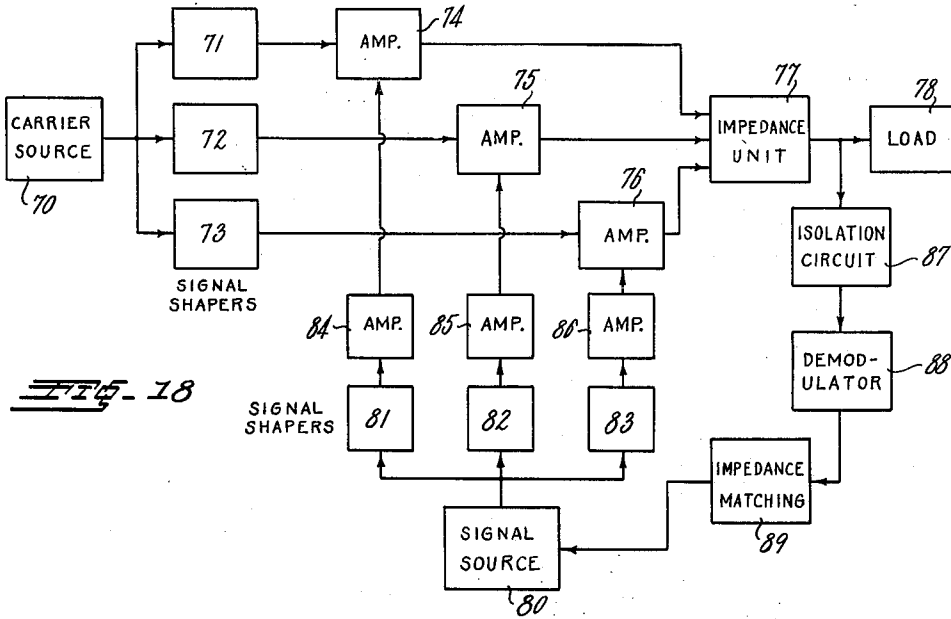
C. B. FISHER

2,379,513

ELECTRONIC AMPLIFICATION

Filed June 10, 1942

4 Sheets-Sheet 4



MODULATED WAVE (EXPANDED)

INVENTOR.
Charles B. Fisher
BY

Don A. Renschel
ATTORNEY

UNITED STATES PATENT OFFICE

2,379,513

ELECTRONIC AMPLIFICATION

Charles B. Fisher, Washington, D. C.

Application June 10, 1942, Serial No. 446,436

10 Claims. (Cl. 179—171)

This invention relates to electronic amplifiers and more particularly to a novel method of and means for substantially increasing the efficiency of operation of vacuum tube power amplifiers.

The present invention is generally applicable to audio frequency and radio frequency circuits incorporating linear power amplification. The increased efficiency of power amplification by the invention may be used for amplifying carrier waves, modulating signals, or signal-modulated carrier waves, for the generation of radio waves by the oscillation principle, and so forth. The well known class B type amplifier is used where high efficiency linear power amplification is desired. However, the plate-circuit efficiency of such amplifiers depends upon the magnitude of the signal voltage, since the efficiency is substantially proportional to the ratio of the signal voltage output to the applied direct-current voltage. Where the signal is of variable amplitude, the average efficiency of the power amplification by such prior-art systems is relatively low. Where, however, the signal is at a constant maximum, higher efficiency values for the class B and C amplification result, ranging in practice from 40 to 65%.

In accordance with the present invention, a substantially higher power-conversion efficiency is afforded than by class B linear amplification. The invention is particularly useful for signal-modulated carrier-wave amplification, where the modulating signal is of a varying amplitude, as occurs for example in speech. A plurality of parallel amplifying paths or branches are provided for individually amplifying separate portions of the impressed signal. Each amplifier is responsive only to a predetermined magnitude level or portion of the impressed signal, thereby selectively amplifying sections of the signal. The outputs of the amplifiers are combined to reconstruct the original impressed signal wave form. Each of the amplifier branches is preferably biased for class B amplification, as will be hereinafter set forth in detail. Thus, each of the parallel amplifier branches is operated at a signal value corresponding to its maximum capacity, and correspondingly amplifies its signal portion at the maximum operating efficiency the amplifier branch is capable of. When no signal portion is impressed on an amplifier branch no di-

rect current energy is dissipated therein. The overall result for the system is accordingly an amplification efficiency substantially higher than heretofore possible in practice. Practical examples and applications thereof are described in detail hereinafter.

It is well known that the maximum power-handling capacity of any vacuum tube is ordinarily limited by the maximum permissible values of its average and peak plate currents, its peak plate voltage, and its average plate power dissipation capacity. If the efficiency of its average plate power dissipation is for example increased from 50% to 75% as is feasible by the invention, the power-handling capacity of the vacuum tube is doubled. Since, in accordance with the present invention, the average plate current is much closer to the peak plate current than in conventional amplifiers, it has been found that in practical embodiments of the invention such double power output from a given tube complement is readily obtained as compared to conventional circuits. This is of substantial advantage in high power installations from the standpoint of cost. In lower power mobile radio transmitting equipment a substantial reduction in space and weight requirements is afforded. The invention system results, for amplifiers of about one-third, and for transmitters of about one-half the conventional space and weight requirements. This is due mainly to a substantial reduction in the heat dissipation of the tubes and for other reasons to be later set forth. The present invention has been found more economical than conventional arrangements for amplifiers or transmitters having power outputs greater than about 100 watts. The principles of the invention are useful for all commercial and military communication services, including point-to-point and trans-oceanic telephony, civilian and military aviation, and other services in general.

These and further advantages, capabilities and objects of the present invention will become more apparent from the following detailed description of preferred embodiments thereof, illustrated in the accompanying drawings, in which:

Fig. 1 is a schematic diagram illustrating the principles of the invention; Fig. 2 is a circuit diagram of one embodiment which the invention may assume in practice; Figs. 3 to 9 are curves

used in describing the principles and operation of the invention; Figs. 10 to 12 are curves representing efficiencies of amplification for varying numbers of amplifier branches; Fig. 13 is a schematic output impedance-matching diagram for the form of the invention shown in Fig. 2; Fig. 14 is a circuit diagram of a modified output coupling unit, for the circuit of Fig. 2; Figs. 15 to 17 are curves used illustrating the operation of the modified form of the invention corresponding to Fig. 14; Fig. 18 is a schematic diagram of a further application of the invention; Figs. 19 to 22 are curves illustrating one mode of operation of the system of Fig. 18; Fig. 23 is a block diagram of an oscillator employing the circuit of Figure 2.

Fig. 1 schematically indicates the principle of the present invention. Signal source 20 of a wave form S is shown applied to the input of a plurality of "signal shapers" 21, 22, 23. A sinusoidal wave shape is used for S for simplicity of presentation. The invention is of course applicable to any wave form. The signal shapers are units arranged to divide the input signal S into separate components as A, B, C respectively. Such division is effected by suitable circuit arrangements to be described, whereby predetermined sections of the wave S are passed through the respective branches I, II, III of the system. The branches have individual amplifier units 24, 25, 26.

The wave forms A', B', C' passed through amplifiers 24, 25, 26, result from the corresponding introduced sinusoid sections A, B, C for one form of circuit coupling. The outputs of the amplifiers 24, 25, 26 are impressed upon an impedance unit 27, across which the signal components A', B', C' combine substantially to reconstruct the original wave shape. The re-formed wave shape S' is shown as containing harmonic components. For many applications a minor harmonic content is not objectionable. However, by use of suitable filters or degenerative feed-back, such harmonics may be reduced to any extent desired. The load circuit is connected to impedance unit 27 and receives the signal indicated at S'', corresponding to the input wave form S, and without the harmonics if desired.

Fig. 2 is a circuit diagram of one form which the invention may assume in practice. This form comprises the three branches I, II, III. The input circuit of each of these branches is connected to the signal source 20. The outputs of the branches are coupled to a transformer unit 30. The output of transformer 30 is connected to load 31. Load 31 may be a suitable translating device, such as a radiation circuit, as will be understood by those skilled in the art. The branch circuits are preferably designed in push-pull arrangement, namely with opposed pairs of tubes for each portion. The signal shapers comprise triodes 32, 33 for branch I; 34, 35 for branch II; and 36, 37 for branch III. The amplifiers similarly comprise triode paths 38, 39 for branch I; 40, 41 for branch II; and 42, 43 for branch III. Triodes have been shown for simplicity. However, pentodes or other suitable vacuum tubes may instead be used.

The amplifier units are connected in a conventional manner, and are coupled to the outputs of the signal-shaper tubes by the indicated resistance-capacity coupling. Input resistance units 44 to 49 are provided in pairs for the respective branches. The resistances are of such values as to give the required voltages in each of the three

branches into which the circuit is divided. The amplitude of the voltage applied to branch I is controlled by resistances 44, 45; to branch II, by resistances 46, 47; and to branch III, by resistances 48, 49. Direct-current grid-bias potentials 50, 51, 52 are provided for the grid circuits of the respective signal-shaper portions. The division of the applied signal from source 20 to the grid electrodes of the signal shapers of the respective branches is accordingly predetermined by the values of the respective resistances 44, 45 and bias 50 for branch I; resistances 46, 47 and bias 51 for branch II; and resistances 48, 49 and bias 52 for branch III.

It is thus feasible to divide the applied signal into three predetermined sections which, when amplified and recombined, reform the original wave shape. In accordance with the invention such division of the input signal is made so that each of the resultant waves is of such form and amplitude that it is transmitted through the amplifier units of the respective branches with substantially higher efficiency than in the original wave shape. The overall efficiency obtained is accordingly substantially higher than heretofore possible with prior circuits. This condition can be derived in a number of ways to attain the objects of the present invention. One of such methods which has been found satisfactory will now be set forth in detail.

For the three-branch embodiment illustrated in Fig. 2, the ratio of the maximum power outputs of the respective branches is designed to be 1:2:4 for the branches I, II, III. That is to say, the load currents from the three branches are in the ratios 1:1.4:2. These outputs are applied to the primary winding 53 of transformer 30. The output of branch I is shown connected across the outer terminals of primary winding 53; the output of branch II, across an intermediate section of winding 53; and the output of branch III, to the central section of winding 53. The taps on the output-transformer winding 53 are selected to suit the respective branches so that each pair of output tubes connects into an appropriate load impedance. Also, each of the output tube pairs 38, 39, 40, 41 and 42, 43 is biased to the point where the anode current thereof is normally reduced to zero. The amplifier units are accordingly operated as class B or class C amplifiers. The tube pairs comprising the signal shapers are essentially driver stages for the respective amplifiers, and are used to shape the signals impressed thereon from source 20 for the grid electrodes of the power-amplifier tube units.

Figs. 3, 4 and 5 illustrate preferred wave forms of the voltages passed by the signal-shaped portions to the inputs of their corresponding amplifiers. The principles of the invention are for the sake of simplicity illustrated in connection with an original signal having a sinusoidal wave shape. Figs. 3, 4 and 5 are curves representing a manner in which the original sinusoidal signal S is divided by the signal shaper portions of the three branches I, II, III. The forms of the waves in these figures are drawn to have the same amplitude, which condition is, however, not essential. In a circuit in which it is desired that no grid current shall flow in the power amplifier tubes, the maximum value of the wave impressed upon the grid electrodes of the respective power-amplifier units is the value of their respective grid-bias voltage, or the value which will result in maximum permissible plate current for the tubes, whichever is less. However, in a circuit where

grid current is permissible, the peak grid drive impressed upon the amplifier units is adjusted so that the maximum plate current is obtained.

The invention takes advantage of the well known fact that a vacuum tube amplifier unit will operate at its maximum effective efficiency, when the amplitude of its input or driver signal is at the peak value and the plate current of each of the tubes is transmitting its peak current value. In a conventional class B or class C amplifier an efficiency of the order of 90% is realized at the moment when it is delivering its instantaneous peak output, this efficiency being the ratio of the peak output voltage to the D. C. input voltage for the tubes. Thus, if a considerable portion of the output energy is transmitted while the tubes are operating at such peak current points, then the whole output power of the tubes is obtained at a relatively high efficiency. In accordance with the present invention, the respective branches are designed with signals impressed upon their amplifier units to operate close to their peak current ratings, resulting in a higher operating efficiency for the system than heretofore obtainable. The signal-shaping circuits are arranged to divide the input signal into signal sections having relative amplitudes corresponding to the relative peak power outputs of the amplifier sections.

In practice I have found that a 3 decibel (db.) separation or current ratio between adjacent branches is a satisfactory and practical one. Thus, the load-current ratio for the respective power amplifier units for the three branches would be in the ratio of 1:0.7:0.5 for branches I, II, III. The load currents for the system are divided among the three branches in this manner. For the sine-wave signal S, branch I will pass signal section A as indicated in Figs. 1 and 3. Resistances 44, 45 and bias 50 of branch I are designed so that it will pass all portions of the input signal S below 0.5 in relative amplitude; section A thus corresponding to one-half of the applied signal amplitude. The next 3 db. amplitude range, namely from 0.5 to 0.7 is transmitted by branch II, corresponding to signal section B shown in Figs. 1 and 4. Resistances 46, 47 and bias 51 of branch II are designed so that driver tubes 34, 35 pass only a signal corresponding to section B from the impressed signal, and no other portion. Finally, the third 3 db. signal section, corresponding to C and lying between 0.7 and 1.0 in amplitude, is transmitted only by branch III. Resistances 48, 49 and bias 52 for signal-shaper tubes 36, 37 of branch III are designed to pass only the corresponding 3 db. current section C.

It is to be understood that the invention is not limited as to the branches or to the signal intervals. Thus, if 3 db. intervals are used between adjacent branches, and there are more than three branches, the relative current values below 0.5 would be handled by more than one branch. Also, the interval ratio between the signal sections for the branches may be as much less than 3 db. as desired, with the use of a correspondingly larger number of branches. Furthermore, the interval ratio of the signal sections between adjacent branches need not be the same as that between any other adjacent branches. A high efficiency system still results with a ratio interval of more than 3 db.

The particular ratios for the signal sections are determined in practical design by the ratings of available tubes used, and also by the average

configurations of the wave shapes to be amplified. If the volume range is large, and during the major portion of the time the wave has a relatively small amplitude, then there preferably should be a relatively large interval between the maximum current-capacity of the highest branch and the adjacent branch. Also, there preferably should be a relatively small interval between the lowest-power branch and the branch adjacent to it, with the intervening intervals having intermediate values. Such a general scheme is preferred for a signal amplitude-modulated carrier wave. On the other hand, where the range of amplitude variation is small, and the wave is at or near the peak value for the greater part of a cycle, then the interval between the highest-power branch and the adjacent branch is preferably relatively small, and the lowest-power branch should preferably handle a relatively large current. Other factors remaining equal, there is generally more justification for a relatively large number of branches in the first category referred to herein, and for a relatively small number, possibly only two, in the latter case.

The grid biases 50, 51, 52 for the respective signal-shaper circuits for push-pull driver tubes, are adjusted to provide conventional class B operation. Also, the respective gains of the signal-shaper drivers are adjusted in conjunction with the plate coupling resistances so that the peak power is used to cause plate-current saturation in their respective coupled power-amplifier units. As the input signal from source 20 progresses from 0° phase angle to 30°, the circuit is such that only branch I conducts, the other driver tubes being biased too far down to permit any plate current to then flow in the other branches. Fig. 3 shows the relative signal thus passed by the signal shaper section of branch I.

Fig. 6 shows the corresponding current passing through the plate circuit of the corresponding power-amplifier tubes 38, 39 of branch I. At the 30° phase angle, the power-amplifier tubes 38, 39 will have reached their maximum current rating, and at this point also the power-amplifier tubes 40, 41 of branch II begin to conduct. This causes a much higher resistance to be reflected back to the power-amplifier tubes 38, 39 of branch I, and their load current promptly drops off in the succeeding few degrees to almost zero, as indicated in Fig. 6. The branch II power-amplifier tubes 40, 41 at the same time then rapidly rise to their peak current, reaching the 0.707 relative value at a phase angle of 45° as seen in curve B' in Fig. 7. The signal section B of Fig. 4 is seen passing into driver tubes 34, 35 between the 30° and 45° phase angular relations, and levelling off at 45° with the relative signal grid voltage at one-half the peak value for signal S. At this point also, the branch III tubes start conducting, and the output current of branch II rapidly drops off as a result of the much higher load impedance thereupon presented to the branch II output.

Curve C' of Fig. 8 illustrates the relative load current passing through output tubes 42, 43 of branch III, reaching its maximum current rating at the 90° phase angle position, and decreasing to zero at about 135°. When signal C' reduces to zero, there results a reduction in the load impedance reflected into power-amplifier tubes 40, 41 of branch II, which almost immediately start to conduct at their maximum current value, as indicated in Fig. 7. As it reduces in value with the advance of the phase angle, the plate current B' of the tubes of branch II ap-

proaches zero at about the 150° position. Thereupon, the load impedance reflected into the output of branch I is rapidly reduced permitting amplifier tubes 38, 39 to conduct and complete the wave form A' of Fig. 6 at 180°. It is to be understood that the relative signal-shaping actions resulting in the signal sections for the branches are correlated with the output currents of the branches, and the respective reflected impedance efficiently to produce the corresponding wave form therefor.

The functioning of the output transformer in reflecting the resistances between the outputs of the respective branches may be better understood by reference to the schematic diagram of the system represented by Fig. 13. This schematic circuit is an idealized representation of the three branches of Fig. 2. The impedances of the respective branches are indicated at z_1, z_2, z_3 . The load resistance is Z_L . The signal voltage of the respective branches are indicated as e_1, e_2, e_3 . The impedances of the respective sections of the transformer coupled to the branches are indicated as Z_1, Z_2, Z_3 . The switches indicated at S_1, S_2, S_3 represent the operation of the signal shaping sections of the respective branches. Assume switch S_1 closed and switches S_2 and S_3 open. The voltage at tap Z_2 is equal to

$$e_1 \sqrt{\frac{Z_2}{Z_1 + Z_2}}$$

Now, if switch S_2 is closed, and the voltage of Z_2 delivered by branch II is slightly greater than this, then the voltage appearing at Z_1 will be raised slightly and the current flowing into z_1 is no longer the former value of

$$\frac{e_1}{z_1 + Z_1}$$

but is equal to

$$\frac{e_1 - e_2}{Z_1 + Z_2}$$

where e_2 is the back voltage at the tap Z_1 . The corresponding current i_1 in branch I is reduced as voltage e_2 increases. When voltage e_2 becomes equal to e_1 , current i_1 in branch I becomes zero. Thus, the impedance of the transformer winding facing branch I approaches infinity. This same process is repeated for the transition between branch II and branch III.

The output signals from branches I, II, III impressed upon the primary 53 of the output transformer 30 combine to induce the resultant signal S' in the secondary winding 54, and at load 31. Fig. 9 shows the resultant signal S', substantially corresponding to the sinusoidal input signal S in wave shape. The signal components A', B', C., corresponding to the curves of Figs. 6, 7 and 8 are integrated to form the signal S'. The wave form of S' has a high frequency harmonic content. As the number of branches for the system is increased above three, the order of the harmonic content correspondingly increases. However, the amplitude of the corresponding harmonic decreases substantially inversely proportionately therewith. It is to be noted that for most applications to which the present invention is indicated, such amount of distortion, in practical designs lying between 6% and 14%, is tolerable. In practice it is known that a distortion content of 20% is tolerable for commercial and military communication services, such as point-to-point and trans-oceanic radio telephony, civil and military aviation, tank radio, and other military and naval applications.

Where low-distortion systems are required, the well-known principle of degenerative or negative feed-back may be employed to reduce the harmonic content of the output wave form to any desired value. The application of negative feed-back is indicated in the form of the invention disclosed in connection with Fig. 18. It is to be noted that the frequency range required to be transmitted with little discrimination between the plate circuit of the signal shaper or driver tubes and the input circuit of the power amplifier tubes is more strict than for other systems of amplification in view of the non-sinusoidal wave form of the signal sections. In practice, the use of a plurality of branches in the system design does not involve difficulties as to unequal amplification. In the first place, all branches are subject to the same gain-determining factors, such as temperature, humidity, aging, atmospheric pressure, etc. In any event, the use of negative feed-back counteracts any distortion which might tend to occur in this connection.

The signal-shaping portion of the respective branches may be provided in different form than that illustrated in Fig. 2. For example, three-electrode gaseous conducting "trigger" tubes of the Thyatron type could readily be adopted for this purpose. The grid electrodes of the Thyatrons are biased so that conduction therethrough would start at the desired phase angle of the input wave. Also, in order that the Thyatron would become extinguished at the required phase angle of each cycle, it is necessary, for example, to supply them with a relatively high-frequency anode power supply, such as 50-kilocycle current. In such a case, the combined output current must be rectified so as to pass only the signal frequency, rejecting the 50-kilocycle signal and the associated high frequency components. On the other hand, it is also feasible to set up the signal components of the input wave by means of mechanical contacts.

With such alternative arrangements it is possible to obtain a resultant wave form somewhat more preferable than that illustrated at S' in Fig. 9. A still further arrangement for the signal-shaping action is to use the input circuit of the power amplifier tubes of each branch to shape the signal pulses. This may be accomplished by adjusting the amplitude of the input wave, and the grid bias of the power amplifiers, so that the plate current cut-off is obtained at the requisite signal phase angle, and the peak grid voltage is of the required value to produce maximum permissible plate current, or by using the plate current of branch I to reduce the bias of branch II power amplifier tubes and thereby bring them into operation at the required time. What is significant in the present invention is the resultant division of the original signal wave form on an amplitude basis into component sections by suitable means, namely by the "signal shapers"; which component signal sections can be amplified and transmitted by separate amplifiers each operating at relatively high efficiency.

Fig. 10 illustrates the power efficiency of the invention system for different numbers of branches. The curve of Fig. 10 is based upon 3 db. intervals between the branches. The efficiency is plotted on the vertical coordinate and is equal to the ratio of the peak output signal voltage to the direct current plate voltage, expressed in percent. The horizontal coordinate is a percentage scale. One hundred represents the maximum amount of plate current of the

highest power branch. Line OHJ shows the efficiency of this highest power branch alone, operating on a sine-wave input. When two branches are used, the efficiency rises to a maximum at 70.7% on the horizontal scale, the point at which the lower power branch reaches its maximum output circuit. This produces the line OFG. If the lower-power branch is dropped out immediately at point G, the efficiency would drop to point H, the point on the higher-power branch where the current is 0.707 of the peak value, and then would rise along the line HJ. In practice, however, the lower-power branch continues for a short time to deliver power at a relatively high efficiency, and the resulting efficiency follows that shown by the curved line GJ. A similar process is involved as additional branches are added to the system, resulting in the following efficiency characteristics:

Efficiency curve for three branches=OEGJ
 Efficiency curve for four branches=OCEGJ
 Efficiency curve for five branches=OACEGJ
 Efficiency curve for ten branches=OKACEGJ

If an input wave having a sinusoidal form is impressed on systems with different numbers of branches, different average efficiencies of transmission will result. The manner in which the efficiency thus varies is shown by Fig. 11. This curve is readily obtained by averaging over one cycle the efficiency of a sine wave with a peak value coinciding with 100 on the horizontal scale of Fig. 10. Fig. 12 shows a similar efficiency characteristic for a signal corresponding to a sine-wave signal-modulated carrier signal. It is to be noted that Figs. 11 and 12 apply only to systems wherein there is a 3 db. interval between the respective branches. It is to be understood that the efficiency values indicated herein can be appreciably improved by a suitable adjustment of the maximum current ratio between the branches, as hereinabove set forth. The curves of Figs. 11 and 12 indicate the large improvement in efficiency which the present invention makes possible. The data represented by these curves has been verified experimentally, and in all cases the efficiencies measured have been slightly greater than these theoretical curves show. This may be explained by the slight variations in the shapes of the curves joining the points of peak efficiencies in Fig. 10.

The usual efficiency of a conventional class B amplifier is about 50% for a sine wave output. A class C amplifier has a higher efficiency than the class B case but is not linear and accordingly is suitable only as a carrier amplifier. For three branches, the present invention affords an efficiency of the order of 70%; for ten branches 80% as seen in Fig. 11. A conventional class B amplifier has an efficiency of about 33% for a 100% modulated wave. This compares with about a 50% efficiency for a class C carrier amplifier, plate-modulated by a class B signal amplifier, and about a 60% overall efficiency for the modulated wave amplifier exemplified by U. S. Patent No. 2,210,028 of W. H. Doherty. However, the Doherty amplifier has the disadvantage of a complicated load circuit which is operable only at a single carrier frequency. The efficiency of the three branch system illustrated in Fig. 2 for the case of a signal modulated carrier wave is seen in Fig. 12 as of the order of 60%. By increasing the number of branches in the circuit, and by careful choice of the ratio of maximum load ratings of adjacent branches, the efficiency

can be increased much beyond that of such three-branch circuit. Fig. 12 shows a corresponding efficiency of about 78% therefor.

The impedance unit 27 indicated in Fig. 1, whereby the output circuits of the several branch units are combined to re-form the signal wave, may take different forms. The form illustrated in Fig. 2 comprises a transformer 30 which affords close coupling between the outputs of the respective branch circuits. Such close coupling results in the amplified wave shapes A', B', C' illustrated in Figs. 6, 7, 8 for corresponding wave sections A, B, C of Figs. 3, 4, 5. The matching of the power-amplifier units to the load may be performed by an impedance-matching unit which gives a close coupling between each branch and the output load, and substantially zero coupling between the respective branches. Fig. 14 shows one embodiment for the latter type impedance-coupling unit. This unit comprises bridge or hybrid-coil circuits. Bridge unit 55 comprises four arms 56, 57, 58, 59 across which the output circuits of branches I and II are connected. The second bridge unit 60 is connected across the terminal of one of the bridge arms 59. A diagonal pair of terminals of unit 60 is coupled to the output circuit of branch III. Bridge 60 comprises arms 61, 62, 63, 64. The load 65 is shown coupled to bridge arm 64 through coupling coil 66. Load 65 may, however, be connected directly in bridge 60, replacing arm 64 thereof. Where more than three branches are used, additional bridge units are employed connected in a similar manner to that shown for three branches in Fig. 14. Also, if only two branches are used in the system, a single impedance bridge unit such as 55 is sufficient.

Figs. 15, 16 and 17 illustrate the resultant amplified wave forms A'', B'', C'', corresponding to the respective divided signal wave forms A, B, C, produced at the signal-shaping units in a manner described in connection with Figs. 3, 4 and 5. The wave shapes A', B', C' are of the same wave form as the original signal-wave sections A, B, C. In this case the amplified waves comprise square-top horizontal pulses, rather than the vertical narrow pulses produced by the transformer coupling, as shown at A', B', C' in Figs. 6, 7, and 8. The amplified wave forms A'', B'', C'' are recombined at the load 65 to reconstruct the original wave forms as will now be evident to those skilled in the art. In practice, this alternative form of circuit for the output-impedance unit results in about the same efficiencies for sine-wave amplification as the vertical-division coupling system of Fig. 2 provided by transformer 30. For a sine-modulated carrier wave, the resultant efficiency is of the order of 5 to 10% greater than that given by the system of Fig. 2.

Fig. 18 is a schematic diagram illustrating a number of general applications of the fundamental aspects of my present invention. The system of Fig. 18 is applicable for signal-modulating a carrier wave. Separate sets of branch amplifiers are indicated for both the carrier wave and the signal wave. Referring particularly to Fig. 18, the carrier-frequency source is indicated at 70, the output of which is connected to the inputs of a plurality of signal-shaping circuits 71, 72, 73. A three-branch amplification circuit is indicated, and the signal shapers may correspond to those shown in Fig. 2, or modifications thereof, as indicated hereinabove. The output of each of the signal shapers 71, 72, 73 is connected to respective power amplifiers 74, 75, 76. The amplifiers 74, 75, 76 correspond to those set forth in

connection with Fig. 2. The outputs of amplifiers 74, 75, 76 are in turn connected to impedance unit 77. Impedance unit 77 corresponds to unit 27 in Fig. 1, 30 in Fig. 2, or may be an impedance circuit as shown in Fig. 14. The output of impedance unit 77 is connected to the load generally indicated at 78.

The signal wave which is to modulate the carrier wave is in turn amplified by a three-branch arrangement comprising signal shapers 81, 82, 83 directly coupled to source 80. The signal shapers 81, 82, 83 are in turn connected to the power amplifiers 84, 85, 86. The outputs of the respective amplifiers 84, 85, 86 are in turn connected in a suitable modulating circuit connection to respective amplifier units 74, 75, 76. In accordance with the general arrangement provided by the system of Fig. 18, the carrier wave is split up into a plurality of signal sections by the signal shapers and correspondingly amplified at 74, 75, 76. The modulating signal 80 is also split up into a number of sections in accordance with the principle of the invention, which sections are amplified at 84, 85, 86 and in turn used to modulate the amplified carrier sections at 74, 75, 76. The component modulated sections are combined at impedance unit 77 to form the resultant desired signal-modulated carrier wave, which signal is connected to the load circuit 78.

If it is desired substantially to decrease the undesired harmonic signal components, a degenerative or negative feed-back circuit arrangement is provided for the system as already mentioned. Such negative feed-back circuit is indicated in the system of Fig. 18 and comprises an isolation circuit unit 87 connected to a demodulator 88 which in turn is coupled to the signal source 80 by an impedance-matching unit 89. It is noted, however, that many applications of the invention are commercially practical without such negative feed-back arrangement.

The system generally indicated in Fig. 18 is in practice capable of several different operative arrangements as follows. The arrangement which provides the greatest overall efficiency is that in which the carrier and the modulating signal are split up into a number of branches in accordance with the fundamental principles of the invention and as indicated in Fig. 18, and wherein the amplifier branches of the signal 80 at 84, 85, 86 are arranged to plate-modulate a corresponding amplified carrier-branch signal at 74, 75, 76. The resultant wave shape at outputs 77, 78 will not be the conventional signal-modulated wave shape, but will have the same power and frequency content which, when demodulated by any type of detector, will provide the identical signal output as the conventional type. Experimentally, I found that the efficiency of such a signal-modulated system is of the order of 70% using a 3 db. ratio of signal division between the respective branches. It is to be understood that the number of amplifier branches for either the carrier or the modulator signal is not necessarily three, but may be more or less in accordance with the desired design characteristics. Also, the signal division need not be 3 db. as set forth generally hereinabove in connection with Fig. 2. Also, it is not requisite that the carrier amplifier contain signal shapers. Instead class C amplifiers operating in parallel may be used, which amplifiers are in turn modulated by the invention-type signal-divided amplifiers. In this latter case I have found that the power-conversion efficiency is of the order of 60% in one embodiment,

Furthermore, another arrangement is effected by branch amplifying signal-shaped sections of a constant-voltage carrier wave, but conventionally amplifying the modulating signal by a number of parallel amplifiers. The output of the signal amplifiers is then connected to the carrier-branch amplifiers for the modulation. It is to be understood that it is not necessary that a like number of amplifiers be used for carrier and signal source amplification. In Fig. 18 each branch of the signal amplifier is shown as modulating a single branch of the carrier amplifier. However, this is merely schematic and not requisite. Several branches of the signal amplifier may be combined by an output circuit and used to modulate a single branch of the carrier amplifier. Also, one branch of the signal amplifier may modulate several branches of the carrier amplifier. The only requirement is that the maximum amplitude of each signal pulse must be great enough to give the required depth of modulation, ordinarily 100%, to the associated carrier branch or branches.

Other modifications for operating the system of Fig. 18 will be apparent to those skilled in the art. For example, instead of employing plate-modulations between the signal-amplified branches and the carrier branches, so-called low-level modulation may be used. Thus, each carrier branch is modulated by a signal branch at either the control-grid, suppressor-grid or screen-grid electrodes of the respective power tubes. A further equivalent of this arrangement is to similarly modulate or plate-modulate the signal-shaper or drive stages preceding the power-amplification stages. A somewhat lower efficiency results with the low-level modulation as against the plate modulation.

An extension of the principle of my present invention will now be described in connection with Figs. 19 to 22. This is a method of amplifying a signal-modulated wave which, when used with the circuit of Fig. 2, results in an output having a considerably reduced D. C. power requirement as compared with conventional types of modulation systems. The modulated wave signal is schematically indicated by curve *a*, Fig. 19. Signal *a* is rectified and filtered to produce a direct-current pulse having a wave shape corresponding to the envelope of curve *a*. Fig. 20 shows the rectified pulse at *b*. The uni-directional current pulse, corresponding to curve *b*, is connected in series with the original wave, corresponding to curve *a*, resulting in wave *c* shown in Fig. 21. The signal *c* contains all the components of the original wave, but is uni-directional in nature, and is not an alternating current. Its amplitude is zero when no modulation is present. The current corresponding to wave *c* is then applied to the system of Fig. 2 at the position corresponding to signal source 20. Plate current proportional to curve *c* will flow upon application of signal *c* through the system. The output at 31 will appear as indicated by curve *d*, Fig. 22. It is to be noted that the horizontal scale of Fig. 22 is expanded for clarity. Similar operation is effected when signal *a* is a modulating signal, and the system used as a signal modulator of a carrier wave.

In the system just described, there is no output energy from the signal-modulated carrier amplifier until the signal is applied. As indicated by Fig. 22, the carrier is completely modulated for all levels of the signal wave. Thus it is seen that the carrier level is automatically adjusted

so that its peak amplitude is always just equal to the peak amplitude of the signal wave. The advantages of such an amplification method for the system of Fig. 2 are more apparent at modulations below 100%. However, a large overall reduction in input power is obtained by a reduction in the carrier level. For steady speech it is known that such reduction is by a factor lying between 0.80 and 0.88. When this factor is combined with the considerable improvement and efficiency at 100% modulation that the present invention makes possible, it is found that the power input for a variable signal modulated carrier wave with a specified peak value is less by a factor of about 20 to 1 over a conventional system. Such resultant advantages will accrue where the carrier-wave modulation is by telephonic currents, and possibly also by telegraphic pulses of audio-frequency energy.

The design technique of rectifier and filter circuits which provide a uni-directional bias at all times equal to the peak value of the input signal wave is a well known and highly developed art. No design or operating difficulties of unknown character are involved. Circuits of this type have been in wide use in film-recording systems for many years, and the novelty of the present invention involves their application to a signal-modulated carrier amplifier of high efficiency, in such way as to render the input power substantially proportional to the amplitude of the output wave. For a description of such variable-bias circuits in film recording, reference is made to the Journal of the Society of Motion Picture Engineers of February 1942, pages 125-147.

Variations of the principles of the present invention and their application in practice will become evident to those skilled in the art. The significant advantages of the linear amplification performed by the present invention reside in the substantial increase in power-conversion efficiency of direct-current input to alternating-current output. Such efficiency improvement in practical engineering design is much greater than the actual percentage difference might appear to convey. The maximum power handling capacity of a given vacuum tube ordinarily is limited by maximum permissible values of average and peak plate currents, peak plate voltage and average plate-power dissipation. On the factor of plate-power dissipation alone, if its efficiency is increased from 50% to 75% by the invention system, the power handling capacity of a vacuum tube is doubled. Also, since in each of the branches of the multiple-path amplifier arrangement, the average plate current is much closer to the peak plate current than in a conventional amplifier, and the peak plate voltages are the same, it has been found possible to obtain in a practical design embodying the disclosed principles about double the power output from a given tube complement as compared to a conventional system. This is of great advantage in high-power systems from the standpoint of cost. In low-power mobile radio transmitting equipment, it provides a marked improvement in space and filament-power requirements.

The principles of the invention are particularly indicated for amplifiers with power outputs of about 100 watts and upwards. The applications of the invention principles are numerous, and are flexible as to frequency ranges, function, or power rating. The extra cost of sockets, small components and wiring for ap-

plications of my invention to systems of over 100 watts is negligible, being not more than 1 to 5% of the total. Also, although the filament-power requirements may be 25% greater due to the larger number of tubes, the fact that the filament power is obtained at high efficiency and low cost makes this difference unimportant. What is significant is that for a given output requirement, the invention permits an amplifier of about one-third, and a transmitter of about one-half, of the conventional cubic space and weight requirements. This is mainly due to the reduction in heat dissipation referred to. Also, this same factor will result in an improvement in tube life of the order of 2:1. These factors do not include the large improvements further made possible by the arrangements disclosed in Figs. 19 to 22. For radio transmitter power output above 1000 watts, the use of the multiple-branch carrier amplifier modulated by a multiple-branch signal amplifier as disclosed in connection with Fig. 18 is preferred. For transmitter power ratings between 100 and 1000 watts, a single-branch carrier amplifier modulated by a multiple-branch signal amplifier or a straight modulated-wave multiple-branch linear amplifier is preferred.

The significant practical improvements made possible by the present invention may be further emphasized by a consideration of the following. It is well known that the efficiency of a conventional class B amplifier is proportional to the signal amplitude so that its efficiency varies between 0 and 70% for speech amplification. The average value of the speech wave is, in standard engineering practice, considered as not more than 25% of the peak value. Thus, the efficiency of such amplifier when averaged over a period of speech modulation is less than $0.25 \times 70\%$ or about 17%. With an amplifier for this purpose designed in accordance with the present invention, overall efficiencies of 77%, 72% and 60% result for corresponding peak sine-wave inputs of 100%, 50% and 25% relative signal value. Thus, an average speech efficiency of about 60% is realized as compared to the 17% for the conventional arrangement. The same consideration for a 100% signal-modulated carrier wave results in a 32% efficiency by the conventional class B amplifier, and 72% by the invention multiple-branch amplifier.

An important commercial application of the invention amplifier is its use as a linear amplifier in the output stage of a radio transmitter in which the carrier wave is suppressed and only the side bands transmitted. Considering a carrier wave of 100 watts, the total power output of the transmitter when completely modulated by a signal wave is 150 watts, including carrier wave and side bands. For the varying degree of modulation that occurs during the telephonic transmission, the output power of a conventional transmitter varies between 100 and 150 watts, and if low-level modulation is used, then the varying modulated wave is amplified by a linear output stage. If, however, the carrier is suppressed by a bridge circuit or by a balanced modulator, then the output power from the transmitter varies between 0 and 50 watts. This represents a much wider amplitude range than the previous 100 to 150 watts and therefore is a case in which the improvement of the multiple-branch amplifier over the conventional single-branch amplifier is very large.

The following is a tabulation comparing the relative efficiencies of several conventional output

systems with corresponding ones employing the principles of the present invention:

plifiers having signal output capacities in the ratio of about three decibels between adjacent

		Output power (watts) for modulation per cent of—			D-C input (watts) for modulation per cent of—			Efficiency per cent for modulation per cent of—		Efficiency relative to case 1A for modulation per cent of—	
		0	20	100	0	20	100	20	100	20	100
1A.	Conventional plate-modulated system.....	100	102	150	150	172	262	67	57.5	1.0	1.00
1B.	3-branch plate-modulated system.....	100	102	150	140	145	230	70	65.5	1.19	1.14
2A.	Conventional grid-modulated system.....	100	102	150	300	300	300	33	50	0.50	0.87
2B.	3-branch grid-modulated system.....	100	102	150	167	215	264	47	57	0.80	0.99
3A.	Conventional plate-modulated system with carrier control.....	0	6	150	0	53	262	12	57	3.24	1.00
3B.	3-branch plate-modulated system with carrier control.....	0	6	150	0	18	230	33	65	9.55	1.14
4A.	Conventional grid-modulated system with carrier suppression.....	0	2	50	0	30	150	6	33	5.72	1.75
4B.	3-branch grid-modulated system with carrier suppression.....	0	2	50	0	6	70	33	70	28.7	3.74

The present invention may also be used to materially improve the efficiency in electronically generating a radio wave by the oscillator principle. An oscillator is essentially an amplifier which obtains its input wave as a portion of the output power. Thus, the circuit of Fig. 2 can be made to oscillate by feeding part of the output energy from secondary winding 54 back into the input circuit of the amplifier at signal source 20, in the correct phase. An efficiency of the order of 65% is realized in a conventional class C oscillator. Using similar tubes for a three-branch circuit with 3 db. separation between adjacent branches, an oscillator efficiency of more than 75% is obtainable.

Fig. 23 diagrammatically indicates such an oscillator. The frequency source for the oscillator is indicated at 90, and may be any suitable type of signal generator such as quartz crystal, vacuum tube, or the like. The output of signal source 90 is impressed upon the input of a multiple-branch amplifier 91 constructed in accordance with the invention. The three-branch amplifier indicated at 91 may well correspond to the amplifier of Fig. 2. The output of amplifier 91 is impressed upon output circuit 92. A portion of the output energy at 92 is fed back to the input of amplifier 91, as schematically indicated by lead 93. Such feed-back is in proper phase so as to combine with the signal from source 90, and results in the high efficiency oscillator output at terminals 94.

Although the invention has been described in connection with various applications, modifications and exemplifications, it is to be understood that further embodiments and variations thereof, falling within the broader spirit and scope of the invention, may be practiced by those skilled in the art, and accordingly it is not intended to be limited except as set forth in the following claims.

What is claimed is:

1. An amplifying system comprising a plurality of amplifiers, means connecting the input of each of said amplifiers to a signal source, said means having elements for predetermining the magnitude levels of the signal impressed upon each amplifier, a translating unit connecting the output of each amplifier to a load circuit for combining the amplified signal portions into the original signal wave form, said unit comprising bridge circuits arranged to effect substantially zero coupling between the outputs of the respective branches while effecting substantial coupling between each amplifier and the load circuit.

2. An amplifying system comprising an alternating signal source, a plurality of class B am-

plifiers, signal shaping means individually connecting the input of each of said amplifiers to said signal source, said means including electronic paths for predetermining the magnitude of a signal portion to be impressed upon each amplifier in correspondence with its output capacity, an impedance unit connecting the output of each amplifier to a load circuit for combining the amplified signal portions into the original signal wave form, said unit comprising bridge circuits arranged to effect substantially zero coupling between the outputs of the respective branches while effecting substantial coupling between each amplifier and the load circuit.

3. An amplifying system comprising a plurality of amplifiers, each with substantially the same phase shift, means connecting the input of each of said amplifiers to a signal source, said means each with substantially the same phase shift and having elements for predetermining the magnitude levels of the signal impressed upon each amplifier, and a translating unit connected to the output of each amplifier for combining the amplified signal portions into the original signal wave form.

4. An amplifying system comprising a signal source, a plurality of amplifiers, each with substantially the same phase shift, signal shaping means individually connecting the input of each of said amplifiers to said signal source, said means each with substantially the same phase shift and having elements for predetermining the magnitude levels of the signal impressed upon each amplifier, and an impedance unit connected to the output of each amplifier for combining the amplified signal portions into the original signal wave form.

5. An amplifying system comprising a signal source, a plurality of amplifiers, each with substantially the same phase shift, signal shapers including circuit connections between the input of each of said amplifiers and said signal source, each of said signal shapers with substantially the same phase shift and including an electronic path with biasing elements for predetermining the magnitude levels of the signal impressed upon each amplifier, and a translating unit connected to the output of each amplifier for combining the amplified signal portions into the original signal wave form.

6. An amplifying system comprising a plurality of linear amplifiers of different signal output capacities, each with substantially the same phase shift, means including circuit connections individually connecting the input of each of said amplifiers to a signal source, said means each

with substantially the same phase shift and having elements for predetermining the magnitude levels of the signal impressed upon each amplifier in correspondence with its output capacity, and an impedance-matching unit connected to the output of each amplifier for combining the amplified signal portions into the original signal wave form.

7. An amplifying system comprising an alternating signal source, a plurality of class B amplifiers having signal output capacities in the ratio of about three decibels between adjacent amplifiers, each with substantially the same phase shift, signal shaping means individually connecting the input of each of said amplifiers to said signal source, said means each with substantially the same phase shift and predetermining the magnitude levels of the signal impressed upon each amplifier in correspondence with its output capacity, and an impedance unit connected to the output of each amplifier for combining the amplified signal portions into the original signal wave form.

8. An amplifying system comprising an alternating signal source, a plurality of class B amplifiers having signal output capacities in the ratio of about three decibels between adjacent amplifiers, each with substantially the same phase shift, signal shaping means individually connecting the input of each of said amplifiers to said signal source, said means each with substantially the same phase shift and including electronic paths for predetermining the magnitude of a signal portion to be impressed upon each amplifier in accordance with its output capacity, and a transformer connected to the output of each amplifier for combining the amplified signal portions into the original signal wave form.

9. An amplifying system comprising a plurality of amplifiers, each with substantially the same phase shift, means connecting the input of each of said amplifiers to a signal source, said means each with substantially the same phase shift and having elements for predetermining the magnitude levels of the signal impressed upon each amplifier, a translating unit connected to the output of each amplifier for combining the amplified signal portions into the original signal wave form, and a negative feedback circuit responsive to the outputs of said amplifiers and in circuit connection to the inputs thereof for substantially suppressing harmonic distortion in the combined signal.

10. An amplifying system comprising an alternating signal source, a plurality of class B amplifiers having a signal output capacities in the ratio of about three decibels between adjacent amplifiers, each with substantially the same phase shift, signal shaping means individually connecting the input of each of said amplifiers to said signal source, said means each with substantially the same phase shift and including electronic paths for predetermining the magnitude of a signal portion to be impressed upon each amplifier in correspondence with its output capacity, a translating unit connected with the output of each amplifier for combining the amplified signal portions substantially into the original signal wave form, and a negative feedback circuit responsive to the output of said amplifiers and in circuit connection to the inputs thereof for substantially suppressing harmonic distortion in the combined signal.

CHARLES B. FISHER.