April 9, 1940. J. M. WEST 2,196,844

WAVE AMPLIFYING SYSTEM

Filed April 26, 1939

FIG. 1

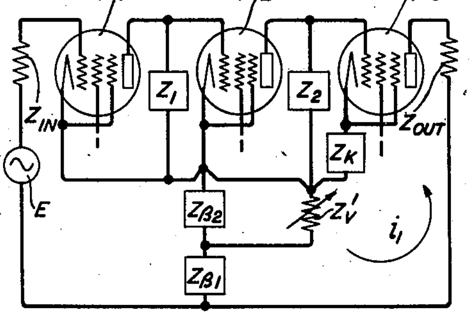


FIG. 2

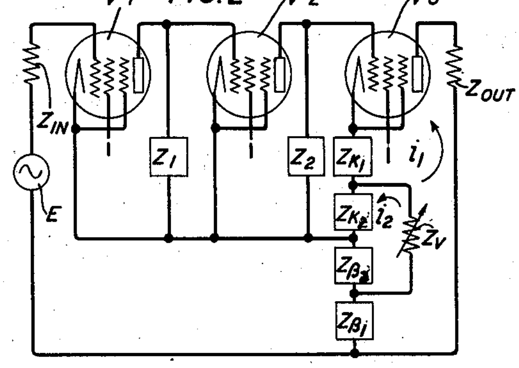


FIG. 3

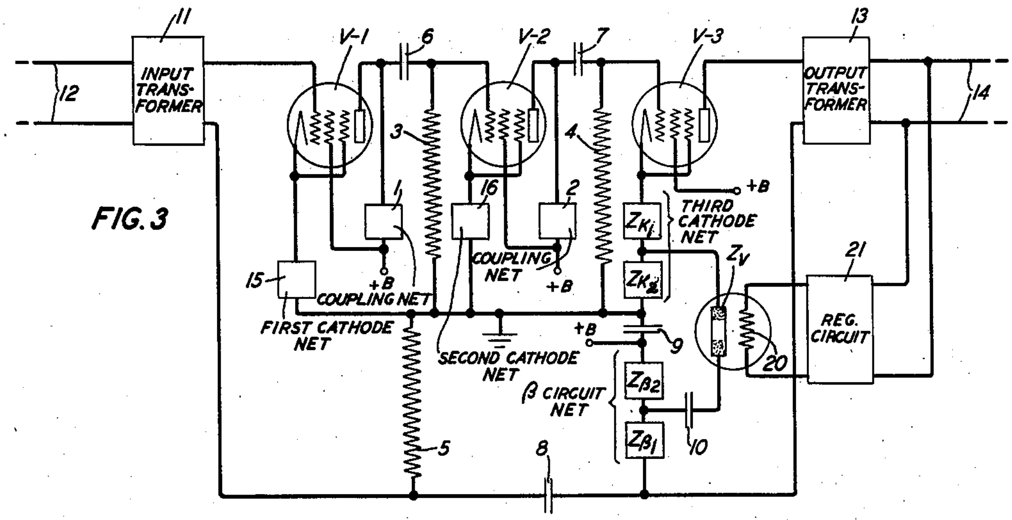
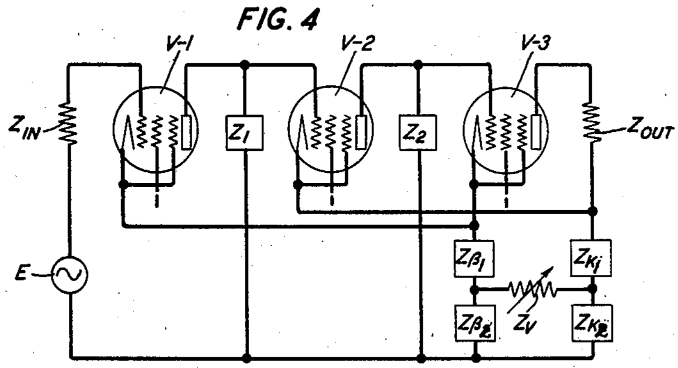


FIG. 4



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WAVE AMPLIFYING SYSTEM

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7 Claims. (Cl. 179—171)

This invention relates to wave amplifying systems, as for example, vacuum tube amplifiers.

Objects of the invention are to control transmission properties of such systems, for example gain and distortion introduced by the systems, to facilitate application of feedback in the systems, and to reduce singing tendency or maintain proper margin against singing in the systems.

In one specific aspect the invention is applied to an amplifier with a forwardly transmitting wave amplifying portion and a feedback path from the output to the input of the amplifying portion for producing negative or gain-reducing feedback around the amplifying portion, for example to stabilize the gain or reduce the modulation introduced by the amplifier, in accordance with the principles described by H. S. Black in his article entitled "Stabilized feed-back amplifiers", Bell System Technical Journal, January 1934, and in his Patent 2,102,671, December 21, 1937.

With sufficient feedback, the amplification of such an amplifier varies substantially as the negative reciprocal of β, the propagation through the feedback path or β circuit, and is substantially independent of μ, the amplification of the amplifying portion or μ circuit; for example, the decibel gain of the amplifier varies substantially as the decibel loss in the feedback path. It is usual to control the amplification of the amplifier for any given frequency by changing β for such frequency. However, this change causes variation in the feedback factor or $\mu\beta$ gain (i. e., in $\mu\beta$ the complex quantity by which a voltage is multiplied in a single journey around the feedback loop, which will be regarded herein as the amount of feedback), and the variation in the feedback may be objectionable. For example, it may unduly reduce the singing margin or the amount of modulation reduction or amplifier gain stability obtained by the feedback action; or it may objectionably change the amplifier input or output impedance or the effect (discussed hereinafter) which has been called the $\mu\beta$ finitude effect, an effect relating to departure of the amplification of the amplifier from the value

$$-\frac{1}{\beta}$$

(due to the finitude of $\mu\beta$).

Objectionable variation of the feedback can be avoided by making equal but inverse or complementary changes in μ and β, so that $\mu\beta$ remains constant.

In one specific aspect the invention is a stabilized feedback amplifier with means comprising a variable impedance element common to the μ circuit and the β circuit for varying the amplification of the amplifier while maintaining $\mu\beta$ constant.

For example, in a regulating amplifier with an equalizer in the β circuit to compensate for variations of cable losses due to temperature variations, the desired regulation of the amplification of the amplifier is accomplished without material variation of $\mu\beta$ by varying a impedance common to the μ circuit and the β circuit so as to change μ and β simultaneously and substantially equally but inversely. For instance, the amplifier may be a three-stage amplifier with this simultaneous μ circuit and β circuit regulation effected by a variable impedance common to the μ circuit and the β circuit varying the local negative feedback on the third stage and substantially equally but inversely varying the negative feedback around all of the stages.

In accordance with a feature of the invention, a single variable element in a feedback amplifier varies the amplification of the amplifier while $\mu\beta$ remains fixed. This has marked advantages over use of separate variable elements in the μ circuit and the β circuit. For instance, necessity is avoided for calibration of an element in the μ circuit and an element in the β circuit relative to each other, to make them "track"; and, moreover, danger of the amplifier becoming unstable due to failure of one of them is avoided.

The variable impedance in accordance with the invention may be of any suitable character as, for example, capacity, inductance or resistance. For instance, silver sulphide or other temperature dependent resistance may be used. The variable impedance may be adjusted manually or by any suitable automatic regulator, as for instance, a pilot wire or pilot channel regulator.

Other objects and features of the invention will be apparent from the following description and claims.

In the drawing:

Fig. 1 is a circuit diagram of an amplifier of a known type, for facilitating explanation of the invention and of an example of its application;

Fig. 2 is a block schematic circuit diagram of an amplifier embodying a form of the invention; and

Figs. 3 and 4 are block schematic diagrams of modifications of the amplifier of Fig. 2.

Fig. 1 shows a typical three-stage amplifier employing series type negative feedback, with its gain adjustable by a variable impedance Z'v in the β circuit. The amplifier comprises vacuum tubes V—1, V—2 and V—3 cascaded by coupling networks Z_1 and Z_2. It amplifies waves from a source or sending circuit of electromotive force E and impedance Z_{in} and transmits the amplified waves to a load circuit or impedance Z_{out}. The third stage has a cathode network or impedance Z_K. The β circuit includes a β circuit impedance comprising impedances $Z_{\beta1}$ and $Z_{\beta2}$ connected in series across the feedback path, and the impedance Z'_V shunted across $Z_{\beta2}$. All of these impedances are generalized impedances, and may be resistances or impedances of any suitable character. Their designations are taken as their vector values.

In Fig. 1 the insertion gain of the amplifier is given by:

$$\text{insertion gain} \doteq \frac{Z_{in}+Z_{out}}{Z_{\beta1}+Z_{\beta2}\dfrac{Z'_V}{Z_{\beta2}+Z'_V}}$$

and

$$\mu\beta \text{ gain} \doteq S_{m1}Z_1 S_{m2}Z_2 \frac{S_{m3}}{1+S_{m3}Z_k}\left(Z_{\beta1}+Z_{\beta2}\frac{Z'_V}{Z_{\beta2}+Z'_V}\right)$$

where S_{m1}, S_{m2} and S_{m3} are the transconductances of tubes V—1, V—2, and V—3.

Fig. 2 is like Fig. 1 except: (1) the cathode net or impedance of the third tube has been made into or replaced by one composed of impedances Z_{K1} and Z_{K2} in series which have the same configurations, respectively, as $Z_{\beta1}$ and $Z_{\beta2}$ or which have the impedance-frequency characteristics of Z_{K1} and Z_{K2} the same shapes as those of $Z_{\beta1}$ and $Z_{\beta2}$, respectively, over the frequency range for which $\mu\beta$ is to be maintained constant; and (2) instead of leaving Z'_V in circuit and shunting Z_{K2} with a variable impedance for producing variations in μ equal but inverse to those produced in β by variation of Z'_V, Z'_V is omitted and the two points where the variable elements across Z_{K2} and $Z_{\beta2}$ would respectively connect to the junction of Z_{K1} with Z_{K2} and the junction of $Z_{\beta1}$ and $Z_{\beta2}$ are connected through a single variable element or impedance Z_V, or in other words, Z'_V is omitted and a variable impedance Z_V is shunted across Z_{K2} and $Z_{\beta2}$. When Z_{K2} is K times as large as $Z_{\beta2}$ and Z_V is equal to (1+K) Z'_V the new configuration shown in Fig. 2 will give exactly the same insertion gain as that indicated above for Fig. 1. If Z_{K1} is K times as large as $Z_{\beta1}$, Z_{K2} is K times as large as $Z_{\beta2}$, and $S_{m3}Z_{K1}$ is large compared to unity, $\mu\beta$ will be substantially independent of the setting of Z_V. Proof of this, and derivation of an expression for the insertion gain in Fig. 2 are given below.

Referring to Fig. 2 we can set down the following expressions:

$$i_1=S_{m3}e_{g3} \tag{1}$$

$$e_{g3}=e_3-i_2Z_{k2}-i_1Z_{k1} \tag{2}$$

$$e_3=S_{m1}Z_1S_{m2}Z_2e_{g1} \tag{3}$$

$$e_{g1}=E-i_1Z_{\beta1}-i_2Z_{\beta2} \tag{4}$$

$$i_2=i_1\frac{Z_V}{Z_V+Z_{K2}+Z_{\beta2}}=S_{m3}e_{g3}\frac{Z_V}{Z_V+Z_{K2}+Z_{\beta2}} \tag{5}$$

Substituting from (1) and (5) in (2) gives:

$$e_{g3}=e_3-S_{m3}e_{g3}\left[\frac{Z_VZ_{K2}}{Z_V+Z_{K2}+Z_{\beta2}}+Z_{K1}\right] \tag{6}$$

Solving (6) for e_{g3} gives:

$$e_{g3}=\frac{e_3}{1+S_{m3}\left(Z_{K1}+\dfrac{Z_VZ_{K2}}{Z_V+Z_{K2}+Z_{\beta2}}\right)} \tag{7}$$

Substituting from (7) in (1) yields:

$$i_1=\frac{S_{m3}e_3}{1+S_{m3}\left(Z_{K1}+\dfrac{Z_VZ_{K2}}{Z_V+Z_{K2}+Z_{\beta2}}\right)} \tag{8}$$

Substituting from (5) in (4) gives:

$$e_{g1}=E-i_1\left(Z_{\beta1}+\frac{Z_VZ_{\beta2}}{Z_V+Z_{K2}+Z_{\beta2}}\right) \tag{9}$$

Substituting from (8) in (9) gives:

$$e_{g1}=E-\frac{S_{m3}e_3\left(Z_{\beta1}+\dfrac{Z_VZ_{\beta2}}{Z_V+Z_{K2}+Z_{\beta2}}\right)}{1+S_{m3}\left(Z_{K1}+\dfrac{Z_VZ_{K2}}{Z_V+Z_{K2}+Z_{\beta2}}\right)} \tag{10}$$

Substituting from (10) in (3) gives:

$$e_3=S_{m1}Z_1S_{m2}Z_2\left[E-\frac{S_{m3}e_3\left(Z_{\beta1}+\dfrac{Z_VZ_{\beta2}}{Z_V+Z_{K2}+Z_{\beta2}}\right)}{1+S_{m3}\left(Z_{K1}+\dfrac{Z_VZ_{K2}}{Z_V+Z_{K2}+Z_{\beta2}}\right)}\right] \tag{11}$$

Solving (11) for e_3:

$$e_3=\frac{S_{m1}Z_1S_{m2}Z_2E}{1+S_{m1}Z_1S_{m2}Z_2\dfrac{S_{m3}\left(Z_{\beta1}+\dfrac{Z_VZ_{\beta2}}{Z_V+Z_{K2}+Z_{\beta2}}\right)}{1+S_{m3}\left(Z_{K1}+\dfrac{Z_VZ_{K2}}{Z_V+Z_{K2}+Z_{\beta2}}\right)}} \tag{12}$$

Substituting from (12) in (8) and rearranging terms gives:

$$i_1=\frac{S_{m1}Z_1S_{m2}Z_2\cdot\dfrac{S_{m3}E}{1+S_{m3}\left(Z_{K1}+\dfrac{Z_VZ_{K2}}{Z_V+Z_{K2}+Z_{\beta2}}\right)}}{1+S_{m1}Z_1S_{m2}Z_2\dfrac{S_{m3}}{1+S_{m3}\left(Z_{K1}+\dfrac{Z_VZ_{K2}}{Z_V+Z_{K2}+Z_{\beta2}}\right)}\left(Z_{\beta1}+\dfrac{Z_VZ_{\beta2}}{Z_V+Z_{K2}+Z_{\beta2}}\right)} \tag{13}$$

Since the denominator in (13) is equal to $1+\mu\beta$ and $\mu\beta$ is much greater than unity we may simplify (13), getting

$$i_1\doteq\frac{E}{Z_{\beta1}+\dfrac{Z_VZ_{\beta2}}{Z_V+Z_{K2}+Z_{\beta2}}} \tag{14}$$

For the reference condition without the amplifier between the source and load we have:

$$i_{1\ \text{reference}}=\frac{E}{Z_{in}+Z_{out}} \tag{15}$$

Dividing (14) by (15) yields the insertion gain ratio:

$$\frac{i_1}{i_{1\ \text{reference}}}\doteq\frac{Z_{in}+Z_{out}}{Z_{\beta1}+Z_{\beta2}\dfrac{Z_V}{Z_V+Z_{K2}+Z_{\beta2}}} \tag{16}$$

By inspection from (13):

$$\mu\beta=S_{m1}Z_1S_{m2}Z_2\frac{S_{m2}\left(Z_{\beta1}+Z_{\beta2}\dfrac{Z_V}{Z_V+Z_{K2}+Z_{\beta2}}\right)}{1+S_{m3}\left(Z_{K1}+Z_{K2}\dfrac{Z_V}{Z_V+Z_{K2}+Z_{\beta2}}\right)} \tag{17}$$

When,

$$1 << S_{m3}Z_{K1} \qquad (18)$$

and

$$Z_{K1} = KZ_{\beta 1} \qquad (19)$$

and

$$Z_{K2} = KZ_{\beta 2} \qquad (20)$$

it is easy to show from (17) that

$$\mu\beta \doteq S_{m1}Z_1S_{m2}Z_2\frac{1}{K} \qquad (21)$$

This is, therefore, a set of conditions that makes $\mu\beta$ (as regards both its phase and its magnitude) independent of Z_V.

If Equation (20) is satisfied and in addition the condition

$$Z_V = (1+K)Z'_V \qquad (22)$$

then

$$\frac{i_1}{i_{1\ \text{reference}}} \doteq \frac{Z_{in}+Z_{out}}{Z_{\beta 1}+Z_{\beta 2}\dfrac{Z'_V}{Z'_V+Z_{\beta 2}}} \qquad (23)$$

which can be shown to be the same as that for the circuit of Fig. 1.

Expression (18) is satisfied if the local negative feedback around the last stage is much greater than unity. Thus, with considerable local negative feedback and considerable over-all negative feedback, $\mu\beta$ will be substantially independent of adjustment of Z_V, provided Z_V is shunted across equal percentages of the cathode net impedance $Z_{K1}+Z_{K2}$ and the β circuit impedance $Z_{\beta 1}+Z_{\beta 2}$, (it being understood that Z_{K1} and Z_{K2} have their impedance-frequency characteristics the same shapes as those of $Z_{\beta 1}$ and $Z_{\beta 2}$, respectively. The greater the local feedback, the more nearly will the over-all feedback be independent of the setting of Z_V.

The β circuit network composed of impedances $Z_{\beta 1}$, $Z_{\beta 2}$ and Z_V may be made such as to give the amplifier a desired insertion gain-frequency characteristic. A procedure often facilitating this is first to determine the impedances $Z_{\beta 1}$, $Z_{\beta 2}$ and Z'_V required in the case of Fig. 1 for the desired insertion gain-frequency characteristic, from the expression given above for insertion gain of the amplifier in Fig. 1, then to determine Z_V from the relation $Z_V=(1+K)\ Z'_V$, given above as that for making the insertion gains of the amplifiers of Figs. 1 and 2 the same. The β circuit network of impedances $Z_{\beta 1}$, $Z_{\beta 2}$ and Z_V may thus be made to give the amplifier of Fig. 2 an insertion gain which, over the used frequency is flat; or it may be chosen to make the amplifier insertion gain vary in some chosen linear or nonlinear manner with frequency.

The variable impedance Z'_V in Fig. 1, and in Fig. 2 the variable impedance Z_V which is equal to $(1+K)\ Z'_V$, may be such that adjustment of the variable impedance Z'_V changes the loss of the β circuit network composed of $Z_{\beta 1}$, $Z_{\beta 2}$ and Z'_V equally at all of the used frequencies or by desired different amounts at the different used frequencies, (for example in the manner of the adjustable impedance in the variable equalizer network of Fig. 18 of H. W. Bode Patent 2,096,027, October 19, 1937, for "Attenuation equalizer"), so that the adjustment of the impedance Z'_V and consequently the adjustment of Z_V will accordingly change the insertion gain of the amplifier equally at all of the used frequencies or by desired different amounts at the different used frequencies.

Fig. 3 is like Fig. 2 except: (1) B supply, coupling impedances **1** and **2**, grid leak resistors **3**, **4** and **5**, and stopping condensers **6**, **7**, **8**, **9** and **10** are shown; (2) the source or sending circuit is shown as input transformer **11** connected to circuit **12** and the load is shown as output transformer **13** connected to circuit **14**, either or each of the circuits **12** and **14** being, for example, a section of coaxial line or cable for broad frequency band multiplex carrier or television transmission; (3) cathode networks or impedances **15** and **16** are shown for tubes V—**1** and V—**2**, respectively, these networks serving, for example, to provide grid biasing voltages or alternating current feedback voltages, or both, for these tubes; and (4) the impedance Z_V is shown as a temperature dependent resistance, for example silver sulphide, having its temperature (and consequently its resistance) variable by means of a heating element **20** controlled by pilot channel or pilot frequency operated regulator circuit **21** to vary μ and β substantially equally but inversely. This maintains $\mu\beta$ constant while varying the amplification or the gain of the amplifier, for example, to compensate for variations of cable temperature and cable length.

The regulator circuit may be of any suitable type. For example, it may be of the type disclosed in E. I. Green Patent 1,918,390, July 19, 1933, R. W. Chesnut Patent 2,154,062, April 11, 1939, R. R. Blair Patent 2,100,375, November 30, 1937, R. R. Blair Patent 2,179,915, November 14, 1939, for "Gain control circuits", or R. R. Blair Patent 2,178,333, October 31, 1939, for "Gain control circuits."

In this figure, as in the case of Fig. 2, when Z_V varies, the local negative feedback on the third tube varies in the same sense as the negative feedback around all of the stages tends to vary due to change of β, and the amount of the change in the local feedback is such as to cause the change in μ to equal the inverse change in β, so that $\mu\beta$ remains constant as the amplifier gain is changed.

For simplifying the drawing, in Fig. 3, as in the other figures, the circuits for heating the cathodes are omitted. In each of the figures they may be of any usual or suitable type.

Likewise, for simplifying the drawing, in Figs. 1 and 2, and also in Fig. 4 about to be described, the circuits including direct current sources, stopping condensers, etc., for supplying plate currents and providing grid biasing potentials to condition the amplifier for operation are omitted. In each of the figures they may be of any usual or suitable type, as for example, of the general type indicated in Fig. 3.

The invention may be embodied in various forms. For example, Fig. 4 shows a modification of Fig. 2 in that the impedance $Z_{K1}+Z_{K2}$, composed of the networks Z_{K1} and Z_{K2} in the cathode-plate circuit of tube V—**3** is in the cathode-grid circuit of tube V—**2** instead of tube V—**3**. Thus, the network $Z_{K1}+Z_{K2}$ provides a local negative feedback around the last two tubes. As in the case of Fig. 2, with considerable local negative feedback (which obtains in Fig. 4 when $S_{m2}Z_2S_{m3}Z_{K1}>>1$), and considerable over-all negative feedback: the $\mu\beta$ gain around the outer loop will be substantially independent of the adjustment of impedance Z_V provided Z_{K1} divided by Z_{K2} equals $Z_{\beta 1}$ divided by $Z_{\beta 2}$, and the insertion gain of the amplifier will be the same as in Fig. 1 provided $Z_V=(1+K)Z'_V$.

In Figs. 2 and 4, the variable impedance Z_V

may, if desired, be a temperature dependent impedance, such as that of Fig. 3; and in Fig. 4 the adjustment of this impedance may, if desired, be automatic, for example, as in Fig. 3.

In a feedback amplifier, the $\mu\beta$ finitude effect referred to above is the factor by which

$$-\frac{1}{\beta}$$

the amplification that would obtain if the feedback $\mu\beta$ were infinite, or more generally if $\mu\beta$ were equal to $1-\mu\beta$, must be multiplied in order to obtain the actual or exact value

$$\frac{\mu}{1-\mu\beta}$$

of the amplification. That is, the amplification with feedback, A_F, is

$$A_F=\frac{\mu}{1-\mu\beta}=-\frac{1}{\beta}\left(\frac{1}{1-\frac{1}{\mu\beta}}\right)$$

which approaches

$$-\frac{1}{\beta}$$

the exact inverse (or negative reciprocal) of the propagation through the feedback path, as $\mu\beta$ approaches infinity. In controlling the gain of the amplifier by varying Z_V in accordance with the invention, avoiding change of $\mu\beta$ (during gain adjustment) avoids varying the factor

$$\frac{1}{1-\frac{1}{\mu\beta}}$$

and thus renders departure of the amplification from

$$-\frac{1}{\beta}$$

independent of the setting of Z_V. This is advantageous, for example, as facilitating equalization or control of transmission over the circuit in which the amplifier is connected by control of the transmission properties of the feedback path, for instance as facilitating design of impedances $Z_{\beta 1}$, $Z_{\beta 2}$ and Z_V to compensate for line or cable attenuation changes, variable with frequency, due to changes of line length or of temperature or other weather conditions to which the line or cable in Fig. 3 is subject. By way of further example, the feature of simultaneously changing μ and β substantially equally but inversely is advantageous in enabling the over-all gain of the amplifier to be changed, by change of the transmission efficiency of the feedback path, while avoiding disturbance of particular operating conditions that may be desired, as for instance, the condition that the cosine of the phase angle of $\mu\beta$ equal unity divided by the absolute value of $\mu\beta$, which is the condition for perfect amplifier stability.

What is claimed is:

1. A wave translating system comprising a wave amplifying path, a feedback path connected around said amplifying path for producing negative feedback in said system of waves amplified in said amplifying path, and means for varying the transmission efficiency of said feedback path and simultaneously substantially equally but inversely varying the transmission efficiency of said amplifying path, said means comprising a two-terminal temperature responsive impedance common to said paths.

2. An amplifier comprising an amplifying path, a feedback path around said amplifying path for producing negative feedback in said amplifier, a two-terminal impedance in said first path, a two-terminal impedance in said second path, and means for producing simultaneous inverse changes in propagation through said paths, said means comprising a two-terminal variable impedance connected across a portion of each of said two first-mentioned impedances.

3. A wave amplifying system comprising an amplifying path, a feedback path from the output of said amplifying path to its input for producing negative feedback in said system, a two-terminal impedance in said amplifying path, a two-terminal impedance in said feedback path, said second impedance having one of its terminals common with one of the terminals of said first impedance, and means for simultaneously producing approximately equal but inverse changes in propagation through said paths, said means comprising a two-terminal variable impedance connected across substantially equal percentages of said first and second impedances.

4. A wave translating system comprising an amplifying path with partly common amplifying portions one of which has smaller amplification than another, a feedback path for producing negative feedback around said amplifying path, a two-terminal impedance so connected in said first path as to produce local negative feedback around said one portion, a two-terminal impedance included in said second path having one of its terminals common with one of the terminals of said first impedance, and means for simultaneously producing approximately equal but inverse changes in propagation through said paths, said means comprising a two-terminal variable impedance connected across substantially equal percentages of said first and second impedances.

5. An amplifier comprising an amplifying path, a feedback path for producing negative feedback around said amplifying path, cascaded amplifying devices included in said first path, a two-terminal impedance so connected in said first path as to produce local negative feedback around certain of said devices, a two-terminal impedance included in said second path having one of its terminals common with one of the terminals of said first impedance, and means for simultaneously producing approximately equal but inverse changes in propagation through said paths, said means comprising a two-terminal variable impedance connected across substantially equal percentages of said first and second impedances.

6. A multistage amplifier comprising a feedback circuit coupling the output circuit of the last stage of the amplifier and the input circuit of that stage for producing local negative feedback in that stage, a feedback circuit coupling the output circuit of that stage to the input circuit of the first stage for producing over-all negative feedback around all of the stages of the amplifier to control the amplifier gain, and a two-terminal temperature responsive impedance connected between such points of said first-mentioned feedback circuit and said second-mentioned feedback circuit that variation of said temperature responsive impedance varies the propagation of said second feedback circuit and inversely varies the propagation of said last stage.

7. A multistage amplifier comprising an impedance connected in the output circuit of the last stage and having a portion in the input circuit of the first stage for producing over-all

negative feedback around all of the stages to reduce the amplifier gain and another portion in the input circuit of an intermediate stage for producing local negative feedback around a group of stages, and a two-terminal variable impedance electrically connecting such points of said portions that variations of said variable impedance varies the propagation of the over-all feedback path of the amplifier and simultaneously approximately equally but inversely varies the propagation of said group of stages.

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