

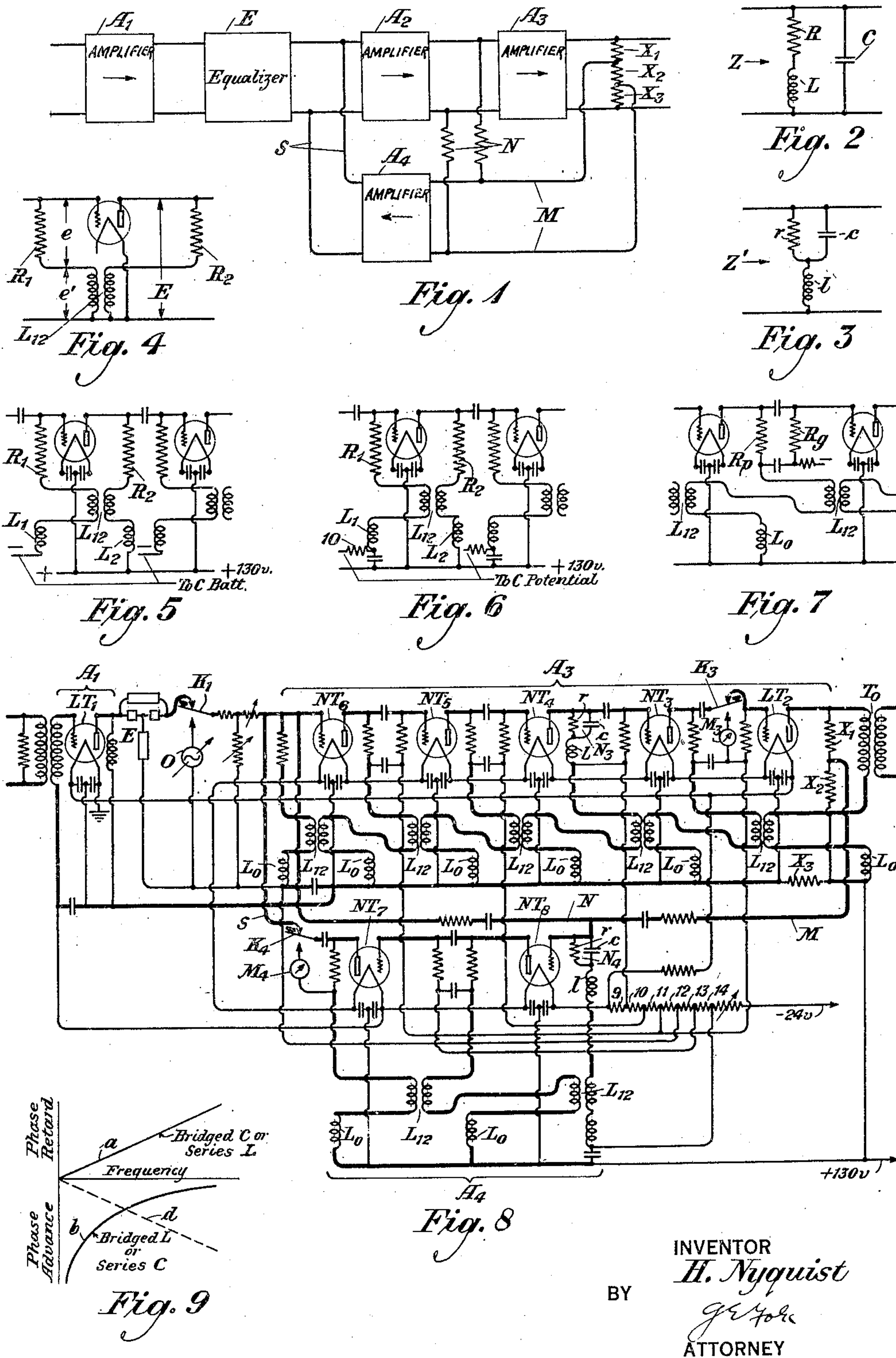
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MEANS FOR ELIMINATING DISTORTION IN REPEATERS

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MEANS FOR ELIMINATING DISTORTION IN REPEATERS

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This invention relates to wave translation systems, as, for example, systems for amplifying electrical variations with the aid of electrical space charge devices, and, more particularly, it relates to improvements in such systems and in the circuit arrangements of the space charge devices therein.

Repeaters have been proposed for neutralizing distortion by picking off some of the output wave from the output of an amplifier which distorts, neutralizing the undistorted portion of the wave thus picked off by means of an undistorted wave from the input of the amplifier, and then impressing the resultant wave, which comprises distortion components only, upon the input of the amplifier in such phase and amplitude as to neutralize the distortion due to the amplifier. Such a system, if properly adjusted will not only be substantially distortionless, but will also compensate for variations in the gain of the amplifier due to variations of its circuit constants and will thus tend to maintain the gain uniform.

In order that the repeater be effective to produce these results, the effect of reactance elements in the repeater itself should be neutralized or compensated, particularly capacities between the grids and plates of the vacuum tubes and the capacities to ground of the interstage wiring and coupling elements which are in effect bridged capacities which tend to cause phase shifts which vary with frequency.

In accordance with the present invention, it is proposed to neutralize or compensate such capacity reactances by bridging across each amplifying element a circuit including an inductance in series with resistance so proportioned with respect to the inherent bridged capacity of the circuit as to neutralize the capacity so far as effects involving the first order of frequency are concerned. Where necessary to compensate for effects of the second order or higher powers, an auxiliary network may be provided at some point in the system having such characteristics that its impedance will be real so far as concerns terms lower than the second order; while for terms of the second order (or even higher

powers) its impedance will be complementary to the impedance of the circuit as previously compensated.

The invention will now be more fully understood from the following description when read in connection with the drawing, in which Figure 1 is a schematic diagram of a type of repeater to which the invention may be applied; Figs. 2 and 3 are diagrams illustrating arrangements for compensating the effect of reactance in accordance with the invention; Fig. 4 is a diagram used in connection with the derivation of certain formulæ; Figs. 5, 6 and 7 show amplifier circuits compensated in accordance with the invention; Fig. 8 is a detailed circuit diagram of a multistage distortion neutralizing repeater to which the compensation in accordance with the invention is applied, and Fig. 9 is a series of curves illustrating the principles of the invention.

While the methods of compensating the effects of reactances in amplifiers as herein disclosed are of general application, they are particularly useful in connection with repeaters of a type arranged for neutralizing distortion. In order to understand the necessity for the invention in connection with such a repeater and how it is to be applied thereto, it is desirable to describe briefly the principles of the repeater to which the invention is applied.

A distortion neutralizing repeater is illustrated schematically in Fig. 1 and comprises amplifier elements A_1 , A_2 , A_3 and A_4 , connected as shown, together with an attenuation equalizer E to compensate for the variation in the attenuation of the currents with frequency as they are transmitted over the line. In this type of repeater, the amplifying unit A_3 is the principal amplifying unit for bringing the currents up to a desired large volume, the amplifying units A_1 , A_2 and A_4 being worked at such low levels that the non-linear distortion due to their action may be neglected. Due to the high levels at which the amplifier A_3 must be worked, said amplifier will have non-linear distortion which it is the function of the amplifiers A_2 and A_4 ,

with their associated circuits M, N and S, to compensate.

Let us assume that a pure sinusoidal wave is applied to the input of the repeater and that the amplifier A_4 is not functioning. A pure sine wave will then appear at the point between amplifier units A_2 and A_3 . On the output side of amplifier A_3 , a similar sine wave appears, but it has superposed thereon certain distortion currents. By means of the resistance coupling X_1 , X_2 and X_3 , the circuit M picks off a portion of the output wave with its distortion, and, by means of the circuit N, the wave picked off is combined with a portion of the wave appearing between the amplifiers A_2 and A_3 . If care is taken that the phase and relative amplitudes of these two waves are properly related, the sinusoidal wave coming over the circuit N from the point between amplifiers A_2 and A_3 will just neutralize the sinusoidal part of the wave coming from the output of the amplifier A_3 . As a result, the current which is applied to the input of the amplifier A_4 is made up of the distortion only.

Now, if the amplifier A_4 is made to function, this distortion will be introduced into the main circuit at the point between the equalizer E and the amplifier unit A_2 . Accordingly, it will be amplified by amplifiers A_2 and A_3 and will appear in the output. If care is taken to properly relate the amplitude and phase of this distortion current (which was applied to the circuit over the path S) to the phase and amplitude of the distortion components of the sine wave after transmission through the amplifier A_3 , this distortion may be made to neutralize the distortion generated in the amplifier A_3 so that the ultimate output of the amplifier A_3 will be an undistorted sine wave. On the other hand, if the gain in the amplifier A_4 is made somewhat too great (or too small) the repeater may be made to overcorrect (or undercorrect) for the distortion, so that, for instance, distortion generated in the amplifier A_1 or A_2 may be compensated, assuming, however, that amplifiers A_1 and A_2 have the same proportion of second and third harmonics as the amplifier A_3 .

A repeater such as above described has another desirable property in that it tends to compensate for variations in gain. For example, suppose the gain in amplifier A_3 changes for some reason, such as a variation in battery voltage. As a result, the fundamental wave is not completely neutralized before entering the amplifier A_4 . In other words, a portion of the fundamental wave is amplified by the amplifier A_4 as well as the distortion. The net result of this fundamental wave component, when applied to the amplifier A_3 , is to keep the output into the line constant. For example, if the fundamental component coming from the circuit M

is greater than that coming from the circuit N, the resultant wave passing through the amplifier A_4 will be in such phase as to oppose the excess transmitted from the output of the amplifier A_3 to the circuit M. On the other hand, if the fundamental component coming from the circuit M is smaller than that coming from the circuit N, the phase of the resultant wave passing through the amplifier A_4 will be such as to add to the fundamental component appearing in the output circuit of the amplifier A_3 . In other words, the circuit not only tends to keep the distortion zero, but tends to keep variations in the gain of the amplifier A_3 from having an effect on the over-all gain.

In order to have proper functioning of this type of apparatus, it is necessary that the phase relations between the various waves be approximately right. This leads to the following requirements:

1. The amplifiers A_2 , A_3 and A_4 must be resistance coupled, or very nearly so.
 2. The total number of stages in amplifier A_3 must be an odd number.
 3. The total number of stages in amplifier A_4 plus amplifier A_2 must be an even number.
- In considering the various component amplifiers, it should be noted that the amplifier A_1 is not inherently a part of the distortion compensating circuit, but is provided for the purpose of overcoming the effect of resistance noise. In many cases, resistance noise would be the limiting factor in the operation of amplifiers. Now, the resistance noise is effectively increased by placing the equalizer in front of the repeater, because the resistance noise originating in the equalizer is superposed on that coming from the line. The effect of the amplifier A_1 , therefore, is to increase the power of the incoming current so that the effect of the resistance noise introduced by the equalizer will be made relatively unimportant. This amplifier does not have the benefit of the distortion correcting properties of the circuit for the reason that there will be unavoidable phase shifts in the equalizer. Any distortion introduced in the amplifier A_1 must, therefore, be kept small.

The impedance looking from the amplifier A_2 towards the equalizer E should be a pure resistance in order to insure resistance coupling between the amplifiers A_4 and A_2 . This result can be readily brought about by properly choosing the design of the equalizer. The equalizer itself may be of any type well known in the art and is not inherently a part of the distortion correcting repeater.

Various numbers of stages may be used in the amplifiers A_2 , A_3 and A_4 , subject to the requirement that the number of stages in the amplifier A_3 should be odd, and the total number in A_2 and A_4 even. Any number necessary to obtain the desired gain will be

used. Of course, stages may be taken from amplifier A_3 and added to A_2 so long as the number in A_3 remains odd, and the sum of the stages in A_2 and A_4 is even. There is a distinct disadvantage in this, however, in that the stages in the amplifier A_2 will not be within the compensated portion of the circuit, and, therefore, any distortion generated in these stages would be imperfectly compensated. Furthermore, variations in the gain of the amplifier A_2 would not be properly compensated. In fact, the stages of the amplifier A_2 may all be embodied in the amplifier A_4 , provided the number of stages is even. On the whole, the preferred design would appear to be, to have a limited even number of stages in amplifier A_2 eliminated entirely, so that the paths S and N will be bridged together across the coupling between the equalizer E and the amplifier A_3 . In the detailed design given hereinafter, this modified form of circuit is utilized.

In order for the type of repeater under discussion to work at its best, it is necessary that the phase shift due to reactances be kept at a very low value. This is desirable not only for some one frequency but for the whole range of frequencies which it is wished to amplify. The circuits involved in vacuum tube coupling are of much higher impedance than the natural impedance of the wiring used. Since, for capacity, the phase shift is proportional to

$$\frac{\omega CR}{2},$$

and, for inductance, the phase shift is proportional to

$$\frac{\omega L}{2R},$$

the stray capacity is much more likely to cause undue phase shift than stray inductance.

There are three principal sources of capacity which interfere with the ideal operation of the circuits. First, there is the matter of unavoidable capacity to ground of the resistances used for the resistance coupling between stages. Secondly, there is the capacity to ground of the leads connecting the plate of one tube to the grid of the next. In this class, should be included the capacity to ground of the series condenser which is used in this lead. Third, there are the inter-electrode capacities in the tube itself, of which the capacity between the grid and the plate is particularly objectionable because its action is multiplied by the amplification factor of the tube.

Although it is possible to compensate for these capacities it is desirable to keep them at a low value; first, because it is inherently impossible to obtain perfect compensation and the smaller the capacities are to begin

with the smaller will be the uncompensated part, other things being equal. Secondly, there are unavoidable variations from one tube to another and it is, of course, more difficult to compensate for capacities which are of a variable nature than those which stay fixed. In addition there are variations in tube resistance which would alter the phase shift even if the capacity did not change. It is desirable then to keep variations small and it is thought that one way of accomplishing this is to make the capacities small to begin with.

The series condenser which is used between the plate of one tube and the grid of the next should preferably be enclosed in a metal container to avoid crosstalk from stray fields. Unless special care is taken, the capacity between the condenser proper and the container will be great enough to have serious effects. This capacity can be kept within a few micro-farads by keeping the dimensions of the condenser fairly small and keeping the separation from the condenser proper to the container of the same order of magnitude as the dimension of the condenser.

The leads between the plate of one tube and the grid of the next should have small capacity. This may be ensured by making them short, giving them a small diameter and keeping them far away from grounded parts.

The resistances which supply grid and plate potentials to the tubes should have as little distributed capacity as possible. This can be accomplished by making them of as small dimensions as possible particularly in cross-section and keeping them as far from ground as possible and keeping the high potential leads short.

The tube capacities and tube resistance should be made as small as possible. The tube resistance can be made low by using such potential on the grid and plate as to work the tube on the steep part of its characteristics. Another expedient is to use tubes of small dimensions. If of two given tubes one is a small scale model of the other the amplification factor and resistance are said to be the same for the two tubes whereas the capacities are directly proportional to the linear dimension.

The capacities which have been discussed are in the nature of bridged capacities, and their effect is to retard the phase. This is also true of the capacity between the plate and the grid, although it is not strictly a bridged capacity. Now, series capacity has the opposite effect. That is to say, it tends to advance the phase. Unfortunately, however, it is not suitable as a compensating means, because it has a totally different frequency characteristic from what is desired. The retarding effect of bridged capacity increases as the frequency increases, as shown by the curve α of Fig. 9, whereas the advanc-

ing effect due to a series condenser decreases as the frequency increases, as shown by the curve *b* of Fig. 9. If the series condenser were so chosen as to compensate perfectly at some particular frequency, the compensation would be very imperfect at frequencies above and below the chosen frequency.

Bridged inductance has the same effect as series capacity, but it also has the same sort of frequency characteristic as shown by the curve *b*, and, therefore, is no more suitable as a compensating means than series capacity. Furthermore, a bridged inductance would inevitably introduce bridged capacity due both to the capacity between the turns and the capacity to the core and container.

In accordance with the present invention, however, it is proposed to overcome these difficulties by neutralizing the effect of the bridged capacities by means of a bridged circuit in which a small inductance is in series with a resistance. Notwithstanding that a pure bridged inductance produces a variation of phase advance with frequency, as shown by the curve *b* of Fig. 9, a combination of inductance and resistance, when properly designed as hereinafter described, will introduce a phase change with frequency which is complementary to that due to the bridged capacity as shown by the curve *d* of Fig. 9. This compensation may be made accurate so far as first-order effects are concerned, although, as will be pointed out later, further compensation may be made by special networks for second power or other higher order effects, if desired.

In using a bridged circuit comprising an inductance in series with the resistance, there will, of course, be a certain amount of difficulty due to stray capacity in the coils, but it should be noted that the E. M. F. across the coils is relatively small, since most of the drop in potential will take place in the resistance in series with the coil, which will be used to supply the grid and plate batteries. For this reason, stray capacities in these coils are not so objectionable.

In order to understand how the combination of a resistance in series with an inductance bridged across the circuit will have the effect of compensating for a bridged capacity, let us suppose we have an effective bridged capacity *C*, as shown in Fig. 2, and it is desired to neutralize the phase change due to such capacity. The capacity *C* may be assumed to be any of the various capacities heretofore discussed in connection with a vacuum tube, for example, the grid-plate capacity. The proposition is to neutralize the effect of such a capacity by means of a small inductance *L* in series with a resistance *R*, the whole being bridged across the circuit, as shown in Fig. 2.

That such an arrangement will have the

desired effect will be apparent from the following considerations:

A network, such as shown in Fig. 2, will introduce no out-of-phase component if its impedance is real, as the absence of any imaginary factor indicates that the reactance effects are neutralized. Bearing in mind that the impedance of *C* is $\frac{1}{i\omega C}$ and that of *L* is $i\omega L$, where ω is 2π times the frequency, the impedance *Z* of the combination may be written

$$Z = \frac{(R + i\omega L) \left(\frac{1}{i\omega C} \right)}{R + i\omega L + \frac{1}{i\omega C}} \quad (1) \quad 80$$

which by simple algebraic transformation becomes

$$Z = \frac{R + i\omega L}{1 + i\omega CR - \omega^2 LC} \quad (2) \quad 85$$

Now, if in equation (2) we neglect second order effects (those involving powers higher than the first power of the frequency) the impedance may be written

$$Z = \frac{R + i\omega L}{1 + i\omega CR} \quad (3)$$

But from inspection of the foregoing, this impedance *Z* will be made real if we make *L* of such value that the following proportion holds:

$$R : i\omega L :: 1 : i\omega CR \quad (4) \quad 100$$

for, if this proportion holds, the imaginary operator *i* cancels out. Incidentally, the frequency factor ω also disappears. Solving proportion (4), we have

$$L = CR^2 \quad (5) \quad 105$$

as the condition for making the impedance real so far as effects of the first order are concerned.

If, now, we substitute the value of *L* given by equation (5) in equation (2), we may write

$$\frac{1}{Z} = \frac{1 + i\omega CR - \omega^2 C^2 R^2}{R(1 + i\omega CR)} = \frac{1}{R} - \frac{\omega^2 C^2 R}{1 + i\omega CR} \quad (6) \quad 115$$

By expanding the last term, this becomes

$$\frac{1}{Z} = \frac{1}{R} - \omega^2 C^2 R + i\omega^3 C^3 R^2 + \quad (7)$$

from which we get

$$Z = R + \omega^2 C^2 R^3 - i\omega^3 C^3 R^4 \quad (8)$$

Analysis of equation (8) shows that the impedance is real and independent of frequency for all terms lower than those involving the second power of frequency or higher powers, being in fact equal to *R*. It should also be noted that the second power term $\omega^2 C^2 R^3$ is also real though not independent of frequency. Computations for practical

cases indicate that third power and higher terms are negligible and need not be compensated for frequencies up to 100,000 cycles. The effect of this second power term should not be neglected, however. While this term is real and hence involves no phase shift, its effect in an amplifier system is to increase the gain slightly with frequency. This effect can be compensated, as will be described later, by introducing an auxiliary network of such character that it introduces no first order distortion but for the second power term produces a gain characteristic which decreases with frequency.

Before proceeding with the consideration of the design of such auxiliary network, let us consider how the principles so far developed may be applied to the design of an amplifier. One form of application is illustrated in Fig. 5. Here, the grid biasing potential is supplied from a grid battery through an inductance L_1 , self-inductance of a winding of a transformer L_{12} and the usual battery supply resistance R_1 . The plate battery will be supplied through an inductance L_2 and the self-inductance of the other winding of the transformer L_{12} in series with the plate supply resistance R_2 . A condenser of large capacity is introduced in the lead between the plate of one tube and the grid of the next tube between the battery supply resistances, but this condenser is of very large capacity, for the purpose of insulating the grid and plate circuits with respect to the direct current supply, and does not introduce any material effect from an alternating current standpoint. The same holds true of the two condensers associated with the filament, for the purpose of connecting the grid and plate to a neutral point in the filament circuit. The effective bridged capacities which are to be neutralized are principally the capacity from grid to plate and the various capacities to ground elsewhere referred to. The coil L_{12} represents a transformer of perfect coupling whose mutual inductance and self-inductance per winding equal L_{12} . This coil compensates for the grid plate capacity C_{12} . The coil L_1 compensates for the capacity C_1 which is made up of the capacity from the grid to ground and filament plus incidental capacity in the grid wire. L_2 compensates for C_2 which is the capacity of the plate and its wire. The formulæ for computing the inductances are:

$$L_1 + L_{12} = (C_1 + C_{12}) R_1^2 \quad (9)$$

$$L_2 + L_{12} = (C_2 + C_{12}) R_2^2 \quad (10)$$

$$L_{12} = C_{12} R_1 R_2 \quad (11)$$

where R_1 is the resistance connected to the grid, and R_2 is the resistance connected to the plate.

Equations (9) and (10) follow obviously from equation (5). In order to understand

the derivation of equation (11), however, consider Fig. 4 which is Fig. 5 in simplified form, the inductances L_1 and L_2 being omitted as their effect in compensating for the capacity C_{12} is negligible. Assume that in Fig. 4 a voltage E is applied to the plate. Then, current I_x flows from plate through C_{12} , R_1 and L_{12} . The impedance of L_{12} is negligible in comparison with R_1 and C_{12} . Hence, impedance Z_x of the circuit is

$$Z_x = R_1 + \frac{1}{i\omega C_{12}} \quad (12)$$

and the current flowing through such impedance is

$$I_x = \frac{E}{Z_x} = \frac{E}{R_1 + \frac{1}{i\omega C_{12}}} \quad (13)$$

The drop across L_{12} is negligible. Hence, the drop e across R_1 is

$$e = \frac{ER_1}{R_1 + \frac{1}{i\omega C_{12}}} \quad (14)$$

A plate current I_y also flows through R_2 and L_{12} . The impedance Z_y of this circuit is

$$Z_y = R_2 + i\omega L_{12} \quad (15)$$

and the current flowing therethrough is

$$I_y = \frac{E}{R_2 + i\omega L_{12}} \quad (16)$$

This current through primary of L_{12} induces drop e' across secondary of L_{12} which will be positive or negative according to the way transformer is poled. It may be written

$$e' = \pm \frac{Ei\omega L_{12}}{R_2 + i\omega L_{12}} = \pm \frac{EL_{12}}{L_{12} + \frac{R_2}{i\omega}} \quad (17)$$

If C_{12} is neutralized, there is no change in potential of the grid due to E . Hence $e + e'$ must equal 0 and L_{12} must be poled so that e' opposes e . Then

$$e + e' = \frac{ER_1}{R_1 + \frac{1}{i\omega C_{12}}} - \frac{EL_{12}}{L_{12} + \frac{R_2}{i\omega}} = 0 \quad (18)$$

or

$$\frac{1}{1 + \frac{1}{i\omega R_1 C_{12}}} - \frac{1}{1 + \frac{R_2}{i\omega L_{12}}} = 0 \quad (19)$$

whence

$$L_{12} = C_{12} R_1 R_2 \quad (11)$$

which was to be proven.

A modified arrangement is shown in Fig. 6, and the theoretical considerations already given apply equally to this figure. Fig. 6 differs from Fig. 5 in that the terminal of the inductance L_1 is connected to the grid lead through a condenser, and the biasing po-

tential for the grid may then be obtained by means of a connection 10 from taps in the direct current filament supply circuit in a manner well understood in the art. In Fig. 5, as already stated, the terminal of the inductance L_1 is connected to the negative side of a C battery whose opposite terminal is grounded.

It is desired to keep the L's small. Noting formulæ (9), (10) and (11) it will be seen that this can be accomplished by making the R's small. On the other hand, it is desirable to keep the R's great, as any bridge across the circuit should be of high impedance in order to prevent shunting energy from the succeeding tube. The arrangement shown in Fig. 7 illustrates how two resistances may be combined for alternating current purposes. Here, the resistances R_p and R_g are connected in parallel in a bridged circuit including windings of transformers L_{12} associated with two succeeding vacuum tubes and a common inductance L_o . The interstage capacities shown between the resistances R_p and R_g may be neglected in considering alternating current. It will be seen, therefore, that the two resistances in parallel may be used in computing the L's. The formulæ now are:

$$L_o = C_o R^2 \quad (20)$$

$$L_{12} = C_{12} R^2 \quad (21)$$

where C_o is the total capacity to ground of the interstage wiring including the grid plate capacity, and R is the combined resistance of the plate and grid supply resistances R_p and R_g in parallel. The method of compensating shown in Fig. 7 is applied to a large number of stages in a complete distortion neutralizing repeater illustrated in Fig. 8, as will be described later.

The compensation so far discussed is of the first order in frequency. The second order, (that is, terms involving the second power of frequency), is not compensated. The effect of the second order term ($\omega^2 C^2 R^3$) of equation (8) is to increase the gain slightly as the frequency increases within the frequency range of interest. Computations indicate that with existing vacuum tubes it will be desirable to compensate for this second order effect as well as the first in order to operate up to about 100,000 cycles. This apparently need not be done at each stage, however, if the precautions above enumerated are observed. Apparently, the third order term ($-\omega^3 C^3 R^4$) of equation (8) need not be compensated under these conditions.

In accordance with the present invention, the second order effect may be compensated by introducing at some point in the circuit a network of the type shown in Fig. 3, which comprises an inductance e in series with a shunt combination comprising a resistance r and a capacity c . Such a network, in order

to perform its function, should produce no first order distortion, and the second order term of its impedance should be complementary to the term involving the second power of frequency in equation (8).

The impedance of a network such as shown in Fig. 3 may be written

$$Z' = i\omega e + \frac{r i\omega c}{r + \frac{1}{i\omega c}} \quad (22)$$

which reduces to

$$Z' = \frac{r + i\omega e - \omega^2 e c r}{1 + i\omega c r} \quad (23)$$

If we neglect in equation (23) terms higher than the first power of frequency, this may be written

$$Z' = \frac{r + i\omega e}{1 + i\omega c r} \quad (24)$$

The impedance as expressed in equation (24) will be real, and hence will introduce no phase shift if r , e and c be chosen in accordance with the following proportion:

$$r : i\omega e :: 1 : i\omega c r \quad (25)$$

whence,

$$e = c r^2 \quad (26)$$

In order to determine the effect of the assumed value of e upon the higher power terms of the impedance, let us substitute the value of e given in equation (26) in equation (23), so that

$$Z' = \frac{r(1 + i\omega c r) - \omega^2 c^2 r^3}{1 + i\omega c r} = r \left(1 - \frac{\omega^2 c^2 r^2}{1 + i\omega c r} \right) \quad (27)$$

Expanding equation (27), we have

$$Z' = r(1 - \omega^2 c^2 r^2 + i\omega^3 c^3 r^3 \dots \dots \dots) \quad (28)$$

Comparing equation (28) with equation (8), it will be seen that the impedance of the network of Fig. 3, so far as first order effects are concerned, is, like that of Fig. 2, a pure resistance r , and its second order term $-\omega^2 c^2 r^2$ is opposite in sign but otherwise similar to the corresponding second order term of equation (8). Obviously, then, if the elements e , c and r of the network of Fig. 3 be given the values L , C and R , so that $L = CR^2$, the impedance of the network of the Fig. 3 to the second order may be written

$$Z' = R(1 - \omega^2 CL \dots \dots \dots) \quad (29)$$

The second order term of equation (29) $-\omega^2 CLR$ will annul the corresponding term $+\omega^2 C^2 R^3 = +\omega^2 CLR$ of equation (8).

Further comparison of equations (8) and (28) shows that the terms of the third order of frequency are of similar form but opposite in sign, so that if a network such as that of Fig. 3 be provided for each stage of the amplifier, the effect of the reactance could be

compensated for all terms up to and including the term involving the third power of frequency.

Figure 8 shows a distortion neutralizing repeater of the type shown in Fig. 1, to which the reactance neutralizing networks of Figs. 2 and 3 have been applied. In this figure, the amplified A_1 is represented by a single stage vacuum tube LT_1 . The amplifier A_3 has five stages, and the amplifier A_4 has two stages. The phase compensating member, as shown in Fig. 2, is applied to each of the stages of the amplifiers A_3 and A_4 in the form shown in Fig. 7, and, therefore, for each stage of each of these, the phase retarding effects of the grid-plate capacities, as well as the capacities of the grid wiring to ground and the plate wiring to ground, are compensated to the first order by the use of the coils L_0 and L_{12} in combination with the grid and plate supply resistances connected in parallel.

Second order effects in the amplifier A_3 are compensated by introducing the network N_3 between the third and fourth stages, as shown, and the same result is accomplished for the amplifier A_4 by introducing a similar network N_4 in the grid circuit of the first stage.

The filaments of all of the tubes of the three amplifiers of Fig. 8 are connected in series and supplied from a twenty-four volt battery, as shown. In order that the grid biasing potentials may be supplied from the filament circuit, it is desirable to arrange the order of the filaments in the filament supply circuit, so that, beginning from ground, the filaments of the tubes come in the following order: First, the filament of the amplifier A_1 followed by the filaments of the five tubes of the amplifier A_3 in reverse order, beginning with the last stage tube LT_2 and ending with the first stage tube NT_6 , and these in turn being followed by the filaments of the tubes NT_7 and NT_8 of the amplifier A_4 . The reason for this is that in the particular design illustrated, the tube of the amplifier A_1 is an L tube, and, likewise, the last stage of the amplifier tube A_3 has an L tube LT_2 , while all of the other tubes of the amplifiers A_2 and A_4 are so-called N tubes.

The drop through the filaments in each of the L tubes is about four volts and that through each of the N tubes is about one volt. Each of the N tubes should have its grid biased about six volts negative with respect to the negative side of its filament, while the grids of the L tubes should be biased about nine volts negative with respect to their filaments. In order to give the proper grid taps for each of the tubes, therefore, the filaments of the tubes are arranged in the order above stated, and additional resistance drops of about one volt each, numbered 9 to 14, inclusive, are provided. If the connection of each grid to a tap in the filament supply circuit

is traced, it will be found that each L tube will have its grid connected about nine volts more negative than its filament, and, accordingly, each N tube will have its grid connected about six volts more negative than its filament.

In connection with the amplifier of Fig. 8, the method of obtaining the feed-back voltage into the amplifier A_4 from the last stage of the amplifier A_3 should be noted. The output impedance of the last stage tube LT_2 and the impedances X_1 , X_2 and X_3 form the four sides of a Wheatstone bridge. The feed-back voltage impressed across the grid and filament of the first stage tube NT_6 of the amplifier A_4 is picked off across one diagonal of the bridge, namely, the junction point of the resistances X_1 and X_2 and the junction point of the resistance X_3 with the filament plate impedance of the tube LT_2 . The output transformer T_0 is connected across the opposite diagonal of the bridge. It follows, therefore, that the transformer and the line into which it works are in conjugate relation to the amplifier A_3 , so that the transformer does not introduce any phase shift in the current fed back to the amplifier A_4 . Moreover, the performance of the circuit will not be affected by changes in the line impedance.

The compensating networks N_3 and N_4 of the amplifiers A_3 and A_4 should preferably be made adjustable in order that they may be readjusted to take care of the changed characteristics of the amplifier when tubes are replaced. In order to readjust the network N_4 , the key K_4 is thrown to the meter M_3 , thereby opening the circuit of the amplifier A_4 which is now disabled. When the amplifier A_4 is operating normally, there should be no gain in the local round trip circuit through this amplifier, beginning with the connection N, through the amplifier and over the output connection S back again to the input connection N. The reason for this may be made clear if we refer again to Fig. 1 and consider the local round trip circuit including amplifier A_2 , path N, amplifier A_4 and path S. It will be remembered that amplifiers A_2 and A_4 in this diagram are combined in the one amplifier A_4 in Fig. 8, but the principle of operation is the same. Remembering that the function of the amplifiers A_4 and A_2 is to bring the distortion component from M back to the input of the amplifier A_3 with such phase and amplitude as to neutralize the distortion in the output of A_3 , it is evident that if there were any gain in the round trip circuit through the two amplifiers A_2 and A_4 , the distortion component from M would be over-compensated; and hence the normal adjustment of the amplifier A_4 of Fig. 8 is one in which there will be no gain in the round trip circuit through this amplifier, but, on the contrary, the amplifier will be substantially at its singing point. There-

fore, when the amplifier A_3 is opened by throwing the key K_3 , the amplifier A_4 , if properly adjusted, should be just on the verge of singing. If any singing occurs, this fact will be indicated on the meter M_3 . The network N should be readjusted so that the amplifier A_4 is just at the singing point for each frequency over the range involved. To make this adjustment, the key K_1 may be thrown to a variable oscillator O . As the oscillator O is adjusted to each frequency, the fact that the amplifier A_4 at that frequency is at a near-singing condition will be indicated on the meter M_3 , and the network N_4 can be adjusted accordingly.

In order to adjust the amplifier A_3 by means of the network N_3 , key K_3 should be restored and key K_4 thrown to the meter M_4 . The latter key opens the output of the amplifier A_4 . The gain from the input of the amplifier A_3 through said amplifier and over the feed-back connection to the input of the amplifier A_3 should be zero, because at this point, referring again to the operation previously outlined for Fig. 1, the pure sine wave from the output of the amplifier A_3 is met by a pure sine wave from the input of the amplifier A_3 of opposite sign and equal magnitude. If, therefore, the key K_4 is thrown to the meter and the amplifier A_3 is properly adjusted, nothing but distortion should appear upon the meter M_4 . The fact that the amplifier A_3 is properly adjusted will be indicated by a minimum indication of the meter M_4 . By throwing the key K_1 and connecting various frequencies from the oscillator to the amplifier A_3 , the network N_3 may be adjusted in order to introduce minimum current on the meter M_4 , in which case the amplifier A_3 will be adjusted for proper compensation.

It will be obvious that the general principles herein disclosed may be embodied in many other organizations widely different from those illustrated, without departing from the spirit of the invention, as defined in the following claims.

What is claimed is:

1. In an amplifier circuit in which an effective bridged capacity C exists, means to compensate first order of frequency effects of said capacity comprising a series combination of inductance L and resistance R shunted across said circuit, the resistance R being of appreciable magnitude as compared with the inductance L .

2. In an amplifier circuit in which an effective bridged capacity C exists, means to compensate first order of frequency effects of said capacity comprising a series combination of inductance L and resistance R shunted across said circuit, said inductance and resistance being related to said effective capacity substantially in accordance with the formula $L=CR^2$.

3. In an amplifier circuit in which an effective

bridged capacity C exists, means to compensate first order of frequency effects of said capacity comprising a series combination of inductance L and resistance R shunted across said circuit, said inductance and resistance being so related to said effective capacity that the impedance of the combination will be real for terms involving powers as high as the first power of frequency.

4. In an amplifier circuit in which an effective bridged capacity C exists, means to compensate first order of frequency effects of said capacity comprising a series combination of inductance L and resistance R shunted across said circuit, said inductance and resistance being so related to said effective capacity that the impedance of the combination will be real and independent of frequency for terms involving powers as high as the first power of frequency.

5. In an amplifier circuit in which an effective bridged capacity C exists, means to compensate first order of frequency effects of said capacity comprising a series combination of inductance L and resistance R shunted across said circuit, said inductance and resistance being so related to said effective capacity that the impedance of the combination will be real for terms as high as the second power of frequency and will be independent of frequency for terms below the second power of frequency.

6. In an amplifier circuit in which an effective bridged capacity C exists, means to compensate first order of frequency effects of said capacity comprising a series combination of inductance L and resistance R shunted across said circuit, and means to compensate second order of frequency effects of said capacity comprising a bridged network including an inductance e in series with a shunt combination of a resistance r and a capacity c .

7. In an amplifier circuit in which an effective bridged capacity C exists, means to compensate first order of frequency effects of said capacity comprising a series combination of inductance L and resistance R shunted across said circuit, said inductance and resistance being related to said effective capacity substantially in accordance with the formula $L=CR^2$, and means to compensate second order of frequency effects of said capacity comprising a bridged network including an inductance e in series with a shunt combination of a resistance r and a capacity c , the elements of said network being related substantially in accordance with the formula $e=cr^2$.

8. In an amplifier circuit in which an effective bridged capacity C exists, means to compensate first order of frequency effects of said capacity comprising a series combination of inductance L and resistance R shunted across said circuit, the impedance of the combination comprising capacity C ,

inductance L and resistance R to the second order of frequency being $R + \omega^2 CRL$, and means to compensate second order of frequency effects of said capacity comprising a bridged network including an inductance l in series with a shunt combination of a resistance r and a capacity c , the impedance of the network to the second order of frequency being $r - \omega^2 crl$.

9. In an amplifier circuit in which an effective bridged capacity C exists, means to compensate first order of frequency effects of said capacity comprising a series combination of inductance L and resistance R shunted across said circuit, said inductance and resistance being so related to said effective capacity that the impedance of the combination will be real for terms as high as the second power of frequency and will be independent of frequency for terms below the second power of frequency, and means to compensate second order of frequency effects of said capacity comprising a bridged network including an inductance e in series with a shunt combination of a resistance r and a capacity c , the elements e , c and r of the network being so related that the impedance of the network to the first order of frequency will be real and independent of frequency and the second power term of its impedance will be complementary to that of the combination comprising L , C and R .

10. In a multi-stage amplifier circuit including a plurality of vacuum tubes each having a grid to plate capacity C_{12} and capacity C_0 from the interstate wiring and apparatus to ground, means to compensate first order of frequency effects of said capacities comprising a bridged circuit including grid and plate battery supply resistances having a combined resistance R in series with the mutual inductances L_{12} of transformers for coupling the plate of a given tube to the grid of the same tube and a self-inductance L_0 .

11. In a multi-stage amplifier circuit including a plurality of vacuum tubes each having a grid to plate capacity C_{12} and capacity C_0 from the interstage wiring and apparatus to ground, means to compensate first order of frequency effects of said capacities comprising a bridged circuit including a grid and plate battery supply resistances having a combined resistance R in series with the mutual inductances L_{12} of transformers for coupling the plate of a given tube to the grid of the same tube, and a self-inductance L_0 , said mutual inductance having substantially the value $L_{12} = C_{12}R^2$ and said self-inductance having substantially the value $L_0 = C_0R^2$.

12. In a multi-stage amplifier circuit including a plurality of vacuum tubes each having a grid to plate capacity C_{12} and capacity C_0 from the interstage wiring and apparatus to ground, means to compensate first order of

frequency effects of said capacities comprising a bridged circuit including grid and plate battery supply resistances having a combined resistance R in series with the mutual inductances L_{12} of transformers for coupling the plate of a given tube to the grid of the same tube, and a self-inductance L_0 , said inductances and resistances being so related to the corresponding capacities that the impedance of the combination comprising grid-plate capacity, battery supply resistance and mutual inductance L_{12} and also the impedance of the combination comprising interstage capacity to ground, battery supply resistance and self-inductance L_0 will each be real and independent of frequency for terms of the first order of frequency.

13. In a multi-stage amplifier circuit including a plurality of vacuum tubes each having a grid to plate capacity C_{12} and capacity C_0 from the interstage wiring and apparatus to ground, means to compensate first order of frequency effects of said capacities comprising a bridged circuit including grid and plate battery supply resistances having a combined resistance R in series with the mutual inductances L_{12} of transformers for coupling the plate of a given tube to the grid of the same tube, and a self-inductance L_0 , said inductances and resistances being so related to the corresponding capacities that the impedance of the combination comprising grid-plate capacity, battery supply resistance and mutual inductance L_{12} and also the impedance of the combination comprising interstage capacity to ground, battery supply resistance and self-inductance L_0 will each be real and independent of frequency for terms of the first order of frequency and will each be real for second power terms.

14. In a distortion neutralizing repeater, a principal multi-stage amplifier, a feed-back connection from the output of said principal amplifier to its input through an auxiliary multi-stage amplifier, and a connection from the input of said principal amplifier to said auxiliary amplifier, each stage of each amplifier, having inherent capacities effectively bridged across the circuit, means to compensate first order of frequency effects of said capacities comprising a circuit bridged across each stage and including series inductance and resistance related substantially according to the formula $L = CR^2$, and means to compensate second order of frequency effects comprising a bridged network for each amplifier, said bridged network comprising an inductance e in series with a shunt combination of capacity c and resistance r proportioned substantially in accordance with the formula $e = cr^2$.

15. A path for transferring waves of a substantial frequency range, comprising shunt resistance and effective shunt capacity, and impedance means forming with said resist-

ance and capacity a shunt impedance that is substantially pure resistance impedance over said frequency range.

16. In combination, a transfer path for waves representing a signal, a reactance included in said path, an impedance network shunted across said path at a point between the ends of said path, reactances included in said network, the impedance of said network and path between their junction points being a substantially pure resistance over the frequency range of said waves.

17. A one-way wave propagating path having an input section and an output section, a network with its input impedance shunted across said input section and shunted across said output section and presenting to each of said sections approximately a pure resistance impedance over a substantial frequency range.

18. In combination, a source of waves and two wave transfer paths connected to said source in parallel relation to each other, one of said paths comprising a filter capable of selectively transmitting with substantially uniform low attenuation waves of a band of frequencies of substantial width which has one end connected to said source, said filter having a shunt condenser included in its initial impedance element at said one end.

19. Two vacuum tubes and a circuit for coupling them in tandem relation, said circuit forming with inter-electrode capacities of said tubes a network that has two input terminals, one connected to the cathodes of said tubes and the other connected to another electrode of each tube, the impedance presented by said network to said terminals being approximately pure resistance impedance over a substantial frequency range.

20. A path for transmitting waves, comprising vacuum tubes in tandem relation, impedance means forming with interelectrode capacities of said tubes a network, a circuit for supplying space current to one of said tubes, a resistor included in said circuit and forming a terminating impedance for said network, said network having an input impedance which is substantially pure resistance impedance for said waves and which faces two of the electrodes of each of said tubes.

21. A wave transmission system comprising two vacuum tubes and coupling means for coupling said tubes in tandem relation for transmission of waves from one to the other, a plate current supply path for said one tube, a resistor included in said path and in said coupling means, and means for rendering the phase shift in waves transmitted by said one tube to the other tube substantially zero, said means comprising an inductance in series with said plate resistor.

22. In combination, a transfer path for waves of a considerable frequency range, a reactance included in said path, an impedance

network shunted across said path at a point between the ends of said path, reactance included in said network, the impedances of said network and path between their junction points being a substantially pure and constant resistance over the frequency range of said waves.

23. A system comprising a plural odd number of electric space discharge devices, interstage coupling circuits for said devices, means for balancing waves from the output side of the last device against waves from the input side of the first device, means for feeding waves resulting from said balancing action through said devices, and phase correcting means in each of said interstage coupling circuits.

24. A system comprising a plural odd number of electric space discharge devices, interstage coupling circuits for coupling said devices in cascade connection, means for balancing waves from the output side of the last device against waves from the input side of the first device, and means for feeding waves resulting from said balancing action through said devices, each of said coupling circuits forming with interelectrode capacities of the two devices which it couples, a network that has two input terminals, one connected to the cathodes of said two devices and the other connected to another electrode of each of said two devices, the impedance presented by said network to said terminals being approximately pure resistance impedance over a substantial frequency range.

In testimony whereof, I have signed my name to this specification this 13th day of September, 1929.

HARRY NYQUIST.