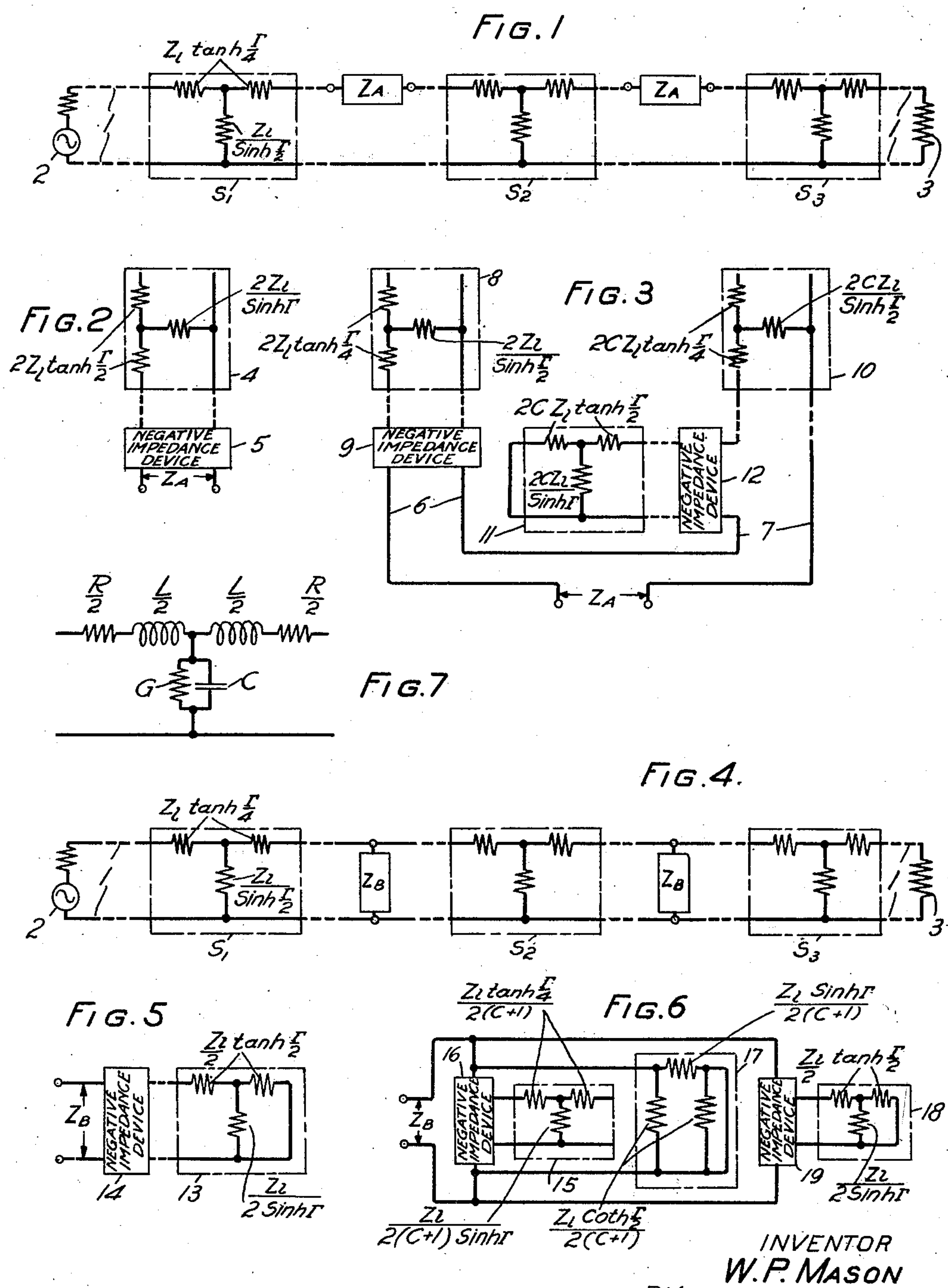
Dec. 22, 1931. W. P. MASON 1,837,229

DISTORTION CORRECTION IN TRANSMISSION SYSTEMS

Original Filed Oct. 3, 1928



INVENTOR
W. P. MASON
BY H. A. Burgess
ATTORNEY

Patented Dec. 22, 1931

1,837,229

UNITED STATES PATENT OFFICE

WARREN P. MASON, OF EAST ORANGE, NEW JERSEY, ASSIGNOR TO BELL TELEPHONE LABORATORIES, INCORPORATED, OF NEW YORK, N. Y., A CORPORATION OF NEW YORK

DISTORTION CORRECTION IN TRANSMISSION SYSTEMS

Original application filed October 3, 1928, Serial No. 310,165, and in Canada July 19, 1929. Divided and this application filed November 29, 1929. Serial No. 410,350.

This is a division of my application Serial No. 310,165, filed October 3, 1928 for distortion correction in transmission systems.

This invention relates to systems for transmitting electrical wave energy, such as telephone transmission systems and the like, and particularly to the correction of distortion in such systems.

From an ideal quality standpoint, a transmission system should be designed so that the currents received thereover are exact copies in every respect of the corresponding currents entering the system at the transmitting end; in other words, the transmission system should be distortionless. When electrical waves are transmitted over conductors of relatively great length, the distortion produced in the waves due to the inherent properties of the conductors becomes of increasing importance. In long, high quality systems, such as are now being used for telephone transmission, program broadcasting, television, etc. the distortion produced by lines is often of such magnitude as to appreciably impair the quality of the received waves, and thus reduces the commercial efficiency of such systems.

Distortion in transmission lines is, in general, of three different kinds; first, attenuation of the transmitted waves bv the line; second, an unequal degree of attenuation in waves of different frequencies transmitted over the line; and third, a relative phase change in the transmitted waves. The cause of such distortion is the improper proportioning of the resistance, the leakance, the capacity, and the inductance of the line.

The Pupin-Campbell and other loading methods have been devised with the object of reducing attenuation in the useful frequency range in transmission systems. Such loading systems have been supplemented in practice by amplifiers, such as the telephone repeater, to compensate for reduction in the amplitude of the transmitted waves. The second type of distortion inherent in transmission systems, an unequal degree of attenuation in the transmitted waves of different frequencies, may be overcome by the use of attenuation equalizing networks at different points in the system, this expedient having been brought to a high state of development. Phase corrective networks or phase compensators to supplement other types of distortion correction, such as loading, have been used in connection with lines to correct phase distortion in the transmitted waves of a desired range of frequencies. Other networks have been devised and utilized in connection with transmission lines to combine the functions of phase distortion correction and attenuation equalization in transmitted waves of a desired range of frequencies. The latter networks have been designed, in part at least, by empirical methods, or else in their design all factors contributing to distortion have not been taken into account. Their use, therefore, enables only an approximation of the ideal distortionless line to be obtained.

An object of the invention is to correct distortion in electric wave transmission.

Another and more specific object is to reduce the attenuation and to minimize variations in the velocity of propagation of electric waves over transmission systems.

In accordance with the invention, exact design formulæ have been developed for the impedance relations which a structure must satisfy when combined with a transmission line in a given manner in order to completely compensate for all distortion including amplitude and phase distortion produced by the line on waves of all frequencies transmitted thereover, and structures have been designed in accordance with these formulæ to accomplish the desired result.

A feature of the invention is a unitary structure or network which when combined with a transmission line will simultaneously compensate both for amplitude and phase distortion in waves of all frequencies transmitted thereover, and at the same time restore the waves to their original amplitudes.

In accordance with the invention, the compensation for the amplitude and phase distortion produced in waves of all frequencies transmitted over a given length of transmission line is obtained by inserting in the line in the path of the transmitted waves a structure having characteristics equaling in value but effectively of opposite sign to those of the given length of transmission line.

In a preferred embodiment this structure is inserted in series with the given line and comprises an open-circuited section of smooth line half as long as the section to be compensated, and having a characteristic impedance twice that of the section of line to be compensated when the structure is not inserted therein, and in tandem therewith a device which will effectively change the positive impedance of the inserted section of line into a negative impedance of equal value.

In another embodiment the compensation for phase and amplitude distortion for waves of all frequencies transmitted over a section of line, together with a desired degree of amplification, is obtained by inserting in shunt to said given section of line a structure comprising a short-circuited smooth line of the same length as the given section to be compensated, and having a characteristic impedance half that of the section of line to be compensated when the structure is not inserted therein, and in tandem therewith a device which will effectively change the positive impedance of the inserted section of line into a negative impedance of equal value.

Substantially distortionless overall transmission for waves of all frequencies over a transmission line of any length may be effectively obtained by inserting at intervals along the line in the path of the waves, a structure such as described above, each structure being designed in accordance with the principles of the invention to completely compensate for the amplitude and phase distortion in the transmitted waves produced by adjacent portions of the transmission line.

The objects and advantages of the invention will be best understood from the following detailed description when read in connection with the accompanying drawings, in which Fig. 1 shows a diagram of a transmission system embodying one form of the invention; Figs. 2 and 3 show diagrammatically different forms of distortion correcting structures which may be used in the system of Fig. 1; Fig. 4 shows a diagram of a transmission system embodying a modification of the invention; Figs. 5 and 6 show different forms of distortion correcting structures which may be used in the system of Fig. 4; and Fig. 7 shows a type of simulating network which may be used in place of the artificial lines in the structures of Figs. 2, 3, 5 and 6 to approximate the results obtainable when said artificial lines are used.

In Fig. 1 is shown a transmission line 1 for transmitting alternating current waves of a plurality of frequencies generated by the source 2 to a load circuit represented by the resistance 3. The line 1 comprises a plurality of smooth line sections S_1, S_2, S_3—of equal length and a plurality of series impedances, represented by the boxes Z_A, inserted between the line sections each of these series impedances being designed in accordance with the invention to compensate for distortion in phase and amplitude in the transmitted waves of all frequencies produced by one section of said line. The sections of line S_1, S_2, S_3, etc. are represented in the figure in well known manner by an equivalent T resistance network having two series arms each of impedance

$$Z_l \tanh \frac{\Gamma}{4}$$

and a shunt arm of impedance

$$\frac{Z_l}{\sinh \frac{\Gamma}{2}}$$

where Z_l is the characteristic impedance of the line 1 and Γ is the propagation constant for a section of the line of length l.

The method of design of the series impedances Z_A is as follows:

The propagation constant P for the complex line 1 including the smooth sections S_1, S_2—and the series impedances Z_A is given by the equation:

$$\cosh P = \Gamma + \frac{Z_A}{2Z_l} \sinh \Gamma \quad (1)$$

Differentiating this equation with respect to ω (where $\omega = 2\pi$ times the frequency of the transmitted waves) the following equation is obtained:

$$\text{Sinh } P \frac{dP}{d\omega} = \sinh \Gamma \frac{d\Gamma}{d\omega} + \frac{\frac{dZ_A}{d\omega} Z_l - Z_A \frac{dZ_l}{d\omega}}{2Z_l^2} \sinh \Gamma + \frac{Z_A}{2Z_l} \cosh \Gamma \frac{d\Gamma}{d\omega} \quad (2)$$

The propagation constant P of the line 1 is composed of an attenuation constant A and a phase constant B. Hence,

$$\frac{dP}{d\omega} = \frac{dA}{d\omega} + j \frac{dB}{d\omega} \quad (3)$$

If

$$\frac{dP}{d\omega}$$

equals zero, then A and B are constants independent of frequency. For this condition, the attenuation distortion in the transmitted waves will be constant, and the velocity of the transmitted waves will be theoretically infinite since

$$\frac{dB}{d\omega}$$

is equal to the delay.

If the left side of Equation (2) is set equal to zero, the following differential equation will be obtained:

$$0=2Z_l\frac{d\Gamma}{d\omega}+Z_A\left(\coth\Gamma\frac{d\Gamma}{d\omega}-\frac{\frac{dZ_l}{d\omega}}{Z_l}\right)+\frac{dZ_A}{d\omega}\quad(4)$$

The solution of this equation is:

$$Z_A=2Z_l\left(\frac{C-\cosh\Gamma}{\sinh\Gamma}\right)\quad(5)$$

where C is an arbitrary constant which is independent of the frequency. Substituting this value for Z_A in Equation (1) it is found that

$$\cosh P=C\quad(6)$$

Hence, if networks corresponding to Equation (5) can be physically realized, and are inserted in line 1 in the manner shown in Fig. 1, the line 1 may be made such as to produce a constant or zero attenuation and a theoretically infinite or very high constant velocity in transmitted waves of all frequencies.

If C=1, Equation (5) reduces to

$$Z_A=2Z_l\left(\frac{1-\cosh\Gamma}{\sinh\Gamma}\right)=-2Z_l\coth\frac{\Gamma}{2}\quad(7)$$

Equation (7) may be physically realized in accordance with the invention by the structure of Fig. 2. The elements of the structure of Fig. 2, which in the system of Fig. 1 would be inserted in the boxes Z_A in series with the terminals thereof comprise a section of open-circuited smooth line 4 half as long as, and with a characteristic impedance which is twice that of the section of line 1 to be compensated by the structure, and in tandem therewith, a device 5 which will effectively change the positive impedance of the open-circuited line 4 to a negative impedance of equal value.

The negative impedance device 5 may be of any suitable type, for example, a feed-back amplifier such as disclosed and claimed in the patent of R. C. Mathes, No. 1,779,382, issued October 21, 1930, which will effectively give between two terminals thereof over a wide range of frequencies, the negative of resistance, inductance, capacity, or complex combination thereof used as the feed-back impedance. If the structure of Fig. 1 of the Mathes patent is used as the device 5 in the structure of Fig. 2 of this application, the terminals Z_A of the latter structure would be connected to terminals 16 and 17 of the former structure, and the two terminals of network 4 of the latter structure would be connected to the terminals of box 14 in the circuit of the former structure so that network 4 acts as the feed-back impedance Z in said circuit.

The open-circuited section of smooth line 4 has been represented in Fig. 2 by its equivalent **T** network comprising two series arms each of impedance

$$2Z_l\tanh\frac{\Gamma}{2}$$

and a shunt arm of impedance

$$\frac{2Z_l}{\sinh\Gamma},$$

the elements of these equations having the same significance as in the equations given above.

If a structure such as shown in Fig. 2 is utilized for the series impedances Z_A in the system of Fig. 1, an overall zero attenuation and zero phase shift will be obtained therein for transmitted waves of all frequencies.

If C> 1, Equation (5) reduces to:

$$Z_A=\frac{2Z_lC}{\sinh\Gamma}-2Z_l\coth\Gamma\quad(8)$$

Equation (8) may be physically realized in accordance with the invention by the structure shown in Fig. 3. The elements of that structure, which in the system of Fig. 1 would be inserted in the boxes Z_A in series with the terminals thereof, comprise a branch 6 and a branch 7 connected in series with the terminals of Z_A. Branch 6 comprises a section of open-circuited smooth line 8 of the same length as, and with a characteristic impedance which is twice that of the section of line 1 to be compensated, and in tandem therewith a device 9, similar to the device 5 of Fig. 2, which will change the positive impedance of the open-circuited line 8 to a negative impedance of equal value.

The branch 7 comprises a section of open-circuited line 10, the same length as, and with a characteristic impedance which is 2C times that of the portion of line 1 to be compensated, and in series therewith a short-circuited section of smooth line 11 half as long as, and with a characteristic impedance which is 2C times that of the section of line 1 to be compensated and in tandem with line 11 a device 12, similar to the device 9, which will effectively change the positive impedance of line 11 to a negative impedance of equal value.

The sections of open-circuited smooth line 8 and 10 and the section of short-circuited line 11 are represented in Fig. 3 by their equivalent **T** networks having shunt and series arms. Each of the two series arms of the equivalent **T** network of artificial line 8 has an impedance of

$$2Z_l\tanh\frac{\Gamma}{4}$$

and the shunt arm thereof has an impedance of

$$\frac{2Z_l}{\sinh\frac{\Gamma}{2}}.$$

Each of the series arms of the T network representing artificial line 10 has an impedance

$$2CZ_l \tanh\frac{\Gamma}{4}$$

and the shunt arm an impedance

$$\frac{2cZ_l}{\sinh\frac{\Gamma}{2}}.$$

Each of the series arms of the T network representing the artificial line 11 has an impedance of

$$2CZ_l \tanh\frac{\Gamma}{2}$$

and the shunt arm an impedance of

$$\frac{2CZ_l}{\sinh\Gamma}.$$

In Fig. 4 is shown a transmission system identical with that of Fig. 1, except that a shunt impedance indicated by the box Z_B, is utilized in place of each series impedances Z_A of the system of Fig. 1 between adjacent line sections to compensate for amplitude and phase distortion in transmitted waves of all frequencies for each section of the line 1. The method of designing the shunt impedances Z_B is as follows:

The propagation constant for the complex line comprising the sections S_1, S_2, S_3, etc. and the shunt impedances Z_B is given by the equation:

$$\cosh P = \cosh\Gamma + \frac{Z_l}{2Z_B}\sinh\Gamma \quad (10)$$

By differentiating Equation (10) with respect to ω equating the left side of the differential equation to zero, and solving, the following solution is obtained:

$$Z_B = \frac{Z_l}{2}\left(\frac{\sinh\Gamma}{C-\cosh\Gamma}\right) \quad (11)$$

Substituting this value for Z_B in Equation (10), it is noted that

$$\cosh P = C \quad (12)$$

Hence, if the structure which will satisfy Equation (11) is physically realizable and is inserted in line 1 of Fig. 4 as the shunt impedances Z_B in the manner shown, the complex line can be made to produce an overall uniform attenuation and a theoretically infinite or very high constant velocity in the transmitted waves of all frequencies.

If C equals 1, Equation (11) reduces to:

$$Z_B = \frac{Z_l}{2}\left(\frac{\sinh\Gamma}{1-\cosh\Gamma}\right) = -\frac{Z_l}{2}\tanh\frac{\Gamma}{2} \quad (13)$$

Equation (11) may be physically realized in accordance with the invention by a structure such as shown in Fig. 5. The elements of this structure, which in the system of Fig. 5 would be inserted in the boxes Z_B in series with the terminals thereof, comprise a short-circuited section of smooth line 13 half as long as, and with a characteristic impedance half that of the section of line 1 to be compensated, and in tandem therewith a device 14, similar to the device 5 in Fig. 2, which will effectively change the positive impedance of the short-circuited line 13 to a negative impedance of equal value. The short-circuited length of line in Fig. 5 has been represented by its equivalent T network, each of the two series arms of which have an impedance of

$$\frac{Z_l}{2}\tanh\frac{\Gamma}{2}$$

and the shunt arm of which has an impedance of

$$\frac{Z_l}{2\sinh\Gamma}.$$

If the structure of Fig. 5 is utilized for the shunt impedances Z_B in the system of Fig. 4, an overall zero attenuation and a zero phase shift may be obtained therein for transmitted waves of all frequencies.

If C>1 Equation (11) reduces to:

$$Z_B = \frac{\frac{Z_l}{2}\left(\frac{\sinh\Gamma}{C+1}\right) - \frac{Z_l}{2}\tanh\frac{\Gamma}{2}}{\frac{Z_l}{2}\left(\frac{\sinh\Gamma}{C+1}\right) + \left(-\frac{Z_l}{2}\tanh\frac{\Gamma}{2}\right)} \quad (14)$$

Equation (14) may be physically realized in accordance with the invention by the structure shown in Fig. 6. This structure, which in the system of Fig. 4 would be inserted in the boxes Z_B in series with the terminals thereof, comprise three different branch networks each connected directly across the terminals of Z_B. One of these networks comprises an open-circuited section of smooth line 15 of the same length as, and with a characteristic impedance which is

$$\frac{1}{2(C+1)}$$

times that of the section of line 1 to be compensated, and in tandem therewith a device 16, similar to the device 5 in Fig. 2, which will effectively change the positive impedance of open-circuited line 15 to a negative impedance of equal value.

The second of the networks in the structure of Fig. 6 comprises a short-circuited length of smooth line 17 of the same length as, and having a characteristic impedance which is

$$\frac{1}{2(C+1)}$$

times that of the section of line 1 to be compensated.

The third branch network in the structure of Fig. 6 comprises a short-circuited length of line 18, half as long as, and with a characteristic impedance which is one-half that of the section of line to be compensated, and in tandem therewith a device 19, similar to the device 16, which will effectively change the positive impedance of the short-circuited line 18 to a negative impedance of equal value.

The open-circuited line 15 is represented in Fig. 6 by its equivalent T network, each of the series arms of which has an impedance of

$$\frac{Z_l}{2(C+1)}\tanh\frac{\Gamma}{4}$$

and the shunt arm of which has an impedance of

$$\frac{Z_l}{2(C+1)\sinh\Gamma}.$$

The short-circuited section of line 17 is represented in Fig. 6 by its equivalent network, the series arm of which has an impedance of

$$\frac{Z_l}{2(C+1)}\sinh\Gamma$$

and each of the two shunt arms of which has an impedance of

$$\frac{Z_l}{2(c+1)}\coth\frac{\Gamma}{2}.$$

The short-circuited line 18 is represented in Fig. 6 by its equivalent T network, each of the two series arms of which has an impedance of

$$\frac{Z_l}{2}\tanh\frac{\Gamma}{2}$$

and the shunt arm of which has an impedance of

$$\frac{Z_l}{2\sinh\Gamma}.$$

If the structure of Fig. 6 is utilized for the shunt elements Z_B in the system of Fig. 4, an overall uniform attenuation and a zero phase shift may be obtained therein for transmitted waves of all frequencies.

A simulating network made up of inductances, resistances and capacities, such as illustrated in Fig. 7, may be utilized in place of each of the artificial lines of the structures of Figs. 2, 3, 5 and 6 to approximate the results obtainable when the artificial lines are used. This simulating network is a T structure, each of the series arms of which comprises a resistance of value

$$\frac{R}{2}$$

and an inductance of value

$$\frac{L}{2}$$

in series, and the shunt arm, a capacity of value C and a resistance of value

$$\frac{1}{G}$$

in parallel, where R is the resistance, L the inductance, C the capacity and G the leakance of the section of line to be compensated by the compensating structure.

It should be noted that each impedance element in the structures of the invention which have been illustrated and described contributes both to attenuation distortion correction and phase distortion connection this being an important distinguishing feature from the structures of the prior art in which attenuation correction or phase distortion correction is the sole function of separate elements therein.

Although the invention has been directed principally to the obtaining of complete compensation for attenuation and phase distortion, it is apparent that it may be utilized for obtaining any desired amount of attenuation and phase distortion correction.

Although the invention has been described in connection with a particular transmission system comprising a plurality of uniform smooth sections of line and a plurality of distortion compensating structures spaced at equal intervals along a transmission line, the invention is not so limited, but is applicable to a system comprising a smooth or a loaded line in combination with a single distortion compensating structure, or a plurality of distortion compensating structures spaced at unequal intervals along the line, or any other combination within the scope of the appended claims.

What is claimed is:

1. In combination with a transmission line for transmitting electrical waves of different frequencies, means for effectively compensating for all distortion both in phase and amplitude produced on transmitted waves of all frequencies by a given portion of said line, said means comprising an electrical structure in shunt with said given portion of said line, and having characteristics equivalent in value to those of said given portion of line but of opposite sign.

2. In combination with a transmission line for transmitting electrical waves of different frequencies, means for effectively compensating for all distortion produced by said line in the transmitted waves of all frequencies including distortion in phase and amplitude, said means comprising an electrical structure inserted in shunt with said line and traversed by said waves, said structure having a propagation constant and a characteristic impedance substantially equal to that of said line but impedance characteristics which are equivalent in value to those of said line but of opposite sign.

3. In combination, a transmission line for transmitting electrical waves of different frequencies, and means for compensating for all distortion in amplitude and phase produced in said waves of different frequencies by a given section of said line, said means com-

prising an electrical structure inserted in shunt with said given line section and traversed by said waves, said structure comprising a network having impedance characteristics equivalent to those of a short-circuited smooth line the same length as said given line section and with a characteristic impedance half that of said given line section, and in tandem therewith a device which will effectively change the positive impedance of said network to a negative impedance of equal value.

4. A combination in accordance with that of claim 1, in which said electrical structure in shunt with said given portion of said line comprises a short-circuited smooth line the same length as said given portion of said line and having a characteristic impedance half that of said portion of line before said structure was inserted therein, and in tandem therewith a device which will effectively change the positive impedance of said short-circuited line to a negative impedance of equal value.

5. In combination, a transmission line for transmitting electrical waves varying in frequency, and means for compensating for phase and amplitude distortion in waves of all frequencies transmitted over a given portion of said line, said means comprising a structure inserted in shunt with said portion of line having an impedance of

$$-\frac{Z_l}{2}\tanh\frac{\Gamma}{2},$$

where Z_l is the characteristic impedance and Γ is the propagation constant of said portion of line before the insertion of said structure therein.

In witness whereof, I hereunto subscribe my name this 27 day of November, 1929.

WARREN P. MASON.