

Feb. 13, 1940.

A. ALFORD

2,190,131

REENTRANT NETWORK

Filed Jan. 2, 1937

8 Sheets-Sheet 1

FIG. 1.

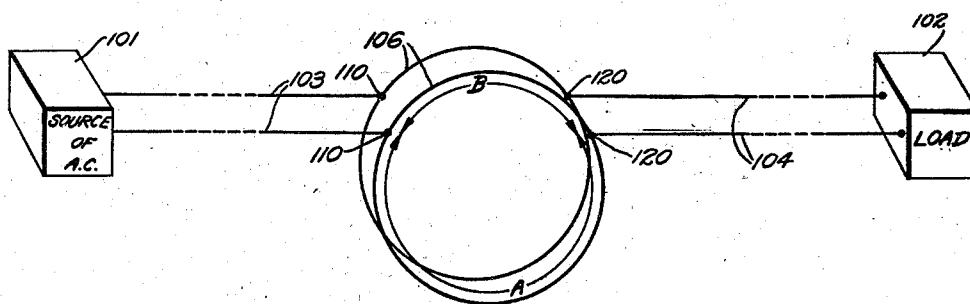


FIG. 2.

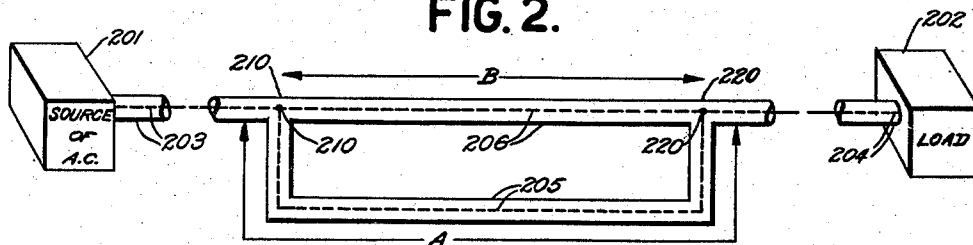
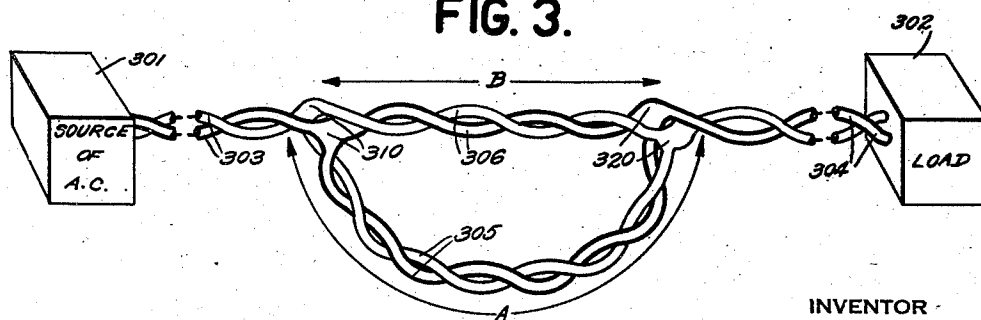


FIG. 3.



INVENTOR
ANDREW ALFORD
BY *E. O. McKinney*
ATTORNEY

Feb. 13, 1940.

A. ALFORD

2,190,131

REENTRANT NETWORK

Filed Jan. 2, 1937

8 Sheets-Sheet 2

FIG. 4.

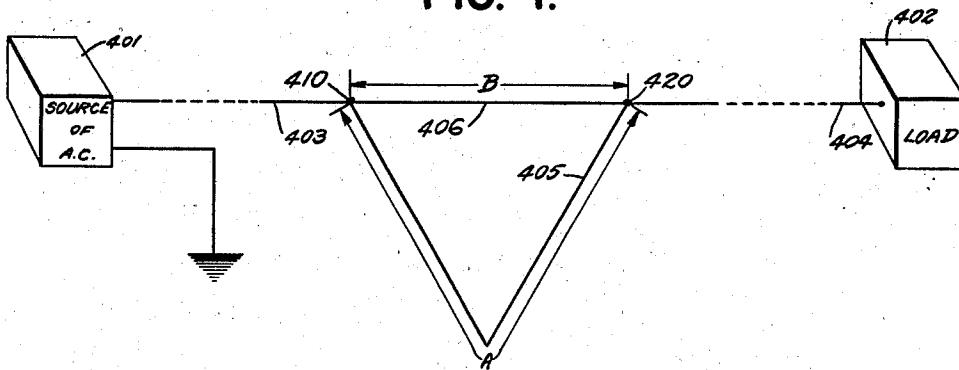


FIG. 5.

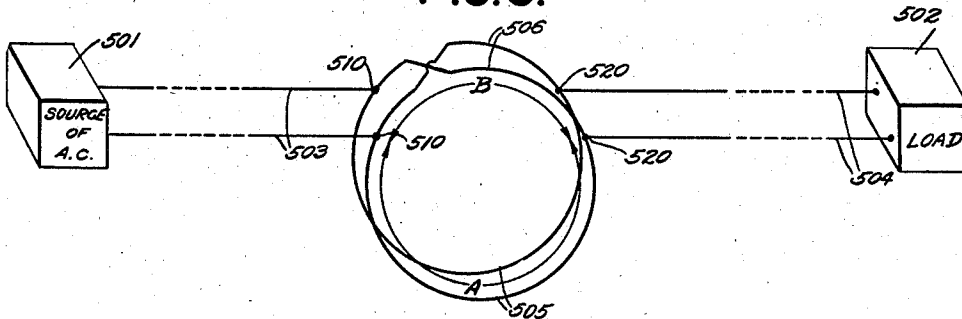
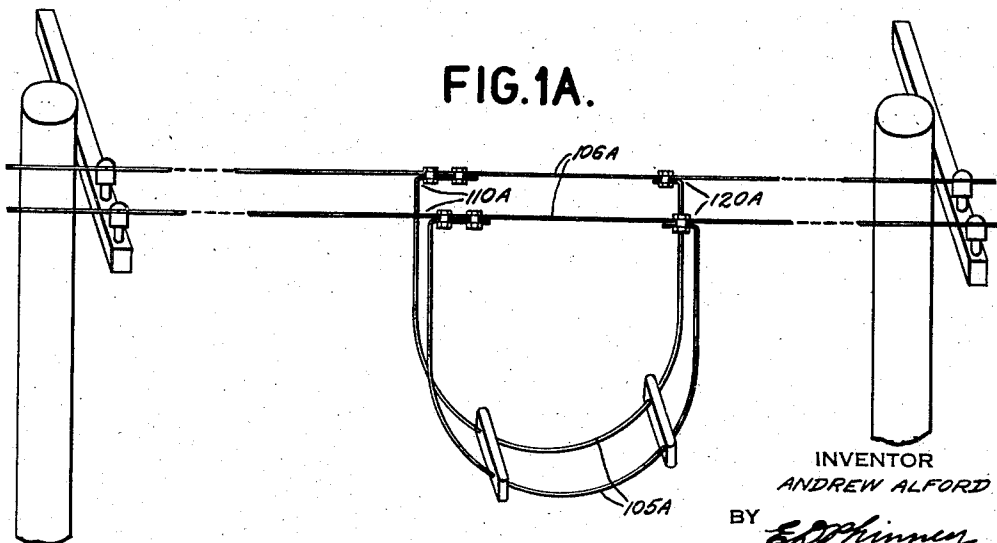


FIG. 1A.



INVENTOR
ANDREW ALFORD

BY *E. O. Hinney*
ATTORNEY

Feb. 13, 1940.

A. ALFORD

2,190,131

REENTRANT NETWORK

Filed Jan. 2, 1937

8 Sheets-Sheet 3

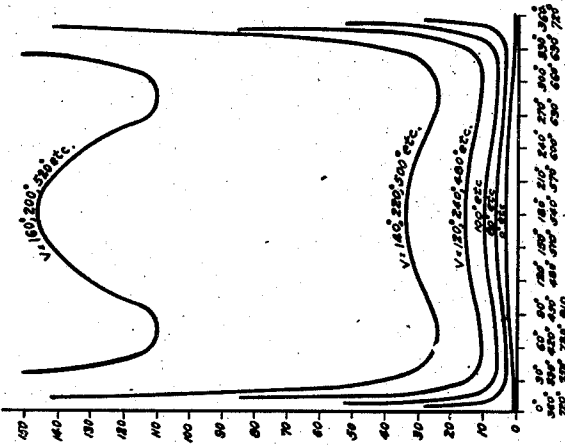


FIG. 8.

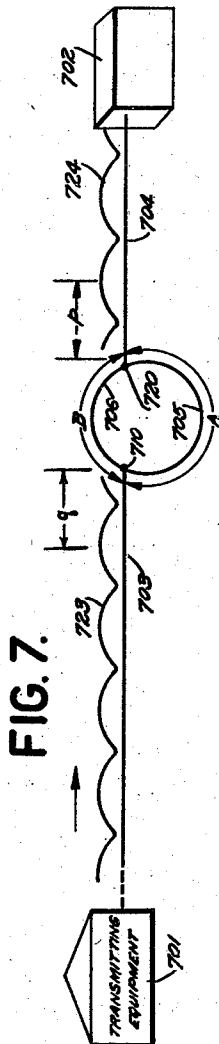


FIG. 7.

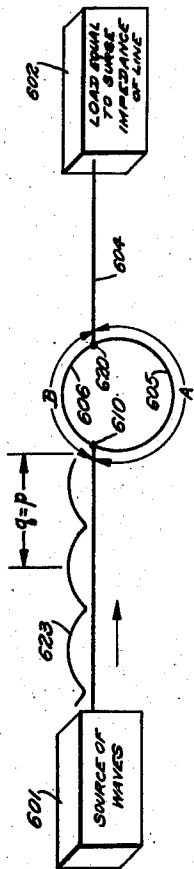


FIG. 6.

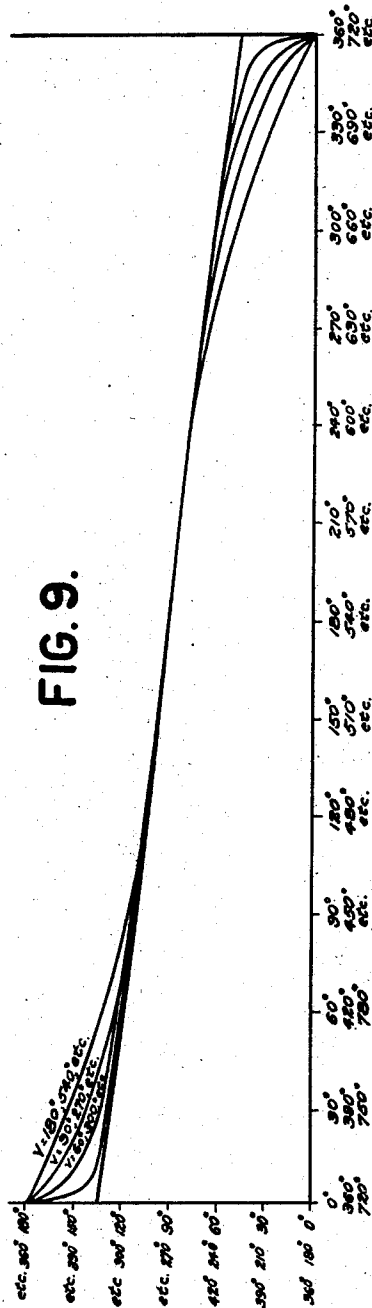


FIG. 9.

INVENTOR
ANDREW ALFORD
BY *E. C. Hinney*
ATTORNEY

Feb. 13, 1940.

A. ALFORD

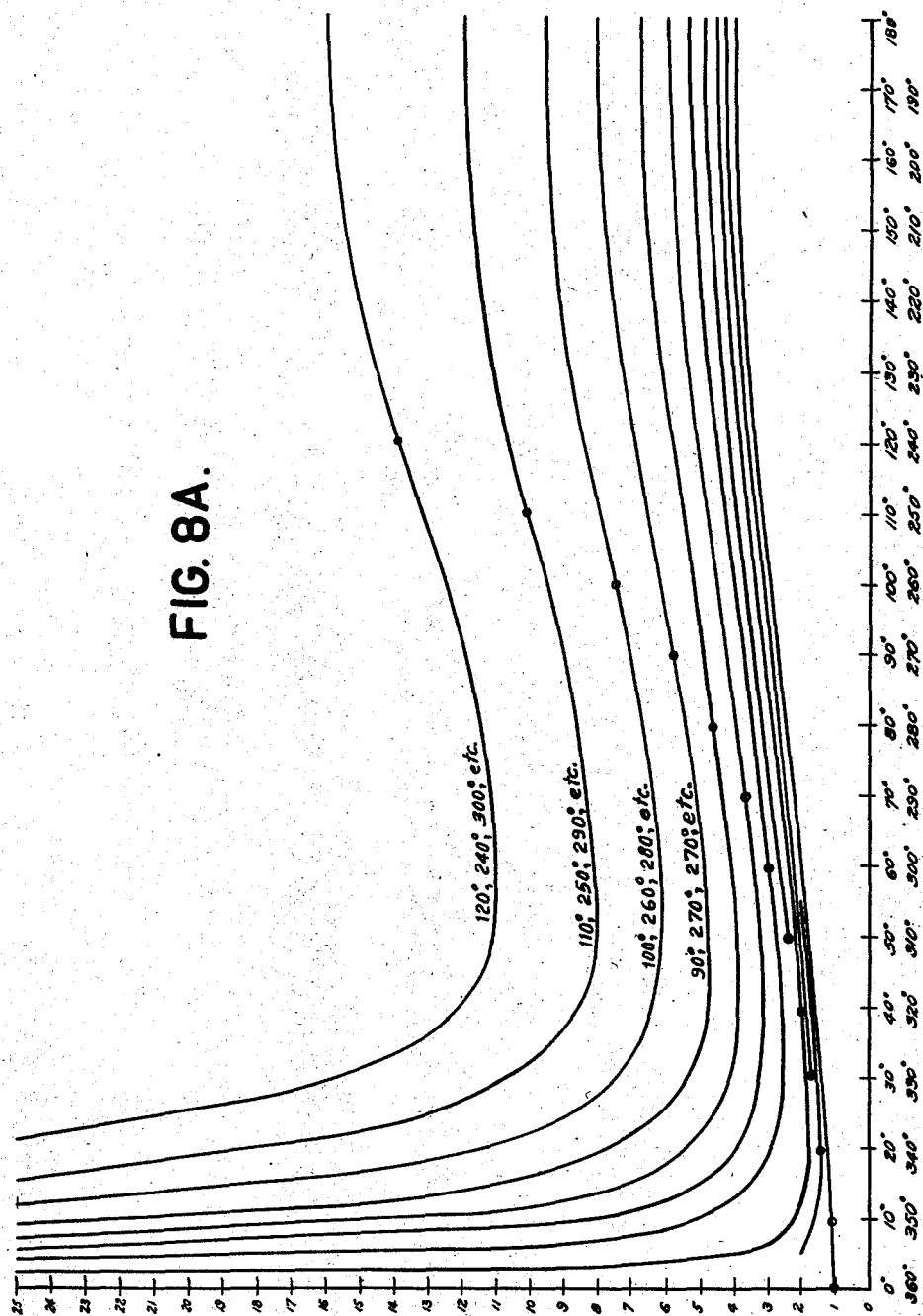
2,190,131

REENTRANT NETWORK

Filed Jan. 2, 1937

8 Sheets-Sheet 4

FIG. 8A.



INVENTOR
ANDREW ALFORD
BY *E. D. Kinney*
ATTORNEY

Feb. 13, 1940.

A. ALFORD

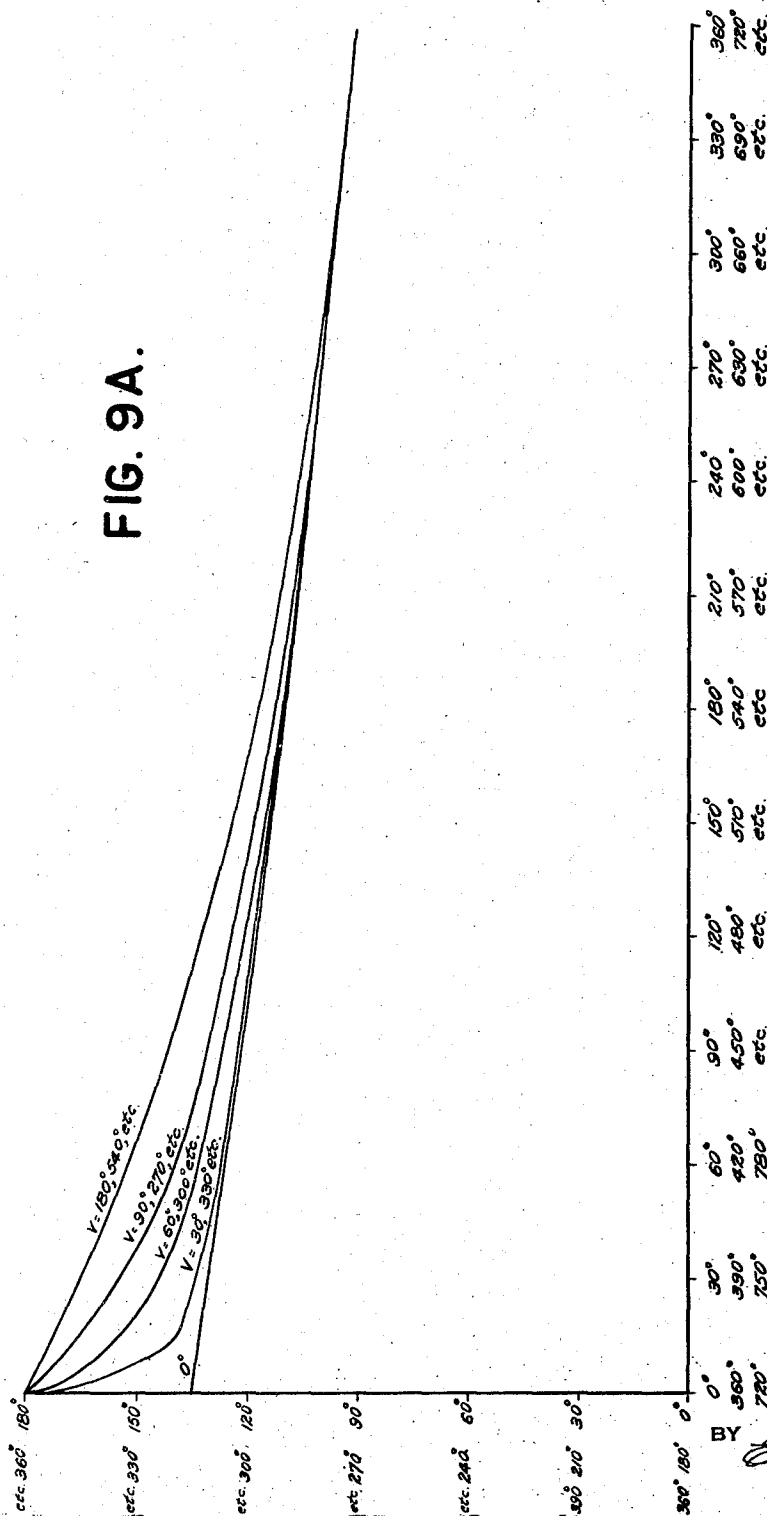
2,190,131

REENTRANT NETWORK

Filed Jan. 2, 1937

8 Sheets-Sheet 5

FIG. 9A.



INVENTOR
ANDREW ALFORD
BY *E. J. Hinney*
ATTORNEY

Feb. 13, 1940.

A. ALFORD

2,190,131

REENTRANT NETWORK

Filed Jan. 2, 1937

8 Sheets-Sheet 6

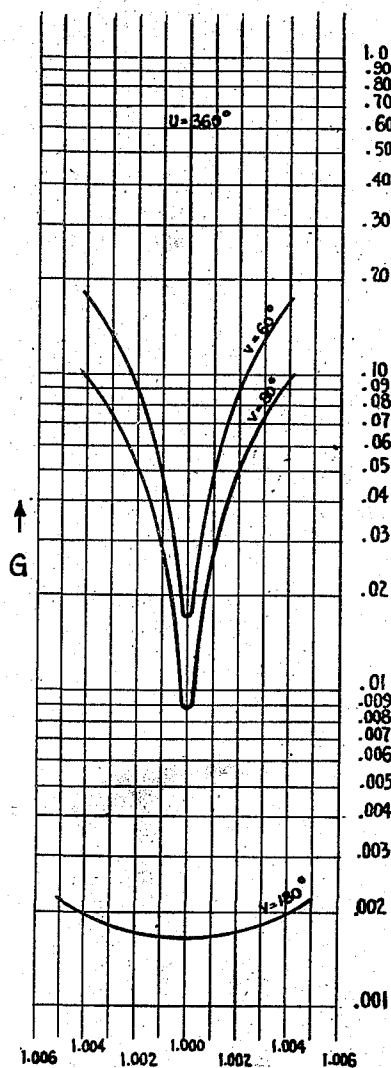


FIG. 10

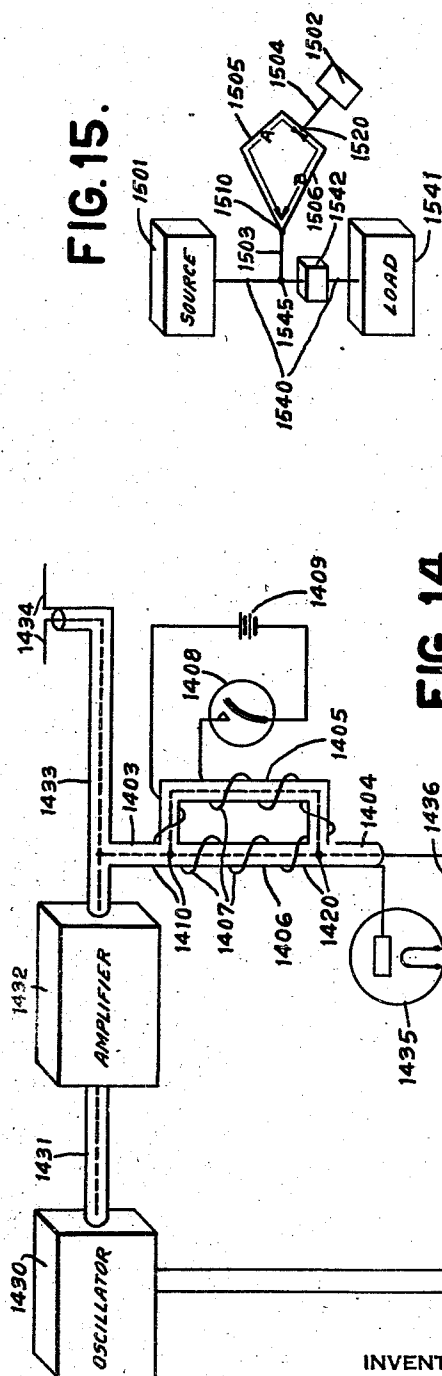


FIG. 14.

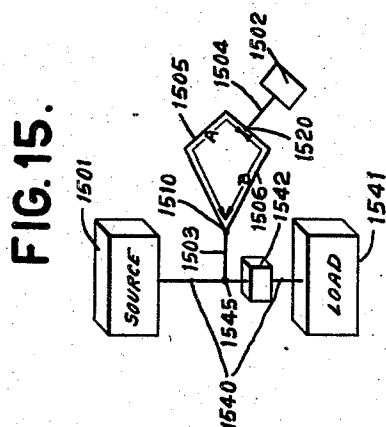


FIG. 15.

INVENTOR
ANDREW ALFORD
BY *Ed Phinney*
ATTORNEY

Feb. 13, 1940.

A. ALFORD

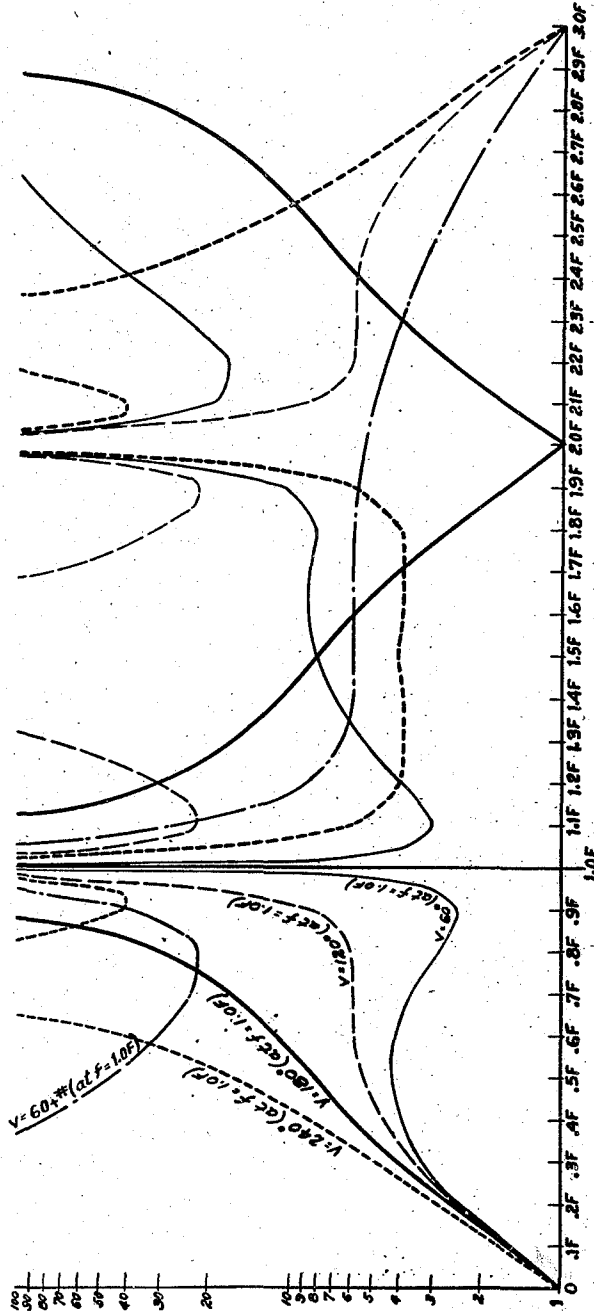
2,190,131

REENTRANT NETWORK

Filed Jan. 2, 1937

8 Sheets-Sheet 7

FIG. 11.



INVENTOR
ANDREW ALFORD
BY *E. O. Hines*
ATTORNEY

Feb. 13, 1940.

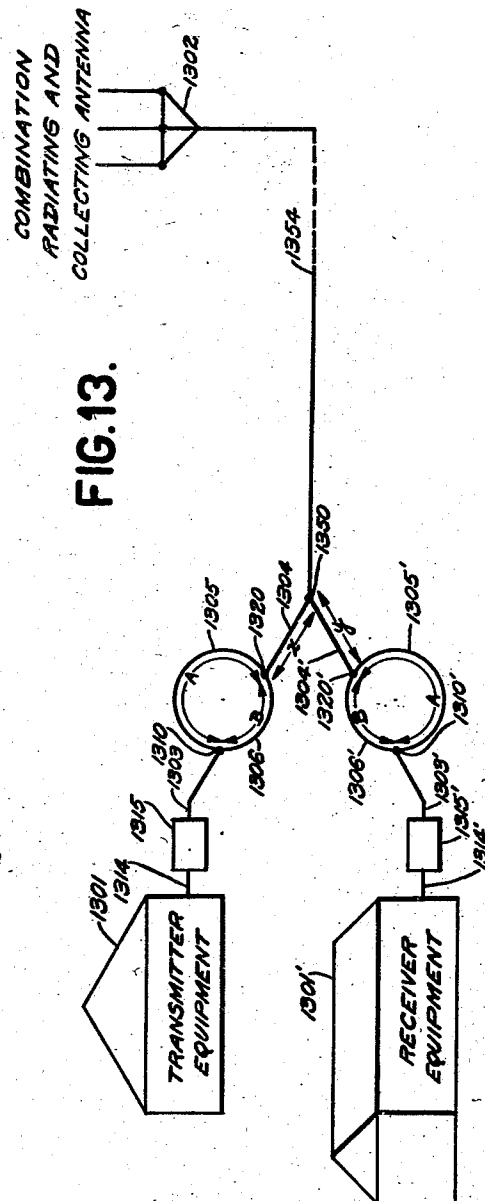
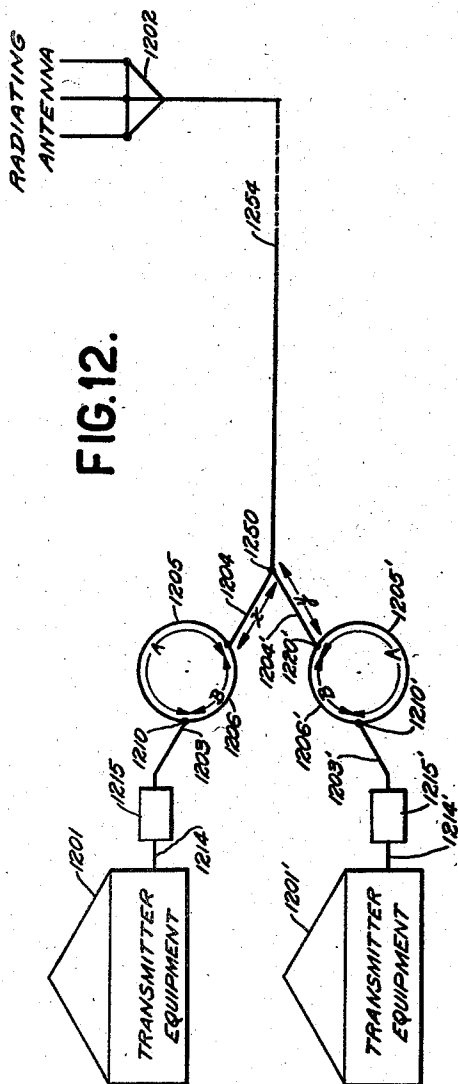
A. ALFORD

2,190,131

REENTRANT NETWORK

Filed Jan. 2, 1937

8 Sheets-Sheet 8



INVENTOR
ANDREW ALFORD
BY *E. P. Hinney*
ATTORNEY

UNITED STATES PATENT OFFICE

2,190,131

REENTRANT NETWORK

Andrew Alford, New York, N. Y., assignor to
Mackay Radio and Telegraph Company, New
York, N. Y., a corporation of Delaware

Application January 2, 1937, Serial No. 118,886

17 Claims. (Cl. 178-44)

This invention relates to transmission modifying networks connected between a high frequency source and a load, or a passive circuit, for altering the magnitude and/or phase of the transmissions and/or reflections of the high frequency waves traveling between the source and the load. In its simplest embodiment this invention comprises a reentrant network inserted in a single conductor or two conductor transmission line which is connected to transmit energy from a source of high frequency alternating current to a load. The reentrant network may be a simple section of single conductor or two conductor line similar to the main single conductor or two conductor line in which it is inserted, the ends of this section being connected together to form a closed loop. The energised part of the main transmission line joins into this loop at some point of its circumference. The passive part of the main transmission line branches from this loop at some other point of its circumference. The loop introduces reflections in any waves transmitted over the transmission line in which it is inserted and modifies the transmission of waves along that line. The magnitude and/or phase of the reflections and the modifications in transmission depend on the circumference of the loop in terms of wavelengths and on the relative positions around the loop of the two points of junction with the main line. In certain special cases the circumference alone or the relative position of the junction points alone is controlling.

A principal object of the present invention is to provide a structure which may be used variously as a highly efficient transformer, filter or phase shifting device. Another object is to provide such a structure which shall be simple, economical, and well adapted for application to existing construction. A further object is to provide such a structure which may be applied to an existing line without cutting the line.

One distinctive feature of the present invention resides in the fact that the reentrant network is made up of sections of transmission line having distributed constants as distinguished from lumped impedances. Another feature of the present invention is that it provides a transmission influencing network whose dissipation is ordinarily exceedingly low, thus giving low losses when the network is employed as a transformer and giving low losses and sharp cut-off characteristics when the device is employed as a filter. Furthermore, my invention provides a filter whose characteristics result in a sharp cut-off even if in

special circumstances the dissipation is comparatively high.

It is another object of the present invention to provide a transmission modifying network which shall be conveniently adjustable and which shall have sufficient degrees of freedom so that it may be flexibly adapted to widely different conditions.

Although in the simplest applications of my invention the network is connected in a transmission line between a source of alternating current and a useful load to which the alternating current energy is to be delivered, it is also contemplated that the network may be connected between any live circuit such as a circuit containing both the source of alternating current energy and the useful load to which said energy is to be delivered and any passive circuit, which need not be truly a load in the ordinary sense. This passive circuit may for example, be a non-dissipative impedance whose function is to modify the distribution of energy in the live circuit. In such a case my network serves the purpose of modifying the influence which the non-dissipative passive circuit exerts upon the live circuit.

The invention may be more clearly understood by reference to the accompanying drawings. Fig. 1 represents a simple embodiment of my invention in which the transmission modifying reentrant network is connected between a source of alternating current and a load. Fig. 1A represents one particular detailed structural form of Fig. 1.

Figs. 2, 3 and 4 represent alternative embodiments of my invention in which the network is connected similarly to Fig. 1 but in which different types of transmission line are employed.

Fig. 5 represents an alternative form of Fig. 1 in which a transposition is used to replace a 180° length of line.

Fig. 6 schematically represents an arrangement whose structural form may be like any one of Figs. 1, 2, 3 or 4 but whose load is assumed to be matched to the surge impedance of the line.

Fig. 7 schematically represents an arrangement whose structural form may be like any one of Figs. 1, 2, 3 or 4.

Figs. 8 and 9 are sets of curves which represent the intensity and position of the standing waves in such a special circuit as Fig. 6 and which may be used for determining the influences exerted on the transmission and/or reflection of waves by any of the networks in accordance with my invention.

Fig. 10 is a family of curves which may be used in determining the influence of a network in

accordance with my invention, particularly when such a network is employed as a rejection filter.

- Fig. 11 represents a further set of curves which may be useful in the preliminary design of a network in accordance with my invention especially when the network is intended to reject a certain predetermined frequency and pass or reject certain other predetermined frequencies.

- Figs. 12, 13 and 14 represent schematically certain embodiments of my invention in which the reentrant networks serve as filters connected between sources of alternating current energy and loads.

- Fig. 15 represents schematically an embodiment of my invention in which a network is employed as a filter between an active circuit containing both a source of alternating current and a useful load and a passive circuit, which comprises an essentially non-dissipating impedance.

Figs. 8A and 9A are enlarged reproductions of certain portions of the curves shown in Figs. 8 and 9.

- Referring more particularly to Fig. 1, 101 is a source of alternating current, 102 is a load. This source and load are connected together by a simple, parallel two-wire transmission line 103, 104. At an intermediate point in this transmission line a reentrant network is inserted which comprises the two limbs 105 and 106. These two limbs are composed of sections of transmission line having the same characteristics as the transmission line 103 and are generally of different lengths A and B respectively. For convenience in notation the total perimetral length around the reentrant network, that is, A+B, will be represented by u while the difference in the lengths of the limbs of the reentrant network, which for definiteness is considered to be A-B even if B is larger than A, will be represented by v .

- The lengths A and B of the limbs of the network, as well as the derived lengths u and v , are measured in degrees with respect to the frequency under consideration, the wavelength of traveling waves of this frequency along the transmission line being taken as 360°. It will be noted that this wavelength is twice the distance between successive peaks of standing waves, and is equal to

$$\frac{c'}{f}$$

- where c' is the velocity of propagation of the traveling waves along the transmission line. The above interpretation of the lengths A, B, u , and v is used throughout the specification.

- The structure shown in Fig. 1 is illustrated in greater detail in Fig. 1A which shows one particularly advantageous type of construction. This construction enables the reentrant network to be effectively associated with an existing transmission line without cutting the line. Also this construction permits the difference v in the lengths of the limbs A, B of the reentrant network to be readily adjusted without altering the position of junction points 120A and without altering the total circumference u of the network.

- The network of Fig. 2 is constructed of two-wire transmission line of the concentric type. This type of line is well known. The network of Fig. 3 is made up of rubber insulated two-wire twisted pair. This twisted pair may be ordinary lamp cord but for high frequency transmission it should preferably be slightly modified either by omitting the textile layer usually served on the

wire under the rubber insulation or by employing a very non-hygroscopic textile or paper for this layer. Also the rubber should be free from hygroscopic fillers or other materials which increase the high frequency losses. If an outer textile braid is provided over the rubber it is advantageous to varnish this braid or impregnate it with a water resisting compound.

The network of Fig. 4 is built of single-conductor line and is connected in a single-conductor line which might be employed for example, in feeding an antenna.

Although these various constructions differ in structure and in their practical applications, they may be treated together as regards the electrical theory of their reentrant networks. Thus, unless certain forms are specifically excluded, the analysis given hereafter may be considered as applying to any of the structures of Figs. 1, 2, 3 and 4 as well as to polyphase or single-phase multiple-conductor lines and to structures comprising different types of lines in the different branches. The schematic representations of Figs. 6, 7, 12, 13 and 14 also are to be understood as representing structures built of any type or types of single-conductor or multiple-conductor transmission line, although for simplicity the line is represented by a single line in these figures. To avoid unnecessarily complicating the formulae and rules of dimensioning, these formulae and rules have been derived on the assumption that all sections of line in one system have the same impedance and, where the attenuation is significant, the same attenuation, but although this form is preferred structures built up of sections of line of different characteristics are within my invention and may, in special cases, be advantageous.

For simplifying the preliminary explanations reference will first be made to Fig. 6 which schematically represents an arrangement similar to any one of Figs. 1, 2, 3 or 4, excepting that the load 602 is an impedance whose value is the same as the surge impedance of the transmission line 603-604. The influence exerted by network 605-606 upon the transmission between this transmitter and load can be described in terms of the vector reflection coefficient $Re^{j\tau}$ of the network and its vector transmission coefficient $Ge^{j\theta}$. These vector coefficients have the ordinary accepted significance and refer to the voltage wave, so that a zero value of τ represents reflection without phase change of voltage, such as for instance reflection from the end of an open line. All phases are referred to the phase of the incoming wave at the point where it arrives at the network. These coefficients are given by the following equations in which it is assumed that k represents the number of decibels of attenuation in 0.115 degree of line length, i. e., in 0.000320 wavelength of line

$$Re^{j\tau} = \frac{3e^{-u(j+k)} - 8 + e^{-v(j+k)} + 3e^{u(j+k)} + e^{v(j+k)}}{e^{-u(j+k)} - 8 - e^{-v(j+k)} + 9e^{u(j+k)} - e^{v(j+k)}} \quad (1)$$

$Ge^{j\theta} =$

$$\frac{4e^{j\theta(u+v)(j+k)} + 4e^{j\theta(u-v)(j+k)} - 4e^{-j\theta(u+v)(j+k)} - 4e^{-j\theta(u-v)(j+k)}}{e^{-u(j+k)} - 8 - e^{-v(j+k)} + 9e^{u(j+k)} - e^{v(j+k)}} \quad (2)$$

If, however, the attenuation coefficient k is sufficiently small so that it may be neglected for the frequencies of waves and lengths of wires under consideration, the above formulae may be considerably simplified. Setting k equal to zero and separately expressing the absolute magnitudes R

and G and their vector angles r and g respectively, we obtain

$$R = \frac{-4 + 3 \cos u + \cos v}{\sqrt{(-4 \cos v + 5 \cos u)^2 + (4 \sin u)^2}} \quad (3)$$

$$\tan r = \frac{4 \sin u}{4 + \cos v - 5 \cos u} \quad (4)$$

The quadrant of r may be readily determined, remembering that R is always positive as indicated by the absolute symbols in Equation 3, from the following auxiliary equation

$$\frac{\cos r}{R} = \frac{4 + \cos v - 5 \cos u}{4 - 3 \cos u - \cos v} \quad (4a)$$

$$G = +\sqrt{1 - R^2} \quad (5)$$

$$g = 90^\circ + r \quad (6)$$

These coefficients R , r , G and g define the electrical effects of a loop network according to my invention in terms of reflection and transmission regardless of whether the line in which the loop is connected contains other points of reflection or not. If however the system which contains the network is a simplified arrangement such as shown in Fig. 5, then these coefficients may be very simply interpreted to directly represent the waves traveling in lines 603 and 604. Assume for example that the total forward wave entering the network 605-606 has a unit amplitude and a zero phase at the terminals 610, then the total backward wave along line 603 is Re^{jr} . Also the total forward wave along line 604 is Ge^{jg} . These phases refer respectively to the phase of the wave as it leaves terminals 610 and 620 and are measured with respect to the phase of the forward wave incoming to the network at terminals 610. Even when the network is connected in some more general arrangement than that of Fig. 6 Ge^{jg} and Re^{jr} represent the transmission and reflection coefficients in the usual manner, though the above described simple relationship between these coefficients and the total forward and backward waves no longer holds.

If we consider as standing waves not only those "pure" standing waves whose minima are zero but also those whose minima have definite values, we may find it convenient to define the ratio of the maxima and minima. For any standing wave the ratio of the maximum r. m. s. voltage, measured at the voltage antinodes, to the minimum r. m. s. voltage, measured at the voltage nodes, is hereinafter called the "standing wave ratio" or "Q ratio" of the wave and is designated by Q .

Because of the greater facility with which standing waves can be measured it is for many purposes more convenient to define the properties of a reentrant network in terms of standing waves rather than by its reflection and transmission coefficients—which refer to traveling waves or traveling wave components. Use is therefore made of two auxiliary coefficients called the "natural standing wave ratio" of the network and the "natural position parameter" of the network. These characteristics of any network may most conveniently be defined by supposing that the network is connected in an arrangement such as shown in Fig. 6 in which the load is matched to the surge impedance of the transmission line. In this arrangement, which is assumed for analysis, there will be no reflections from the load 602 and hence no standing waves in the line 604. In general, however, there will be standing waves in each of the limbs 605 and 606 and also standing

waves, as represented by curve 623, in line 603. The ratio of the maximum r. m. s. voltage to the minimum r. m. s. voltage of standing waves 623, which is the Q ratio of waves 623, will hereinafter be known as the "natural standing wave ratio" of the network and will be designated by the letter P . Also the distance from a voltage maximum of these standing waves 623 to the terminals 610 will hereinafter be known as the "natural position parameter" of the network and will be designated by the letter p . These natural coefficients P and p are characteristics of the network itself, and may be referred to even when the network is connected in some more general arrangement than that shown in Fig. 6. In such a case, however, P or p will still represent the standing wave ratio Q or position length q of the waves which would be produced in such an ideal arrangement as Fig. 5 and should not be taken to represent the Q ratio or position coefficient of the waves which are actually produced in the more complex arrangement wherein the network happens actually to be connected.

Since the value of Q of the waves 623 in the special arrangement of Fig. 6 is equal to

$$\frac{1+R}{1-R}$$

the natural standing wave ratio for any network is

$$P = \frac{1+R}{1-R} \quad (7)$$

Similarly since the position coefficient q of the standing waves 623 in Fig. 6

$$\frac{r}{2}$$

the natural position coefficient of the network is

$$p = \frac{r}{2} \quad (8)$$

The curves of Fig. 8 and Fig. 8A show how the value of P varies with the perimeter u of the network, the difference in length v between the limbs of the network being kept constant for any one curve. From these curves it is possible to find the value of P for any given values of the dimensions u and v . Similarly the curves of Fig. 9 and Fig. 9A show the variations of p with the variations of the perimeter u , v again being kept constant for any one curve. From this family of curves it is, therefore, possible to find the value of p for any given values of network dimensions u and v .

Conversely any desired value of P may be obtained by properly adjusting the dimensions u and v . For example, to obtain a value of 7.0 for P in any network we may dimension the network so that $u=121^\circ$ and $v=90^\circ$; or so that $u=88^\circ$ and $v=100^\circ$; or so that $u=33^\circ$ and $v=100^\circ$, etc. These primary sets of values are obtained without interpolation from the successive curves of Fig. 8A which correspond to the left lower portion of Fig. 8 but are drawn to a larger scale. By interpolation an infinite number of such primary sets of dimensions can be obtained. Furthermore, each of the sets of primary values obtained from these curves or from interpolation has associated with it an infinite number of "equivalent" values. For example, in the first set of primary values given above $u=121^\circ$, $v=90^\circ$, there may be used for u any one of the values 121° , 239° , 481° , 599° , 841° , etc., obtained from $N \times 360^\circ \pm 121^\circ$ and similarly there may be used for v any one of the values 90° , 270° , 450° , etc., obtained from $N \times 360^\circ \pm 90^\circ$.

Examining all the above sets of values for u and v , it will be noted that some of these sets of values are not physically realizable with real positive lengths A and B . Referring to the third primary set of values ($u=33^\circ$, $v=100^\circ$), for example, it is impossible to construct a network whose perimeter has a length of 33° and whose two limbs differ in length by 100° . In such a case use is made of one or more of the "equivalent" values above mentioned. For example, by selecting a u of 327° , which is equivalent to a u of 33° as above noted, and by retaining the value of 100° for v a physically realizable set of dimensions is obtained. Such a network would, for example, have a length, A , of 213.5° and a length, B , of 113.5° . However, a great number of the structures which may be read off directly from the curves, including many of the best ones from a practical standpoint, are physically realizable without any replacement of u or v by equivalent values. For example, the first set of primary values previously mentioned ($u=121^\circ$, $v=90^\circ$) is physically realizable. Generally the region to the right of the small circles in Fig. 8A represents sets of values which are physically realizable without resorting to equivalents.

There is another set of equivalent structures which may be obtained by the use of a transposition in one of the limbs of the reentrant network. Since a transposition in any limb is equivalent to a delay of 180° it is possible to shorten the length of some of the structures by replacing 180° of physical length by a transposition. For example, the structure referred to above in which $A=213.5^\circ$ and $B=113.5^\circ$ may be replaced by a structure in which $A=33.5^\circ$ with a transposition and $B=113.5^\circ$. A structure which includes such a transposition but which is otherwise similar to Fig. 1 is illustrated in Fig. 5. The use of a transposition is particularly applicable to networks built of two-wire line such as shown in Fig. 1 and to twisted wire lines such as shown in Fig. 3. Other phase changing means may also be employed to replace part of the physical length of the network, but the transposition is particularly desirable because of its simplicity and its freedom from reflections at all frequencies.

In one very useful embodiment of my invention a reentrant network as illustrated in Fig. 7 serves, in conjunction with certain portions of the transmission line 703—704, as a transformer. In this figure, 701 represents a transmitting equipment; 703—704 a transmission line connecting that transmitter with a load 702 and 705—706 a network inserted in this transmission line. If the load 702 is not exactly matched to the surge impedance of the transmission line there will be standing waves 724 dependent on the mismatch of the load in the portion 704 of the transmission line. Also, in general, there will be standing waves 723 in the portion 703 of the transmission line.

In accordance with the present invention the dimensions of the reentrant network 705—706 may be so adjusted that standing waves 723 will have any desired Q ratio. Let the Q ratio of the given standing waves 724 which are produced by the load be represented by L . The natural standing wave ratio and the natural position parameter of the network are P and p . Now the network may be positioned along the transmission line so that the distance between its terminals 720 and a voltage peak of standing waves 724

is equal to p ; then the standing wave ratio Q of waves 703 will be equal to

$$\frac{P}{L} \text{ or } \frac{L}{P}$$

whichever is larger. Alternatively the network may be positioned so that the distance between its terminals 720 and a voltage peak of wave 724 is equal to $P+90^\circ$ in which case the Q ratio of waves 723 will be equal to PL .

If it is desired to give waves 723 a smaller standing wave ratio than waves 724, the first mentioned location of the network must be used. On the other hand, if it is desired to give waves 723 a very high standing wave ratio, the second mentioned position may sometimes be more convenient.

In the most usual application of this embodiment of my invention the network 705—706 is adjusted so that waves 723 will be completely eliminated, i. e., will have a Q ratio equal to unity. To obtain this result the network should be so adjusted that its natural standing wave ratio P is the same as L , the standing wave ratio Q of waves 724, and should be located in the first mentioned position so that its terminals 720 are at a distance p from a peak wave 724.

By this adjustment of the network, waves 723 will be eliminated. Thus, the impedance of that portion of the circuit beyond terminals 710 will be the same as the surge impedance of the transmission lines, or in other words, the total impedance of the network together with line 704 and the load 702 will be equal to the surge impedance of line 703.

In certain cases it may be desired to adjust the network so as to act as a transformer having a ratio different from that required to match the load to the line. In other words, it may be desired, instead of matching the load to the transmission line, to introduce a deliberate amount of mismatch for some purpose. In this case it is merely necessary to express the desired mismatch in terms of the standing wave ratio desired in waves 723. Then by the use of the above rules for proportioning and positioning the network the waves 723 may be caused to have the desired Q ratio.

In addition to its use as a transformer the reentrant network structure of my invention may also be adjusted to act as a cut-off filter. In other words, the network may be adjusted so that for one particular frequency its natural standing wave ratio P is substantially infinite. In terms of the reflection and transmission coefficients this means that $R=1$ and $G=0$. The frequency at which the cut-off takes place will be referred to as the cut-off frequency and will be designated by F . At certain special other frequencies the network will again cut off as will be more fully described in connection with Fig. 12. In general, however, at a frequency f , which is not the cut-off frequency F , the filter will transmit more or less satisfactorily.

The conditions for cut-off are substantially satisfied either when $u=360^\circ$, or 720° , 1080° etc., or when $v=180^\circ$, or 540° , 900° etc., and especially complete cut-off occurs when both these conditions are simultaneously satisfied.

The cut-off networks having $v=180^\circ$ will be referred to as "difference" filters and the networks having $u=360^\circ$ will be referred to as "sum" filters. The special network which has $u=360^\circ$ and $v=180^\circ$ and which is thus a sum filter as well as a difference filter will be referred to as a

"hybrid" filter. Although this hybrid filter is theoretically a sum filter as well as a difference filter it is, in the following discussion, considered to be excluded from each of these classes; thus general statements as to the properties of sum and/or difference filters are not considered as applying to the hybrid filter unless it is specifically included.

The transmission and reflection coefficients of all these three classes of filters are given by Equations 1 and 2 as set forth above.

Fig. 10 shows a set of curves which directly represent the coefficient G in terms of frequency for filters of the sum and hybrid types. In these curves the attenuation is assumed to be .043 decibel per wave length of line (i. e., 0.0000137 decibel per 0.115 degree length of line which correspond to $k=0.0000137$). This attenuation is of the order actually found in ordinary open-wire transmission lines. A simple, parallel, two-wire line structure of number 6 A. W. G. copper clad steel wire with a 12 inch spacing, for example, has an attenuation of approximately 1 decibel in 2000 feet at a frequency of 10 megacycles. Since the wavelength at 10 megacycles is approximately 95 feet, this attenuation amounts to very nearly .043 decibel per wavelength. This value for attenuation, moreover, will not vary rapidly with frequency because as the frequency is increased the attenuation per foot of wire also increases; at the same time the number of feet per wavelength of line becomes smaller so that to a certain extent these two changes counteract each other. Thus, the curves of Fig. 10 fairly accurately represent the transmissions through a sum or hybrid filter in the neighborhood of the cut-off frequency for all frequencies between 6 and 16 megacycles. From Equations 1 and 2 it is possible to plot a corresponding set of curves for the difference and hybrid types of filters. Also similar sets of curves for sum, difference and hybrid filters may be plotted using other values of k than that assumed for Fig. 10. For coaxial lines the attenuation is ordinarily higher and, therefore, typical curves for this type of line would show a somewhat broader cut-off. For the twisted pair lines also attenuation would ordinarily be higher.

In the regions more remote from the cut-off point the transmission and reflection coefficients may be reasonably accurately calculated from the approximate Equations 3, 4a, 5 and 6 instead of from the more complex Equations 1 and 2. Generally, moreover, in the regions remote from the cut-off the primary interest is in the natural standing wave ratio P since in this region the problem is one of passing another frequency f without developing standing waves of high Q ratio, which would result in comparatively great losses. In this region remote from the cut-off point, therefore, Figs. 8 and 8A serve to indicate the behavior of the network at frequencies which it is desired to pass. If, however, it is desired to visualize clearly the pass characteristics of a given filter or if the problem of designing filters is to be facilitated it may be convenient to plot a set of curves such as shown in Fig. 11. The curves of Fig. 11, like the curves of Figs. 8 and 8A, represent the value of the natural standing wave factor P . But instead of being plotted against u these curves are plotted against the value of frequency F (expressed in terms of the cut-off frequency F taken as unit frequency). Also, the curves of Fig. 11 are drawn to logarithmic scale. All the curves of Fig. 11 repre-

sent sum filters which have a u of 360° at the cut-off frequency F . The first four curves, respectively, represent filters whose v at the cut-off frequency is 60° , 120° , 180° , 240° . The additional curve, designated as $60+\#$, represents a sum filter whose perimeter has a physical length of 180° and whose limbs differ in physical length by 60° , the longer or the shorter limb of the filter being equipped with a transposition so that the effective value of u at frequency F is 360° while the effective value of v at the cut-off frequency F is 240° or 120° . It will be noted that the curve of the filter $60+\#$ is very different from the curve marked 240° although at the cut-off frequency itself, both curves represent filters having a u of 360° and a v of 240° . The reason for the divergence between the two curves is, that as the frequency is varied from F the transposition which is designated by $\#$ continues to represent a fixed electrical length, namely 180° , whereas a length of wire which at frequency F represents 180° will vary in electrical length as the frequency is changed.

It will be noted in general that a simple sum filter will cut off not only at the nominal cut-off frequency F but also at $2F$, $3F$, $4F$, etc. Similarly a difference filter generally cuts off at $3F$, $7F$, etc.

In order to cut off at F and yet pass $2F$ a sum filter may be used having a transposition such that $u=180^\circ+\#$ and $v=60^\circ+\#$, or $u=180^\circ+\#$ and $v=90^\circ+\#$. Or a difference filter such that $u=230^\circ$ and $v=180^\circ$, or a hybrid, may be used. If it is desired to cut off F and pass $3F$ a sum filter with a transposition or a sum filter whose value of v is such that $3v=N360$ where N is any integer, may be used.

In some cases the above described multiple cut off properly may be used to great advantage. A network which is particularly useful for passing frequency f while suppressing the principal harmonics of f , for example, can be constructed by making $u=180^\circ$ and $v=60^\circ$ at frequency f . Then at $2f$ $u=360^\circ$, at $3f$ $v=180^\circ$, at $4f$ $u=720^\circ$. Thus the second, third and fourth harmonics are eliminated.

From this Figure 8 it is apparent that whenever $u=360^\circ$ then $p=0^\circ$; which means that the cut-off frequency voltage maximum always occurs at the terminals of sum or hybrid networks. Since the reflection of waves at the cut-off frequency is very nearly complete it follows that the impedance looking into such networks at the cut-off frequency is extremely large in comparison with the surge impedance of the line. This property is independent of the value of v of the particular network and is a characteristic of hybrid networks and of all sum networks with one exception, namely, those which have $v=0^\circ$, 360° , etc. Such networks are not cut-off networks at all.

The filter networks of my invention may be used for a variety of purposes. For example, Fig. 12 shows a system in which two high frequency transmitters 1201 and 1201', working on two different frequencies f and f' , are connected to the same antenna 1202. In this figure reentrant networks 1205—1206 and 1205' and 1206' are utilized for the purpose of minimizing the interference between the two transmitters. Network 1205—1206 is designed so that its perimeter u equals 360° at frequency f delivered by transmitter 1201', while network 1205'—1206' is designed so that its perimeter is equal to 360° at frequency f delivered by transmitter 1201. Thus reentrant network 1205—1206 does not allow frequency f delivered by transmitter 1201' to enter

transmitter 1201. At the same time, however, this network passes frequency f coming from transmitter 1201 without unduly serious reflections. A matching network schematically represented by 1215 is placed between the transmitter and the network 1205—1206. This matching network is designed and positioned according to the principles previously explained so as to match the surge impedance of transmission line 1214 to the impedance resulting at terminals 1210 of network 1205—1206 at the frequency f of transmitter 1201. Similarly reentrant network 1215' matches the impedance resulting at terminals 1210' of network 1205'—1206' to the surge impedance of the transmission line 1214'.

The distance between network 1215 and network 1205—1206 will, in accordance with the rule previously given for positioning matching networks, be simply the natural position parameter p of network 1215 plus the natural position parameter p of network 1205—1206 both computed with respect to frequency f . Preferably network 1215 is designed so as to also to act as a cut-off filter for frequency f' thus providing double filtering. Usually this is most conveniently accomplished by making networks 1215 and 1205—1206 identical to each other. In this case the distance between these networks will be twice the natural position parameter p of either network at frequency f . Similar considerations hold with respect to networks 1215' and 1205'—1206'.

The distance x should be such that at frequency f' the impedance of line 1204, with all the structure connected to it, will be substantially infinite as seen from junction point 1250. If network 1205—1206 is a sum or hybrid filter x should be 0° , 180° , 360° , etc. If, however, this network is a difference filter the natural position parameter p of the network at frequency f' must be computed. Then x should equal this p , or should exceed it by an integral number of half wavelengths.

Fig. 13 shows an arrangement similar to that of Fig. 12 except that one of the transmitters has been replaced by a receiver. The networks 1305—1306 and 1305'—1306' enable simultaneous operation of the transmitter and receive without interference with one another. Or either may be used individually.

The networks utilized in such arrangements as shown in Figs. 12 and 13 should be designed in such a way that the standing waves which they cause at the transmitted frequencies are not so intense as to cause either great losses due to circulated currents or undue voltages on the various limbs of the networks or in lines 1203 and 1203' or 1303 and 1303'. That is, the design of network 1205—1206 should be such that the standing waves in line section 1203 have a sufficiently low Q ratio.

In order to avoid the danger of rise in voltage and current along the section of transmission line 1210 it is desirable to select the constants of network 1205—1206 in such a manner that the amount of reflection at its terminals at the passing frequency is relatively small. In practice, however, I have found that standing wave ratios of the order of 7 or lower are entirely practical. By means of curves like those of Figs. 10 and 11 it is possible to choose for any given frequency ratio a set of values of u and v which results in a standing wave ratio Q of 7 or less.

When choosing the value of u and v under these circumstances it is well to keep in mind that the completeness of cut-off which may be obtained at the cut-off frequency, in sum filters,

depends on the value of v and in difference filters on the value of u . Thus under some circumstances it may be unwise to select a set of values which gives a very low standing wave ratio on line 109, if at the same time these values result in an insufficiently complete cut-off. A compromise must be effected.

For example, in network 1305—1306 the amount of filtering which is required is usually not nearly as high as would be required in network 1305'—1306'. On the other hand, in line section 1303 the standing wave losses would be of more moment than the losses in the section of line 1303'. Thus in actual practice the network 1305'—1306' would usually be designed so as to have maximum or nearly maximum cut-off and with only minor regard to the standing waves and the losses which result therefrom on line 1303', while network 1305—1306 in the same arrangement would be designed to provide a less complete cut-off but with greater consideration to the losses in line 1303.

Fig. 14 represents a system in which a reentrant filter network is utilized for stabilizing the frequency of an oscillator. In this figure 1430 is an oscillator adapted to generate a high frequency, for example 100 megacycles, and connected by means of coaxial line 1431 to an amplifier 1432. The output of this amplifier is connected over line 1433 to a radiating antenna 1434. A small portion of the energy delivered to line 1433 by amplifier 1432 is diverted into the branch line 1403—1404 in which the network 1405—1406 is connected. The current delivered by line 1404 after detection in diode 1435 is passed through resistor 1436. The voltage thus developed across this resistor, after smoothing in filter 1437, is applied across a portion of the oscillator circuit suitable for controlling the oscillator frequency. Heater 1407 is connected through thermostatic control 1408 to a source of power 1409.

The operation of the device of Fig. 14 is as follows: The reentrant network is adjusted so that the perimeter u is nearly equal to 360° at the assigned frequency of the oscillator, preferably so that the frequency which is cut off by the network is slightly different from the assigned frequency of the oscillator, for example, just below this assigned frequency. The heating wires 1407 in conjunction with thermostat 1408 maintain the temperature of the limbs of the reentrant network nearly constant so that the cut-off frequency will remain substantially the same. The v of this network is made small, for example, 30° , so that the network would be relatively compact. In accordance with Fig. 10 it may be seen that the amount which a sum filter transmits varies very rapidly with the frequency in the neighborhood of the cut-off frequency. For this reason in the arrangement of Fig. 14 the total amount of current which is transmitted to detector 1435 will depend in a critical manner on the frequency of oscillator 1430. If the cut-off frequency of the reentrant network 1405—1406 lies below the normal oscillator frequency, then as the latter increases the amount of current transmitted to detector 1435 increases and vice versa. Accordingly, the direct current output of the detector which is carried by wires 1438 to the oscillator also decreases and increases in accordance with the fluctuations of the frequency delivered by the oscillator. This direct current which is carried by wires 1438 may be applied to vary, for example, the grid voltage of the oscil-

lator in a well known manner in order to affect the frequency delivered by it. In this manner the frequency of the oscillator may be decreased when the oscillator is drifting upward in frequency and vice versa, whereby the frequency of the oscillator may be kept substantially constant. It will be clear from the above discussion that it is not necessary in order to carry out the above control of frequency by means of a reentrant network such as 1405-1406 to have all of the elements shown in Fig. 14. In fact, for example, it is not at all necessary to have an amplifier.

In each of the above described embodiments of my invention the reentrant network has been connected between a source and a load. This is not essential to all applications of my invention. Fig. 15 shows a network 1505-1506 connected between a live circuit and a passive circuit. The live circuit comprises source 1501 connected over line 1540 to load 1541. The passive circuit comprises reactive impedance 1502 which dissipates no power and is therefore not truly a load. This impedance is connected to some point of line 1540 by line 1503-1504. The network 1505-1506 modifies the influence exerted by 1502 on the waves transmitted from source 1501 to load 1540.

This structure is used as follows: source 1501 delivers two different frequencies F , f simultaneously or successively. Matching device 1542 is adapted to match load 1541 to line 1540 at frequency F . This device may for example be a reentrant network dimensioned and positioned for simple matching at one frequency as previously explained. Network 1505 is adjusted as a sum filter to cut off frequency F so that the waves of that frequency are unaffected by adjustments of the position or length of line 1504 nor by adjustments in the impedance of 1502. Line 1503 is made 0° , 180° , 360° etc. in length at frequency F so that at that frequency line 1503 will have an infinite impedance as measured at junction 1545. Now the length of line 1504 is adjusted, thus varying the impedance at frequency f of branch 1503-1504 as seen from junction 1545. Also the position of junction 1545 along line 1540 is adjusted. By these two adjustments the impedance of all the structure beyond junction 1545 may be matched at frequency f to the surge impedance of line 1440. In other words the standing waves of frequency f in that portion of line 1540 between source 1501 and junction 1545 may be eliminated. This may conveniently be performed by the following steps. First the Q ratio of standing waves of frequency f in line 1540 between matching device 1542 and junction 1545 are measured or computed. This is the Q ratio of those standing waves which are caused by the device 1542 and the load 1543. The position of voltage maxima of these waves are also noted. Second, line 1540 is cut open between junction 1545 and matching device 1542, and the cut end of this line is connected to a load equal to the surge impedance of the line so to terminate the line in a reflectionless manner. Third, the effective impedance of line 1503-1504 is adjusted by varying the length of line 1504 until the standing waves between junction 1545 and source 1501 have a Q ratio equal to the Q ratio which was measured or computed in the first step. The distance M of a voltage maximum of these standing waves from junction 1545 is also noted. Fourth, the reflectionless termination used in step two is removed; the cut line is reconnected; the junction point 1545 is adjusted so that its distance

from the voltage maxima position noted in step one is M as measured in step three.

Now it will be found that there are substantially no standing waves between junction 1545 and source 1501 either at frequency F or frequency f . If it is desired to still further reduce any slight standing waves that may be present the perimeter u of loop 1505-1506 may be slightly changed to eliminate the standing waves of frequency F , and then the length of line 1504 and/or the position of junction 1545 may be slightly adjusted to eliminate waves of frequency f . The impedance 1502 is preferably a short circuit. The length of line 1503 is preferably zero.

One reentrant network may be used to neutralize standing waves caused by another reentrant network in the same way in which a reentrant network may be used as a matching transformer to match the impedance of a load to the surge impedance of a line, i. e., to eliminate the standing waves caused by a mismatched load. Such arrangements have already been described in connection with Figs. 12 and 13 in which at least one of the two mutually neutralizing networks served as a filter for cutting off an unwanted frequency. Such a pair of networks which mutually neutralize each other's reflectors at some given frequency is hereinafter referred to as a conjugate pair with respect to that frequency. Expressed in other words a conjugate pair of networks is a pair which is connected in a reflectionless line like that of Fig. 6 would cause no reflections except inside the networks themselves and in the section of line between them.

Two networks are conjugate if the P of one equals the P of the other and if the distance along the line between the closest terminal of the network is equal to the p of one network plus the p of the other. Since the conjugacy of two networks depends not only on the dimensions of the networks but also on their relative position it will be useful to consider the two networks of a conjugate pair together with the section of line between them as a unit having for two conductor lines two input terminals and two output terminals, or in the case of single conductor line, one input and one output terminal. Such a complete unit will be called a "complete conjugate net."

A complete conjugate net may be used to change phase of forward or backward traveling waves without changing the magnitude of these waves. The total phase delay due to insertion of a complete conjugate net is 180° minus the length of the section of line which joins the two reentrant networks and together with them constitute the complete conjugate net. In other words if we call the insertion delay D and represent the natural position parameters p of the component reentrant networks by p_1 and p_2 , then $D = 180^\circ - p_1 - p_2$. Ordinarily of course the reentrant networks are applied to a line without cutting the line as shown in Fig. 1A. In such a case the phase delay introduced by adding the two conjugate networks can be computed by imagining that a piece of line as long as the over-all length of the complete conjugate net is cut out and then the complete conjugate net is inserted. Usually the over-all length of the complete conjugate net will be $p_1 + p_2 + B_1 + B_2$ where B_1 and B_2 are the lengths of the shorter sides of the two reentrant networks which are comprised in the complete conjugate net. In such a case the phase delay introduced by applying the networks is $180^\circ - 2p_1 - 2p_2 - B_1 - B_2$.

A complete conjugate net may also be used to introduce a desired amount of reflection at one frequency without introducing any reflection at the frequency for which it is conjugate. The complete net taken as a whole may be considered as a unit which has a natural standing wave ratio P and a natural position parameter p of its own. The P and p of the complete network will be designated by P_3 and p_3 respectively; the P and p of the component network which is nearest to the source will be designated by P_2 and p_2 ; which the P and p of the other component network which is nearest the load or passive impedance may be designated by P_1 and p_1 . The distance between the nearest terminals of the component networks is designated by S . All distances are in degrees at the frequency under consideration which is usually not the conjugate frequency.

$$P_3 = w + \sqrt{w^2 - 1}$$

where w is given by

$$w = \frac{1}{4} \left(P_1 + \frac{1}{P_1} \right) \left(P_2 + \frac{1}{P_2} \right) - \frac{1}{4} \left(P_1 - \frac{1}{P_1} \right) \left(P_2 - \frac{1}{P_2} \right) \cos(2S - 2p_2 - 2p_1) \quad p_3 = \frac{1}{2}(r_2 + m)$$

where m is given by

$$\tan m = \frac{2P_2n \sin(2S - 2p_2 - 2p_1)}{(P_2^2 - 1)(1 - n \cos[2S - 2p_2 - 2p_1])}$$

the quadrant of m being such that $\sin m$ has the same sign as $\sin(2S - 2p_2 - 2p_1)$

$$n = \frac{(P_2^2 + 1)(P_1^2 - 1)}{(P_2^2 - 1)(P_1^2 + 1)}$$

A complete conjugate net which is conjugate at frequency F and which has a desired P_3 at frequency f may be substituted in Fig. 15 for the branch line 1503—1504 containing network 1505—1506. The complete net is inserted in series in line 1540, which can actually be accomplished without cutting line 1540. Because of the conjugacy at frequency F the matching which has been effected at that frequency by device 1542 is not disturbed. Yet by adjusting the P_3 of the complete net at frequency f matching may be effected at this frequency in accordance with the rules previously explained for matching by means of a single reentrant network.

For the various applications of reentrant networks according to my invention the waves circulating around the reentrant loops themselves may, in exceptional cases, considerably exceed the waves in the main transmission line, thus making it desirable in some cases to consider these waves. The fraction H of the total transmitted power which is dissipated within the loop is given by

$$H = 1 - R^2 - G^2 \quad (9)$$

This fraction H may be evaluated in any given case by computing the values of G and R from Equations 1 and 2. The upper limits of the voltages which may be built up at voltage maxima within the loop are given very nearly by the following equations in which a is the upper limit of voltage within the limb whose length is A , b is the upper limit of voltage within the limb whose length is B .

$$a = \frac{|4 - 2e^{-iu} - 2e^{-iv}| + |4 - 6e^{iu} + 2e^{iv}|}{|81e^{iu} + 9e^{-iu} - 72 - 9e^{iv} - 9e^{-iv}|} \quad (10)$$

$$b = \frac{|4 - 2e^{-iu} - 2e^{iv}| + |4 - 6e^{iu} + 2e^{-iv}|}{|81e^{iu} + 9e^{-iu} - 72 - 9e^{iv} - 9e^{-iv}|} \quad (11)$$

In Equations 10 and 11 the attenuation is neglected but the equations may be corrected to take

account of attenuation by replacing j by $j+k$ in the equations as above written. It should be noted that the actual maximum voltages in the limbs may be far lower than the limits a and b if it happens that a voltage peak does not fall within each limb. Also if the attenuation is appreciable the actual maximum voltages will usually be slightly lower than these limits even if Equations 10 and 11 are corrected for attenuation. By use of Equations 9, 10 and 11 it is possible to avoid so dimensioning the reentrant networks of my invention, that intolerable potentials or power losses occur in the networks.

In connection with the preceding description it should be understood that the sources and loads may be interchanged in accordance with the well known reciprocity rule. For example, in Fig. 12 the radiating antenna may be employed as a collecting antenna and the two transmitter equipments may be replaced by receiver equipments having the same terminal impedance.

While I have described particular embodiments of my invention for purposes of illustration, various modifications and adaptations thereof, occurring to one skilled in the art may be made within the spirit of the invention as set forth in the appended claims.

I claim:

1. A filter network for use at a given high frequency in cooperation with a frequency line comprising a closed loop conductor having two terminals connected to said line at spaced points thereby forming two parallel paths through said loop the sum of said paths in electrical degrees at said given frequency being 360 and the difference between said paths being other than zero electrical degrees.

2. A filter network for use at a given high frequency in cooperation with a high frequency line comprising a closed loop conductor having two terminals connected to said line at spaced points thereby forming two parallel paths through said loop, the difference of said paths being 180 electrical degrees at said given frequency.

3. A high frequency transmission circuit comprising a two-wire transmission line, each wire of which has at corresponding points serially connected therein a closed loop conductor in such manner that two parallel paths of unequal lengths through said loop are presented.

4. A high frequency transmission circuit in accordance with claim 3 wherein the total length of said loop is 340 electrical degrees at a frequency which it is desired to cut off.

5. A high frequency transmission circuit in accordance with claim 3 wherein the difference between the two parallel paths of each loop is 180 electrical degrees at a frequency which it is desired to cut off.

6. A high frequency transmission circuit including a two-wire transmission line having a matching device connected thereto for matching the impedance of the line to that of a translating device said matching device comprising a closed loop conductor connected serially between each of said wires and said translating device, thereby forming two parallel paths through said loop, the sum of said parallel paths being other than 360 electrical degrees at the frequency for which a match of impedances is desired and the difference between said paths being other than 180 electrical degrees at said frequency.

7. A high frequency transmission system comprising a first transmission line, a second transmission line connected thereto, and a reentrant

transmission modifying network forming two paths of unequal length operatively associated with each of said transmission lines.

8. A high frequency transmission system comprising two separate sources adapted to supply a first frequency and a second frequency, respectively, a common load for said two sources, a separate transmission line for conducting energy from each of said sources to said load, and a transmission modifying reentrant network operatively forming two paths of unequal length operatively associated with each of said transmission lines.

9. A high frequency transmission system in accordance with claim 8, wherein said reentrant networks each comprise a closed loop conductor serially connected in said associated transmission line, thereby forming two parallel paths through said loop, the sum of said paths of the loop associated with the transmission line carrying said first frequency being 360 electrical degrees at said second frequency and the sum of said two parallel paths of said loop conductor associated with the transmission line carrying said second frequency being 360 electrical degrees at said first frequency, the difference between the paths of each of said loop conductors being other than 180 electrical degrees at the frequency carried by the transmission line in which it is connected.

10. A high frequency circuit comprising a conductor adapted to carry a high frequency current and a transmission modifying network therefor comprising a single conductor connected to said conductor at two spaced points said single conductor being longer than the part of said first named conductor between said space points.

11. A high frequency circuit comprising a transmission line for transmitting energy from a first point to a second point and transmission modifying means associated therewith comprising a second transmission line of a different length from said first line connected in parallel therewith.

12. A high frequency circuit comprising a coaxial cable adapted to transmit energy from a

first point to a second point and a transmission modifying means associated therewith comprising a second coaxial cable having a different electrical length than said first coaxial cable and connected in parallel therewith.

13. A high frequency circuit comprising a source, a load, a transmission line connecting said source and said load, an impedance and means including a reentrant network having two arms of different length for interconnecting said impedance and said line.

14. A transmission line adapted to carry waves of two different frequencies, two closed loops serially connected in said line, the dimensions and spacing of said loops being so interrelated that no reflections are caused at one of said given frequencies in those portions of the transmission line outside said two loops, while at the same time a desired reflection is produced at the other of said given frequencies in one of said outside portions of said line.

15. A high frequency circuit comprising an oscillator, an output circuit therefor, two parallel paths of different lengths adapted to conduct energy from said output circuit to a common junction point and means for controlling the frequency of said oscillator in accordance with the energy received at said common junction point.

16. A high frequency circuit comprising a two-wire transmission line for transmitting energy from a first point to a second point and transmission modifying means associated therewith comprising a second transmission line of different length than said first line connected in parallel therewith, said second transmission line having phase shifting means therein.

17. A high frequency circuit comprising a two-wire transmission line for transmitting energy from a first point to a second point and transmission modifying means associated therewith comprising a second transmission line of different length than said first line connected in parallel therewith, said second transmission line having a transposition therein.

ANDREW ALFORD.