

April 6, 1948.

W. W. HANSEN ET AL

2,438,912

IMPEDANCE TRANSFORMER

Filed June 29, 1942

4 Sheets-Sheet 1

FIG. 2

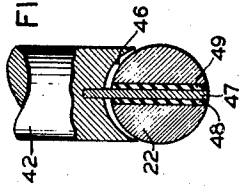


FIG. 1

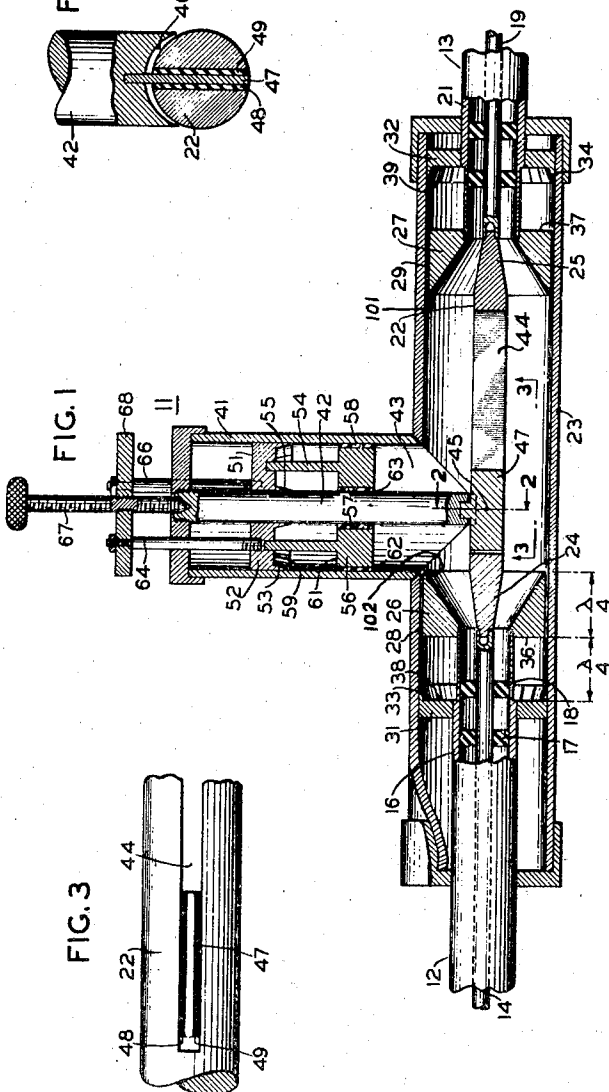


FIG. 3

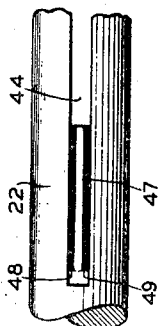
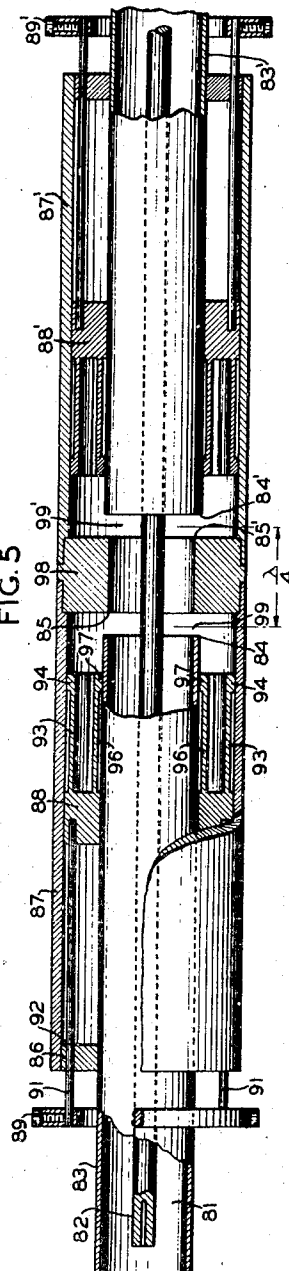


FIG. 5



INVENTORS:
WILLIAM W. HANSEN
JOHN R. WOODYARD
MORRIS RELSON
BY *Paul B. Hunter*
ATTORNEY

April 6, 1948.

W. W. HANSEN ET AL

2,438,912

IMPEDANCE TRANSFORMER

Filed June 29, 1942

4 Sheets-Sheet 2

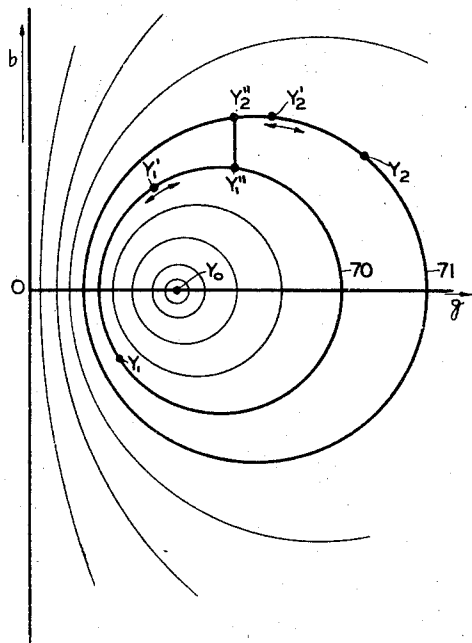


FIG. 4

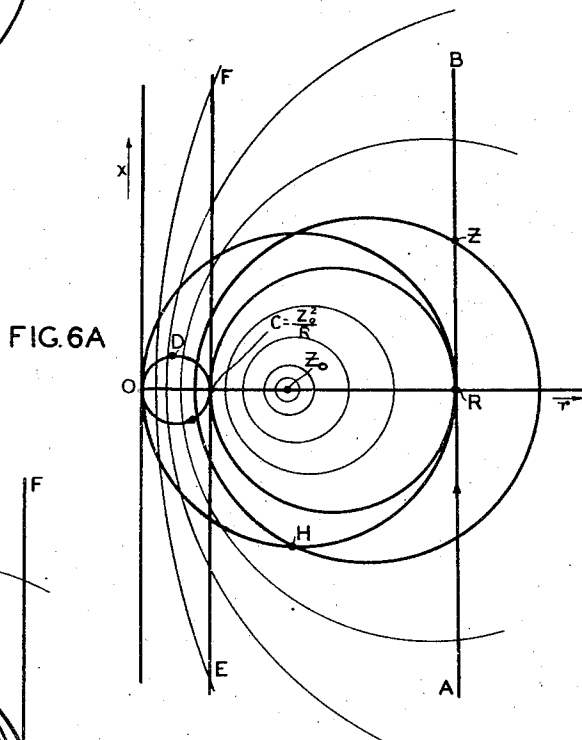


FIG. 6A

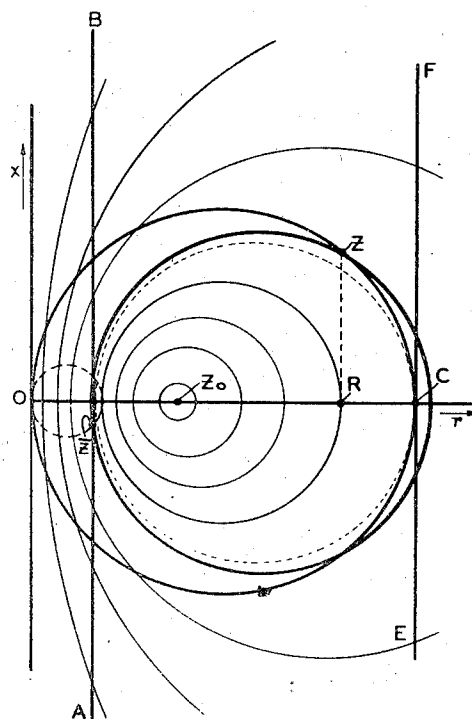


FIG. 6B

INVENTORS:
WILLIAM W. HANSEN
JOHN R. WOODYARD
MORRIS RELSON

BY *Paul B. Hunter*
ATTORNEY

April 6, 1948.

W. W. HANSEN ET AL

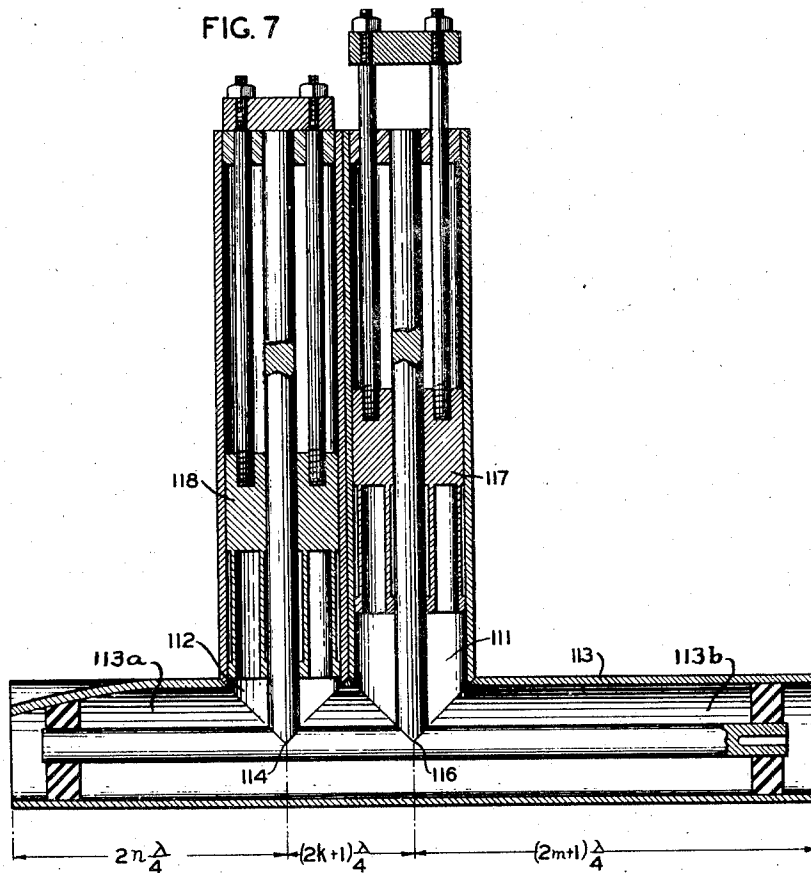
2,438,912

IMPEDANCE TRANSFORMER

Filed June 29, 1942

4 Sheets-Sheet 3

FIG. 7



INVENTORS:
WILLIAM W. HANSEN
JOHN R. WOODYARD
MORRIS RELSON
Paul B. Hunter
ATTORNEY

BY

UNITED STATES PATENT OFFICE

2,438,912

IMPEDANCE TRANSFORMER

William W. Hansen and John R. Woodyard,
Garden City, and Morris Relson, Kew Gardens,
N. Y., assignors to The Sperry Corporation, a
corporation of Delaware

Application June 29, 1942, Serial No. 448,992

17 Claims. (Cl. 178-44)

1

The present invention relates to the art including impedance matching and transforming devices especially adapted for use in systems utilizing high frequency electromagnetic energy.

In transferring energy from one high frequency device to the other, it is well known that the impedances thereof must be properly matched in order to avoid the production of standing waves with attendant increase in losses and decrease in the energy transmitting capacity of the system. In addition, for greatest efficiency it is known that the impedance of a load device must be properly transformed to match that of its source.

The present invention is directed toward the provision of improved impedance matching and transforming devices which are adapted to efficiently couple and match any two arbitrary impedances, and to transform any arbitrary impedance into any other arbitrary impedance, with a minimum of adjustment and a maximum facility and efficiency.

According to the present invention, such impedance transformers are provided of the concentric line type having fixed physical length whereby they may readily be manufactured and permanently and rigidly connected into a system. Concentric line impedance transformers have been disclosed in Hansen and Woodyard Patent No. 2,406,372 granted August 27, 1946. In such devices, it is known that by the provision of only a single adjustment, a very restricted range of transformation is obtained. By providing three adjustments, any desired transformation may be obtained, but the practical difficulties of making three simultaneous interdependent adjustments renders such devices of limited utility. When using two adjustments, the range of possible transformations is increased greatly over that with one adjustment, but it is only in special cases that all transformations may be obtained. Such transformers are described in the present case.

Also, special provision is made for the elimination of losses by the use of special spacing of the insulating spacers required to maintain proper relationship between the concentric conductors of the device, and by the use of special contact-resistance-reducing means useful wherever sliding contact is required.

2

Accordingly, it is an object of the present invention to provide improved impedance matching transformers for matching any two arbitrary impedances.

5 It is another object of the present invention to provide improved impedance matching transformers of fixed effective length suitable for rigid connection in a system.

10 It is still another object of the present invention to provide improved impedance transformers having a minimum number of adjustments and a maximum range of transformations.

15 It is a further object of the present invention to provide improved impedance matching transformers including high efficiency joints therein for reducing the effects of sliding contact.

It is a still further object of the present invention to provide improved sliding joints for concentric transmission line devices.

20 It is another object of the present invention to provide improved means for adjustably connecting one concentric transmission line in shunt with a second.

Further objects and advantages of the present invention will become apparent from the following specification and drawings, in which,

Fig. 1 shows a longitudinal cross-sectional view partly in elevation of one form of the present invention;

30 Fig. 2 shows an enlarged cross-section of a detail of the device of Fig. 1 taken along line 2-2 thereof;

35 Fig. 3 shows an enlarged elevational view of a detail of the device of Fig. 1 taken along line 3-3 thereof;

Fig. 4 shows an admittance bipolar coordinate or circle diagram useful in explaining the theory of operation of the device of Figs. 1-3;

40 Fig. 5 shows a longitudinal cross-sectional view partly in elevation of a modified form of the invention;

Figs. 6A and 6B show impedance bipolar coordinate or circle diagrams useful in explaining the theory of operation of the device of Fig. 5;

45 Fig. 7 shows a similar cross-sectional view of still another modification of the invention;

Fig. 8 shows a longitudinal cross-sectional view of still another embodiment of the invention; and

50 Fig. 9 shows an admittance circle diagram

3

useful in explaining the theory of operation of the device of Fig. 8.

Referring to Figs. 1 to 3, there is shown one form of impedance transformer adapted to efficiently couple and match two arbitrary impedances or to transform an arbitrary impedance into any other impedance. Impedance transformer 11 of Fig. 1 comprises a pair of stationary concentric line end sections 12 and 13 which are adapted to be coupled fixedly to the impedances to be matched by means of suitable concentric line couplings (not shown) which may be of any desired type. Sections 12 and 13 may be of any convenient length. Transmission line concentric end section 12 comprises an inner conductor 14 and an outer conductor 16 held in proper relation by suitable insulating discs 17 and 18. Insulating discs 17, 18 may be provided at suitable points along the length of line section 12 as required by considerations of mechanical support. Preferably, however, these insulating spacers are placed in pairs having their centers spaced apart by a distance electrically equivalent to a quarter wavelength or 90 electrical degrees of the operating frequency. By so doing, the effect of these insulating spacers, due to the discontinuity they present in the dielectric medium within line section 12, is greatly minimized, and standing waves caused thereby are substantially eliminated.

Thus, considering for example an electromagnetic wave travelling from left to right down line section 12, such a wave would meet a dielectric discontinuity at the spacer 17 and a portion of this wave will be reflected thereby. Another portion of the wave will be transmitted further to the right and will be reflected by spacer 18. These two reflected waves will be superposed in the portion of the line section 12 to the left of spacer 17. Since spacers 17 and 18 have been placed a distance apart equivalent to a quarter wavelength, the wave reflected by spacer 18 will be a half-wavelength or 180° out of phase with respect to the wave reflected by spacer 17, and these two waves will tend to neutralize and cancel one another. In this way, the electrical effects of such insulating spacers, which are necessarily present because of the mechanical considerations of the device, are minimized and substantially eliminated.

The impedance transformer 11 of Fig. 1 is adapted to provide an adjustable short-circuited stub transmission line section in shunt with the concentric line sections 12 and 13, the point of connection of this shunt line section with the concentric line sections 12, 13 being made longitudinally adjustable along line sections 12, 13. For this purpose, inner conductor 14 of line section 12 and inner conductor 19 of line section 13 are joined by a conductor 22 which together with a tubular outer conductor shell 23 movable on concentric line sections 12 and 13 form a central concentric transmission line section joining line sections 12 and 13 in cascade.

Conductor 22 is made of larger diameter than inner conductors 14 and 19, and is joined to them at each end by respective tapered portions 24 and 25. The diameters of inner conductor 22 and outer conductor 23 are so chosen that the characteristic impedance of the transmission line section 22, 23 will be equal to that of line sections 12, 13. In order to join line sections 12 and 13 smoothly and without reflections or mismatch to line sections 22, 23, respective internally tapered portions 26, 27 are attached to outer conductors

4

16 and 21 of line sections 12 and 13. The internal tapers of portions 26 and 27 are so selected and are so placed relative to tapered portions 24, 25 of inner conductor 22, that the ratio of inner conductors 14, 24, 22, 25, 19 to the respective outer conductors 16, 26, 23, 27, 21 remains uniform and constant for the entire length of the impedance transformer 11, thereby assuring a uniform characteristic impedance and substantially no reflections or mismatch which might provide undesirable standing waves with consequent reduced efficiency and other attendant disadvantages.

The internally tapered portions 26, 27 are provided with cylindrical outer surfaces 28, 29 having a diameter just slightly smaller than the internal diameter of tubular outer conductor shell 23 whereby portions 26 and 27 do not contact shell 23, and shell 23 may be easily slid along the device. To provide electrical contact between outer conductor shell 23 and outer conductors 16, 26 and 27, 21 to complete the main line section of the device, connecting discs 31 and 32 are provided fastened to outer conductors 16 and 21 and provided at their peripheries with spring fingers 33 and 34 extending peripherally therearound and adapted to form good electrical contact with shell 23.

In this manner, shell 23 may be axially displaced along line sections 12, 13 without in any way changing the electrical properties of the cascaded line sections 14, 16; 24, 26; 22, 23; 25, 27; and 19, 21. In order to provide efficient electrical contact between shell 23 and the stationary outer conductors of these lines it is most desirable that very low resistance appear at the innermost points 101, 102 of the internally tapered portions 26, 27, which are the points at which the electric currents flowing along the composite outer conductor of the device would effectively cross over from outer conductor 21 or 16 to shell 23. For this purpose, the axial length of the cylindrical outer surface of each of the tapered sections 26 and 27 is made to be electrically exactly a quarter wavelength of the operating frequency, and their outer diameters are selected to be as nearly equal to the inner diameter of shell 23 as possible without obtaining direct mechanical contact. In this way, sections 26 and 27 form quarter wavelength low impedance concentric transmission line sections with outer conductor 23. Furthermore, the spacing between the outermost edges such as 36, 37 of portions 26, 27 from the innermost surfaces 38, 39 of contacting discs 31, 32 is also made to be electrically equivalent to a quarter wavelength of the operating frequency whereby a second quarter wave section of concentric transmission line is formed by shell 23 serving as outer conductor, and conductors 16 and 21 of line sections 12, 13 serving as inner conductors. In order to make the characteristic impedance of the latter quarter-wave sections as large as possible, the outer diameter of conductors 16 and 21 is reduced by thinning the wall thickness thereof, whereby the impedances of these sections is increased without affecting that of line sections 12 and 13.

It will be seen that the quarter wave line section 16, 23 is short-circuited at the left by disc 31, this short-circuit being produced by the low radial resistance of disc 31 in series with the contact resistance between fingers 33 and outer conductor 23. This fairly low impedance will be transformed by the high impedance line section

5

16, 23 to a high impedance at point 36 having the value

$$\frac{Z^2}{R}$$

where Z is the characteristic impedance of line section 16, 23 and R is the short-circuiting resistance. It will be noted that this value will be extremely high due to the low value of resistance R and to the high value of the characteristic impedance Z.

By the action of the low impedance quarter wave line section 26, 23 this high impedance is transformed to a low impedance having the value

$$R \left(\frac{Z'^2}{Z^2} \right)$$

at the innermost end 102 of tapered section 26, where Z' is the characteristic impedance of line section 26, 23. Since Z' is much smaller than Z, it will be clear that the effective gap resistance at the innermost point 102 of tapered portion 26 will be much lower than the contact resistance between fingers 33 and sleeve 23, and in this manner a highly efficient and extremely low resistance sliding joint between outer conductor 16 and 23 is provided. If desired, further alternately high and low impedance quarter wave sections formed similarly to 16, 23 and 26, 23 may be inserted here to further decrease the ultimate gap resistance.

As described above, line section 16, 23 forms a quarter-wave section short-circuited at the left by disc 31 and fingers 33. As is well-known, such a line section has a current anti-node or loop at the shorting point, resulting in relatively high current intensity. This high current flowing through the contact resistance of fingers 33 would produce high losses. To minimize these losses, fingers 33 are made of substantial length relative to a quarter wavelength of the operating frequency whereby the actual sliding contact occurs at a point of lower current intensity, thus reducing losses and heating.

It will be clear that the same type of joint is provided between outer conductor 21 and sleeve 23.

In order to adjustably insert a shunt section of concentric transmission line 11, shell 23 is connected perpendicularly to an outer conductor 41 which cooperates with an inner conductor 42 to provide a concentric transmission line section 43. To connect this line section 43 in shunt with line section 22, 23 it is necessary to connect inner conductor 42 to inner conductor 22. However, as described above, it is also desired to adjust the point of connection of line section 43 with respect to concentric line section 22, 23.

For this purpose, conductor 22 is formed with a longitudinally extending slot 44 shown more clearly in Figs. 2 and 3. The end of conductor 42 is provided with an internally circularly rounded portion 46 for cooperation with conductor 22 to provide an extremely small gap between conductors 22 and 42. Suitably fixed to inner conductor 42, as by soldering, etc., is a flat metallic plate 47 extending axially of conductor 42 and within the slot 44 of conductor 22. In this manner, conductors 22 and 42 may be connected in high frequency fashion through the large capacitance formed by the small arcuate gap between conductors 22 and 42 and by the small gap between plate 47 and conductor 22. In order to increase and maintain this capacitance substantially constant, a pair of dielectric plates 48, 49 are preferably

6

fixed to either side of plate 47 to maintain its spacing constant relative to slot 44.

In order to provide as large a capacitance and as small an impedance as possible, it is desirable to have plate 47 of substantial extent along the axis of conductor 22. However, any length in either direction from the center exceeding a quarter wavelength would be superfluous and inefficient, since the effective capacitance becomes a maximum for a quarter wavelength of conductor. Accordingly, the length of plate 47 along the axis of conductor 22 is preferably made substantially equal to a half wavelength, although it may be less if desired. In this manner, the line section 43 may be axially adjusted in position along the line section 22, 23, an efficient connection being provided by the means just described.

Preferably the length of slot 44 in conductor 22 is made of such length that at least a half-wavelength of adjustment of the point of connection 45 between line sections 43 and 22, 23 may be provided.

In order to suitably adjust the length of line section 43, a slidable plunger 51 is provided having a shorting disc 52 provided with two sets of spring fingers 53, 55, and thereby serves to interconnect the inner conductor 42 and outer conductor 41 through a fairly low resistance. In order to still further reduce this contact resistance, impedance transformer means are provided similar to that described with respect to the sliding joint between conductors 16, 21 and sleeve 23.

For this purpose, a cylindrical shell 54 is suitably fastened to shorting disc 52, and concentrically thereof. At the opposite end, shell 54 is connected to an annular disc 56 which is spaced only slightly from inner conductor 42 and from outer conductor 41 by suitable thin rings of dielectric material, such as 57 and 58. The length of cylindrical shell 54 as measured between the inner face 59 of plunger 52 and the outer face 61 of annular disc 56 is selected to be electrically equivalent to a quarter wavelength of the operating frequency. The axial thickness of disc 56 is also chosen to be electrically equivalent to a quarter wavelength. Since dielectric material is provided between disc 56 and both inner conductor 42 and outer conductor 41, the physical length required for conductor 56 will be substantially less than a quarter wavelength in free space.

In this manner, shell 54 and outer conductor 41 form a high impedance quarter-wave line section short-circuited at the outer end by the contact resistance between fingers 53 and outer conductor 41. This line section is in cascade with the low impedance quarter-wave section 56, 41, whereby the contact resistance between disc 52 and conductor 41 is transformed to point 62 as a much lower resistance in the manner already described above.

At the same time, shell 54 and inner conductor 42 form a high impedance quarter-wave line which together with the low impedance quarter-wave line formed by ring 56 and inner conductor 42 also serves to transform the contact resistance between fingers 55 and inner conductor 42 to a much lower resistance at point 63. In this way, extremely low effective contact resistances are produced at points 62, 63, whereby the lower face of annular disc 56 provides an effective short-circuiting plug or piston for line section 43.

As noted above, it is desirable that the characteristic impedances of the two cascaded quarter-wave line sections forming the contact resistance transformer have as high a ratio as pos-

sible in order to provide the lowest transformed contact resistance. For line section 54, 41 this would necessitate the smallest possible outer diameter of shell 54. However, for line section 54, 42 this would necessitate the largest possible innermost diameter of shell 54. Since these two conditions are mutually exclusive, and since the net contact resistance provided by annular disc 56 is the sum of the resistances reflected at points 62, 63, which is to be minimized, shell 54 is made to be as thin as possible and its inner and outer diameters are so chosen that the characteristic impedances of line sections 42, 54 and 54, 41 are substantially equal. This requires that the average diameter of shell 54 be substantially the geometric means between the diameters of inner conductor 42 and outer conductor 41. In this manner a minimum effective contact resistance is obtained.

In order to suitably adjust the position of shorting plunger 56 along line section 43, several thrust rods are provided, of which two, namely, 64 and 66, appear in the section taken. These rods are fastened to disc 52 and are movable axially of line section 43 by means of a suitable screw 67 threaded into member 68, to which rods 64, 66, etc. are also fastened. In this manner, both the length of the line section 43 and its point of connection in shunt with the concentric line formed along the major axis of the device may be suitably adjusted, and by so doing the arbitrary impedance connected at the end of one of line sections 12 and 13 may be properly and efficiently transformed to any other impedance value at the end of the other line section 13 or 12. It will be clear that any other suitable adjusting means may be used.

The operation of the device of Fig. 1 may be explained by reference to Fig. 4 which shows an admittance diagram having coordinate axes representing conductance g and susceptance b , as shown. Point Y_0 on this diagram represents the common characteristic admittance of line sections 22, 23; 14, 16 and 19, 21.

If an arbitrary admittance represented by point Y_1 is connected to an adjustable length transmission line section having characteristic admittance Y_0 , it may be shown that the admittance Y_1' , looking through the line section toward Y_1 , may be represented by the equation

$$Y_1' = \frac{Y_0 \sinh \mu + j Y_0 \sin (\phi + 4\pi x)}{\cosh \mu - \cos (\phi + 4\pi x)}$$

where μ and ϕ are quantities defined by

$$\coth \mu = \frac{G_1^2 + B_1^2 + Y_0^2}{2 Y_0 G_1}$$

and

$$\cot \phi = \frac{G_1^2 + B_1^2 - Y_0^2}{2 Y_0 B_1}$$

Here x is the length of line in wavelengths, G_1 is the conductance of Y_1 and B_1 is the susceptance of Y_1 . Graphically, the locus of resultant admittance Y_1' as x varies is given by the circle defined by setting μ equal to zero, which may be termed a bipolar coordinate circle having Y_0 as pole. Such a circle is shown at 70 in Fig. 4. For each added half-wavelength of line, one complete traverse of circle 70 is made by Y_1' .

Accordingly, if an admittance Y_1 is connected to one end, say the left end, of the transformer of Fig. 1, the resultant admittance Y_1' looking left from the tap point 45 will vary clockwise from

Y_1 along circle 70 as the tap 45 is moved from left to right.

If it is desired to produce a transformed admittance Y_2 at the right end of transformer 11, then the admittance Y_2' at point 45 looking to the right, which is required to produce Y_2 at the end of the line section 13, will lie somewhere on the bipolar coordinate circle 71 passing through Y_2 , but displaced counter-clockwise from Y_2 , depending on the position of point 45. As tap 45 moves rightward, Y_2' also moves on circle 71 clockwise about Y_0 . Since one of these circles 70 is completely within the other circle 71, it will be clear that for some particular setting of the junction 45, Y_1' and Y_2' will be one directly above the other; that is, they will differ only by pure susceptance. Such a position is shown by Y_1'' and Y_2'' in Fig. 4.

When such a position is found, the admittance Y_2'' and therefore the desired transformed admittance Y_2 at the right end may be produced by adjusting the position of plunger 51 to add or subtract the required amount of susceptance to admittance Y_1'' . In this manner any arbitrary admittance Y_1 at one end of transformer 11 may be transformed into any other arbitrary admittance Y_2 at the other end.

Since in practice the condition of matching or proper transformation is most usually tested by observing the standing wave ratio or power output, it will be clear that these two adjustments, namely that of the position of the junction point 45 and of the position of plunger 52, must be made by trial and error to produce the desired result. Usually this will be done by setting one of these values to an optimum position, which generally will not be the desired condition, and then resetting the other to improve upon this optimum condition. Thus by alternately resetting each of the two adjustable portions of the device, the proper transforming condition can be obtained after only a few manipulations.

Fig. 5 shows another type of impedance transformer also adapted to efficiently match two arbitrary impedances. In this instance, transformation is performed by adding a concentric line section serving as an adjustable reactance in series with the arbitrary impedance to be transformed, then, effecting a transformation by a quarter-wave section of line, and adding further adjustable reactance, to derive the desired transformed impedance.

In general, this will not permit the transformation of any impedance at one end to any other impedance at the other end. However, by adding a quarter-wavelength more of concentric transmission line at one end than at the other, any transformation may be obtained if care is taken to connect the impedance element to be transformed at the proper end, as will be shown below. In this manner, the transformer may remain of fixed length, and any transformation may be obtained by adjustment thereof and a possible reversal or turning over of the device.

Thus, referring to Fig. 5 and considering for the moment only the left-hand half, which is substantially duplicated on the right side, there is provided a fixed concentric transmission line end section 81 comprising an inner conductor 82 and an outer conductor 83 of any suitable relative diameters adapted to provide a convenient characteristic impedance. This transmission line section 81 may be suitably formed at its end to provide a convenient coupling with other concentric transmission line devices, as described in

Fig. 1C of Hansen Patent No. 2,404,797 granted July 30, 1948.

Inner conductor 82 extends without change throughout the entire impedance matching device. The outer conductor 83, however, terminates as at 84 and has a convenient length preferably longer than a half wavelength. Suitable insulating spacers similar to spacers 17 and 18 of Fig. 1 may be provided to support inner conductor 82 concentrically within outer conductor 83. Supported on outer conductor 83 by means of an annular disc 86 is a concentric sleeve 87. Sleeve 87 and outer conductor 83 are then adapted to form a further concentric transmission line section. A shorting device for conductively connecting sleeve 87 and conductor 83 is provided in the form of a movable annular piston or plunger 88 adapted to be moved by axial actuation of a control ring 89 fastened to plunger 88 by means of a plurality of rods 91 which pass through suitable openings 92 in the annular supporting disc 86. Any other type of control for plunger 88 may be used here.

Plunger 88 is provided with a plurality of spring fingers 93 which provide a rubbing or sliding contact with the inner surface of sleeve 87. Fingers 93 are preferably spaced from the inner wall of sleeve 87 except at their ends 94 which are in sliding contact therewith. Fingers 93 extend completely around within sleeve 87, forming a substantially complete cylinder with axial slits to form the several fingers. The overall length of fingers 93 including tips 94 is preferably chosen to be substantially a quarter wavelength, to improve the electrical characteristics of the sliding joints of these points.

Thus, it will be seen that the fingers 93 form a quarter wave concentric transmission line section short-circuited at its left end by plunger 88. Accordingly, a current antinode or loop appears at the left end of this transmission line section, at which maximum current will flow. The right end of the quarter wave transmission line, at which the sliding tips 94 then will be located, provides a current node at which minimum current exists. Accordingly, by having sliding contact only at tips 94, it will be clear that such contact and its inherent contact resistance occurs at points of low current intensity, whereby undesirable losses are minimized. It will be seen that where the current is a maximum no sliding contact exists, since plunger 88 is solidly connected to fingers 93. A similar construction is provided for fingers 96 having contacting tips 97.

It will be clear that the type of sliding contact between plunger 88 and sleeve 87 or conductor 83 has no effect upon the electrical characteristics of the system, but is merely useful to provide smooth actuation and variation in position of plunger 88 with respect to the rest of the device.

It will be seen that the transmission line section formed by conductors 83 and 87 is essentially in series with the transmission line formed by conductors 82, 83. This follows from the consideration that the outer conductor 83 of the second of these transmission line sections is directly connected to the inner conductor 83 of the first of these line sections while the output from both lines is taken from the inner conductor 82 of the second line and the outer conductor 87 of the first line. Hence a true series circuit is provided since currents flowing along the outer conductor 83 must successively traverse both conductors of line section 82, 87 before continuing

in the circuit. The same condition can be seen from the fact that at the right end of each of these lines, the electric vectors, which are normally radial, are effectively in series and therefore the two transmission line sections are in series.

This is in marked distinction to two other usual types of connection of transmission lines, namely, a shunt connection and a cascade connection. Both of these other types are illustrated in Fig. 1. For example, transmission line section 22, 23 is in shunt with line section 41, 42, since the inner conductors 42, 22 and the outer conductors 23, 41 thereof are respectively joined together and to the corresponding conductors of the output circuit comprising transmission line section 13. However, transmission lines 22, 23 and 19, 21 are effectively in cascade since their respective conductors are connected together and energy flows successively through these transmission line sections.

The right-hand portion of the impedance matching device of Fig. 5 is substantially identical with that already described, having an end section 82, 83' terminating at point 84' in series with a line section 83', 87' adjustable by means of movable plunger 88'. Section 82, 83' is chosen of a length differing from that of 82, 83 by an odd multiple of a quarter-wavelength.

The space between points 84 and 84' is occupied by a concentric line section comprising an outer conductor 98 having inner diameter substantially identical to the common inner diameter of outer conductors 83 and 85 and connected to conductors 87 and 87', and an inner conductor formed by conductor 82. Outer conductor 98 is made of a length to provide a very narrow gap 99 between it and line section 82, 83, and a very narrow gap 99' between it and line section 82, 83'. Conductor 98 also serves to join rigidly sleeves 87 and 87'. The length of conductor 98 is chosen so that the separation between the centers of gaps 99, 99' is substantially a quarter wavelength. In view of the small size of gaps 99, 99', this causes conductor 98 to cooperate with inner conductor 82 as a quarter-wave transmission line section.

The operation of the device of Fig. 5 may be explained by reference to Figs. 6A and 6B. Thus, referring to Fig. 6A, there is shown an impedance diagram having r and x coordinate axes, and showing a family of bi-polar coordinate circles having the common characteristic impedance of Z_0 of lines 82, 83; 82, 83' or 82, 98 as the pole thereof. If an arbitrary impedance Z having resistance R and reactance X is connected to one end of the impedance transformer, for example, the right end, and if the length of line section 82, 83' is assumed as an even multiple of a quarter wavelength of the operating frequency, then the impedance looking toward the right from point 84' will also have the value Z . To this impedance Z the short-circuited series-connected transmission line section 83', 87' adds an adjustable amount of pure reactance, so that, looking right from point 85', there may be obtained any impedance whose value can be represented by a point on line AB. The quarter-wave section of the transmission line 82, 98 will then transform each point of line AB to a corresponding point of circle OCD. It is to be understood that there is a 1:1 correspondence between the points of line AB and the points of circle OCD, in which point O corresponds to the infinitely distant points along AB and point C corresponds

11

to the point R at which line AB crosses the r -axis. Point C will then represent an impedance

$$\frac{Z_0^2}{R}$$

A traversal of line AB in the direction of the arrow will produce a traversal of circle ODC in a clockwise sense, as shown.

The second short-circuited series-connected transmission line section 83, 87 then adds an adjustable amount of pure reactance to whatever impedance is seen at point 85, namely, it adds adjustable reactance to any point of circle OCD. Consequently the locus of all impedances into which the impedance Z may be transformed by the present device, as so far described, will be contained within the strip bounded by the x -axis and the line ECF parallel thereto. It will thus be seen that unless special provision is made, an arbitrary impedance Z cannot be transformed into any other arbitrary impedance by the present device.

In order to permit such arbitrary transformation, the line section 82, 83 may be made to have a length equal to an odd multiple of a quarter wave length. This performs a further transformation of impedance such that each point of the strip contained between the x -axis and line EF is transformed into a corresponding point of the positive Z plane outside circle OHR, and consequently, for this device, an arbitrary impedance Z may be transformed into any other impedance whose corresponding plot is not contained within the circle OHR.

This condition may be also stated in the form that, if the transformed impedance is denoted by Z' , having resistance R' and reactance X' , then the arbitrary impedance Z may be transformed into any other arbitrary impedance Z' so long as the conductance

$$G' = \frac{R'}{R'^2 + X'^2}$$

of the transformed impedance Z' has a value no greater than the reciprocal of the resistance R of the arbitrary impedance Z.

In order to overcome this restriction on the range of transformation, it is merely necessary to connect the opposite end of the impedance transformer of Fig. 5 to the arbitrary impedance Z to be transformed. Thus, referring to Fig. 6B, if the arbitrary impedance Z is connected to the left end of the impedance transformer of Fig. 5, then the line section 82, 83, being of length equal to an odd multiple of a quarter-wavelength, will be transformed to another impedance, such as Z, located on the same bipolar coordinate circle as impedance Z. The series-connected short-circuited, transmission line section 83, 87 then adds an adjustable amount of reactance to this impedance Z, whereby the impedance seen at point 85 may be adjusted to have any value corresponding to points along line AB. The quarter-wave section 82, 98 then transforms each point of line AB into a corresponding point of circle OCZ. It will be clear that this circle will pass through the point Z since, if zero reactance is added by the short-circuited series-connected section 83, 87, then the impedance Z will be effectively connected in series with a half-wave line or multiple thereof, comprising cascaded sections 82, 83 and 82, 98, which would leave this impedance Z unchanged.

The second series-connected short-circuited section 83', 87' adds an adjustable amount of

12

pure reactance to the impedance seen at point 85', and accordingly any transformed impedance whose plot is contained within the strip bounded by the axis and line ECF may be obtained by these two adjustments. This impedance remains unchanged by half-wave line 82, 83'. It may be shown that the width of this strip is equal to the reciprocal of the conductance of the original arbitrary impedance Z, and accordingly, with the present connection, any arbitrary impedance Z may be transformed into any other arbitrary impedance Z' so long as the resistive component R' of the transformed impedance Z' is equal to or less than the reciprocal of the conductance of the original impedance.

It will be seen that the locus of possible transformations shown in Fig. 6B overlaps the locus of impossible transformations of Fig. 6A, and accordingly between the two any impedance may be transformed into any other impedance, it being necessary merely to reverse the connections to the impedance transformer for transformations within particular ranges.

Although the impedance transformer of Fig. 5 has been described in such manner that one line section 82, 83 is an odd multiple of a quarter wavelength and the other section 82, 83' is an even number of quarter wavelengths long, it is to be understood that the only necessary condition is that these sections shall differ by one-quarter wavelength, and it is not necessary that they be exact multiples of a quarter wavelength. If these sections depart from exact multiples of a quarter wavelength, the above theory still applies, but it is to be understood that the arbitrary impedance to be transformed will now differ from the impedance Z shown in the diagram by an amount corresponding to the amount the length of transmission line connected thereto differs from a multiple of a quarter wavelength, and that the ultimate transformed impedance will differ from the value Z' found from the diagrams of Figs. 6A and 6B by an amount corresponding to the length of transmission line connected thereto. In effect, impedances Z and Z' of the diagram are those at points 84 and 84'. Otherwise the same theory holds and the same results may be produced.

Furthermore it is not necessary, although it is desirable, that line section 82, 98 be exactly a quarter-wave section. Any other length, excluding a half-wavelength and multiples thereof, may be used, but odd multiples of a quarter-wavelength yield the most easily adjustable device, avoiding undesirable resonance conditions in the adjustable sections which make the transformed impedance value highly sensitive to small adjustments.

Fig. 7 shows a further modification of the impedance transformer of the present invention. In this modification, two adjustable shunt concentric line sections 111 and 112 are provided connected to the main concentric line section 113 at points 114 and 116 spaced by a quarter-wavelength. The arbitrary impedance to be transformed may be connected at one end of the main concentric line section 113 of the device.

The line sections 111 and 112 are made adjustable by the use of adjustable short-circuiting plungers 117 and 118 of the same type as those used in Fig. 5. Preferably the length of the central line section 113a to the left of point 114 is made to differ from the length of section 113b to the right of point 116 by a quarter-wave-length or an odd multiple thereof, in a fashion similar to that shown in Fig. 5.

The operation of the device of Fig. 7 may be explained in the same manner as that of Fig. 5, merely replacing the term "impedance" by "admittance," "resistance" by "conductance" and "reactance" by "susceptance" wherever these terms occur in the explanation or in the diagrams. With these changes, and applying the explanation to admittance diagrams similar in all respects to those shown in Figs. 6A and 6B, it will be clear that the transformer of Fig. 7 may transform any impedance into any other impedance so long as the proper choice of connections to the transformer is made.

In Fig. 7 also, it is not absolutely necessary, but is desirable, that the separation between the shunt sections be exactly a quarter-wavelength. The quarter-wave condition yields the best operation.

In both Figs. 5 and 7, the length of travel of the plungers which is actually employed is in no way critical but to utilize the widest range of the instrument, this length should be at least a half-wavelength in each embodiment of the invention.

Fig. 8 shows another form of impedance transformer adapted to transform an arbitrary impedance into any other impedance. The transformer of Fig. 8 comprises a main section of concentric transmission line 121 and three stub transmission line sections 122, 123 and 124 connected in shunt thereto, the points of connection 126, 127 and 128 thereof being positioned at quarter-wave-length intervals along the main line section 121. Each of these shunt sections 122, 123 and 124 is made adjustable in length by means of respective adjustable short-circuiting pistons 129, 130 and 131, preferably of the same type as described with respect to Figs. 5 and 7. The central shunt section 123 may be adjusted by translation of a suitable control 132 connected to piston 130. Pistons 129 and 131 are simultaneously equally adjustable by means of a common control member 133 suitably connected thereto.

The theory of operation of the device of Fig. 8 may be explained by reference to the admittance diagram of Fig. 9, upon which are shown the bipolar coordinate circles corresponding to the pole Y_0 representing the characteristic admittance of the main concentric line section 121 of the impedance transformer.

Let it be assumed that an arbitrary admittance Y_1 is connected to one end of the impedance transformer, for example, the right end. The section of the main concentric transmission line section 121 to the right of point 126 will transform this admittance Y_1 into a further admittance Y_1' looking to the right from point 126. It will be noted that Y_1' is displaced from Y_1 along the bipolar coordinate circle 135 passing through Y_1 by an amount corresponding to the length of the concentric line section 121 to the right of point 126.

Let it be assumed that it is desired to provide an admittance Y_2 at the other end, such as the left end, of the impedance transformer when looking toward the right. The admittance required therefore at a point just to the left of junction 128 may be as shown at Y_2' on the diagram of Fig. 9, being displaced from Y_2 along the bipolar coordinate circle 136 passing therethrough, by an amount corresponding to the length of the line section 121 to the left of point 128.

The shunt section 122 will add an adjustable amount of susceptance to the admittance Y_1' and,

accordingly, the locus of all admittances obtainable when viewing to the right from a point just to the left of junction 126 may be represented by the line AB. The quarter wave section of line between points 126 and 127 will transform points on this line AB into corresponding points on circle $OY_1''C$ with a one-to-one correspondence between the points of line AB and the points of this circle. Thus, to point Y_1' will correspond the point Y_1'' , and to the point B_1' representing the conductive component of admittance Y_1' will correspond point C having a value

$$\frac{Y_1^2}{G_1'}$$

If the susceptance added to admittance Y_1' by shunt section 122 is assumed to be of the sense as to vary Y_1' upward in the direction of the arrow, then the corresponding points on the circle will move in a clockwise direction as shown and accordingly, just to the right of point 127 there may be obtained any admittance represented by points on this circle.

Since the variation of shunt sections 122 and 124 occurs simultaneously by virtue of the ganged adjustment of these two sections, it will be clear that as susceptance is added to Y_1' to vary it in the direction of the arrow, the admittance required just to the right of point 128 to produce Y_2 at the left end of the device will vary oppositely from Y_2' as shown by its corresponding arrow, and accordingly, the locus of the required admittance Y_2' will vary along line DE in correspondence with the variation of Y_1' along AB. The quarter-wave section between points 128 and 127 will change the value Y_2' required at point 128 to the value Y_2'' required just to the left of point 127 to produce Y_2 at the left end of the transformer.

As Y_2' moves downward, Y_2'' will move in a counter-clockwise sense about circle OFY_2'' . Since one or the other of these two circles $OY_1''C$ and OFY_2'' will be within the other, and since for a given sense of adjustment of the ganged pistons 129, 131 the corresponding loci of the transformed and required admittances at point 127 will move oppositely along these circles, it will be clear that for some particular adjustment of the ganged pistons 129, 131, depending upon the value of the arbitrary admittance Y_1 and the required admittance Y_2 , their corresponding transformed values Y_1'' and Y_2'' will be vertically displaced with respect to one another on the diagram of Fig. 9. At such a position, it would require only pure susceptance to produce the required transformation. This pure susceptance may be produced by adjustment of the central piston 130 to the proper position, and thereby the arbitrary admittance Y_1 its fully transformed to the required arbitrary transformed admittance Y_2 .

Although the spacing of junction points 126, 127, 128 and has been described as a quarter-wave-length, it is to be understood that this is an optimum figure only, and may be varied if desired.

Throughout this description, wherever the electrical length of a quarter or half-wavelength are used, it is to be understood that an odd multiple or an even multiple, respectively, of a quarter-wavelength may be used equally as well.

Wherever the term "electrical length" is used in the present specification, it is to be understood as meaning a physical length of such value as to give the same electrical effect as a physical length equal to the electrical length would yield in free

space. All wavelengths are referred to waves in free space.

All distances referred to in terms of wavelength are intended to be electrical lengths as defined above.

As many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. An impedance transformer for transforming an arbitrary impedance into any other desired impedance, comprising a pair of concentric transmission line end sections differing in length by an odd multiple of a quarter-wavelength, means connecting said arbitrary impedance to one of said sections, a quarter wave concentric transmission line section, and an adjustable short-circuited concentric transmission line section formed concentric with and connected in series with each of said end sections and to said quarter-wave section, whereby said arbitrary impedance may be transformed to said desired impedance by adjusting said short-circuited sections.

2. An impedance transformer for transforming an arbitrary impedance into any other desired impedance, comprising a pair of concentric transmission line end sections, means connecting said arbitrary impedance to one of said sections, a central concentric line transmission section, and an adjustable short-circuited concentric transmission line section connected in series between each of said end sections and said central section, whereby said arbitrary impedance may be transformed into said desired impedance by adjusting said two adjustable short-circuited sections.

3. An impedance transformer as in claim 2 wherein each of said adjustable short-circuited concentric transmission line sections comprises an adjustable plunger, means forming sliding contact between said plunger and the conductors of said section, and means for transforming the resistances of said contact to low impedances whereby the effects of said contact resistances are minimized.

4. An impedance transformer for transforming an arbitrary impedance into any other desired impedance, comprising a pair of fixedly separated concentric transmission line end sections, means for connecting said arbitrary impedance to one of said sections, a central concentric transmission line section, and an adjustable short-circuited concentric transmission line section connected in series between the outer conductor of each of said end sections and the outer conductor of said central section, whereby said arbitrary impedance may be transformed into said desired impedance by adjusting said adjustable line sections.

5. An impedance transformer for transforming an arbitrary impedance into any other desired impedance, comprising a pair of concentric transmission line end sections, means connecting said arbitrary impedance to one of said sections, a central concentric transmission line section and an adjustable reactance connected in series between each of said end sections and said central section, one of said end sections being an odd multiple of a quarter-wavelength longer than the other of said end sections, whereby said

arbitrary impedance may be transformed into said desired impedance by adjusting said reactances.

6. An impedance transformer for transforming an arbitrary impedance to another desired impedance, comprising a section of transmission line connected to said arbitrary impedance, a pair of concentric transmission lines connected in shunt to said first section and spaced a quarter-wavelength apart therealong, and means for independently adjusting the lengths of said shunt lines, whereby said desired impedance may be derived at the other end of said first section.

7. An impedance transformer for transforming an arbitrary impedance into any other desired impedance, comprising fixed concentric transmission line means for transforming said arbitrary impedance into a first transformed impedance, adjustable reactance means for transforming said first transformed impedance into a second transformed impedance, a second fixed concentric transmission line means for transforming said second impedance into a third transformed impedance, a second adjustable reactance means for transforming said third impedance into a fourth transformed impedance, a third fixed concentric transmission line means for transforming said fourth impedance into a fifth transformed impedance, a third adjustable reactance means for adjustably transforming said fifth impedance into a sixth transformed impedance, a fourth fixed concentric transmission line means for transforming said sixth impedance into a seventh impedance, and means for simultaneously adjusting two of said adjustable reactance means, whereby said seventh impedance may be adjusted to be equal to said desired transformed impedance.

8. An impedance transformer for transforming an arbitrary impedance into any other desired impedance, comprising a main section of concentric transmission line, three further sections of concentric transmission line connected in shunt to said main section, and means for adjusting the reactance of each of said further sections, whereby said arbitrary impedance connected at one end of said main section may be transformed to said desired impedance at the other end of said main section by adjustment of said reactances.

9. An impedance transformer as in claim 8 comprising means for simultaneously adjusting the outer ones of said further sections.

10. An impedance transformer as in claim 8 wherein said further sections are spaced at quarter-wavelength intervals along said main section.

11. An impedance transformer for transforming an arbitrary impedance into a desired impedance, comprising fixed concentric transmission line means for transforming said arbitrary impedance into a first transformed impedance, adjustable reactance means for transforming said first transformed impedance into a second transformed impedance, said adjustable means comprising a coaxial line, a moveable plunger, means forming sliding contact between said plunger and the conductors of said coaxial line, and means for transforming the resistance of said contact to a low impedance, a second fixed concentric transmission line means for transforming said second transformed impedance into a third transformed impedance, further adjustable reactance means for transforming said third impedance into a fourth transformed impedance, and a third concentric transmission line means

for transforming said fourth impedance into a fifth transformed impedance, whereby said fifth impedance may be made equal to said desired impedance by adjustment of said two reactance means.

12. An impedance transformer as in claim 11 wherein said reactance means are shunt connected to said concentric line means.

13. An impedance transformer for transforming an arbitrary impedance into a desired impedance, comprising fixed concentric transmission line means for transforming said arbitrary impedance into a first transformed impedance, adjustable reactance means series-connected to said concentric line means for transforming said first transformed impedance into a second transformed impedance, a second fixed concentric transmission line means for transforming said second transformed impedance into a third transformed impedance, further adjustable reactance means for transforming said third impedance into a fourth transformed impedance, and a third concentric transmission line means for transforming said fourth impedance into a fifth transformed impedance, whereby said fifth impedance may be made equal to said desired impedance by adjustment of said two reactance means.

14. An impedance transformer for transforming an arbitrary impedance into a desired impedance, comprising fixed concentric transmission line means for transforming said arbitrary impedance into a first transformed impedance, adjustable reactance means for transforming said first transformed impedance into a second transformed impedance, a second fixed concentric transmission line means comprising a quarter-wave section of concentric transmission line for transforming said second transformed impedance into a third transformed impedance, further adjustable reactance means for transforming said third impedance into a fourth transformed impedance, and a third concentric transmission line means for transforming said fourth impedance into a fifth transformed impedance, whereby said fifth impedance may be made equal to said desired impedance by adjustment of said two reactance means.

15. An impedance transformer for transforming an arbitrary impedance into a desired impedance, comprising fixed concentric transmission line means for transforming said arbitrary impedance into a first transformed impedance, adjustable reactance means for transforming said first transformed impedance into a second transformed impedance, a second fixed concentric transmission line means for transforming said second transformed impedance into a third transformed impedance, further adjustable reactance means for transforming said third impedance into a fourth transformed impedance, and a third concentric transmission line means for transforming said fourth impedance into a fifth transformed impedance, said first and third concentric transmission line means comprising

concentric transmission line sections differing in length by an odd multiple of a quarter-wavelength, whereby said fifth impedance may be made equal to said desired impedance by adjustment of said two reactance means.

16. An impedance transformer for transforming an arbitrary impedance into a desired impedance, comprising fixed concentric transmission line means for transforming said arbitrary impedance into a first transformed impedance, adjustable reactance means for transforming said first transformed impedance into a second transformed impedance, a second fixed concentric transmission line means for transforming said second transformed impedance into a third transformed impedance, further adjustable reactance means for transforming said third impedance into a fourth transformed impedance, and a third concentric transmission line means for transforming said fourth impedance into a fifth transformed impedance, said first and third concentric transmission line means comprising concentric transmission line sections differing in length by an odd multiple of a quarter-wavelength of the operating frequency, and said second fixed concentric transmission line means further comprising a quarter wave section of concentric transmission line, whereby said fifth impedance may be made equal to said desired impedance by adjustment of said two reactance means.

17. Ultra-high frequency apparatus comprising a main section of coaxial transmission line, a plurality of further sections of coaxial transmission lines more than two in number connected in shunt to said main section and spaced equidistantly therealong, means for adjusting the reactance of each of said further sections, the spacing between successive ones of said plurality of shunt sections being substantially less than one wavelength at the operating frequency, and further comprising means coupling together predetermined ones of said reactance adjusting means for simultaneously adjusting the reactances of said further sections.

WILLIAM W. HANSEN.
JOHN R. WOODYARD.
MORRIS RELSON.

REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

Number	Name	Date
1,932,448	Clavier	Oct. 31, 1933
2,203,806	Wolf	June 11, 1940
Re. 20,859	Potter	Sept. 13, 1938
2,132,208	Dunmore	Oct. 4, 1938
2,121,855	Buschbeck	June 28, 1938
2,106,769	Southworth	Feb. 1, 1938
2,284,529	Mason	May 26, 1942
1,927,393	Darbord	Sept. 19, 1933
2,226,479	Pupp	Dec. 24, 1940
2,373,233	Dow et al.	Apr. 10, 1945

Certificate of Correction

Patent No. 2,438,912.

April 6, 1948.

WILLIAM W. HANSEN ET AL.

It is hereby certified that errors appear in the printed specification of the above numbered patent requiring correction as follows: Column 14, line 10, for "B₁" read G₁'; line 59, for the word "its" before "fully" read *is*; line 63, strike out "and" before "has"; line 67, for "electrical length" read *electrical lengths*; and that the said Letters Patent should be read with these corrections therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 20th day of July, A. D. 1948.

[SEAL]

THOMAS F. MURPHY,
Assistant Commissioner of Patents,