

July 1, 1969

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3,453,529

ATTENUATORS HAVING CONSTANT OUTPUT RESISTANCE

Filed Feb. 17, 1967

Sheet 1 of 2

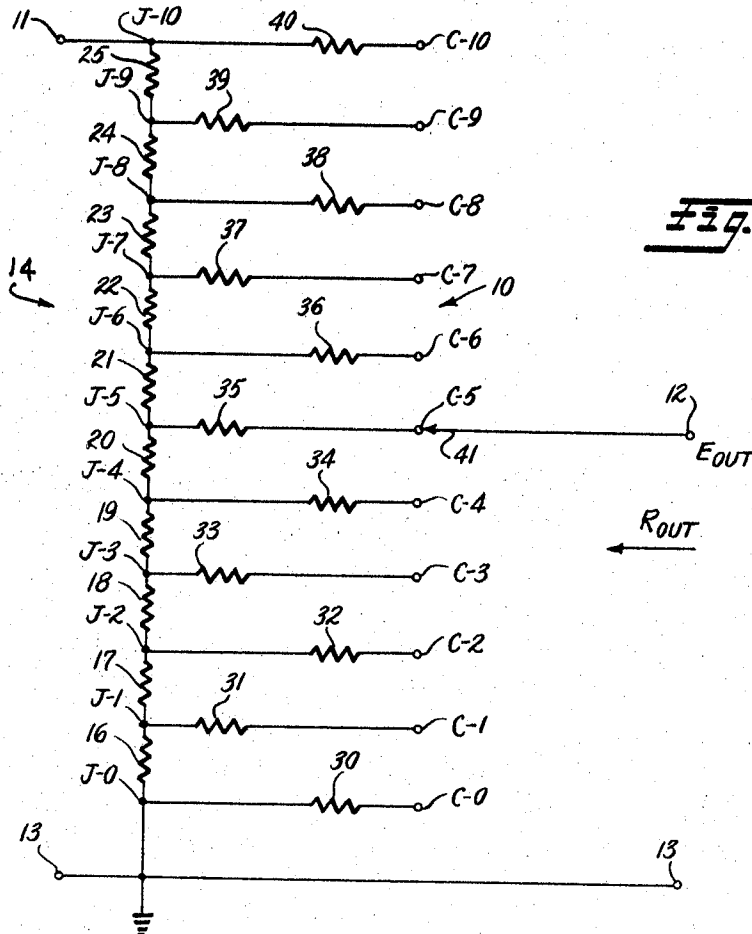


Fig. 1.

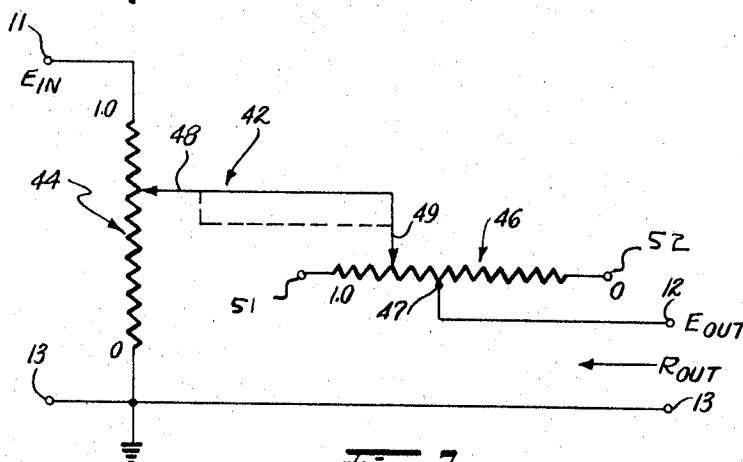


Fig. 2.

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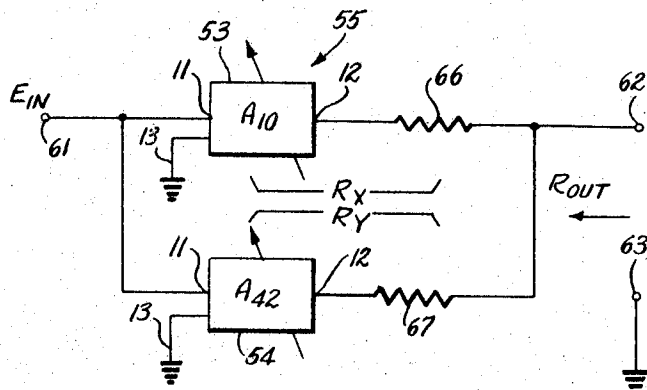


Fig. 3.

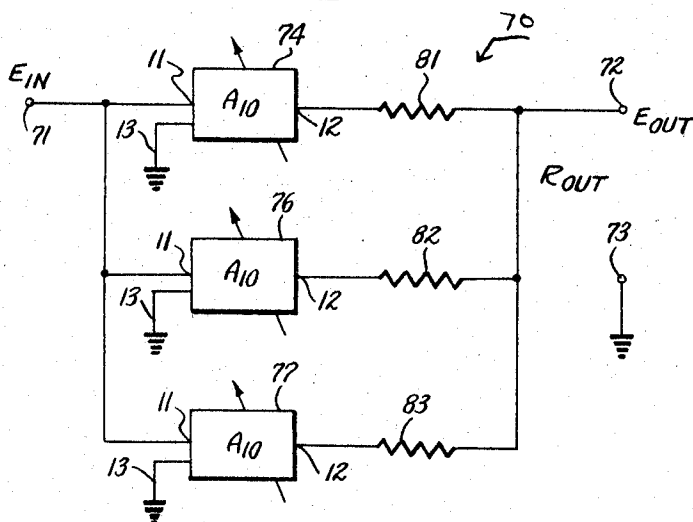


Fig. 4.

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ATTENUATORS HAVING CONSTANT OUTPUT RESISTANCE

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6 Claims

ABSTRACT OF THE DISCLOSURE

High-precision variable attenuators which provide substantially constant output resistance over their entire attenuation ranges. In single-digit embodiments, auxiliary resistances are connected to selectable points on a main resistance so that, for each point selected, the output resistance is composed of a particular auxiliary resistance connected in series with the parallel combination of the two portions of the main resistance defined by the selected point. In one embodiment, the attenuator is fractionally variable, and in another embodiment the attenuator is continuously variable. Multi-digit embodiments comprise combinations of the fractionally variable and the continuously variable single-digit embodiments.

This invention relates to variable attenuators, and more particularly to high-precision variable attenuators having constant output resistance.

High-precision variable attenuators, which have a constant output resistance independent of the attenuation setting, have many uses in the electrical and electronic fields. For example, such an attenuator may be used to match the output impedance of a transmission line over a range of attenuation independent of the attenuation setting. As another example, in the transmission of electrical signals, it is sometimes necessary to variably attenuate or reduce the amplitude of the signal so that the attenuator has a constant effect (i.e., a constant output resistance) on the load signal throughout the range of attenuation.

In the prior art, there are no commercially available high-precision variable attenuators having a constant output resistance. Accordingly, there is a need for commercially available high-precision variable attenuators which have both a constant output resistance and a simple construction, and yet can be manufactured economically.

Accordingly, it is an object of this invention to provide high-precision variable attenuators which have a constant output resistance independent of the attenuation setting and are relatively simple in construction. A related object is to provide such attenuators which can be economically manufactured.

Another object is to provide variable attenuators of the type described which are variable in fractional steps. A related object is to provide such attenuators which are continuously variable. Another related object is to provide high-precision variable, multi-digit attenuators.

A further object is to provide high-precision variable, multi-digit attenuators which include a plurality of individual high-precision variable attenuators, and wherein the output resistance is constant independent of the setting of the individual attenuators.

Broadly considered, high-precision variable attenuators according to the invention include an input terminal, an output terminal, and a common terminal. A main resistance means is connected between the input and the common terminals, and auxiliary resistances are electrically connectable between the output terminal and selectable points on the main resistance means. For any particular setting of attenuation, a particularly auxiliary resistance is connected to the parallel combination of the two por-

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tions of the main resistance defined by the selected point, the output resistance between the output terminal and the common terminal being substantially constant for each point selected.

In order that the manner in which the foregoing and other objects are attained in accordance with the invention, can be understood in detail, particularly advantageous embodiments thereof will be described with reference to the accompanying drawings, which form a part of this specification, and wherein:

FIG. 1 is schematic diagram of a high-precision variable attenuator, according to the invention, which is variable in fractional steps;

FIG. 2 is a schematic diagram of another embodiment of a high-precision variable attenuator, according to the invention, which is continuously variable; and

FIGS. 3 and 4 are block diagrams of multi-digit embodiments of attenuators according to the invention.

In FIG. 1, a high-precision variable attenuator 10 includes an input terminal 11, an output terminal 12, and a common or ground terminal 13. When the attenuator is connected into a circuit (not shown), an input voltage E_{in} is applied to the input and the common terminals, and the output voltage E_{out} appears between the output and the common terminals.

Connected between input terminal 11 and common terminal 13 is a main resistance means 14 comprising ten equal-valued resistors 16-25 connected in series, junctions J-0 to J-10 being established between adjacent resistors and at the input terminal and the common terminal.

A plurality of auxiliary resistors 30-40 are respectively connected between one of the junctions J-0 to J-10 and to a contact C-0 to C-10. Output terminal 12 has connected thereto a wiper arm 41 which is selectively engageable with contacts C-0 to C-10. Contacts C-0 to C-10 correspond respectively to given percentages of the input voltage E_{in} , and the output voltage E_{out} equals the corresponding percentage value when wiper arm 41 engages one of the contacts C-0 to C-10. For example, with wiper arm 41 engaging contact C-5 as shown in FIG. 1, E_{out} equals 50% E_{in} . As will be explained below, the output resistance R_{out} looking into the attenuator between output terminal 12 and common terminal 13, is constant and independent of the contact C-0 to C-10 to which wiper arm 41 is connected.

Consider that there are ten equal-valued resistors 16-25 and that each of the auxiliary resistors 30-40 is short-circuited (so that wiper arm 41 can be considered as being directly electrically connectable to junctions J-0 to J-10), then the equation for the output resistance R_{out} of attenuator 10 for any junction is:

$$R_{out(J-n)} = \frac{nR(10-n)R}{10R} \quad (1)$$

which simplifies to

$$R_{out(J-n)} = \frac{n(10-n)R}{10} \quad (2)$$

where $R_{out(J-n)}$ is the output resistance at a particular junction J-0 to J-10, n is the number of the junction to which the wiper arm 41 is connected (n ranging from 0 to 10 for the attenuator of FIG. 1), and R is the resistance value in ohms of each equal-valued resistors 16-25. Equation 1 represents the parallel combination of (a) the equal-valued resistors in series between wiper arm 41 and input terminal 11 with (b) the equal-valued resistors in series between wiper arm 41 and common terminal 13 for any junction that wiper arm 41 is connected to, since the input voltage E_{in} is considered to have zero source resistance.

Solving Equation 2 by inserting values of n from 0 to

10, the maximum output resistance R_{out} occurs when wiper arm 41 is connected to junction J-5 and is equal to $2.5R$.

Consider now that auxiliary resistors 30-40 are short-circuited, and that it is desired to maintain the output resistance R_{out} at a constant value of $2.5R$: then each auxiliary resistor 30-40 must have a resistance such that when it is connected in series with the parallel combination of equal-valued resistors determined by a particular junction J-0 to J-10, the output resistance R_{out} must equal $2.5R$. The resistance value of each of the auxiliary resistors 30-40 under these circumstances is determined in accordance with the following equation:

$$R_{aux(n)} = 2.5R - \frac{n(10-n)R}{10} \quad (3)$$

Substituting values of n from 0 to 10 (corresponding to auxiliary resistors 30-40 and contacts C-0 to C-10) into Equation 3 yields the following table:

Table I

n	$R_{aux(n)}$
0	2.5R
1	1.6R
2	0.9R
3	0.4R
4	0.1R
5	0
6	0.1R
7	0.4R
8	0.9R
9	1.6R
10	2.5R

From the foregoing, it will be appreciated that the output resistance at output terminal 12 is equal to a constant value of $2.5R$ independent of the contact C-0 to C-10 to which wiper arm 41 is connected. It will also be appreciated that the maximum value of the output resistance need not be equal exactly to $2.5R$; rather, the maximum output resistance must be equal to or greater than $2.5R$. If the maximum output resistance is to be greater than $2.5R$, then the values of $R_{aux(n)}$ will change correspondingly when this maximum output resistance is substituted for $2.5R$ in Equation 3 and a new, Table I is constructed. In any event and no matter what the value of R_{out} maximum is, as long as it is greater than $2.5R$, the output resistance at output terminal 12 will be constant.

While attenuator 10 has been shown and described as being a decade-type attenuator and as having ten equal steps from 0 to 10 at contacts C-0 to C-10, it will be understood that any number of steps may be provided merely by changing the number of equal-valued resistors 16-25, providing the appropriate number of auxiliary resistors 30-40, and then solving Equations 2 and 3 to determine the resistance values of the respective auxiliary resistors. Under these circumstances, Equation 2 becomes

$$R_{out(J-n)} = n \frac{(X-n)R}{R} \quad (2a)$$

and Equation 3 becomes

$$R_{aux(n)} = R_{out(max)} - \frac{n(X-n)R}{X} \quad (3a)$$

where X is the total number of equal-valued resistors and $R_{out(max)}$ is determined by solving Equation 2a.

It will be understood that if resistors for the equal-valued resistors 16-25 and the auxiliary resistors 30-40 can be obtained having the exact value as determined by the above equations, then the output resistance at output terminal 12 will be substantially absolutely constant over the entire range of the attenuator. Usually, however, such exact-valued resistors are not commercially-obtainable; thus, there will be some variation in output resistance depending upon manufacturing tolerances of the resistors used.

While main resistance means 14 has been described as comprising equal-valued resistors, it will be understood by those skilled in the art that the resistors comprising main resistance means 14 need not be equal-valued. Rather it may be desirable to have the resistors comprising main resistance means 14 related in a binary code, some non-linear function, or the like. Those skilled in the art will be able to devise attenuators using such non-equal value resistors having the teaching of this invention before.

In FIG. 2, there is shown another embodiment 42 of a high-precision variable attenuator according to this invention, this embodiment being continuously variable to provide an output voltage E_{out} between output terminal 12 and common terminal 13 in an infinite number of steps from 0 to 100% of an input voltage E_{in} . Attenuator 42 comprises a linear main resistor 44 connected between input terminal 11 and common terminal 13, and a linear auxiliary resistor 46 having its ends 51 and 52 open-circuited and a center-tap 47 connected to output terminal 12, main resistor 44 and auxiliary resistor 46 being commercially available. A first wiper arm 48 is electrically connected in series with and mechanically ganged to a second wiper arm 49 so that the respective wiper arms are selectively connectable to corresponding points on the resistors 44 and 46, main resistor 44 having an infinite number of points a from 0 to 1.0 corresponding to points a from 0 to 1.0 on auxiliary resistor 46. Main resistor 44 has a total resistance value of R , and auxiliary resistor 46 has a total resistance from end to end of $R/2$, auxiliary resistor 46 having a resistance of $R/4$ between center tap 47 and each respective end 51 and 52.

Consider for the moment that auxiliary resistor 46 is to be short-circuited so that wiper arm 48 is electrically connected directly to output terminal 12. Under these circumstances, a general equation for the output resistance R_{out} at any point a on main resistor 44 to which wiper arm 48 is connected is:

$$R_{out(a)} = \frac{aR(1-a)R}{R} \quad (4)$$

which simplifies to

$$R_{out(a)} = a(1-a)R \quad (5)$$

where, a is a number varying from 0 to 1 corresponding to the points on main resistor 44. It will be observed that Equations 4 and 5 are similar to Equations 1 and 2 except that infinite steps of a from 0 to 1 are substituted for values of fractional steps of n .

Solving Equation 5 by inserting values of a from 0 to 1 into the equation, the maximum output resistance R_{out} occurs when a is 0.5 and equals $R/4$.

Consider now that auxiliary resistor 46 is not short-circuited, and that wiper arm 49 is mechanically ganged and electrically connected to wiper arm 48. In order for R_{out} at output terminal 12 to be substantially constant for any point a on main resistor 44 to which wiper arm 48 is connected, a portion of auxiliary resistor 46 is added in series with wiper arm 48, the resistance value of the portion of resistor 46 for a particular point a being determined in accordance with the following equation:

$$R_{40(a)} = \frac{R}{2} \left| \frac{1}{2} - a \right| \quad (6)$$

and the output resistance at output terminal 12 being determined by the following equation:

$$R_{out} = a(1-a)R + \frac{R}{2} \left| \frac{1}{2} - a \right| \quad (7)$$

which is the sum of Equations 5 and 6. Inserting random values of a from 0 to 1.0 into Equation 7 yields Table II:

Table II

a	$R_{out(12)}$
0.0	0.25R
0.1	0.29R
0.25	0.3125R
0.4	0.29R
0.5	0.25R
0.6	0.29R
0.75	0.3125R
0.9	0.29R
1.0	0.25R

From Table II it can be seen that R_{out} varies in accordance with the following mathematical expression:

$$R_{out(12)} = (0.28125 \pm 0.03125)R \quad (8)$$

Although this is a variation of approximately 11%, if auxiliary 46 were not provided in accordance with this invention, R_{out} at wiper arm 48 would be expressed as follows:

$$R_{out(48)} = (0.125 \pm 0.125)R \quad (9)$$

when a Table II is constructed for Equation 5 for different values of a . Note that the variation of output resistance at wiper arm 48 for Equation 9 is 100% when auxiliary resistor 46 is not used, and that the use of auxiliary resistor 46 reduces the output resistance variation by a factor of approximately nine to one.

It will be appreciated by those skilled in this art that the 11% variation for attenuator 42 of FIG. 2, is due to the fact that a commercially available linear resistor is used for auxiliary resistor 46. Auxiliary resistor 46 can be custom constructed so that for each point a on main resistor 44, the resistance at the corresponding a point on auxiliary resistor 46 exactly satisfies Equation 7, the output resistance then being absolutely constant over the entire attenuation range.

Such custom construction can involve non-linear winding of the resistor, or other methods known to those skilled in the art, such custom construction being relatively expensive and often not warranted for a given application. The use of a commercially available resistor for auxiliary resistor 46 has the distinct advantage that the attenuator can be economically constructed using readily available resistors, the 11% variation being tolerable in many applications and in some applications having such a minute effect as to be negligible, as when the attenuator is used as the vernier adjustment of a multi-digit attenuator in a manner to be explained below.

FIG. 3 illustrates a two-digit attenuator 55 according to the invention, comprising a first variable attenuator 53 connected in parallel with a second attenuator 54. Attenuator 53 is identical to decade attenuator 10 of FIG. 1 and attenuator 54 is identical to continuously variable attenuator 42 of FIG. 2. The input terminals 11 of attenuators 53 and 54 are connected in parallel to an input terminal 61, the output terminals 12 are connected respectively through weighting resistors 66 and 67 in parallel to output terminal 62, and the common terminals 13 are connected in parallel to common terminal 63.

When attenuators 53 and 54 are connected as described above to form a two-digit attenuator, attenuator 53 controls the first digit in unit steps from 0 to 10, and attenuator 54 controls the second digit continuously from 0 to 1.

Considering the combination of attenuator 53 in series with resistor 66 to have a total resistance of R_x , and the combination of attenuator 54 in series with resistor 67 to have a total resistance of R_y , then the output voltage E_{out} as a function of the total resistance of each parallel branch can be expressed by the following equation:

$$E_{out} = \frac{n}{10} E_{in} \frac{R_y}{R_x + R_y} + a E_{in} \frac{R_x}{R_x + R_y} \quad (10)$$

which reduces to

$$E_{out} = \frac{R_y}{R_x + R_y} E_{in} \left(\frac{n}{10} + \frac{R_x}{R_y} a \right) \quad (11)$$

5 letting $R_y = 10R_x$,

$$E_{out} = \frac{10}{11} E_{in} \left(\frac{n}{10} + \frac{1}{10} a \right) \quad (12)$$

where, n is a number varying from 0 to 10 and corresponding to the contact C-0 to C-10 to which wiper arm 41 is connected (FIG. 1), and a varies from 0 to 1.0 corresponding to the point a on main resistor 44 and auxiliary resistor 46 to which wiper arm 48 and 49 are respectively connected (FIG. 2). It will be observed from Equation 12 that the desired decimal relationship between the first and the second digit is obtained, the input voltage E_{in} being set to be 11/10 greater than the desired maximum voltage E_{out} .

As mentioned above, it is not usually possible to obtain commercially available resistors which are truly accurate. Therefore, due to the manufacturing tolerances usually found in commercially available resistors, it is desirable to have an overlap of the first and the second digits. In such a case, resistors 66 and 67 are chosen so that the resistance R_y is something less than 10 R_x . For example, letting $R_y = 9R_x$, Equation 11 becomes

$$E_{out} = \frac{9}{10} E_{in} \left(\frac{n}{10} + \frac{1}{9} a \right) \quad (13)$$

in which case the input voltage E_{in} in set to be 10/9 greater than the desired maximum output voltage E_{out} , the contribution of attenuator 54 overlapping the first digit of attenuator 53 by about 11%.

As mentioned above with respect to FIG. 2, attenuator 42 has a variance of approximately 11% when a commercially available resistor is used for auxiliary resistor 46. However, since in FIG. 3, attenuator 42 is being used to control the second digit, the variance of attenuator 42 has very little effect on the total variance of attenuator 55, the total variance being on the order of $\pm 0.1\%$. This extremely low variance is obtained in part because there is a ten or nine to one ratio of the weighting resistors 66 and 67.

In FIG. 4, a three-digit attenuator 70 according to the invention has an input terminal 71, an output terminal 72, and a common terminal 73. Three decade attenuators 74, 76 and 77, each being identical to the decade attenuator 10 of FIG. 1, are connected in parallel. More particularly, each attenuator 10 has its input terminal connected to input terminal 71, the respective common terminals 13 are connected in parallel to common terminal 73, and the respective output terminals 12 are each connected respectively through weighting resistor 81, 82 and 83 in parallel to output terminal 72. Weighting resistors 81, 82 and 83 determine the contribution respectively of each decade attenuator 74, 76, and 77 to the output voltage E_{out} . The decimal ratios of the weighting resistors can be set according to the following equation:

$$R_{83} = 10R_{82} = 100R_{81} \quad (14)$$

Since this embodiment of a multi-digit attenuator does not use a continuously variable attenuator to control the last digit, the output resistance of this embodiment is free from even the minor variation explained above with respect to two-digit attenuator of FIG. 3 and is theoretically constant, assuming that the individual resistors have no resistance tolerance variation.

From the foregoing, it will be appreciated that FIGS. 3 and 4 illustrate only two ways of combining decade attenuators 10 and continuously variable attenuators 42 to produce multi-digit attenuators according to this invention. Among other ways of combining attenuators 10 and

42, the three digit attenuator 70 can be expanded to six or more digits using a plurality of decade attenuators 10 connected in parallel with appropriate weighting resistors, with or without a continuously variable attenuator 42 as the last or any other digit.

It will be understood that the above-described embodiments of single-digit and multi-digit attenuators are merely illustrative of the principles of the invention, and that various changes and modifications can be made to the single-digit and multi-digit attenuators by those skilled in the art without departing from the scope of the invention.

What is claimed is:

1. A variable attenuator having an input terminal, an output terminal, and a common terminal, comprising: a main resistance means connected between the input and the common terminals; and auxiliary resistance means electrically connectable between selectable points on said main resistance means and the output terminal, a particular portion of said auxiliary resistance means being connected in series with the parallel combination of the two portions of said main resistance means defined by a selected point, the output resistance between the output and the common terminals being substantially constant for each point selected, said main resistance means being a continuous resistor; and said auxiliary resistance means being a center-tapped continuous resistor having a total resistance equal to one-half of that of the main resistor, the center-tap being connected to the output terminal; and wherein the output resistance of the attenuator is determined in accordance with the mathematical expression

$$R_{out} = a(1-a)R + \frac{R}{2} \left| \frac{1}{2} - a \right|$$

where R is the resistance of said main resistor, R/2 is the resistance of said auxiliary resistor, and a is a number from 0 to 1 corresponding to a point on said main resistor and to a point on said auxiliary resistor, said particular portion of said auxiliary resistor connected in series between a selected point a on said main resistor and the output terminal being the portion of said auxiliary resistor between the corresponding point a and said center tap.

2. In an attenuator having an input terminal, an output terminal, and a common terminal, the combination comprising first resistance means including a continuous linear resistor connected between the input terminal and the common terminal and having a total resistance value of R; a second resistance means including a center-tapped resistor having a total resistance value R/2, there being a resistance of R/4 between the center-tap and each respective open-circuited end of said auxiliary resistor, said center-tap being connected to the output terminal; and means for selectively connecting any point a on said first resistance means to a corresponding point a on said second resistance means, the portion of said second resistance means between said center-tap and said selected point a thereon being connected between the corresponding point a on said first resistance means and the output terminal, whereby the output resistance of the attenuator is substantially constant for any selected attenuation setting obtained by said selective connecting means.

3. A variable attenuator according to claim 2, wherein said second resistance means is a linear center-tapped resistor.

4. An attenuator according to claim 2, wherein the output resistance of the attenuator is determined in accordance with the mathematical expression

$$R_{out} = a(1-a)R + \frac{R}{2} \left| \frac{1}{2} - a \right|$$

where, a is equal to a number from 0 to 1 and corresponding to said points on said first and second resistance means selected by said connecting means.

5. A multi-digit attenuator comprising a plurality of single-digit attenuators, said single-digit attenuators each having respective input terminals connected in parallel, respective output terminals connected in parallel, and respective common terminals connected in parallel, each of said single-digit attenuators having selectable attenuation settings, wherein at least one of said single-digit attenuators comprises a variable attenuator having an input terminal, an output terminal, and a common terminal, said variable attenuator comprising first resistance means including a continuous linear resistor connected to the input terminal and the common terminal and having a total resistance value of R; a second resistance means including a center-tapped resistor having a total resistance value R/2, there being a resistance of R/4 between the center-tap and each respective open-circuited end of said auxiliary resistor, the center-tap being connected to the output terminal; and means for selectively connecting any point a on said first resistance means to a corresponding point a on said second resistance means, the portion of said second resistance means between said center-tap and said selected point a thereof being connected between the corresponding point a on said first resistance means and the output terminal, whereby the output resistance of said single-digit attenuator is substantially constant for any selected attenuation setting obtained by said selective connecting means.

6. A multi-digit attenuator comprising a plurality of single-digit attenuators, said single-digit attenuators each having respective input terminals connected in parallel, respective output terminals connected in parallel, and respective common terminals connected in parallel, each of said single-digit attenuators having selectable attenuation settings, at least one of said single-digit attenuators comprising a variable attenuator having an input terminal, an output terminal, and a common terminal, said variable attenuator comprising first resistance means including a plurality of equal-valued main resistors connected in series relationship between the input terminal and the common terminal, there being a junction between adjacent ones of said resistors and at the respective input and common terminals; second resistance means including a plurality of auxiliary resistors, a particular one of said auxiliary resistors having one of its terminals connected to a particular one of said junctions, the other end of each of said auxiliary resistors defining a contact; and means for selectively connecting any of said contacts to the output terminal to provide a desired amount of attenuation between the output and the common terminals, each of said auxiliary resistors having a resistance such that when a particular auxiliary resistor is connected to the output terminal and its corresponding junction the output resistance between the output and the common terminal is substantially constant independent of the contact to which the selective connecting means is connected; the last of said single-digit attenuators comprising an attenuator having an input terminal, an output terminal, and a common terminal including first resistance means, said variable attenuator comprising: a continuous linear resistor connected to the input terminal and the common terminal and having a total resistance value of R; a second resistance means including a center-tapped resistor having a total resistance value of R/2, there being a resistance of R/4 between the center-tap and each respective open-circuited end of said auxiliary resistor, the center-tap being connected to the output terminal; and means for selectively connecting any point a on said second resistance means, the portion of said second resistance means between said center-tap and said selected point thereof being connected between the corresponding point a on said first resistance means and the output terminal, whereby the output resistance of the attenuator being substantially constant for any selected

attenuation setting obtained by said selective connecting means.

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U.S. Cl. X.R.

323—80, 94; 333—81

Disclaimer and Dedication

3,453,529.—*Peter L. Richman*, Lexington, Mass. ATTENUATORS HAVING
CONSTANT OUTPUT RESISTANCE. Patent dated July 1, 1969.
Disclaimer and dedication filed Mar. 17, 1971, by the assignee, *Weston
Instruments, Inc.*

Hereby enters this disclaimer to the remaining term of said patent and
dedicates said patent to the Public.

[*Official Gazette April 27, 1971.*]