

May 13, 1930.

R. S. HOYT

1,758,044

WAVE ANTENNA

Filed Jan. 22, 1926

2 Sheets-Sheet 1

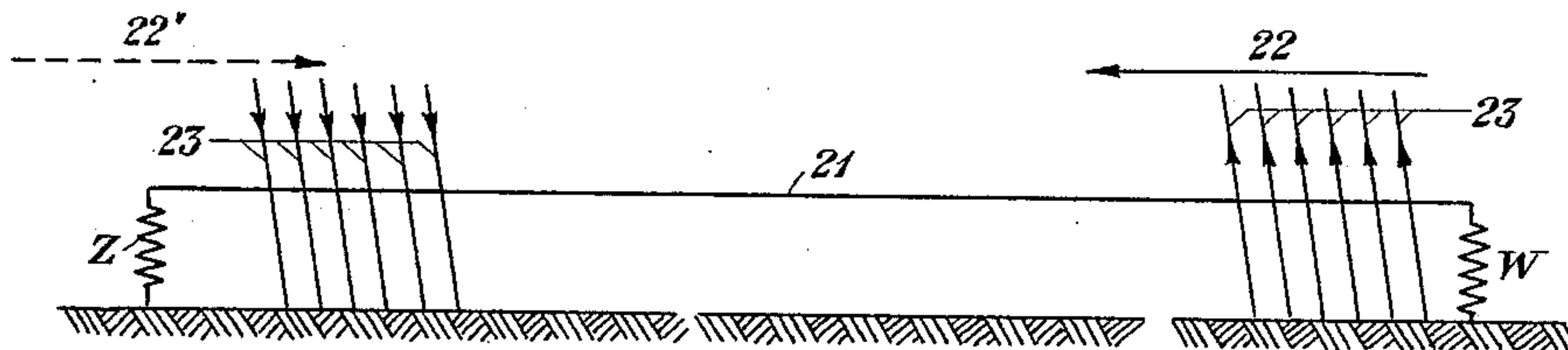


Fig. 1

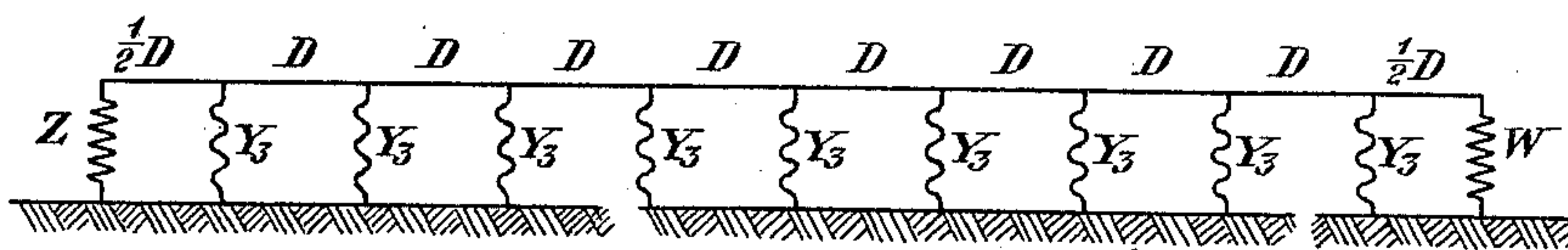


Fig. 2

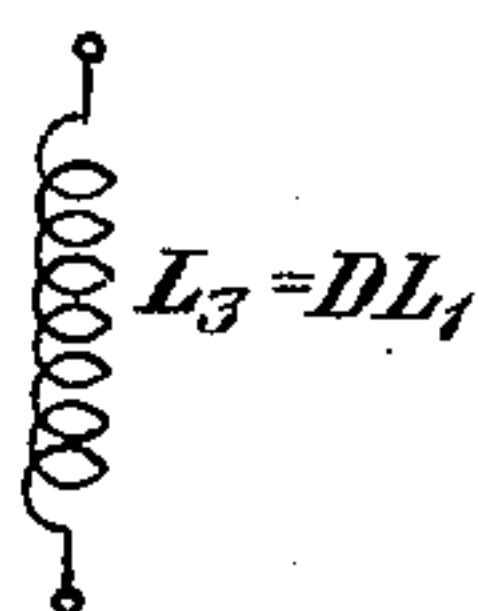


Fig. 3

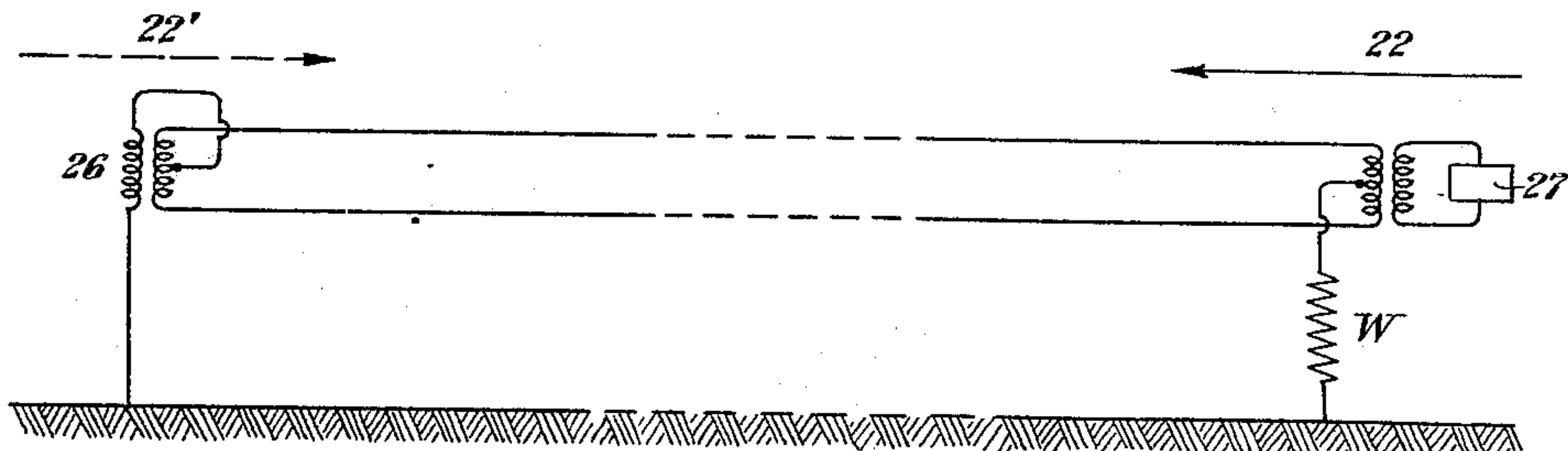


Fig. 4

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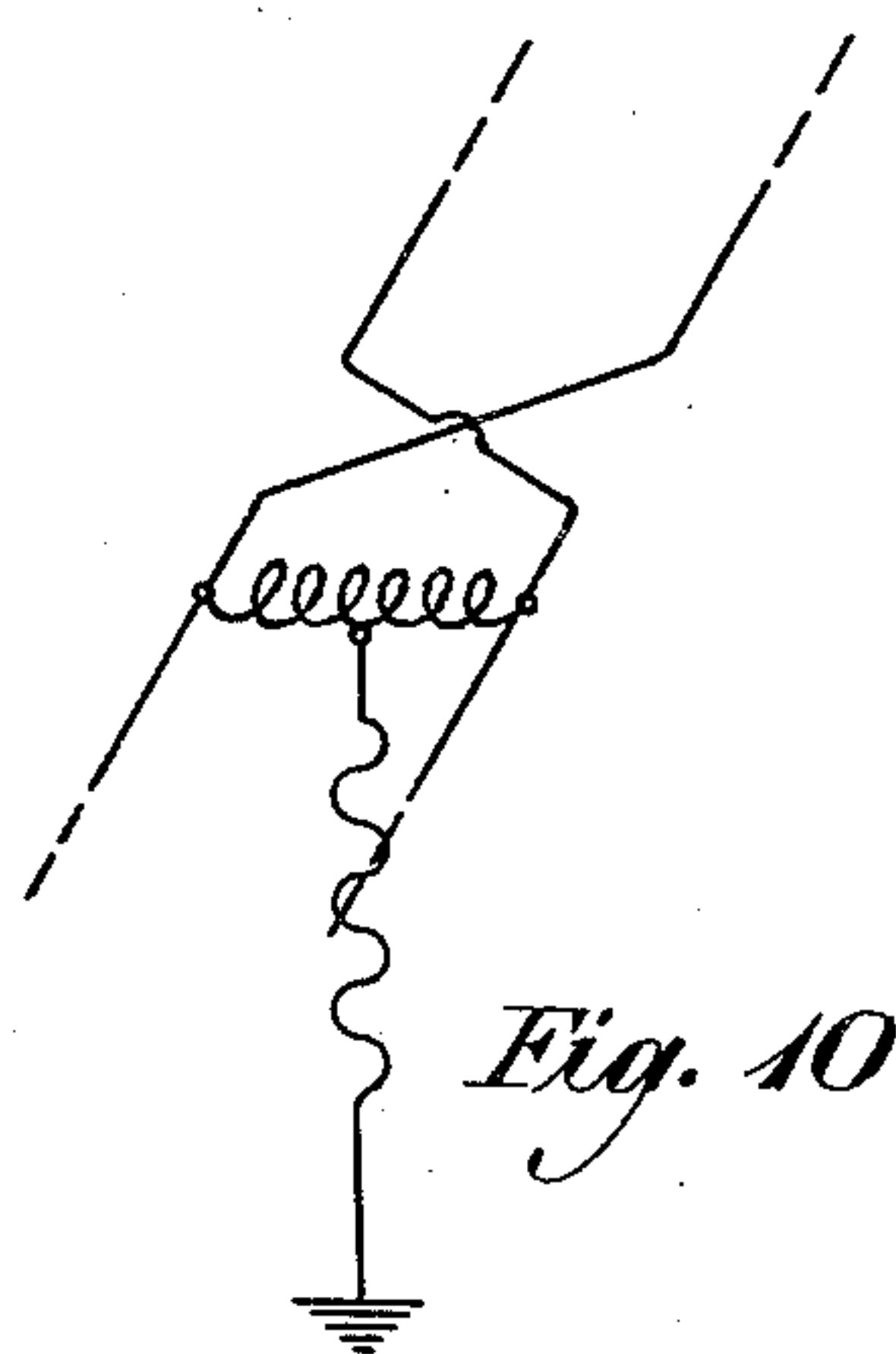
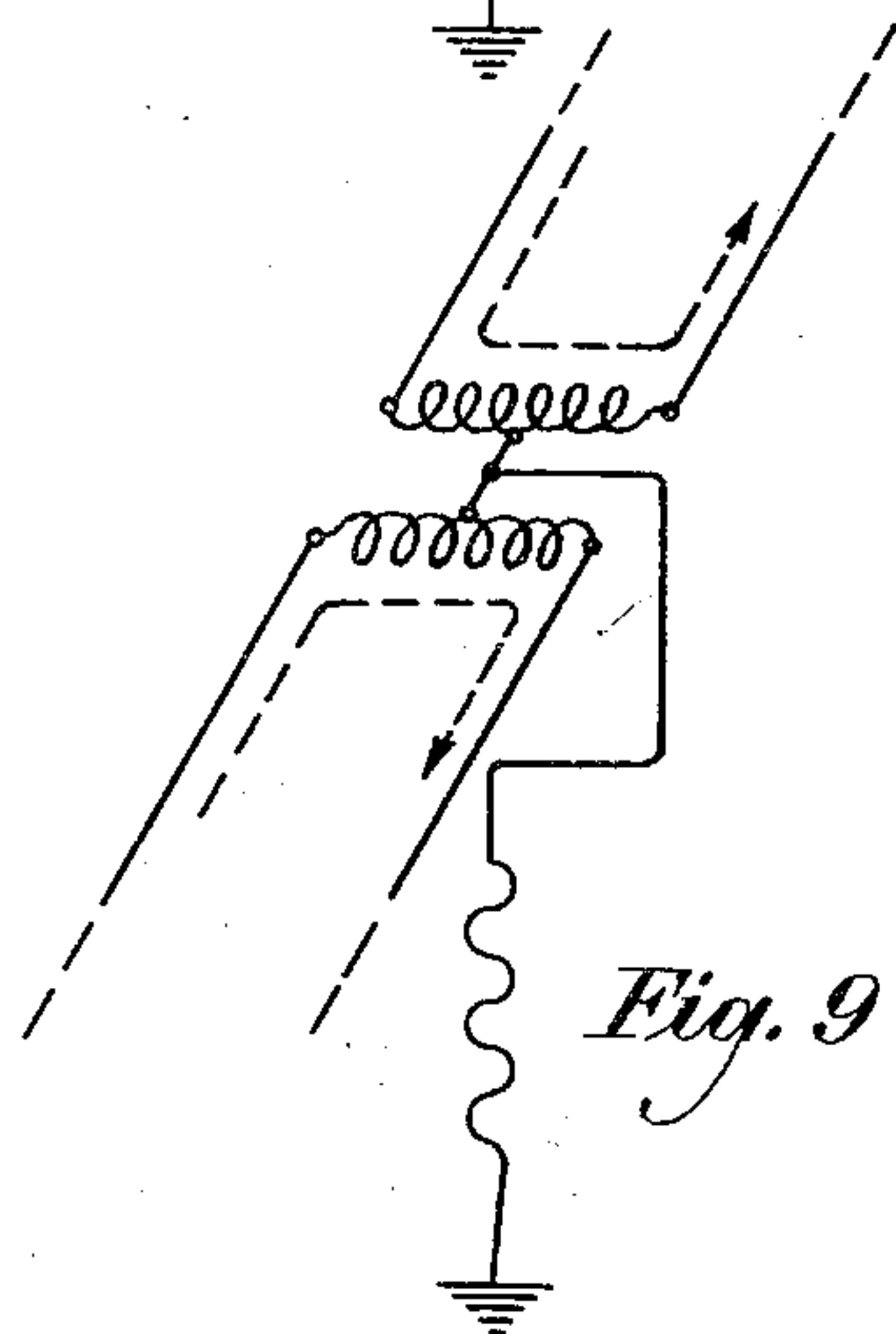
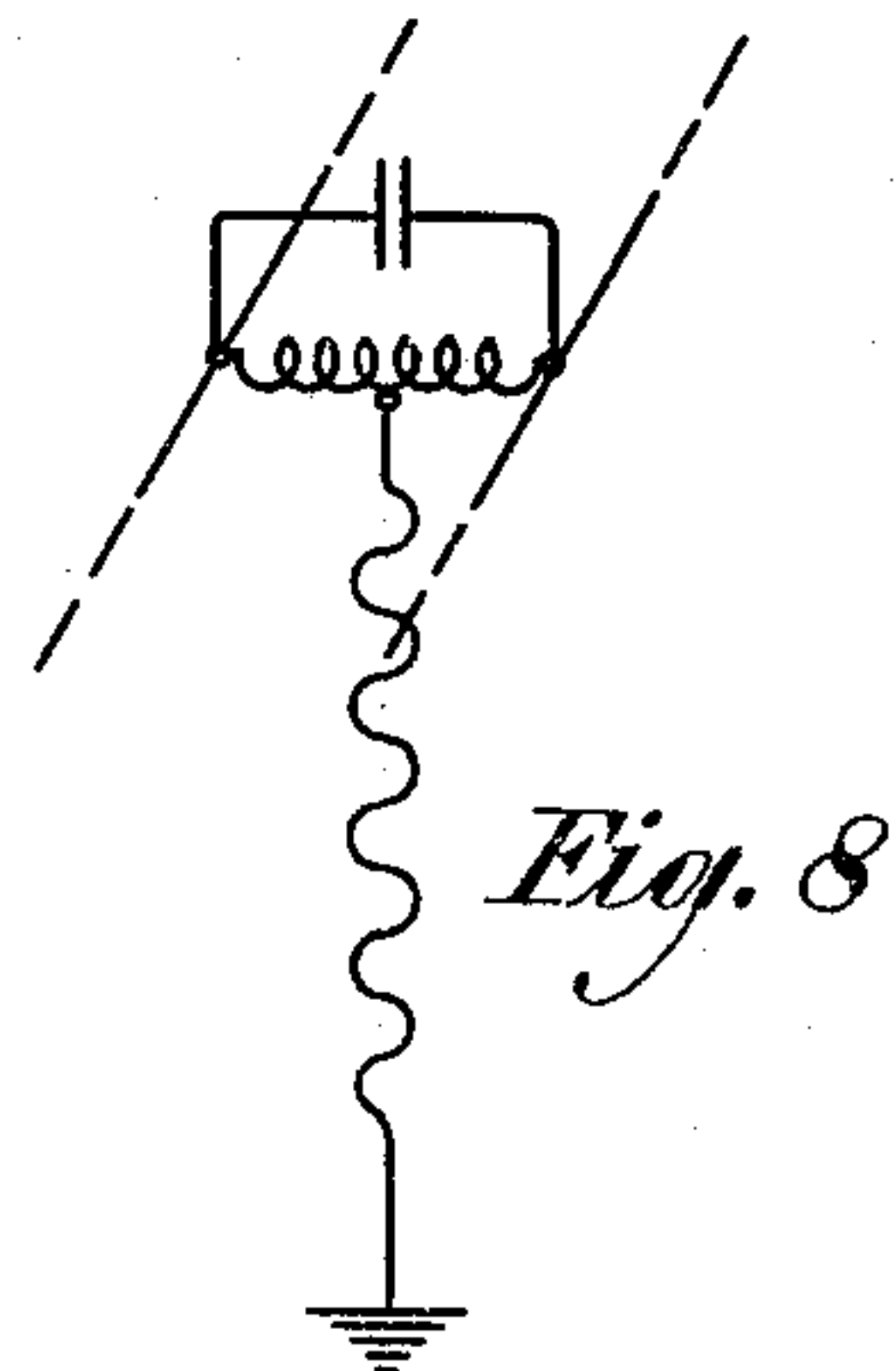
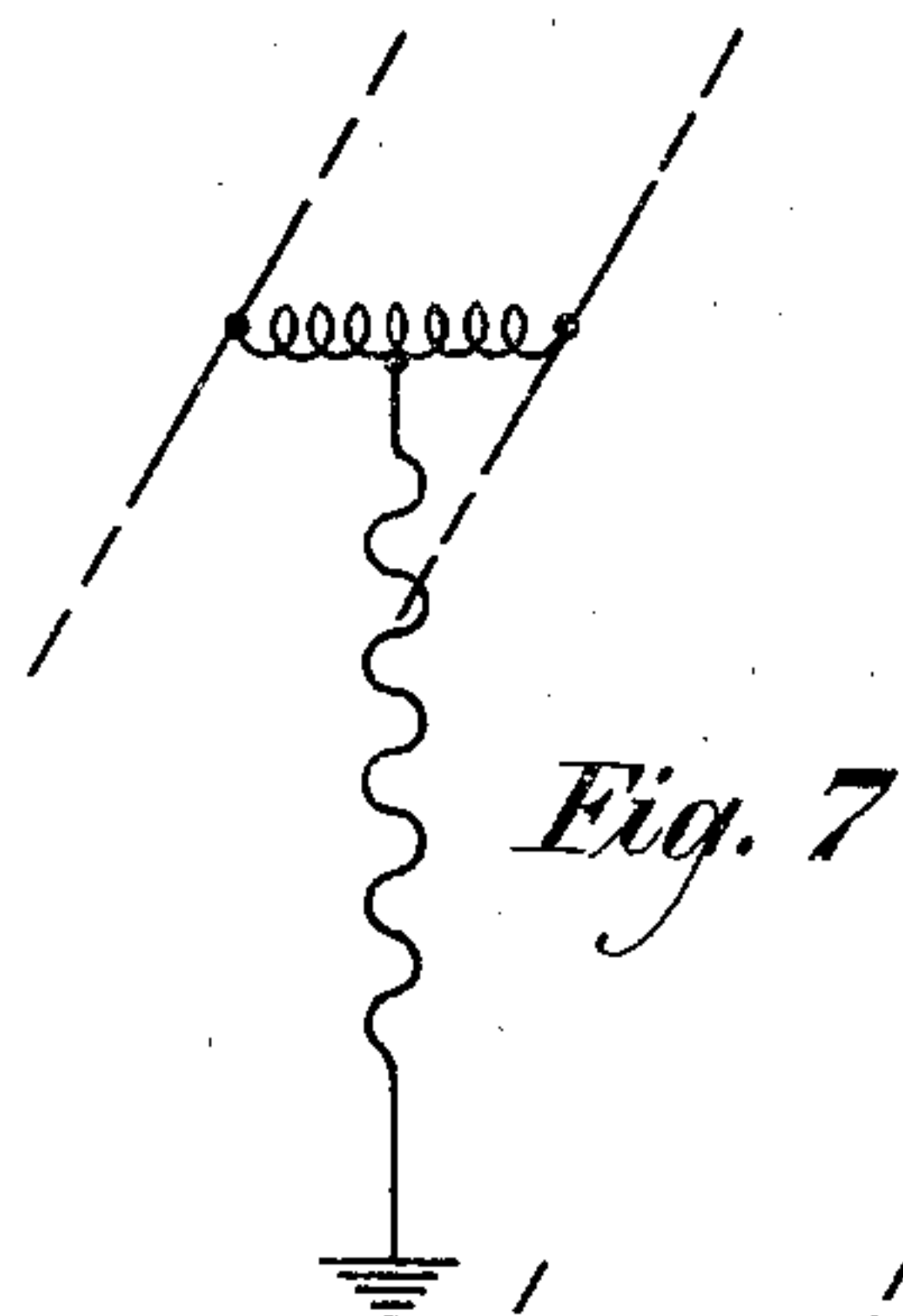
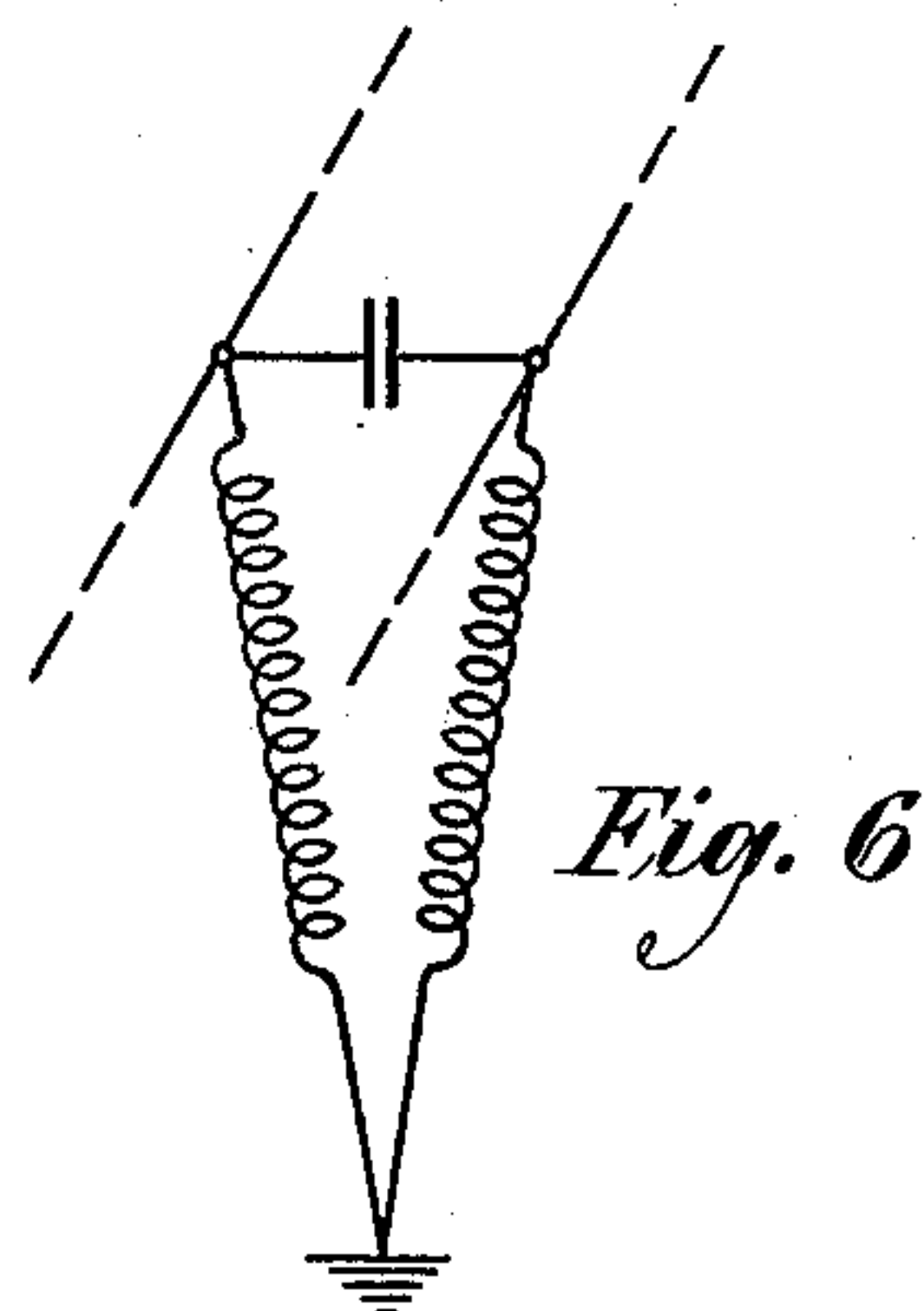
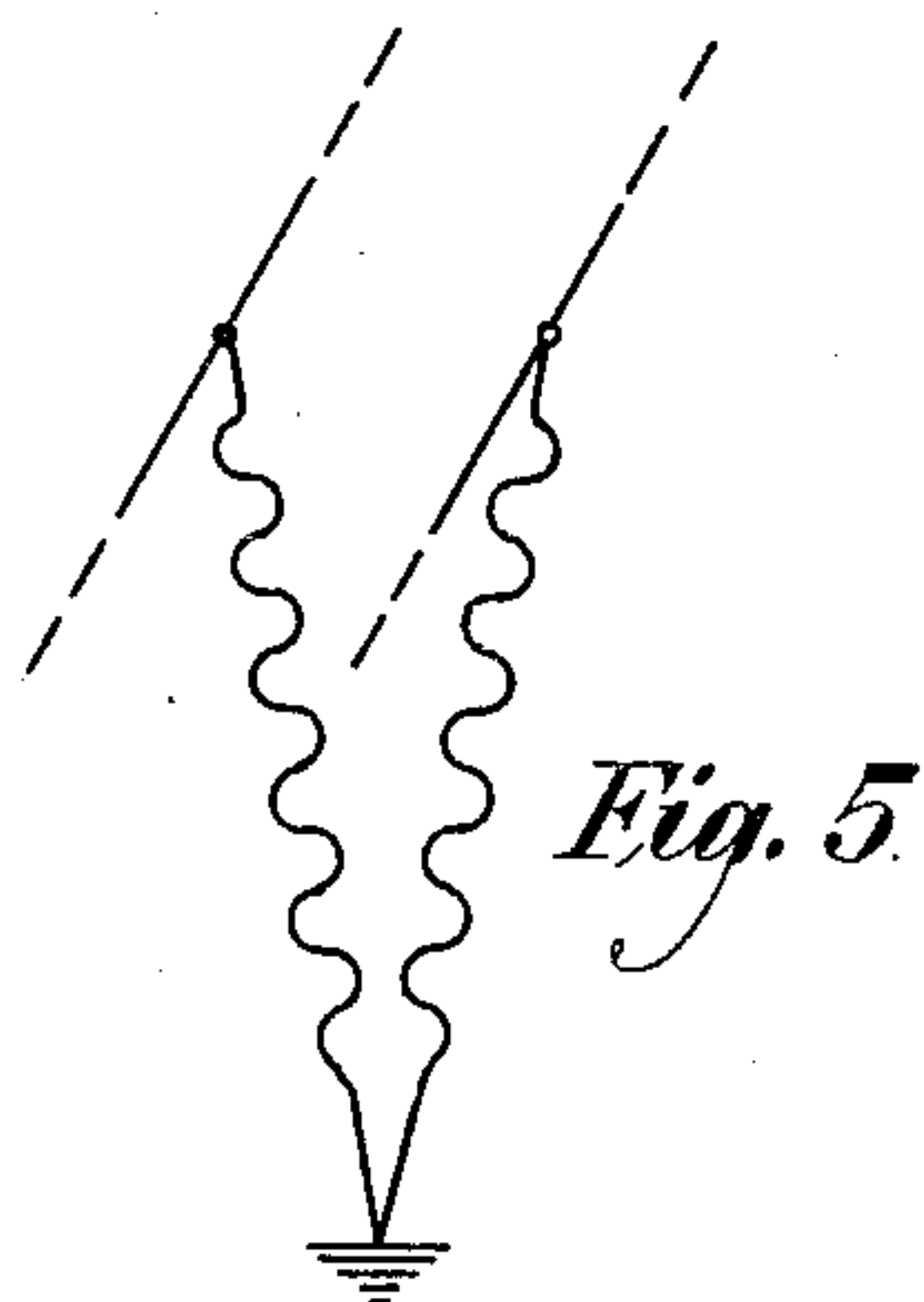
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WAVE ANTENNA

Filed Jan. 22, 1926

2 Sheets-Sheet 2



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UNITED STATES PATENT OFFICE

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WAVE ANTENNA

Application filed January 22, 1926. Serial No. 83,118.

An object of my invention is to provide improved methods and apparatus for radio reception on a wave antenna. Another object is to provide for an improved wave antenna of flexible design for directionally selective radio reception. Other objects are to improve the attenuation characteristic in the design of a wave antenna, and to facilitate making the antenna of effective length. All these objects and others will become apparent in connection with the following disclosure of examples of procedure in the practice of my invention. It will be understood that this specification relates to these examples and that the invention will be defined in the appended claims.

Referring to the drawings, Fig. 1 is a diagrammatic elevation of a comparatively simple wave antenna. Fig. 2 is a diagrammatic elevation of a wave antenna with shunts according to my invention. Fig. 3 is a diagram showing one of the shunts of Fig. 2 in more specific form. Fig. 4 is a diagram for a two conductor wave antenna, providing for return signal currents on the circuit of these conductors, and Figs. 5 to 10 inclusive are sketches illustrating various shunt load arrangements for a two wire antenna.

The horizontal conductor 21 of Fig. 1 is carried on poles above the ground and extends a distance comparable to one or several wave-lengths of the waves desired to be received, and in the direction of these waves as indicated by the arrow 22. At the front end (toward the distant transmitting station) the line 21 is grounded through the impedance W of value equal to the characteristic impedance of the line. At the distant or back end the line is grounded through receiving apparatus of impedance value Z .

The incoming electric waves are ordinarily regarded as comprising advancing vertical lines of electric force in zones alternately directed up and down. More accurately these lines of force are inclined slightly forward as represented by the lines 23 in Fig. 1. Accordingly each such line has a component along the conductor, and if the velocity of propagation along the conductor is substantially the same as the incoming radio waves,

the effect in the conductor will be cumulative and a wave of current will build up along the conductor and be of substantial effect on arrival at the receiver Z . On the other hand, waves from the opposite direction as represented by the dotted arrow 22', will have their cumulative effect only at W , and since this has the characteristic impedance value, there will be no reflection at W by which reflected waves could reach the receiver Z .

In Fig. 2 I have shown shunts each of admittance value Y , at equal distances D along the line. The object of the shunt loading is to alter the characteristics of the wave antenna by increasing its velocity of phase propagation and by decreasing its attenuation constant.

In any actual wave antenna, the unavoidable resistance in the antenna wire and in the earth, and the shunt leakage from the antenna wire to earth, always cause attenuation, and also decrease the velocity of phase propagation. By means of the shunt loading of the present invention, these effects of resistance and leakage can be partly or largely compensated: for the attenuation can be substantially decreased, and the velocity of phase propagation can be greatly increased—even to an extent of over-compensation (that is, the velocity of phase propagation can be made to exceed the value it would have in the absence of resistance and leakage).

This possibility of increasing the velocity of propagation renders the wave antenna more flexible in design to meet specified requirements. The possibility of decreasing the attenuation permits the use of a wave antenna of greater length and hence of greater sensitivity, and usually of greater directional selectivity; in many cases, the reduction in attenuation could not be attained by merely substituting for the wave antenna a wire of lower resistance, owing to the fact that usually the wire contributes to the attenuation much less than does the earth.

I shall employ the formulas for the attenuation constant α and the velocity of phase propagation v . If γ denotes the propagation constant, then

$$\gamma = \alpha + i\beta \quad (1)$$

where $i = \sqrt{-1}$, and β is the so-called phase constant or wave-length constant, related to the velocity v in accordance with the equation

$$v = \omega / \beta \quad (2)$$

ω denoting 2π times the signaling frequency f .

It will now be shown how v and α depend on the shunt admittance of the wave antenna; and thence how the shunt admittance can be modified, in accordance with this invention, in such a way as to increase v and decrease α .

To begin with, consider the non-loaded wave antenna of Fig. 1 having, per unit length, a series impedance $R + iX$ and a shunt admittance $G + iU$; R thus being the series resistance, X the series reactance, G the shunt conductance, and U the shunt susceptance. Then the propagation constant $\gamma = \alpha + i\beta$ is represented by the well-known formula

$$\alpha + i\beta = \sqrt{(R + iX)(G + iU)} = \sqrt{(RG - XU) + i(RU + GX)} \quad (3)$$

The values of β and α can be obtained by squaring both sides of Equation (3) and then equating separately the real and the imaginary parts, thus obtaining for β and α the pair of simultaneous equations

$$\alpha^2 - \beta^2 = RG - XU \quad (4)$$

$$2\alpha\beta = RU + GX \quad (5)$$

To solve these for β and α we may square both sides and add, thus getting

$$(\alpha^2 + \beta^2)^2 = (RG - XU)^2 + (RU + GX)^2 \quad (6)$$

whence

$$\alpha^2 + \beta^2 = + \sqrt{(RG - XU)^2 + (RU + GX)^2} \quad (7)$$

the $+$ sign being employed because $\alpha^2 + \beta^2$ is necessarily positive. Next, by subtracting and adding (4) and (7), we get

$$2\beta^2 = + \sqrt{(RG - XU)^2 + (RU + GX)^2} - (RG - XU) \quad (8)$$

$$2\alpha^2 = + \sqrt{(RG - XU)^2 + (RU + GX)^2} + (RG - XU) \quad (9)$$

On extracting the square roots of these equations we would get two values for α and two for β , one being positive and the other negative for each. In the case of α , only the positive value is physically applicable; but β is not physically restricted to positive values, in the case of a loaded wave antenna. Since only positive values of α are to be considered, Equation (5) shows that β is positive or negative according as $RU + GX$ is positive or negative, respectively; this is also apparent from the last form of (3), since the complex quantity $\alpha + i\beta$ is restricted to the positive real half of the complex plane.

Regarding the sign of β , it may be remarked that, of course, R and G are always positive and that for a non-loaded wave an-

tenna X and U are positive; and hence that β is positive for a non-loaded wave antenna. For a wave antenna having no series loading, X would be positive, but U could be rendered negative by means of suitable shunt loading; and then β would be negative if U were made algebraically less than $-GX/R$.

In the limit, when R/X and G/U are zero, α is zero and β and v have the values β_0 and v_0 such that

$$\beta_0 = \pm \sqrt{XU} \quad (10)$$

$$v_0 = \pm \omega / \sqrt{XU} \quad (11)$$

the sign being $+$ or $-$, respectively, according as the sign of $RU + GX$ is $+$ or $-$ in the limit. (For a non-loaded wave antenna, β_0 and v_0 are always positive.)

Strictly, the foregoing Formulas (3), . . . (11) pertain to a wave antenna whose parameters (R , X , G , U) are smoothly (uniformly) distributed; but the formulas are good approximations when some or all of the parameters are periodically distributed, as in the case of any periodically loaded antenna, provided the spacing D of the loading elements is short compared with the wave-length of the signal propagated on the wave antenna. With this proviso, the formulas will be applied to the shunt loaded wave antenna (Fig. 2) exemplifying my invention, in which the loading is periodically distributed. The desired characteristics of the loaded antenna are capable of a certain amount of adjustment by adjusting the spacing, and furthermore some economy is evidently attainable by increasing the spacing. In case it should be desired to employ a load-spacing which is not small compared with the wave length, it would, of course, be necessary to employ the rigorous formulas for a periodically loaded antenna.

It will be recalled that the object of the shunt loading of this invention is to alter the

characteristics of the wave antenna, by increasing its velocity of phase propagation and by decreasing its attenuation. That this object can actually be attained by means of shunt loading will now be shown by aid of the foregoing formulas for β and α , together with the relation $v = \omega / \beta$.

It should be noted that the only parameters that can be affected by any shunt loading are the shunt leakage G and the shunt susceptance U , making up the shunt admittance $G + iU$. The effects of varying G and U will now be considered separately.

Formula (9) shows that decreasing G always decreases α , for all positive values of G .

The nature of the dependence of β on G is not so readily perceived, but can be deduced

from the following considerations: Equations (3) and (8) each show that $\beta^2 = \infty$ for $G = +\infty$ and for $G = -\infty$; and that $\beta^2 = 0$ for $G = -UR/X$. Furthermore, if (8) is solved for G in terms of β^2 it is found that for every value of β^2 there are two and only two values of G . Consequently β^2 passes through only one extremum, which is the zero value, when G ranges from $+\infty$ to $-\infty$. Thus, when $G > -UR/X$, decreasing G always decreases β^2 and hence decreases β ; but when $G < -UR/X$, decreasing G always increases β^2 and hence decreases β (algebraically). Thus, when G decreases from $+\infty$ to $-\infty$, β decreases from $+\infty$ to $-\infty$ steadily; that is, the slope of β as function of G is always positive. This can be verified by means of the derivative of β with respect to G ,

$$\frac{d\beta}{dG} = \frac{1}{2\beta} \frac{d\beta^2}{dG} = \frac{R}{4\beta} \left(\sqrt{\frac{1+X^2/R^2}{1+U^2/G^2}} - 1 \right) \quad (12)$$

together with the fact that β is positive when $G > -UR/X$ and negative when $G < -UR/X$. Finally, from the relation $v = \omega/\beta$, it is seen that v is positive when $G > -UR/X$, and is negative when $G < -UR/X$; when G decreases from $+\infty$ to $-UR/X$, v steadily increases from 0 to $+\infty$; and when G decreases from $-UR/X$ to $-\infty$, v steadily increases (algebraically) from $-\infty$ to 0.

In application it must be noted that G is physically restricted to positive values. Hence, since v changes sign when $G = -UR/X$ and since X is positive for a wave antenna having no series loading, it is seen that U must be made negative (by some sort of shunt loading) if it is desired to make v infinite or to make v negative by adjustment of G . So long as U and X have a common sign, v is positive and increases steadily with decreasing G (though v does not become infinite); thus, the result of decreasing G is to decrease α and to increase v simultaneously. In particular, this is true for a non-loaded wave antenna, because then U and X have a common sign, both being positive.

However, there are practical restrictions to the alterations attainable by reducing G ; for not only can G not be made negative but it can not even be reduced to zero. There is no such limitation on the susceptance U ; and it will next be shown that, by suitably adjusting the susceptance U , by means of shunt loading, v can be greatly increased; and that α can be decreased (subject to a certain limitation).

The nature of the dependence of β on U , and hence of v on U , can be deduced by arguments analogous to those above pertaining to the dependence of β on G . It is thereby found that, when U decreases from $+\infty$ to $-\infty$, β decreases steadily from $+\infty$ to $-\infty$, passing through the value zero when $U = -GX/R$. Hence, from $v = \omega/\beta$, it is seen

that v is positive when $U > -GX/R$, and is negative when $U < -GX/R$; when U decreases from $+\infty$ to $-GX/R$, v steadily increases from 0 to $+\infty$; and when U decreases from $-GX/R$ to $-\infty$, v steadily increases (algebraically) from $-\infty$ to 0. (In applications to a loaded wave antenna, U is not necessarily restricted to positive values.)

The nature of the dependence of α on U can be deduced as follows: To begin with, Equations (3) and (9) each show that $\alpha^2 = \infty$ for $U = +\infty$ and for $U = -\infty$. Furthermore, for every value of α^2 there are two and only two values of U . Consequently α^2 , and hence α , passes through only one extremum, which is a minimum, when U ranges from $+\infty$ to $-\infty$. The location and value of this minimum of α can be determined by means of the derivative of α with respect to U ,

$$\frac{d\alpha}{dU} = \frac{1}{2\alpha} \frac{d\alpha^2}{dU} = \frac{X}{4\alpha} \left(\sqrt{\frac{1+R^2/X^2}{1+G^2/U^2}} - 1 \right) \quad (13)$$

X and α being positive, this equation shows that α is a minimum when $U = GX/R$; and thence (9) shows that the minimum value, say α'' , of α is

$$\alpha'' = \sqrt{RG} \quad (14)$$

Thus, when U decreases from $+\infty$ to GX/R , α decreases steadily from ∞ to $\sqrt{RG}$; and when U decreases from GX/R to $-\infty$, α increases steadily from $\sqrt{RG}$ to ∞ . By (14), the minimum value α'' of α decreases with decreasing G ; thus, it is usually desirable to make G as small as practicable. It may be remarked that, for a wave antenna having no series loading, the minimum of α occurs at a positive value of U , since X is positive for such a wave antenna. Moreover, for a non-loaded wave antenna, U/G would usually be greater than X/R and hence U greater than GX/R . Thus the adjustment of U to the particular value GX/R requisite for minimizing α would require reduction of U ; this reduction of U can be accomplished by means of shunt loading as herein disclosed.

It is desirable to know the value v'' of v and the value β'' of β corresponding to the minimum value α'' of α . β'' can be found from (8) by substituting $U = GX/R$ therein, and then v'' can be found from (2); thus

$$\beta'' = X\sqrt{G/R} \quad (15)$$

$$v'' = \frac{\omega}{X} \sqrt{\frac{R}{G}} \quad (16)$$

Thus, v'' increases with decreasing G ; while, by (14), α'' always decreases.

Comparing (16) with (11) shows that

$$\frac{v''}{v_0} = \sqrt{\frac{U/G}{X/R}} \quad (17)$$

where, it is to be noted, the parameters U , G , X , R are those of the original wave antenna and hence may have any physically possible values. But, as already remarked, for a non-loaded wave antenna U/G would usually be greater than X/R : hence, after α has been minimized by reduction of U to the particular value GX/R , by means of the shunt loading as herein disclosed, the velocity ratio

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$$U_2 = -G_2 \frac{X}{R} \left(1 - \frac{2\alpha_2^2}{RG_2} \pm \sqrt{\frac{4\alpha_2^2}{RG_2} \left(\frac{\alpha_2^2}{RG_2} - 1 \right) \left(\frac{R^2}{X^2} + 1 \right)} \right) \quad (19)$$

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v''/v_0 would exceed unity; thus the present invention enables the reduction of v caused by R and G to be even more than compensated by reduction of U , and at the same time enables the attenuation constant α to be reduced.

Since v changes sign when $U = -GX/R$, and since X is positive for a wave antenna having no series loading, it is seen that U must be made negative (by some sort of shunt loading) if it is desired to make v infinite or to make v negative. So long as U is positive v is positive and increases steadily with decreasing U , though v does not become infinite. But it will be recalled that α is a minimum when $U = GX/R$, and hence that decreasing U increases α so long as U is less than GX/R . Finally, then, it is seen that, so long as U is greater than GX/R , decreasing U decreases α and simultaneously increases v . There is no limit to the amount by which v can be increased by decreasing U , but there is a practical restriction set by the increase occurring in the attenuation when U is less than GX/R .

There will next be furnished general design-formulas for calculating the requisite susceptance U_1 to be furnished by the shunt loading, per unit length; these formulas will correspond to three specifications, as follows: the phase velocity v to have a specified value; the attenuation constant α to have a specified value; in particular, the attenuation constant α to be a minimum.

When the phase velocity v is to have a specified value v_2 , and hence β a corresponding value $\beta_2 = \omega/v_2$, the requisite design-formula for the total susceptance $U_2 = U + U_1$ (per unit length) is obtained by replacing U and $\beta = \omega/v$ in Equation (8) by U_2 and $\beta_2 = \omega/v_2$, respectively, and then solving for U_2 . It is thus found that

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$$U_2 = -G_2 \frac{X}{R} \left(1 + \frac{2\omega^2}{RG_2 v_2^2} \pm \sqrt{\frac{4\omega^2}{RG_2 v_2^2} \left(\frac{\omega^2}{RG_2 v_2^2} + 1 \right) \left(\frac{R^2}{X^2} + 1 \right)} \right) \quad (18)$$

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Of the two values of U_2 represented by (18), the algebraically larger or the algebraically smaller value is to be chosen according as the specified value v_2 of v is positive or negative, respectively; if only the absolute value of v_2 were specified, there would be two values

of U_2 that would meet the specification, since (18) involves only an even power of v_2 .

When the attenuation constant α is to have a specified value α_2 , the requisite design formula for the total susceptance $U_2 = U + U_1$ (per unit length) is obtainable by replacing α and U in equation (9) by α_2 and U_2 , respectively, and then solving for U_2 . It is thus found that

Both values of U_2 represented by this formula are physically applicable, and will yield the same specified value α_2 of α ; but they do not yield equal values of v —a fact which constitutes a ground of choice between the two values of U_2 .

In particular, when the attenuation constant α is specified to have a minimum value, namely

$$\alpha_2 = \sqrt{RG_2} \quad (20)$$

by Equation (14), then the requisite value for U_2 is

$$U_2 = G_2 X/R \quad (21)$$

as is found by substituting in (19) the particular value of α_2 represented by (20).

There will next be disclosed a particular type of shunt loading for decreasing the susceptance U , so as to increase v and decrease α . This particular type of shunt loading consists of shunt inductance (Fig. 3) and thus possesses the negative susceptance requisite for neutralizing a portion of the positive susceptance U of the original antenna, so that the resultant susceptance will be less than the original. Let L_1 denote the load inductance per unit length, and U_1 its susceptance; then

$$U_1 = 1/i\omega L_1 = -i/\omega L_1 \quad (22)$$

where, as before, ω denotes 2π times the signaling frequency f . The original susceptance being

$$U = i\omega C \quad (23)$$

C denoting the capacity of the wave antenna per unit length, the resultant susceptance $U_2 = U + U_1$ has the following ratio to U , namely

$$\frac{U_2}{U} = 1 - \frac{1}{\omega^2 CL_1} \quad (24)$$

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This shows that U_2 can be made as small as may be desired by suitably choosing L_1 . Thus $U_2 = 0$ when $L_1 = 1/\omega^2 C$. U_2 can even be made negative, but this would have the undesirable effect of unduly increasing the attenuation constant α , α being a minimum when

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$U_2 = GX/R$. Evidently U_2 will remain positive so long as L_1 remains greater than $1/\omega^2 C$.

In practical applications U would be given and the desired value of U_2 would be specified, whence the ratio U_2/U would be known; hence, from (24), the design-formula for L_1 is

$$L_1 = \frac{1}{\omega^2 C(1 - U_2/U)} \quad (25)$$

Since L_1 denotes the requisite inductance per unit length, if uniformly distributed, the requisite inductance L_3 of each loading element is

$$L_3 = DL_1 \quad (26)$$

D denoting the load-spacing chosen.

Equation (24) can be written in the more significant form

$$\frac{U_2}{U} = 1 - \left(\frac{f_1}{f}\right)^2 \quad (27)$$

where f is the signaling frequency, corresponding to U and U_2 ; and f_1 is the anti-resonant frequency of C and L_1 in parallel, that is

$$f_1 = 1/2\pi\sqrt{CL_1} \quad (28)$$

If the resultant susceptance U_2 is to remain positive, f_1 must evidently be less than f ; however, U_2 can be made as small as desired by making f_1 approach f , by properly choosing L_1 —in accordance with the Design-formula (25).

Equation (24) can be written also in the form

$$U_2 = i\omega C_2 \quad (29)$$

where

$$C_2 = C(1 - 1/\omega^2 CL_1) \quad (30)$$

is the effective shunt capacity of the loaded wave antenna, per unit length. Thus C_2 is less than C ; that is, the result of the loading is to decrease the effective capacity of the wave antenna, and thereby increase the velocity of propagation v , since v is approximately equal to the reciprocal of the square root of the product of the capacity and the inductance. This conclusion is evidently consistent with the foregoing conclusion deduced from a consideration of the susceptance U_2 .

The vertical component of the impressed electric field (represented by the lines 23 in Fig. 1), acting on the shunt loading elements, produces currents which complete their circuits through the wave antenna and thus (after undergoing attenuation) contribute to the current in the instrument at the receiving end. The question arises whether the contribution may alter undesirably the directional selectivity of the wave antenna. An investigation to determine the order of magnitude of the current contribution in question and its dependence on the angle of incidence will show that while the contribution referred

to will ordinarily be enough to be noticeable, it will not ordinarily be enough to be harmful.

Fig. 4 shows a two wire wave antenna, so arranged that the receiving apparatus can be located at the front end, the end nearest the transmitting station from which it is desired to receive. The radio waves in the direction 22 affect the two wires alike and build up in them a wave of electric current that discharges to ground at the distant end through the transformer winding 26 thus inducing in the two-wire circuit a circulating current which, transmitted to the front end is inductively effective on the receiver. Waves from the undesired direction 22' build up alike in the two conductors, and hence their effect on the receiver 27 is neutralized in the transformer at the front end; and the impedance W has the characteristic impedance value, so there is no reflection.

Fig. 5 shows a symbolic shunt load for a two wire antenna. However, this affords a path across from one conductor to the other through the two impedances, and thus tends to weaken the return signal current to the front end receiver. Fig. 6 shows the case where the grounded impedances are inductances with the addition of a condenser in parallel with the cross path and of such value as to make the entire shunt path across the conductors anti-resonant and hence of very high impedance to the signaling frequency. Fig. 7 shows the grounded shunt connected to the midpoint of a cross inductance of high impedance value; thus the inductance is neutralized to the waves built up by the radio waves, but is fully effective against the return signal waves. By the addition of a condenser in parallel with the cross-inductance as shown in Fig. 8, and making the combination anti-resonant to the signaling frequency, the cross impedance is increased. In Fig. 9, a 1:1 transformer is interposed and its midpoints connected together and also connected to ground through the desired impedance shunt. The effect is the same as for Fig. 7 and in addition by winding the coils in the proper directions the effect of a transposition of the conductors is obtained, thus making Fig. 9 correspond to Fig. 10 rather than Fig. 7. Transposition is desirable to neutralize interference and for the further reason that if the normal to the wave front has its horizontal component of direction oblique to the direction of the wave antenna then there will be a difference of phase in the two conductors which would cause a circulating current around the circuit thereof.

The velocity of the waves generated in the conductors by the radio waves will in general be less than the velocity of the radio waves, and this difference of velocity may be referred to as a lag value compared to the velocity of the radio waves.

I claim:

1. In a two wire wave antenna, shunt paths to ground from both wires at points along the length of the antenna, and means to make the resultant paths across the conductors at these points of high impedance.

2. In a two wire wave antenna, shunt paths to ground from both wires at points along the length of the antenna, and means comprising these shunt paths at least in part and forming anti-resonant loops across the conductors at said points.

3. In a two wire wave antenna, shunt inductance susceptance paths to ground from both wires at points along the length of the antenna, and cross connected condensers combined therewith to make the complete cross paths anti-resonant.

4. In a two wire wave antenna, shunt inductance susceptance paths to ground from both wires at points along the length of the antenna, at least part of the inductance being neutralized from the wires to ground but effective across the wires.

In testimony whereof, I have signed my name to this specification this 21st day of January, 1926.

RAY S. HOYT.