Jan. 20, 1931.

J. S. STONE

1,789,419

RADIO RECEIVING SYSTEM

Filed May 7, 1925

6 Sheets-Sheet 1

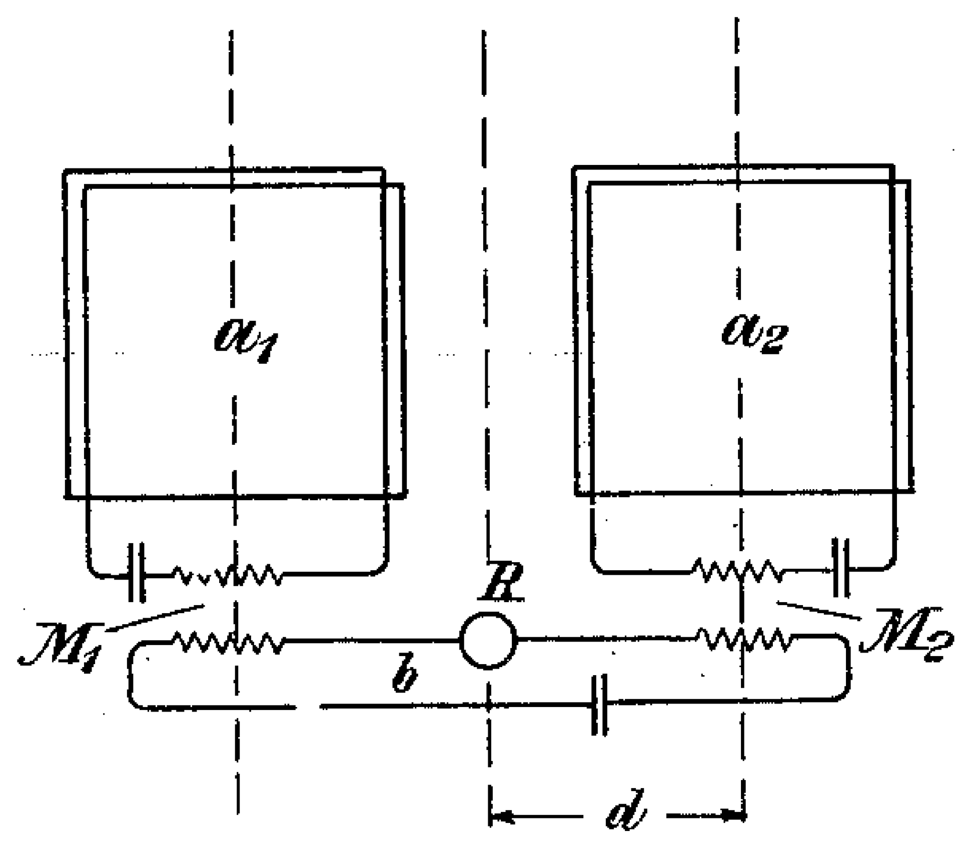

Fig. 1

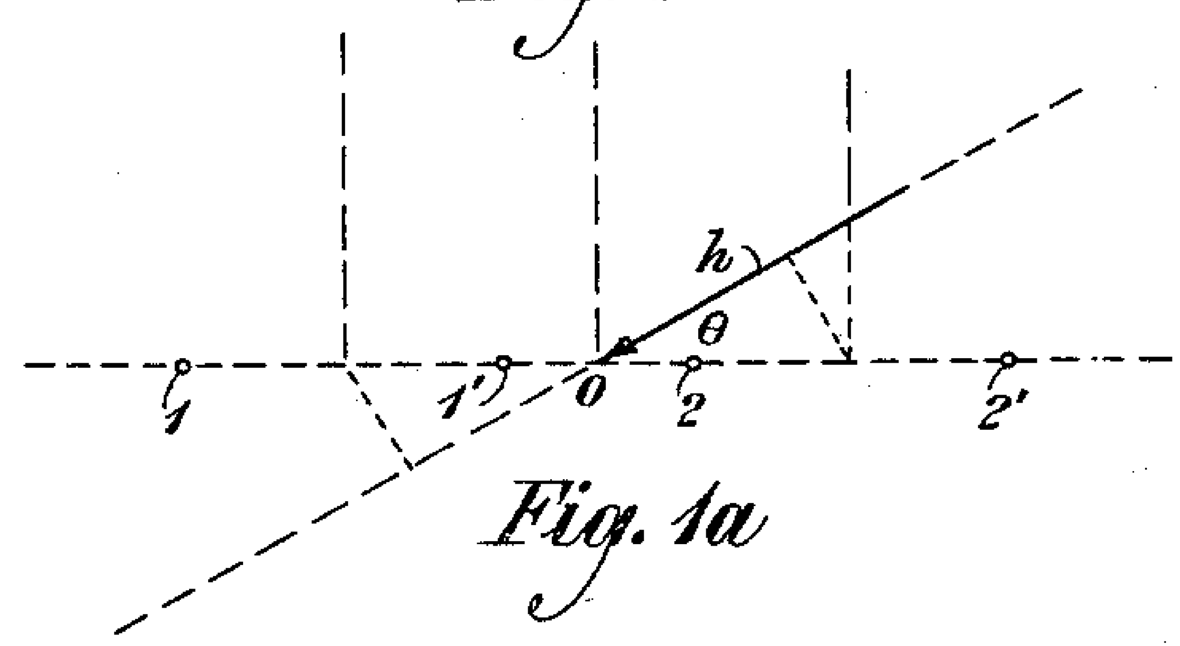

Fig. 1a

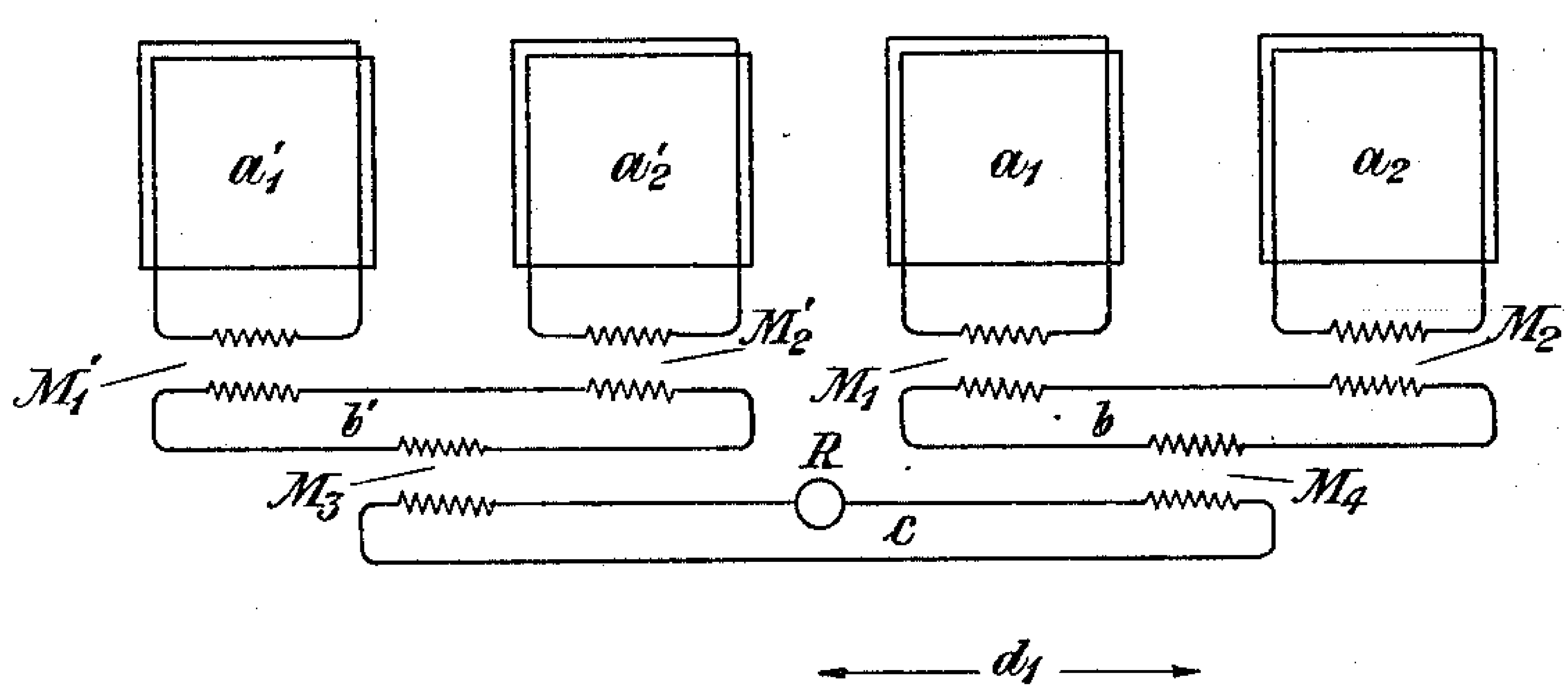

Fig. 2

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Jan. 20, 1931. J. S. STONE 1,789,419

RADIO RECEIVING SYSTEM

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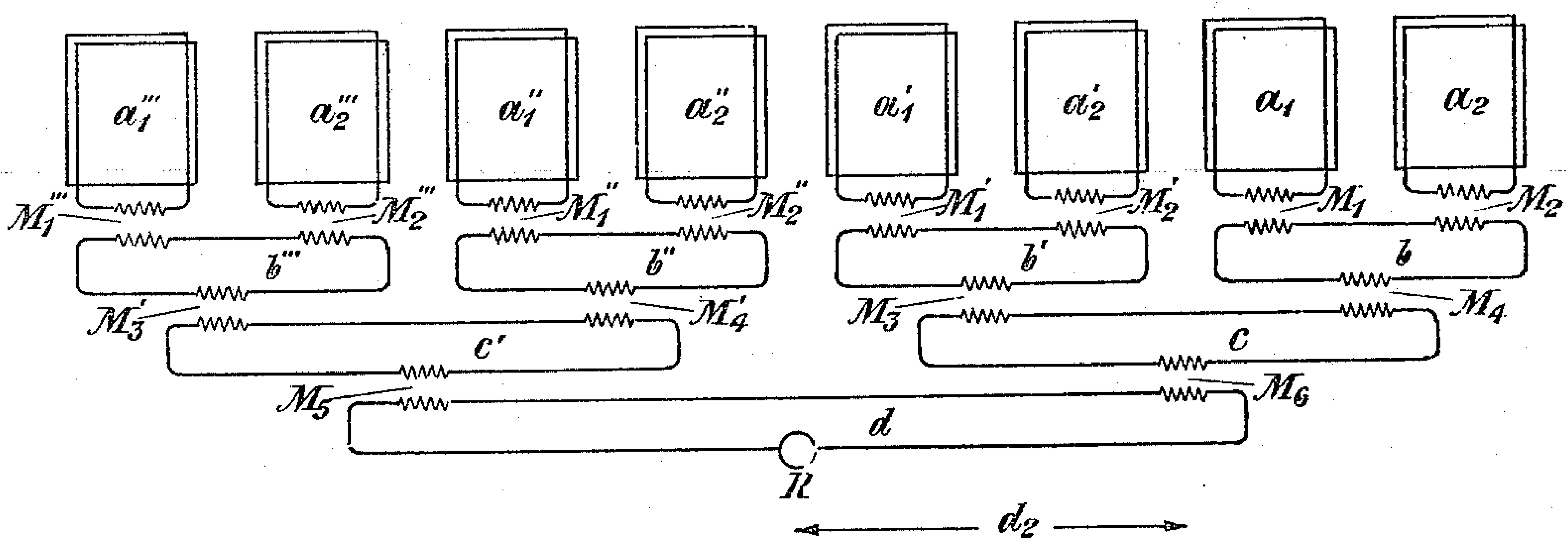

Fig. 3

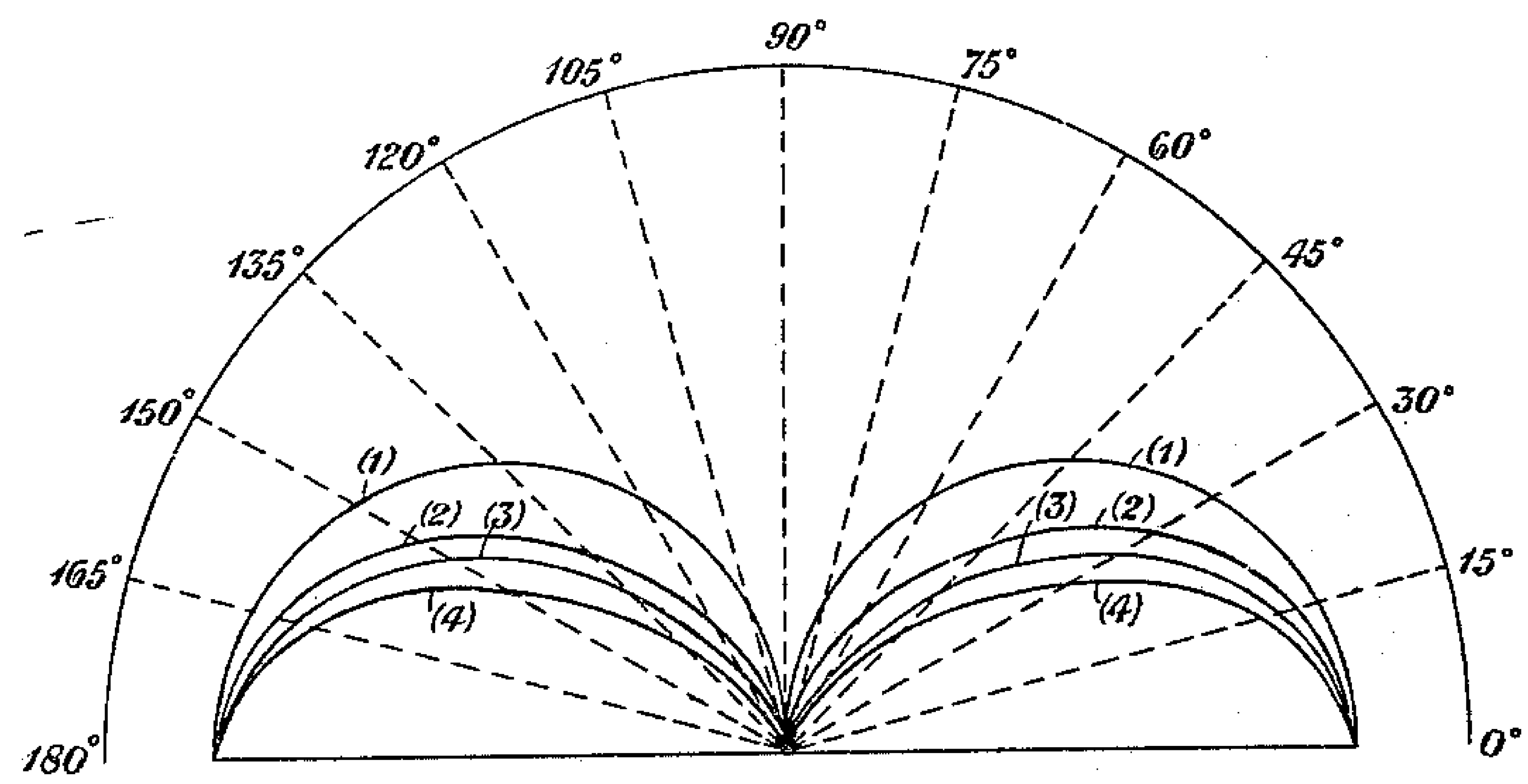

Fig. 4

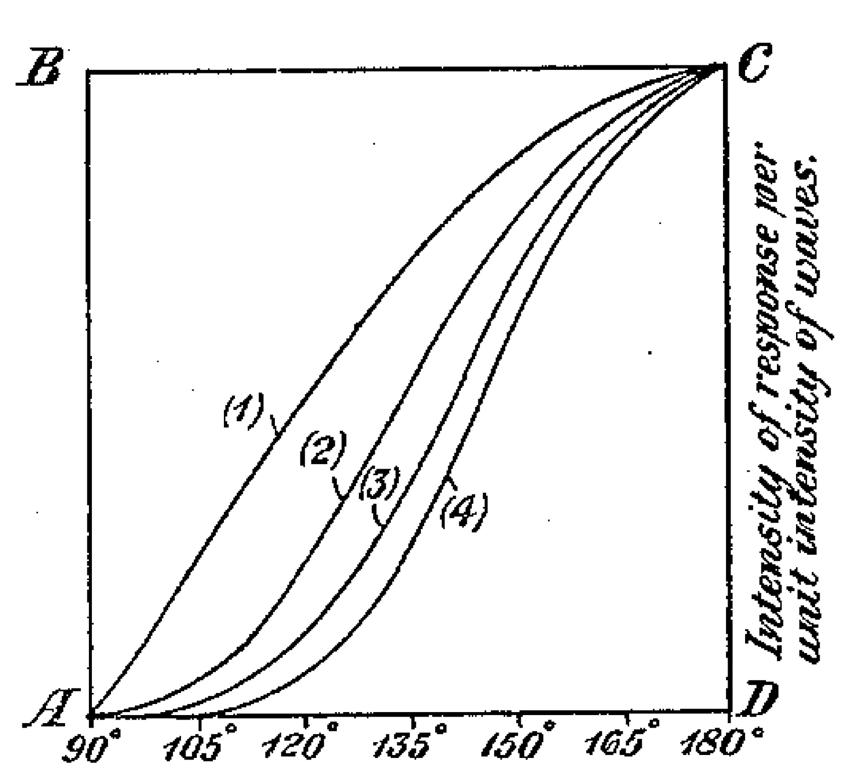

Fig. 5

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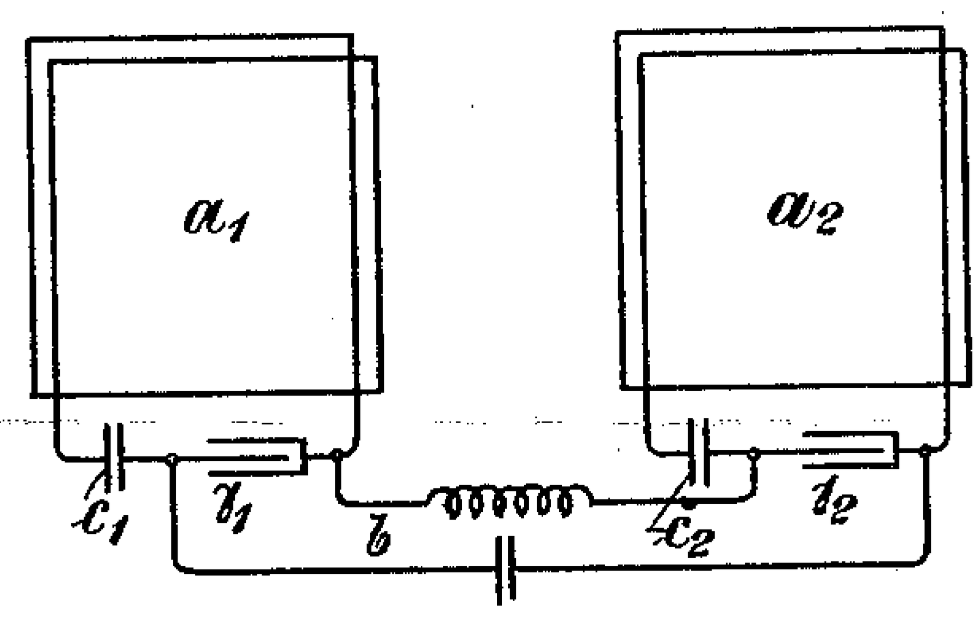

Fig. 6

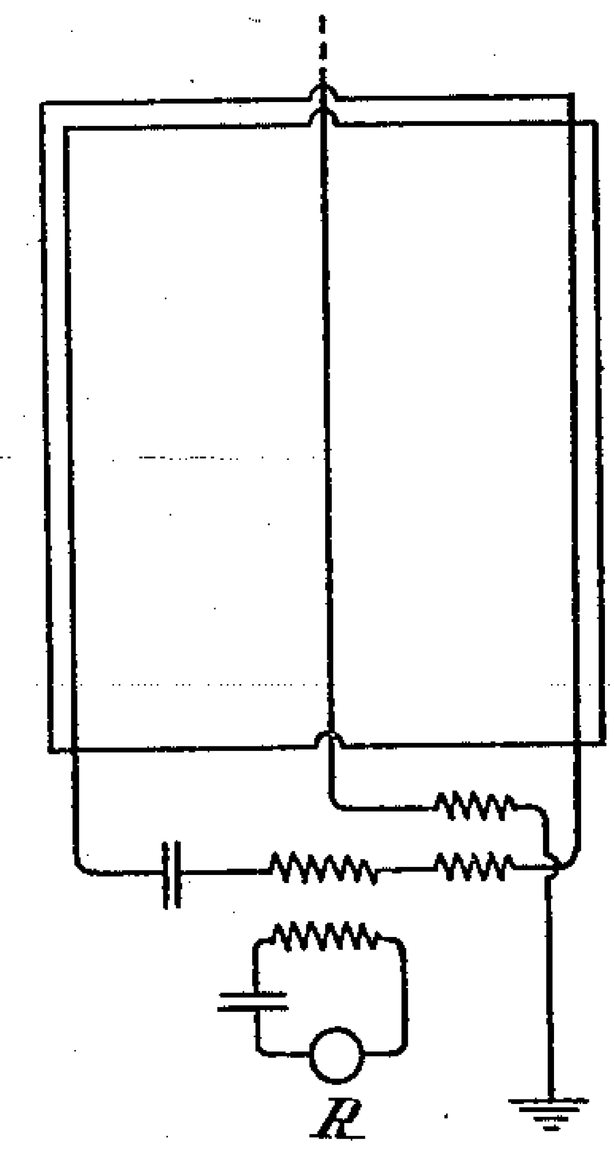

Fig. 7

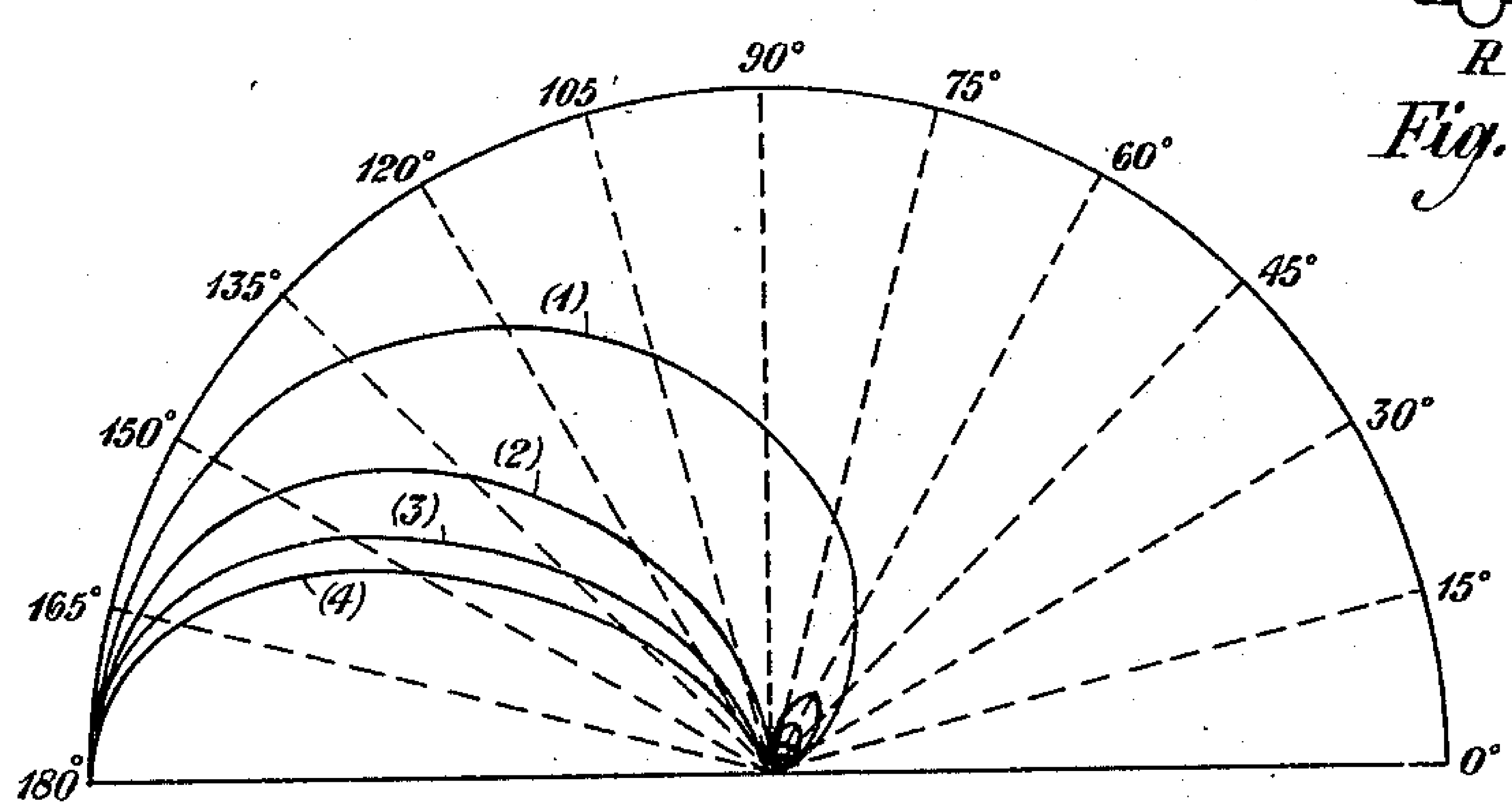

Fig. 8

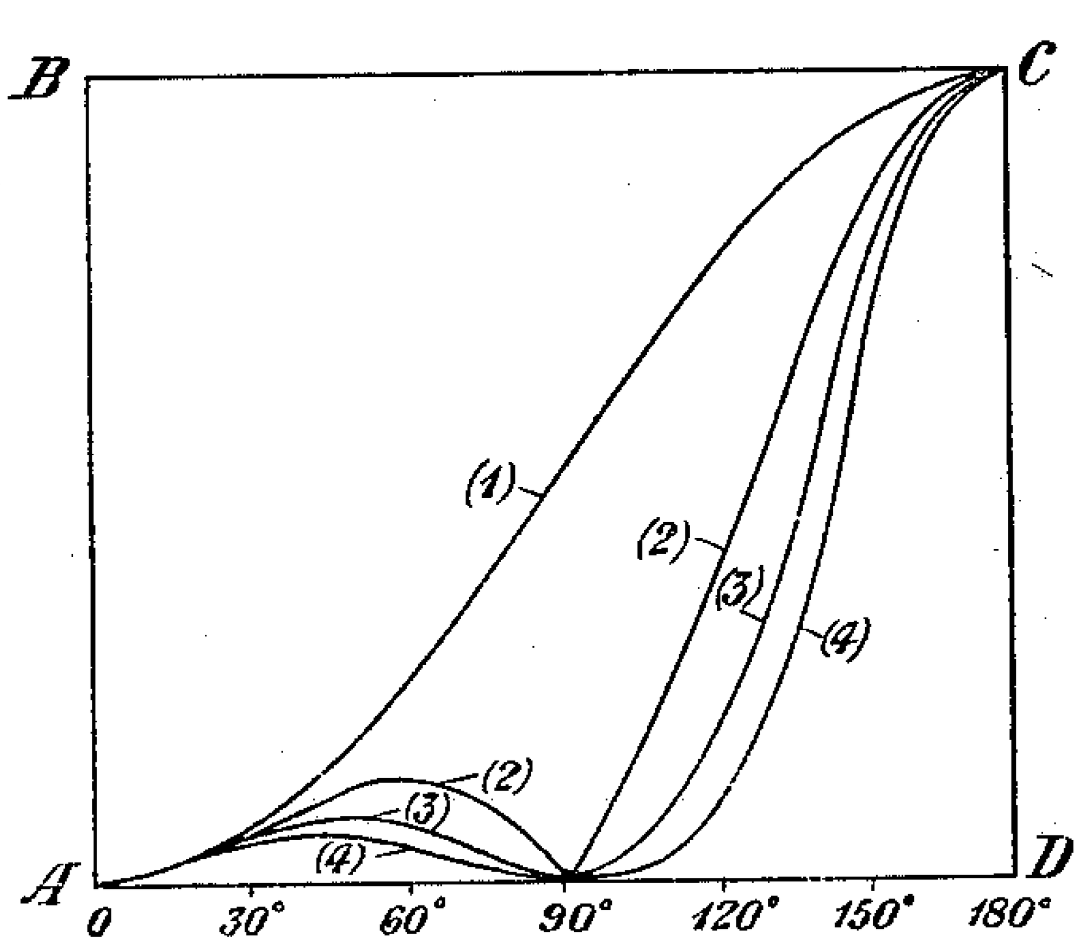

Fig. 9

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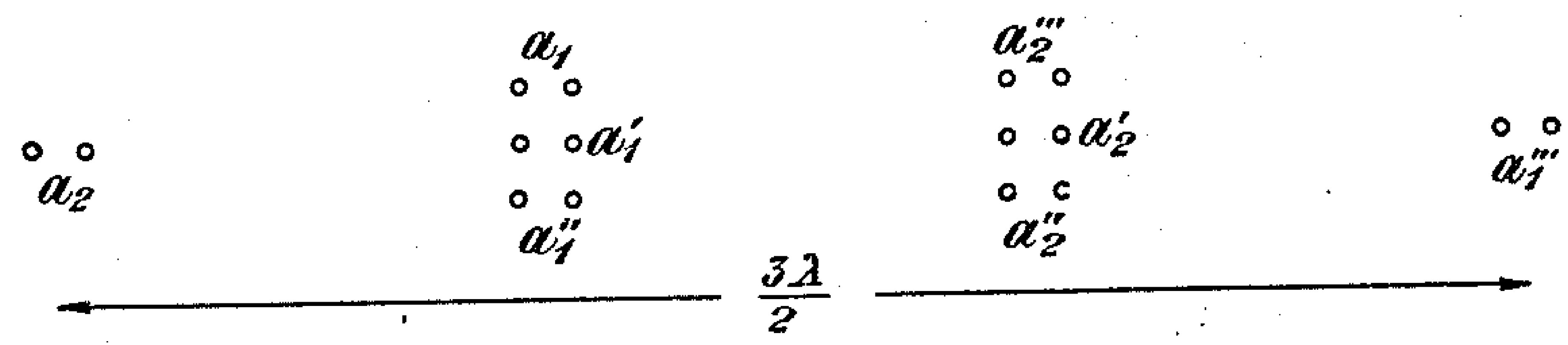

Fig. 10

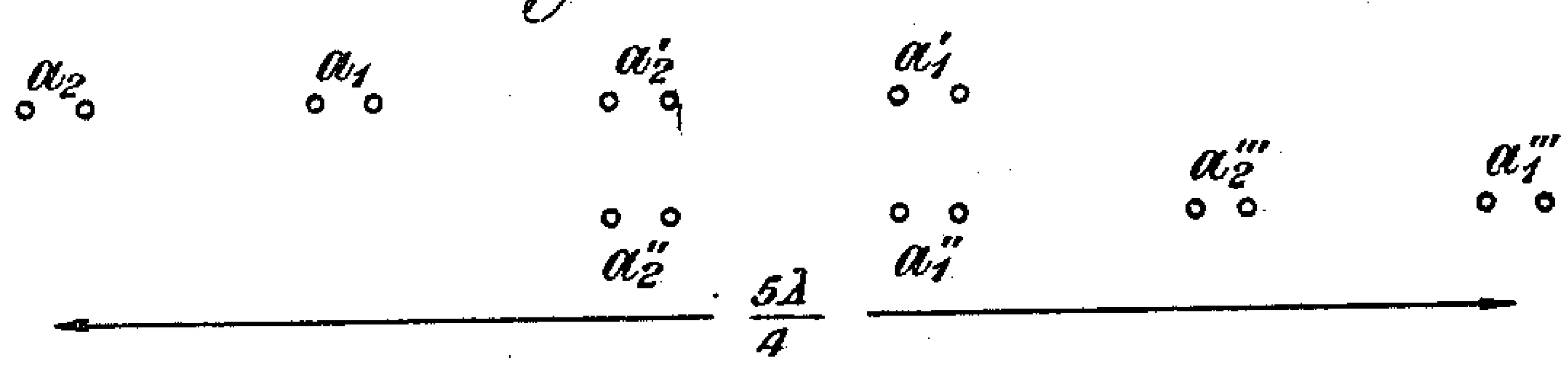

Fig. 11

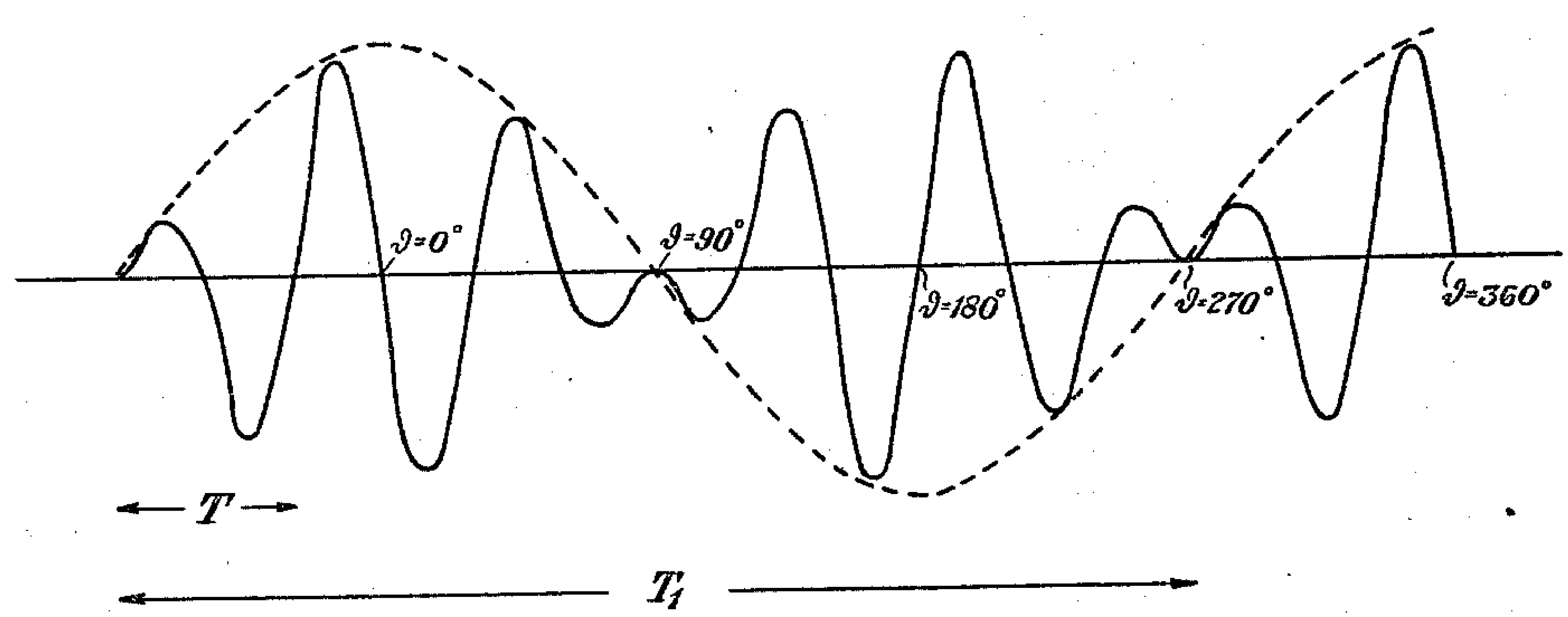

Fig. 12a

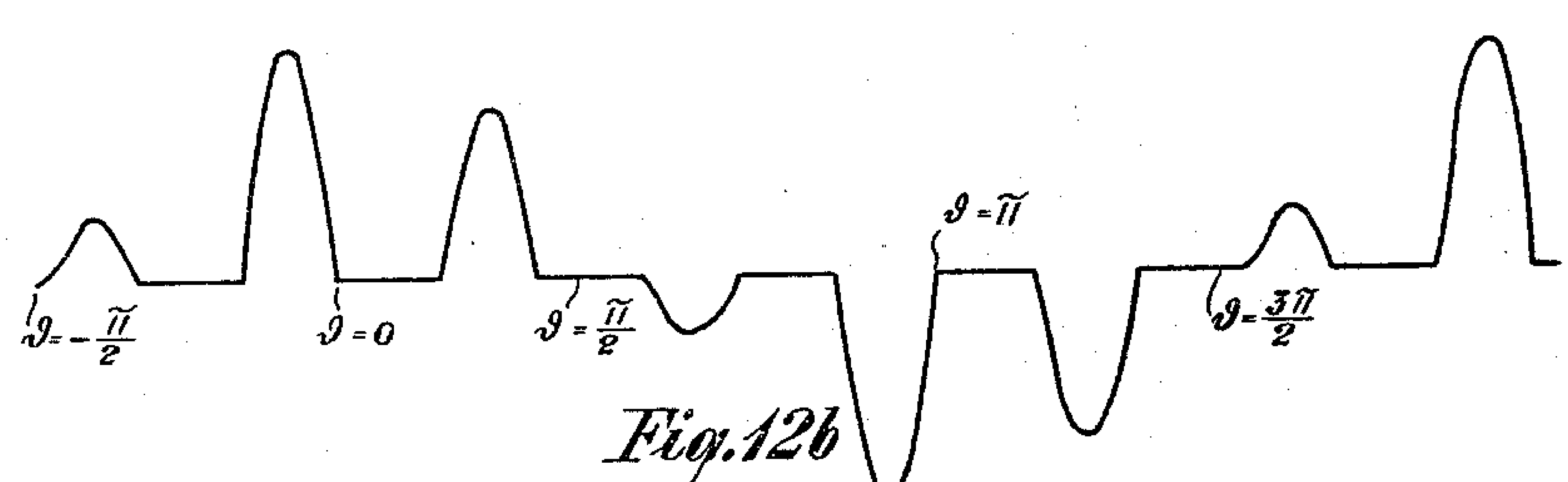

Fig. 12b

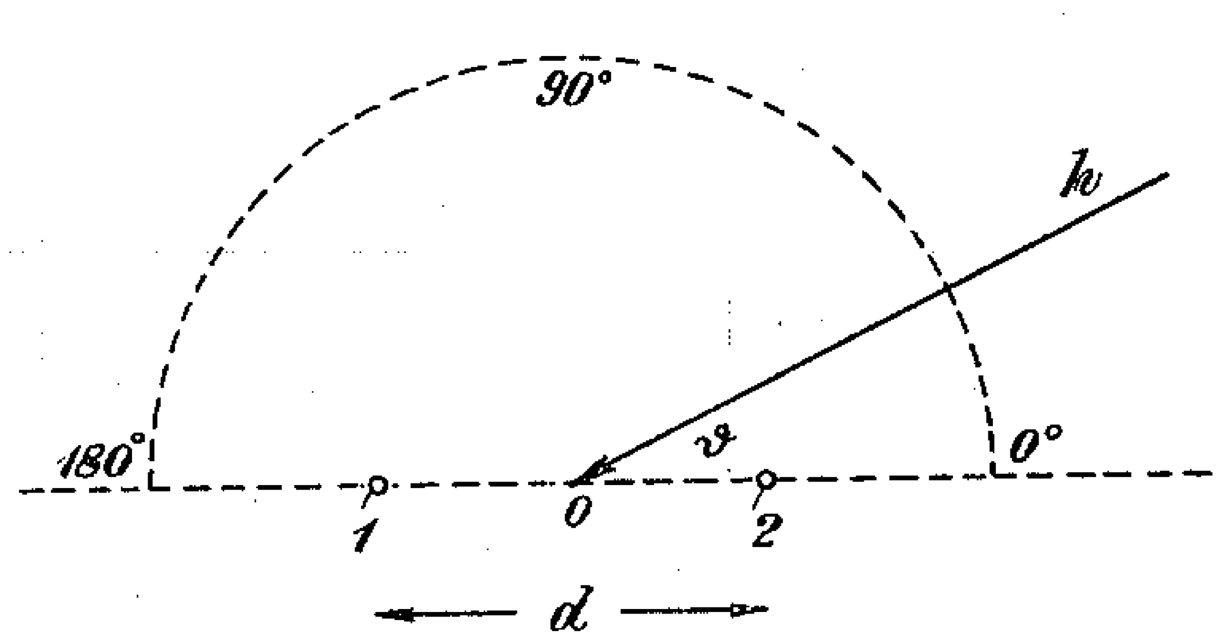

Fig. 12

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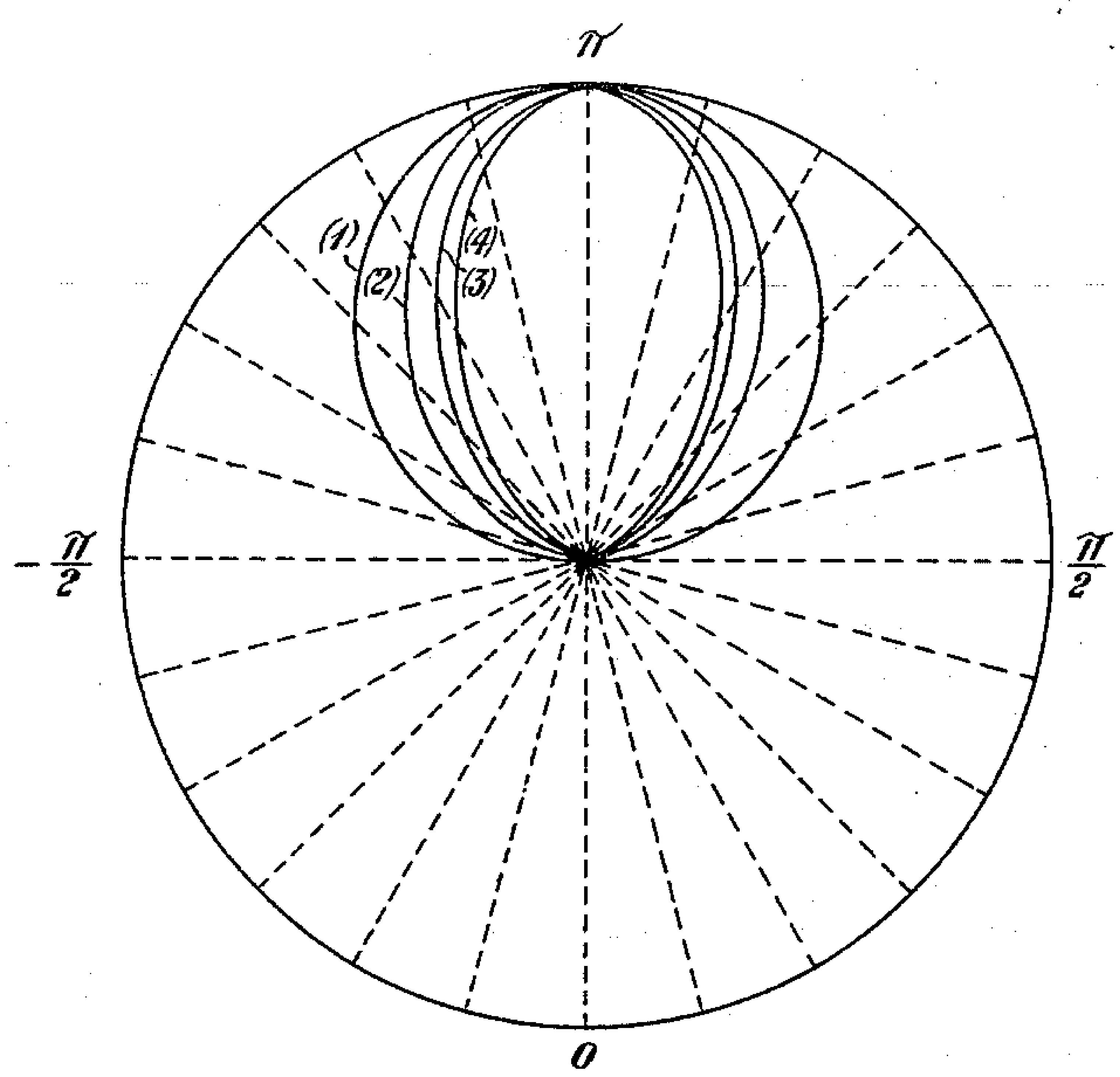

Fig. 13

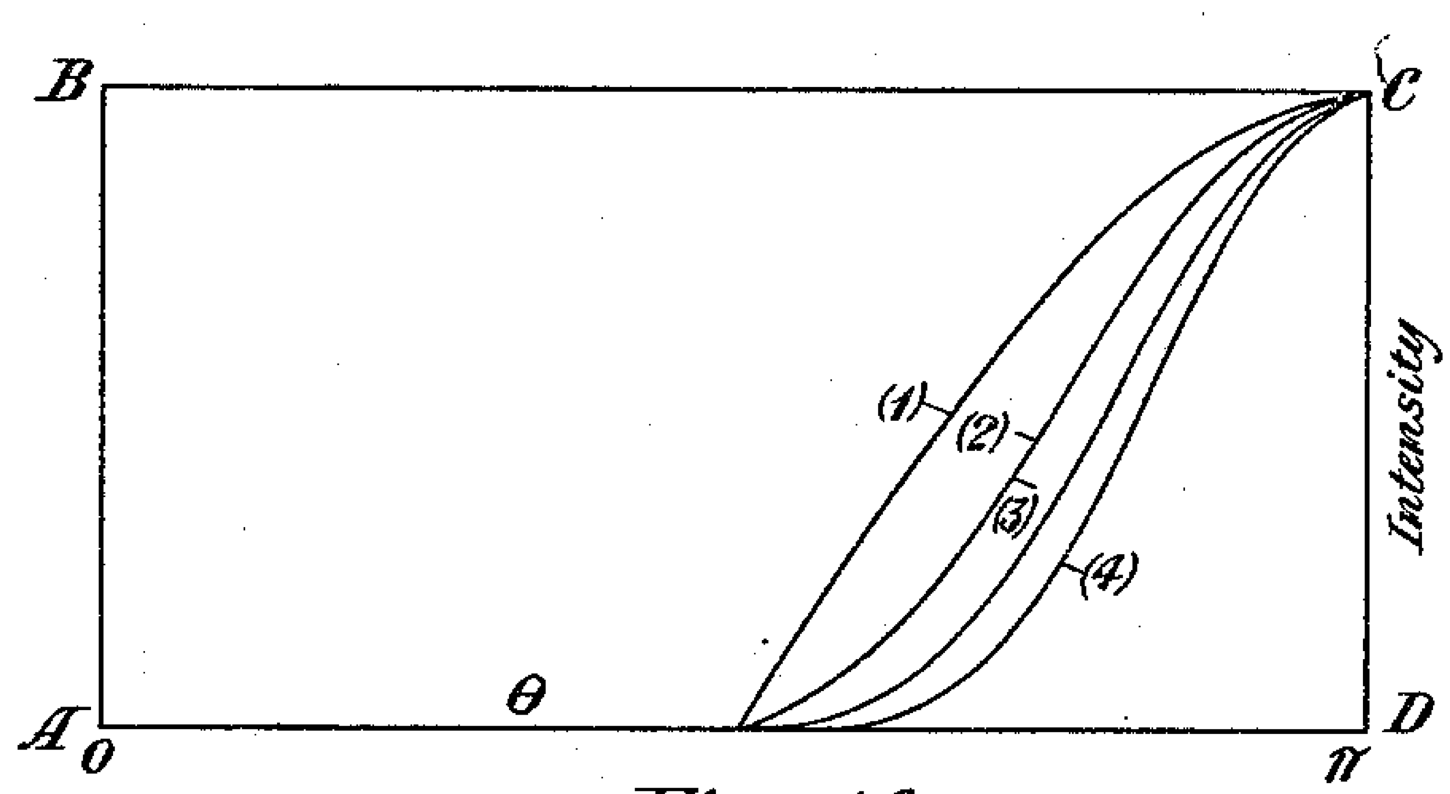

Fig. 14

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1,789,419

RADIO RECEIVING SYSTEM

Filed May 7, 1925

6 Sheets-Sheet 6

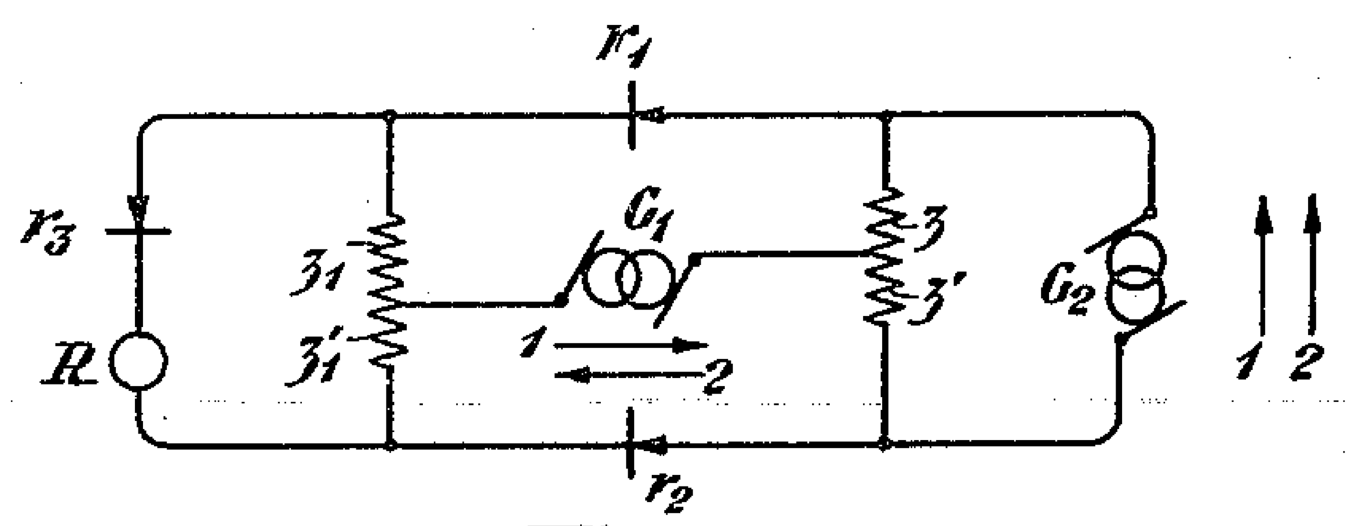

Fig. 15

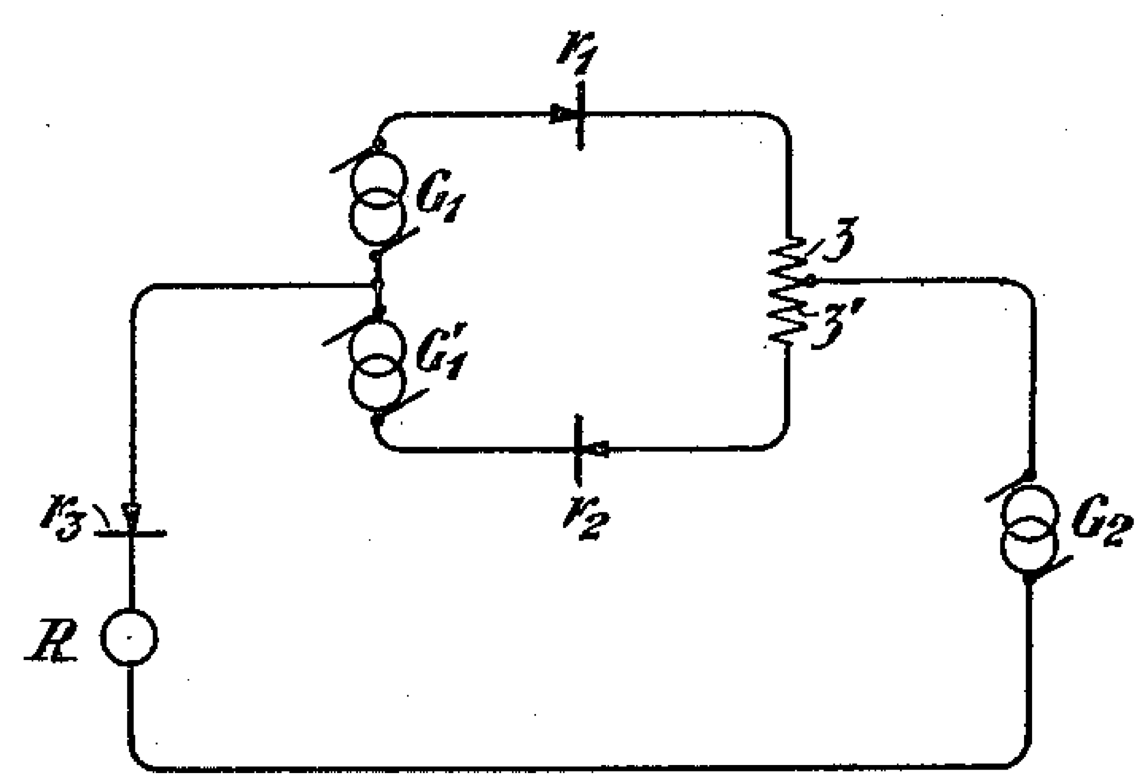

Fig. 16

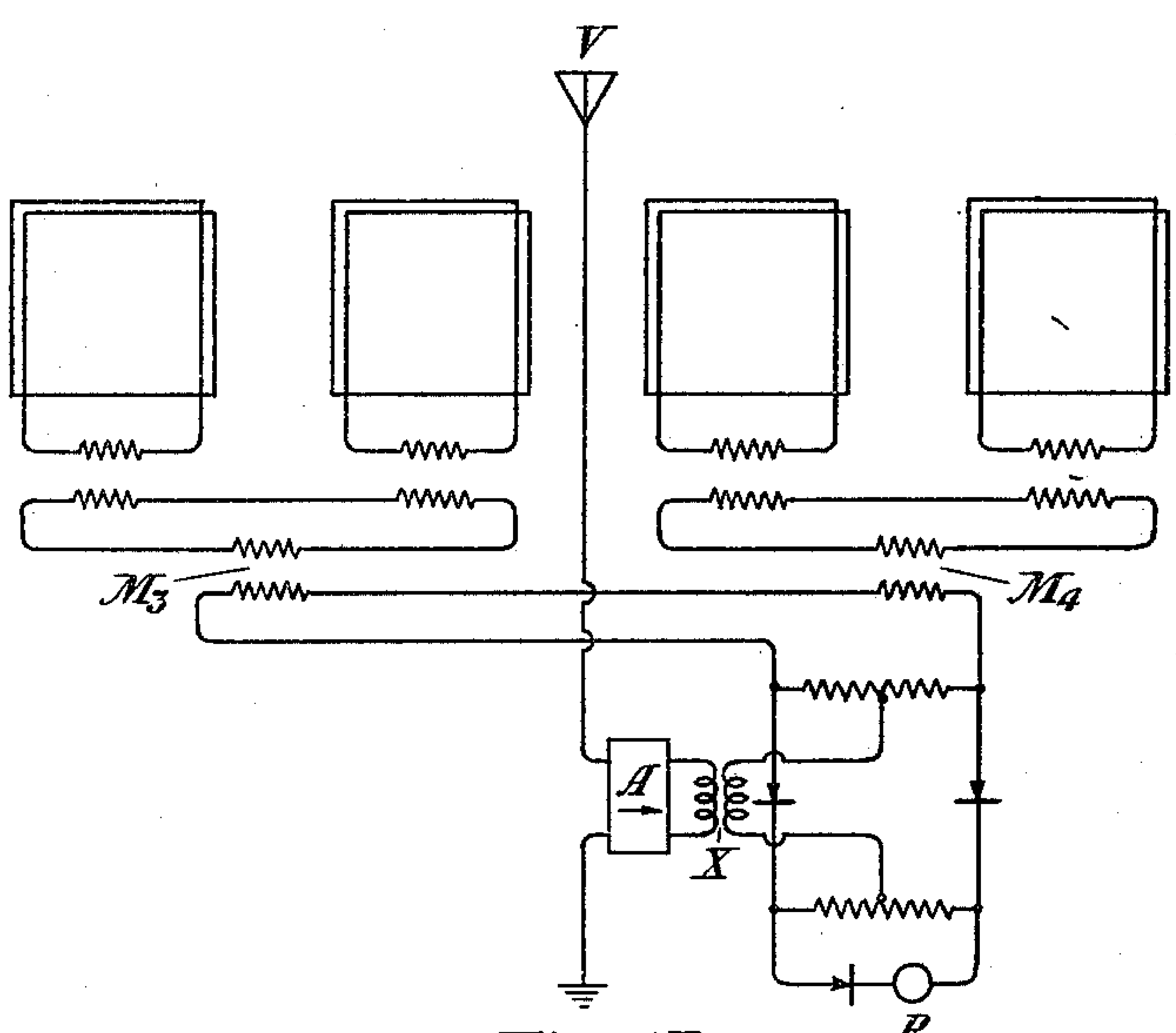

Fig. 17

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Patented Jan. 20, 1931 1,789,419

UNITED STATES PATENT OFFICE

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RADIO RECEIVING SYSTEM

Application filed May 7, 1925. Serial No. 28,633.

An object of my invention is to provide a new and improved system of selective radio receiving. Another object of my invention is to provide a radio receiving system that shall receive with relatively high intensity in a certain direction and with relatively low intensity in materially different directions. Another object of my invention is to combine loop receivers in a directionally selective array. Still another object is to make this array extend over only a moderate distance in its greatest extent. Another object of my invention is to provide apparatus that shall rectify and detect a certain alternating current in accordance with its phase range, and another object is to utilize such apparatus in increasing the directional selectivity of my receiving system. These and other objects of my invention will become apparent on consideration of a limited number of examples of embodiments of the invention, which I have chosen to illustrate in the accompanying drawings, and which I will now proceed to describe in the following specification. It will be understood that the invention is defined in the appended claims and that the following description relates to the particular embodiments of the invention chosen to illustrate it.

Referring to the drawings, Figure 1 is an elevation of a receiving array comprising two loop antennæ; Fig. 1a is a plan diagram of the same; Fig. 2 is an elevation of a receiving array comprising four loop antennæ; Fig. 3 is an elevation of a receiving array comprising eight loop antennæ; Fig. 4 is a polar diagram showing the relative intensity of reception in various horizontal directions for a single loop receiving antenna and for the antenna arrays of Figs. 1, 2 and 3; Fig. 5 is a diagram in Cartesian co-ordinates corresponding to the polar diagram of Fig. 4; Fig. 6 is a diagram corresponding to Fig. 1 but showing an alternative coupling arrangement between the loop antennæ and the common circuit; Fig. 7 is an elevation of a loop antenna and an ordinary vertical antenna combined for directionally selective receiving; Fig. 8 is a polar diagram in a horizontal plane for intensity of reception with the system of Fig. 7 and the systems obtained by combining units like Fig. 7 according to the principles involved in Figs. 1, 2 and 3; Fig. 9 is the diagram in Cartesian co-ordinates corresponding to the polar diagram of Fig. 8; Figs. 10 and 11 show alternative arrangements by which arrays may be built up of loop antennæ; Figs. 12, 12a and 12b are diagrams that will be referred to in explaining the principle involved in the modification shown in Fig. 17; Fig. 13 is a polar diagram for the modification of Fig. 17 and other modifications with other numbers of component loop antennæ combined according to the same principle; Fig. 14 is a diagram in Cartesian co-ordinates corresponding to the polar diagram of Fig. 13; Figs. 15 and 16 are diagrams of rectifiers which discriminate according to phase; and Fig. 17 is an elevation of a receiving array like Fig. 2 with the addition of a vertical receiving antenna and a device such as in Fig. 15 or 16, by which the directional selectivity is enhanced.

Referring to Fig. 1, a_1 and a_2 are two equal multiple turn loop antennæ in the same vertical plane, the circuits of which are tuned to the same frequency $\omega/2\pi$. They are loosely coupled through like transformers M_1 and M_2 with the common receiver circuit b which is also tuned to the frequency $\omega/2\pi$ and contains the receiving indicator R. The transformers M_1 and M_2 are wound in phase opposition, so that equal currents in the same phase in the antennæ a_1 and a_2 will produce a null effect in the receiver R.

Referring to the plan diagram of Fig. 1a, the sides of one coil a_1 are represented in section at 1 and 1′, and the sides of the other coil a_2 are shown in section at 2 and 2′. The arrow h at angle θ with the plane of the loops indicates the direction of incidence of the received waves on the receiving system.

Let λ be the wave length corresponding to the frequency $\omega/2\pi$. Then the current wave in the coil a_1 is of the form B sin $(\omega t+b)$ where b is a phase angle the value of which is determined by when the time is taken as zero and the position from which distances are measured. If α is the phase of the incoming wave when the time t is zero at the vertical central axis of the system shown by 0 of Fig. 1*a* and if d is the distance from 0 to the vertical central axis of the loop a_1 or a_2, then

$$b=\alpha-\frac{2\pi d}{\lambda}\cos\theta.$$

Further, it is evident that the amplitude of the resultant effect in the coil a_1, due to the electromotive force induced in the two vertical sides of the coil, depends upon the direction from which the wave comes so that $B=A\cos\theta$. Thus the current in the coil a_1 may be expressed as

$$A\cos\theta\sin\left(\omega t+\alpha-\frac{2\pi d}{\lambda}\cos\theta\right)\quad(1)$$

and likewise the current in the coil a_2 will be expressed as

$$A\cos\theta\sin\left(\omega t+\alpha+\frac{2\pi d}{\lambda}\cos\theta\right)\quad(2)$$

provided the width of the coils is a small fraction of the wave length.

The electromotive force induced in the common circuit b may then be expressed as

$$A'\cos\theta\left[\cos\left(\omega t+\alpha-\frac{2\pi d}{\lambda}\cos\theta\right)-\cos\left(\omega t+\alpha+\frac{2\pi d}{\lambda}\cos\theta\right)\right]\quad(3)$$

This expression reduces to

$$2A'\cos\theta\sin\left(\frac{2\pi d}{\lambda}\cos\theta\right)\sin(\omega t+\alpha)\quad(4)$$

and with the assumption that

$$\sin\frac{2\pi d}{\lambda}\cos\theta=\frac{2\pi d}{\lambda}\cos\theta\quad(5)$$

The expression (4) reduces to

$$\frac{4\pi d}{\lambda}A'\cos^2\theta\cos(\omega t+\alpha)\quad(6)$$

The foregoing condition (5) is approximately satisfied provided $\frac{2\pi d}{\lambda}$ is less than about one-fourth radian, that is less than about 15°. This condition is met by making the over-all dimensions of the system enough less than the wave length to satisfy the inequality just stated.

Referring to Fig. 4, the curve marked (1) is a polar diagram of intensity of reception for a single loop such as a_1 or a_2 of Fig. 1, and curve (2) is a corresponding polar diagram for the complete Fig. 1, as given by the foregoing expression 6, and assuming the same intensity at maximum as for curve 1. It will be seen that, according to curve 2 of Fig. 4, the array of two loop antennæ of Fig. 1 has greater directional selectivity than a single loop.

Fig. 2 shows an extension of the system to comprise four lops in the array. The assembly will be readily understood from the diagram with the explanation that the transformers M_1 and M_2 must be coupled in opposition; likewise M'_1 and M'_2; and likewise M_3 and M_4.

The pair of loops a_1 and a_2 have the directional factor $\cos^2\theta$ as given by the foregoing expression (6). Hence the amplitude of the electromotive force or current in the circuit c of Fig. 2 is given by the absolute value of the expression

$$A''\cos^2\theta\left[\cos\left(\omega t+\alpha-\frac{2\pi d_1}{\lambda}\cos\theta\right)-\cos\left(\omega t+\alpha+\frac{2\pi d_1}{\lambda}\cos\theta\right)\right]\quad(7)$$

$$\text{where } A''=4\pi d\frac{A'}{\lambda};$$

and this absolute value may be written in the form

$$A_1\cos^3\theta\quad(8)$$

provided that

$$\frac{2\pi d_1}{\lambda}<\frac{1}{4}\quad(9)$$

according to a line of reasoning similar to that given above in connection with Equation (5).

The polar diagram for Fig. 2 is given by the curve 3 of Fig. 4 which corresponds to the foregoing expression (8) when $A_1=A$.

Fig. 3 illustrates a system of eight receiving loops. The manner in which they are combined will be apparent from the drawing, with the explanation that the transformers M_1, M'_1, M''_1, M'''_1, M_3, M'_3 and M_5 are so poled that their electromotive forces oppose those of transformers M_2, M'_2, M''_2 M'''_2, M_4, M'_4 and M_6, respectively. The electromotive force or the current in circuit d of Fig. 3 may be expressed as

$$(A_2\cos^4\theta\cos(\omega t+\alpha)\quad(10)$$

provided that

$$\frac{2\pi d_2}{\lambda}<\frac{1}{4}\quad(11)$$

The corresponding polar diagram for Fig. 3 is shown by curve 4 in Fig. 4 when $A_2=A$.

Fig. 5 corresponds to Fig. 4 except that Cartesian co-ordinates are employed instead of polar co-ordinates, that is, the angles of Fig. 4 are laid off as abscissæ along the line AD of Fig. 5, and the radius vectors of Fig. 4 are erected as ordinates for Fig. 5. The area of the entire rectangle ABCD of Fig. 5 compared with the area under each curve gives a measure of the directional selectivity of the corresponding system. This ratio may be called the "figure of merit" of the system, so far as it relates to minimizing static and general interference. The figures of merit for the systems corresponding to curves 1, 2, 3 and 4 are as follows:

Curve (1)	1.57
Curve (2)	2.00
Curve (3)	2.36
Curve (4)	2.67

With the successively enhanced directive and interference exclusive properties of the systems shown in Figs. 1, 2 and 3, there goes a sacrifice of intensity. In Fig. 1 an amplification of at least two-fold would be required to make the intensity the same as for a single loop; similarly Fig. 2 would require four-fold amplification; and Fig. 3 would require eight-fold amplification.

The necessary loose coupling between the several loops and the circuits common thereto is obtained in Figs. 1, 2 and 3 by means of transformers M. An alternative loose coupling is indicated in Fig. 6 by means of the condensers V_1 and V_2, each of capacity large compared to the condensers C_1 and C_2.

In accordance as the loop antennæ, such as a_1 and a_2 of Fig. 1, differ in size, compensation may be made by correspondingly adjusting the looseness of coupling in the transformers M_1 and M_2, but it will usually be advantageous to make the loops equal and have a like degree of coupling in the transformers.

In Fig. 7 a loop receiving antenna in a vertical plane is shown and combined therewith a vertical antenna lying in the vertical axis of the loop. This is a combination that secures a degree of directional selectivity as shown by the curve 1 in the polar diagram of Fig. 8.

Regarding the assembly of Fig. 7 as a unit, let such units be combined in the same way that the simple coil antennæ of Figs. 1, 2 and 3 were combined. The polar diagrams of receptivity for these combinations will be represented by the respective curves 2, 3 and 4 of Fig. 8 and the corresponding diagrams using the angle θ and intensity as Cartesian co-ordinates are given in Fig. 9. The figures of merit for these combinations are as follows:

Curve (1)	2.00
Curve (2)	3.14
Curve (3)	4.00
Curve (4)	4.71

A comparison of Fig. 8 with Fig. 4 shows that the arrays represented by Fig. 8 do not focus their receptivity along the axis as closely as do the corresponding arrays represented by Fig. 4; but on the other hand, so far as the exclusion of interference is concerned, the arrays of Fig. 8 are unidirectional, whereas those of Fig. 4 are bidirectional. Comparison of Fig. 9 with Fig. 5 shows greater efficiency for the arrays of Fig. 9 in excluding static and strays from miscellaneous directions.

If it were attempted to build up a directionally selective array of eight loop antennæ in accordance with the space relationships which have been found to be most advantageous for open aerials, the arrangements would be arrived at which are shown in either Fig. 10 or Fig. 11, the former corresponding to bidirectional reception and the latter to unidirectional reception. It will be seen that in these cases the extreme dimensions of the array where eight units are involved amount to

$$\frac{3\lambda}{2} \text{ or } \frac{5\lambda}{4}.$$

On the other hand, when eight units are involved in a combination such as that shown in Fig. 3, the corresponding extreme linear dimension is not greater than

$$\frac{7}{2}\times\frac{\lambda}{25}$$

or about

$$\frac{\lambda}{7}.$$

Thus, in the case of a wave length corresponding to a frequency of a million cycles per second, the arrangement shown in Fig. 10 or Fig. 11 would require a linear dimension of something like 450 meters, whereas the arrangement of Fig. 8 would be confined within a range of about 42 meters.

I will now disclose how the addition of a single vertical type antenna to any such system as that of Figs. 1, 2 or 3, may be made to convert the system from bidirectional to unidirectional and thus virtually double its selectivity in respect to interference from random directions. Fig. 17 shows a four-unit array of loop antennæ with the addition of a single vertical type antenna. The principles involved will be appreciated on consideration of an explanation that will now be given in connection with Figs. 12 to 16.

The phase of the received oscillations in a bidirectional receiver passes abruptly through 180° when the angle θ passes through 90° and 270°. Thus, if 1 and 2 in Fig. 12 are the horizontal sections of the sides of a loop antenna and if the waves are incident in the direction of the arrow h, then the electromotive force induced in the loop antenna, provided its width d is a small fraction of a wave length, may be expressed as

$$A\cos\theta\sin\left(\frac{2\pi}{T}t+\alpha\right)$$

where T is the period corresponding to wave length λ and α is the phase of the waves at the time $t=\theta$.

To illustrate, suppose the angle θ increases uniformly with a period T_1 greater than T; then the electromotive force induced by the incident waves will be substantially as shown in the diagram of Fig. 12a. Here it will be noticed that the phase of the electromotive force is reversed at $\theta=90°$ and at $\theta=270°$.

Proceeding with the illustration, let it be assumed that the circuit of the coil of Fig. 12 has a device introduced which periodically opens and closes it with period T; then assuming that this device is suitably phased, the resulting current will be as shown by the diagram of Fig. 12*b*. It will be seen that the circuit controller of period T rectifies the current first one way and then the other. The system has been rendered discriminating between values of θ corresponding to opposite directions. If a galvanometer could be used as a detector it would give a positive deflection for values of θ on one side and a negative deflection for values of θ on the other side of the axis of ordinates. By introducing a device in the receiving system which will pass only the currents in one of the two phases shown in Fig. 12*b*, the system will be responsive only to waves whose angle of incidence lies within 90° of the preferred direction of reception.

Before describing the apparatus to effect the results indicated in the foregoing discussion let attention be directed to the polar diagram of Fig. 13 which is obtained by cutting off all reception from the direction opposite to that desired. It will be seen that the diagram of Fig. 13 is obtained from Fig. 4 by suppressing one of the two sets of loops of Fig. 4.

The corresponding diagram in Cartesian co-ordinates is shown in Fig. 14. The curves have the same shape and dimensions as those of Fig. 5 but the rectangle with which comparison is to be made to get the figure of merit is twice as large and the corresponding figures of merit are

Curve (1)	3.14
Curve (2)	4.00
Curve (3)	4.71
Curve (4)	5.33

It will be seen that these figures are respectively obtained by doubling those given earlier in the specification for Fig. 5.

In Fig. 15, r_1, r_2 and r_3 are rectifying valves. R is a receiving indicator, G_1 and G_2 are two alternating current generators of the same frequency, and the impedances z, z', z_1 and z'_1 are proportioned to make the circuits of R and G_1 conjugate to one another. Let the frequency of the generators G_1 and G_2 correspond to the period T of Fig. 12*a*, and let the electromotive force of G_1 be great relatively to G_2.

If G_1 were not operating, it is readily apparent that some of the current from G_2 would get through to the rectifier r_3 and the receiver R, and that the receiver R would get the rectified current. Consider two cases for operation of generator G_1; in the same phase relation, indicated by the arrows (1), and in the opposite phase relation, as indicated by the arrows (2). In either case the generator G_1 has no effect on receiver R, because of the conjugate relation. But when G_1 and G_2 are in the same phase of arrows (1), the current from G_2 is superposed and gets through to receiver R, the same as if G_1 were not operating. On the other hand, when G_1 and G_2 are in the opposite phase of arrows (2), a reverse electromotive force is built up at the valves r_1 and r_2 so that no current from the generator G_2 can get through to the receiver R. Hence, the receiver R gets only the half waves of current for half of one complete cycle of values of θ, that is R gets only the half waves of current on one side of the horizontal axis shown in Fig. 12*b*, provided G_1 is reversed in phase every half cycle.

Fig. 16 shows a modification as compared with Fig. 15. Here two equal generators G_1 and G'_1 are provided in series, and the circuit for generator G_2 is connected at a point between G_1 and G'_1. The half waves from G_2 will reach R effectively when G_2 is in the same phase with G_1 and G'_1 and they will not reach R effectively when in the opposite phase.

The arrangement of Fig. 15 has been incorporated in Fig. 17, where it will be seen that the generator G_1 is replaced by the transformer X whose primary receives amplified current from the vertical type antenna V. Also, the generator G_2 of Fig. 15 has been replaced by the secondary windings of the transformers M_3 and M_4 of Fig. 2. The result is that the system of Fig. 17 operates according to the curves 3 of Figs. 13 and 14 instead of the curves 3 of Figs. 4 and 5.

I claim:

1. In combination, a plurality of loop receiving antennæ in a horizontal row in a common vertical plane, and all connected through loose couplings with a common receiving indicator, the combination being highly selective in the direction of the said row each way along the row, and a vertical antenna non-selective as to direction, and means connecting said vertical antenna with said combination to make it selective to one of the two opposite directions along the row of loop antennæ.

2. In combination, a plurality of loop receiving antennæ in a horizontal row in a common vertical plane, and all connected through loose couplings with a common receiving indicator, the entire length of said row being small relatively to a wave length of the waves to be received and the combination being highly selective in the direction of said row each way along the row, a vertical antenna non-selective as to different directions, and means connecting the said vertical antenna with the said combination to make it selective in one of the two directions along the

row of loop antennæ and against the opposite direction.

3. In combination, a plurality of loop receiving antennæ in a horizontal row in a common vertical plane, and all connected through loose couplings with a common receiving indicator, the combination being highly selective in the direction of the said row, and means comprising a vertical type antenna to make the combination further selective in one of the two opposite directions along said row.

4. In combination, a plurality of loop receiving antennæ and a vertical type antenna, the greatest horizontal extent of the combination being small compared to a wave length of the waves to be received, each of the said loop antennæ being selective in both of two opposite directions and the said plurality of loop antennæ being combined to increase their selectivity, and means connecting the said loop antennæ and the vertical type antenna to make the combination selective in a narrow angular range in one general direction only.

5. In combination, a receiving antenna system comprising a plurality of loop antennæ all lying in one common plane and selective in two opposite directions in said plane, a common receiving circuit, a rectifier therein, an auxiliary antenna adapted to receive in all directions, and means actuated thereby to block the currents to the said rectifier when received in one of the said two different directions and to pass them when received in the other said direction, whereby the receiver becomes further selective as between the said two directions.

6. In combination, a receiving antenna system selective in two different directions, a vertical type antenna and a receiving circuit having independent conjugate connections with said antenna system and said vertical type antenna to make it selective as between the said two directions.

7. Apparatus for receiving from a source waves in one phase and excluding waves in another phase, consisting of a receiver in circuit with said source, an auxiliary source in conjugate relation with said receiver, and a rectifier in combination with the other elements, said auxiliary source agreeing in phase with one only of the said two phases, whereby the currents reach the receiver in that phase and not in the other phase.

8. Apparatus for selectively receiving currents from a source in only one of two opposite phases, consisting of a receiver and a generator in conjugate relation, a rectifier, said generator agreeing in frequency with said source and being in one of the said two phases whereby the rectifier passes the currents of that phase and blocks the currents of the opposite phase.

9. In combination, a receiver, two sources of the same frequency, one of them of a certain phase and the other alternatively of the same or opposite phase, the said one source and the receiver being connected in conjugate relation, and a rectifier, whereby currents from said other source reach the receiver only when in one phase and not in the other phase.

10. The method of discriminating between received currents according to their phase, which consists in superposing an alternating current electromotive force in a certain part of the circuit of said received currents and always in the phase to be selected and rectifying the composite currents in said certain part of the circuit, whereby only the received currents in that phase are rectified and passed.

11. The method of selecting between two alternating currents in two opposite phases which consists in locally superposing an alternating electromotive force in one of those phases and rectifying the resultant current at the place of such superposition, whereby only those currents of the desired phase are passed and rectified.

12. A circuit comprising a rectifier and a source of alternating current and a receiver, and a local source of alternating electromotive force associated with said rectifier to make it selective of currents to the receiver from the first mentioned source according as they are in the same or the opposite phase of the said local source.

13. A rectifier, a source of alternating current associated therewith and means to make the rectifier selective according to whether said source is in one phase or in the opposite phase, comprising an auxiliary source constantly applied to said rectifier and in the same phase as that desired to be passed selectively.

In testimony whereof, I have signed my name to this specification this 27th day of April 1925.

JOHN STONE STONE.