June 4, 1929. J. S. STONE 1,715,433

ANTENNA ARRAY

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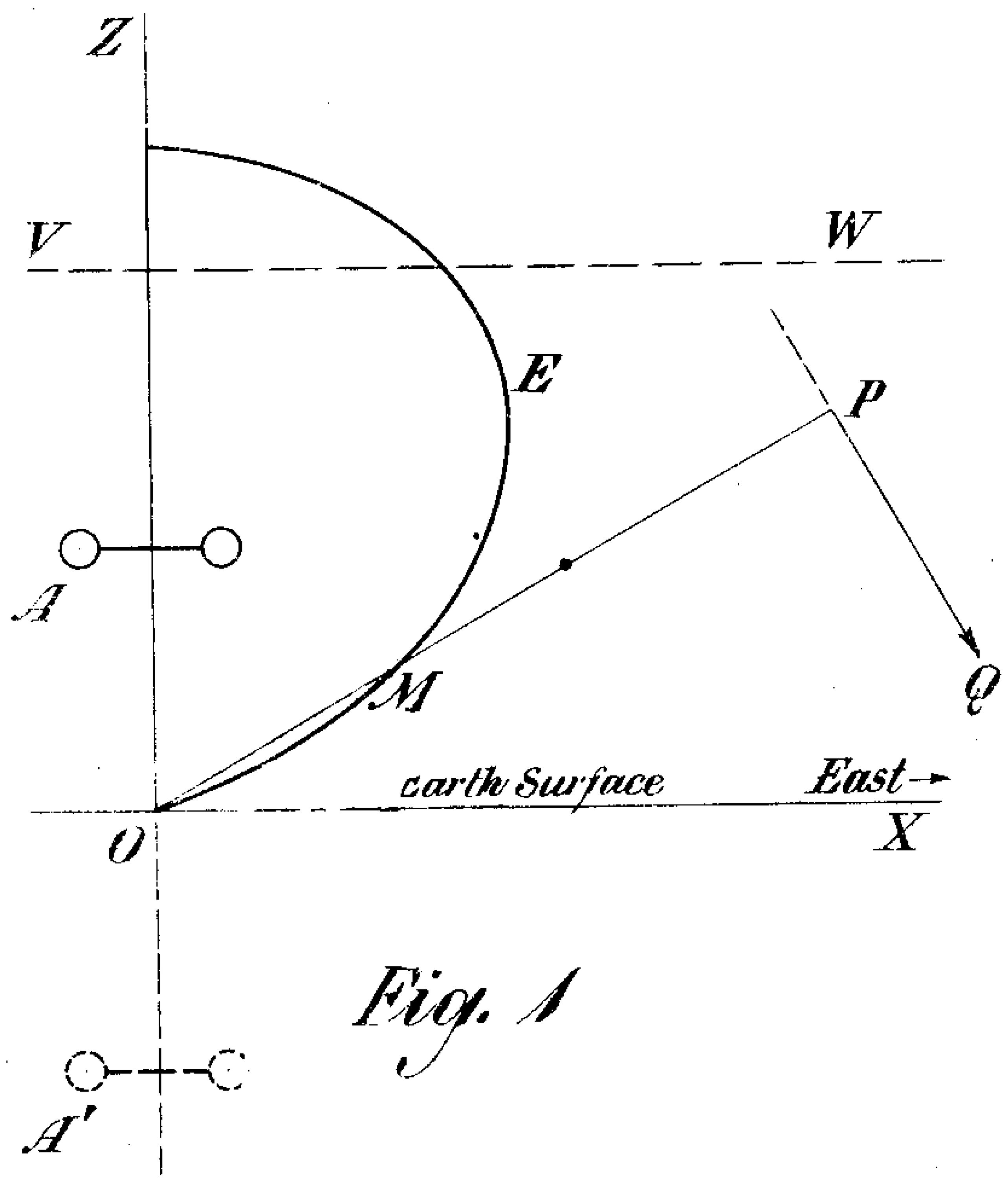

Fig. 1

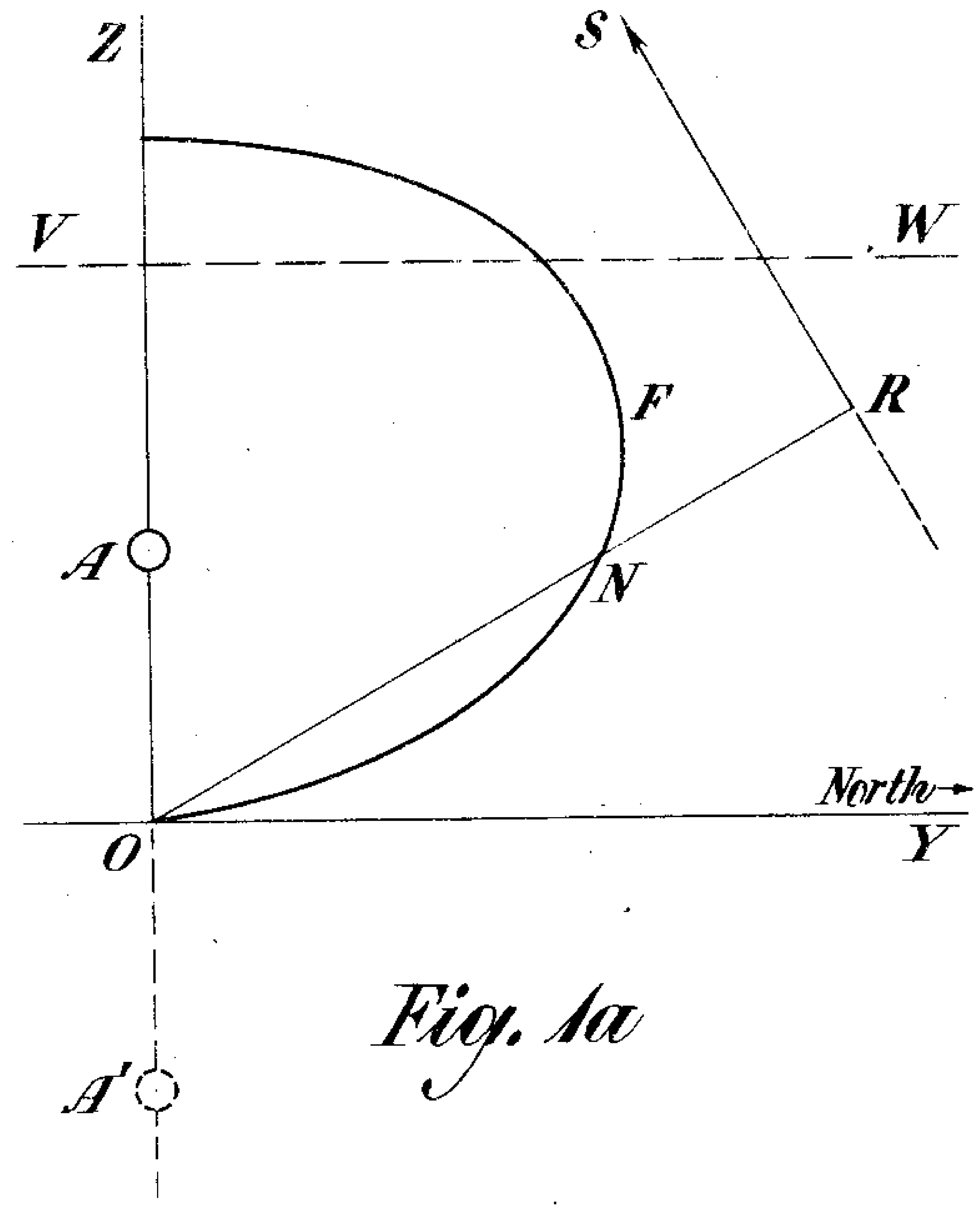

Fig. 1a

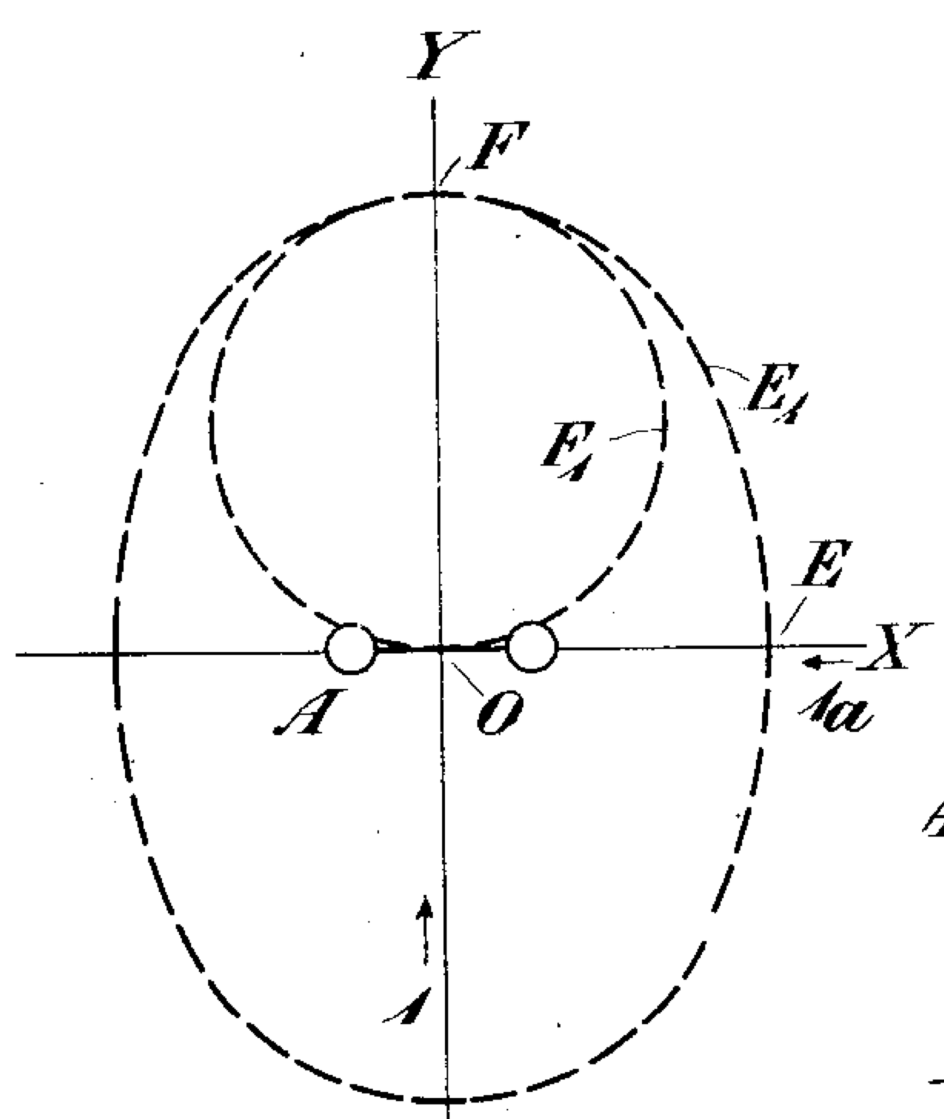

Fig. 1b

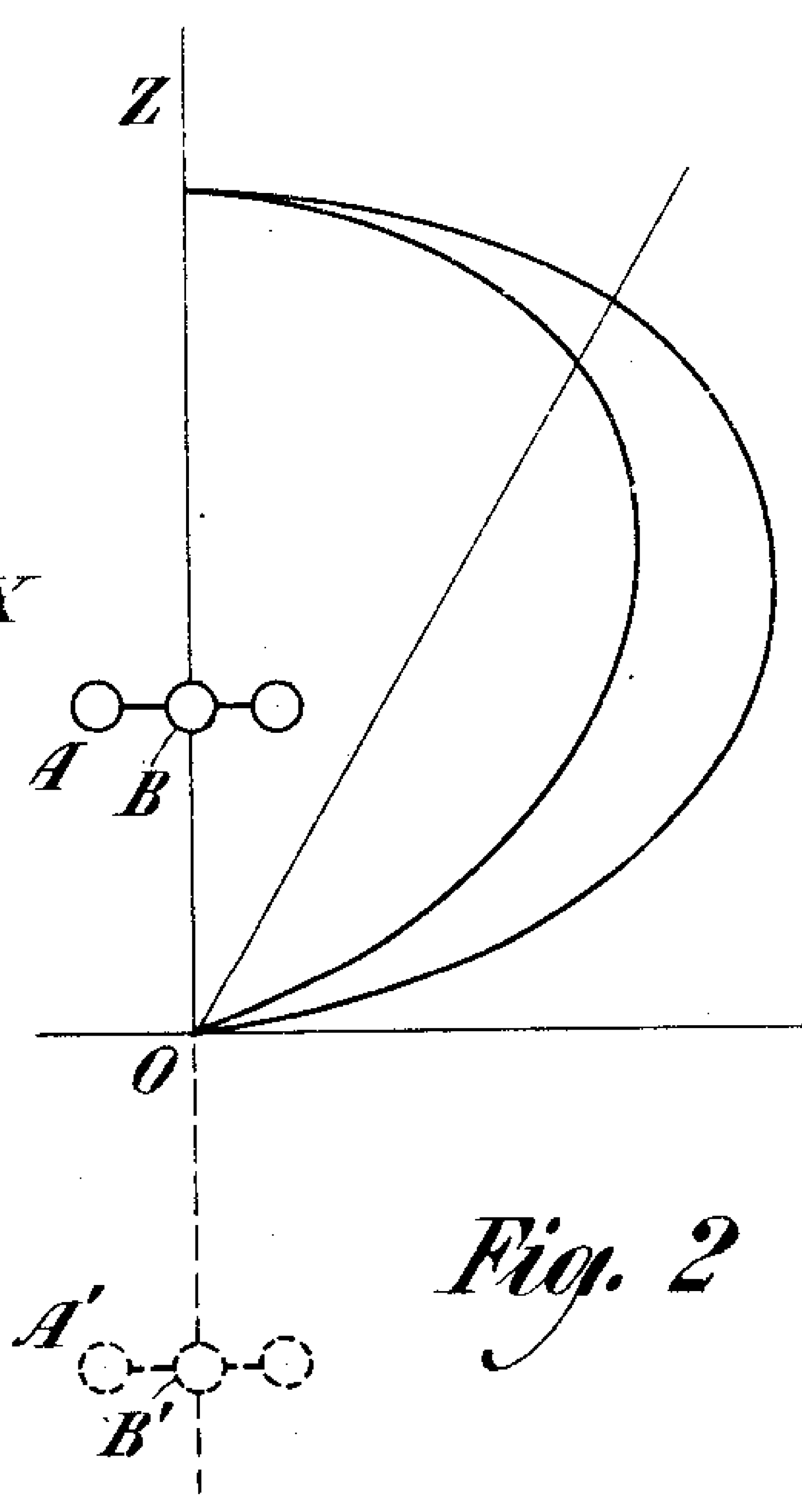

Fig. 2

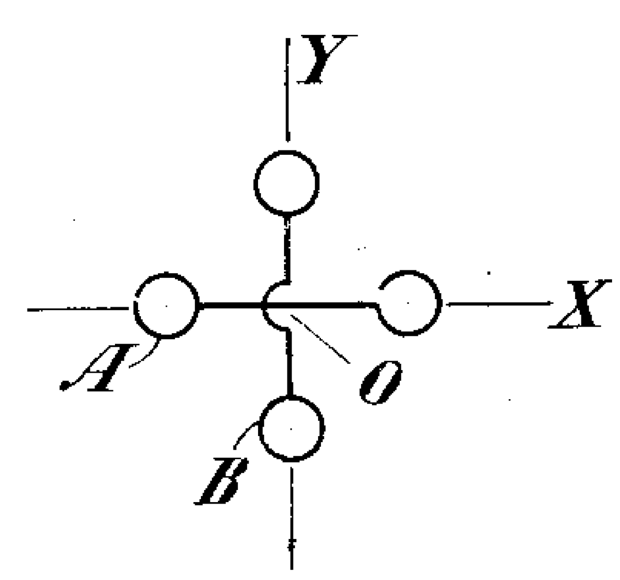

Fig. 2a

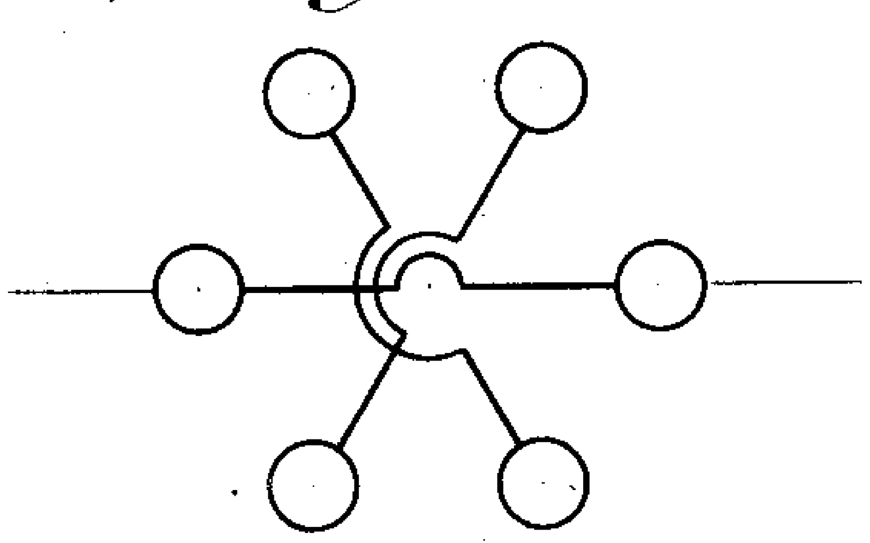

Fig. 2b

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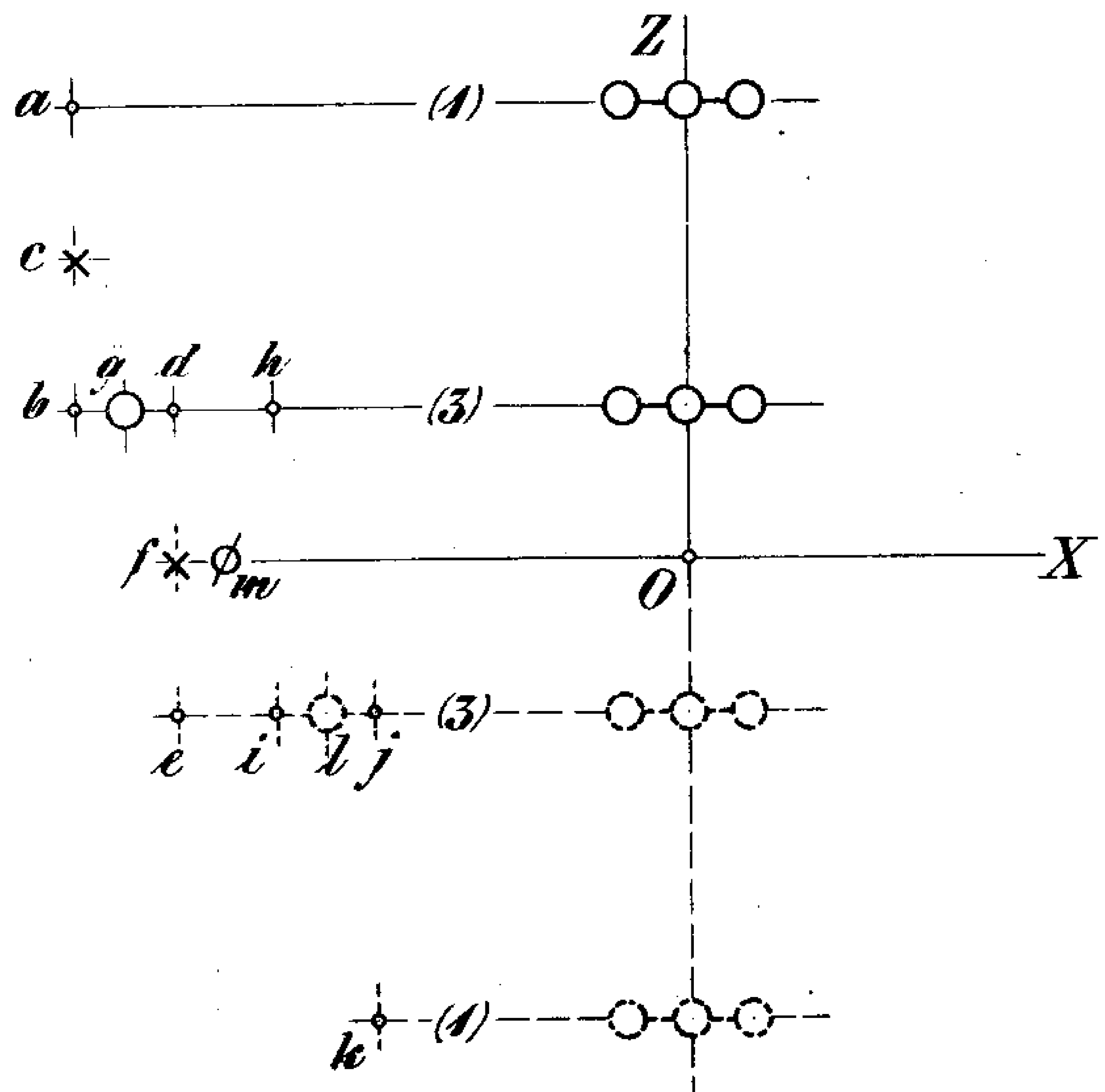

Fig. 3

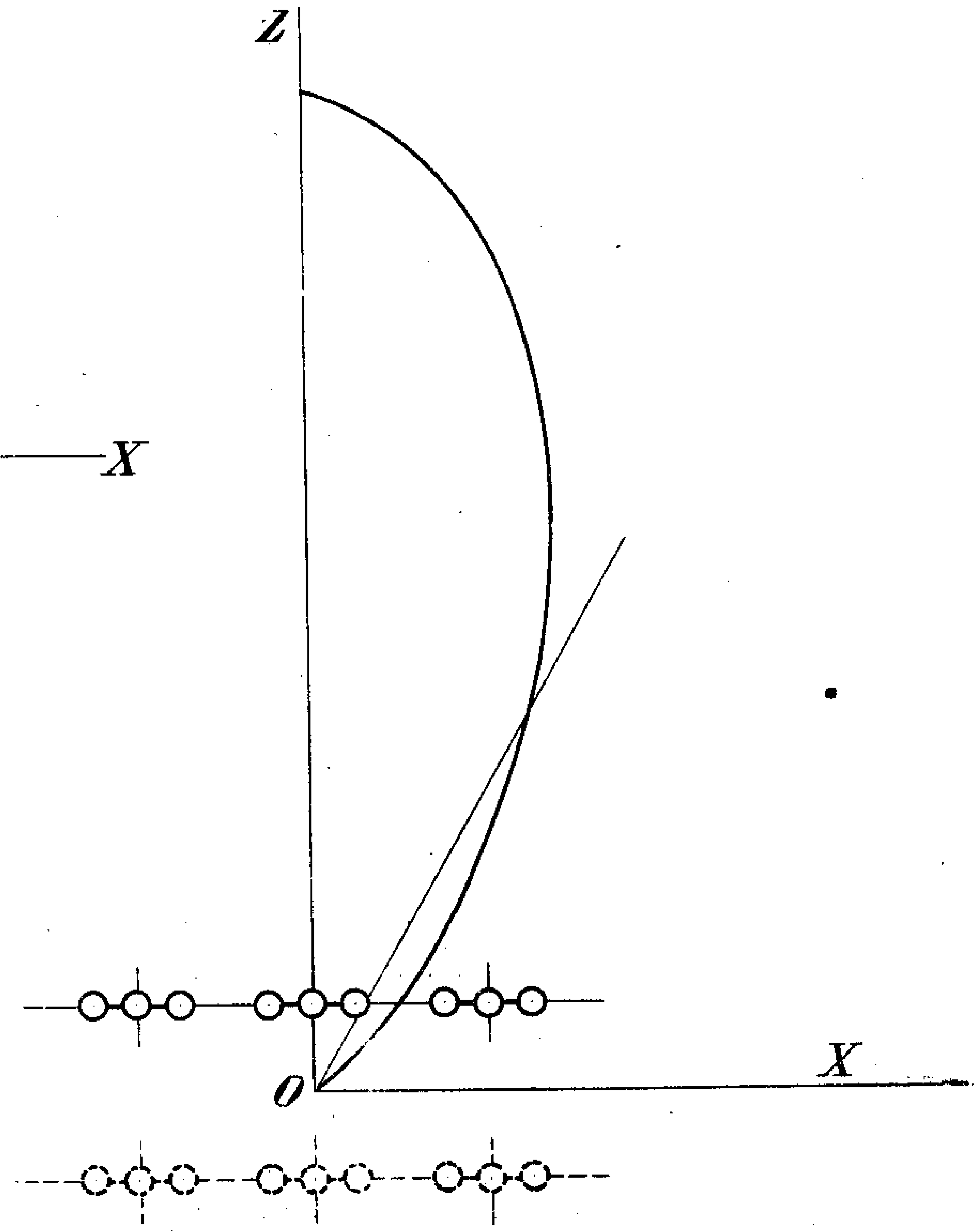

Fig. 5

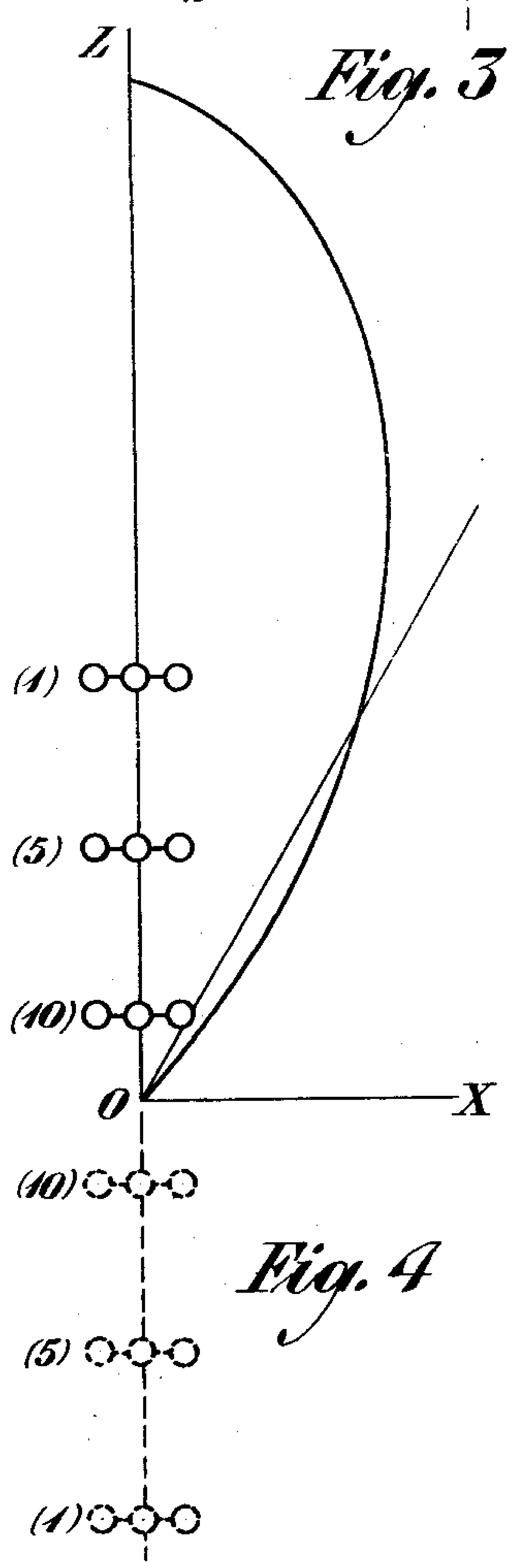

Fig. 4

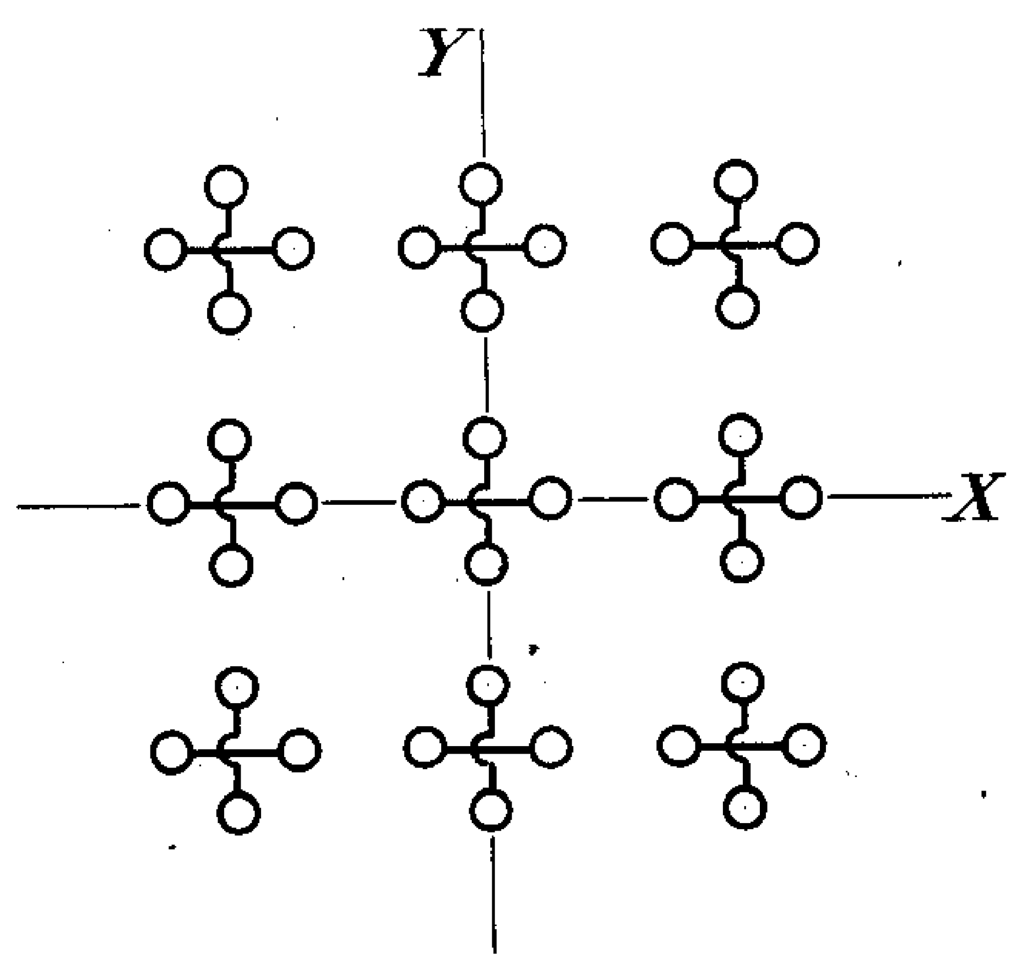

Fig. 5a

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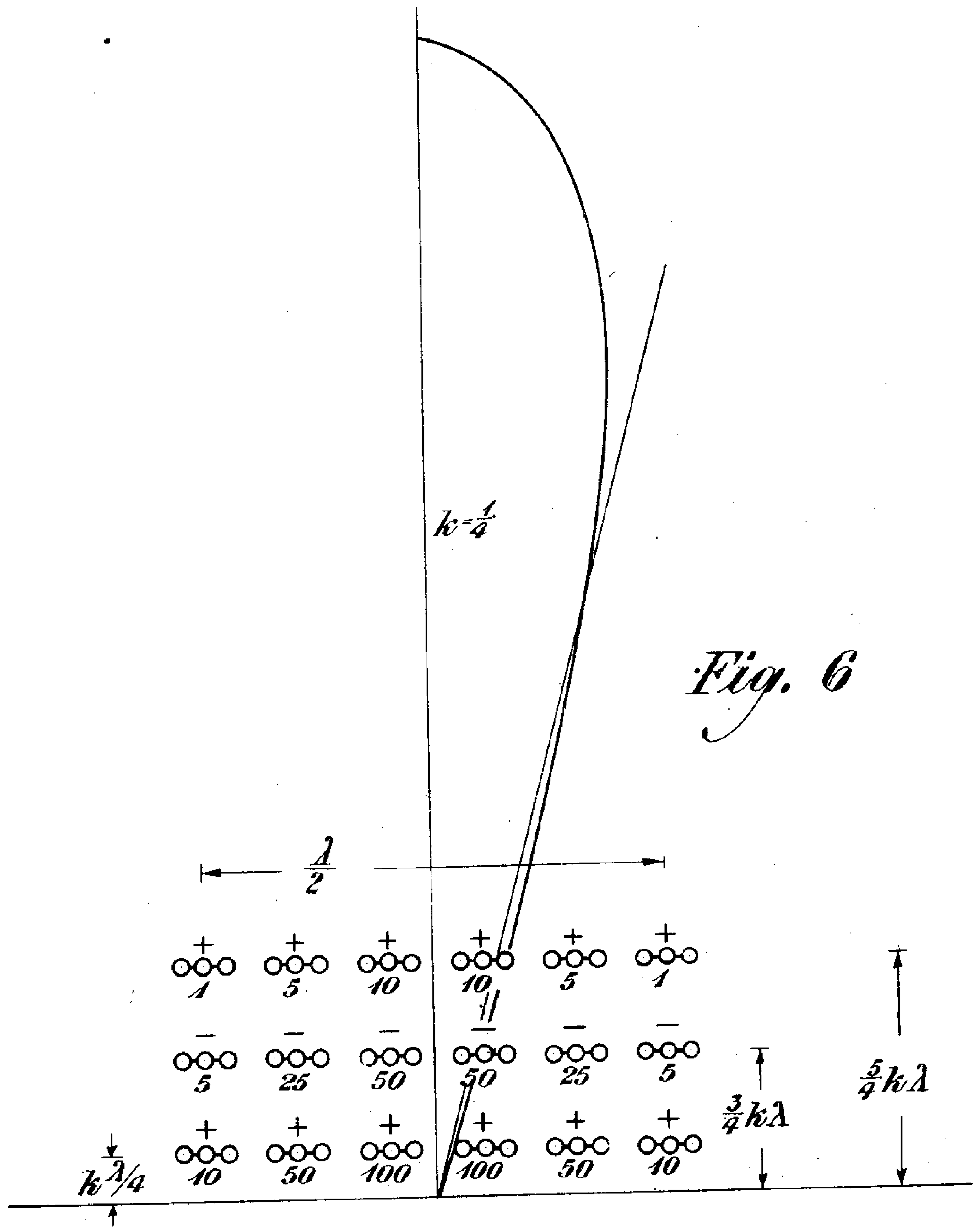

Fig. 6

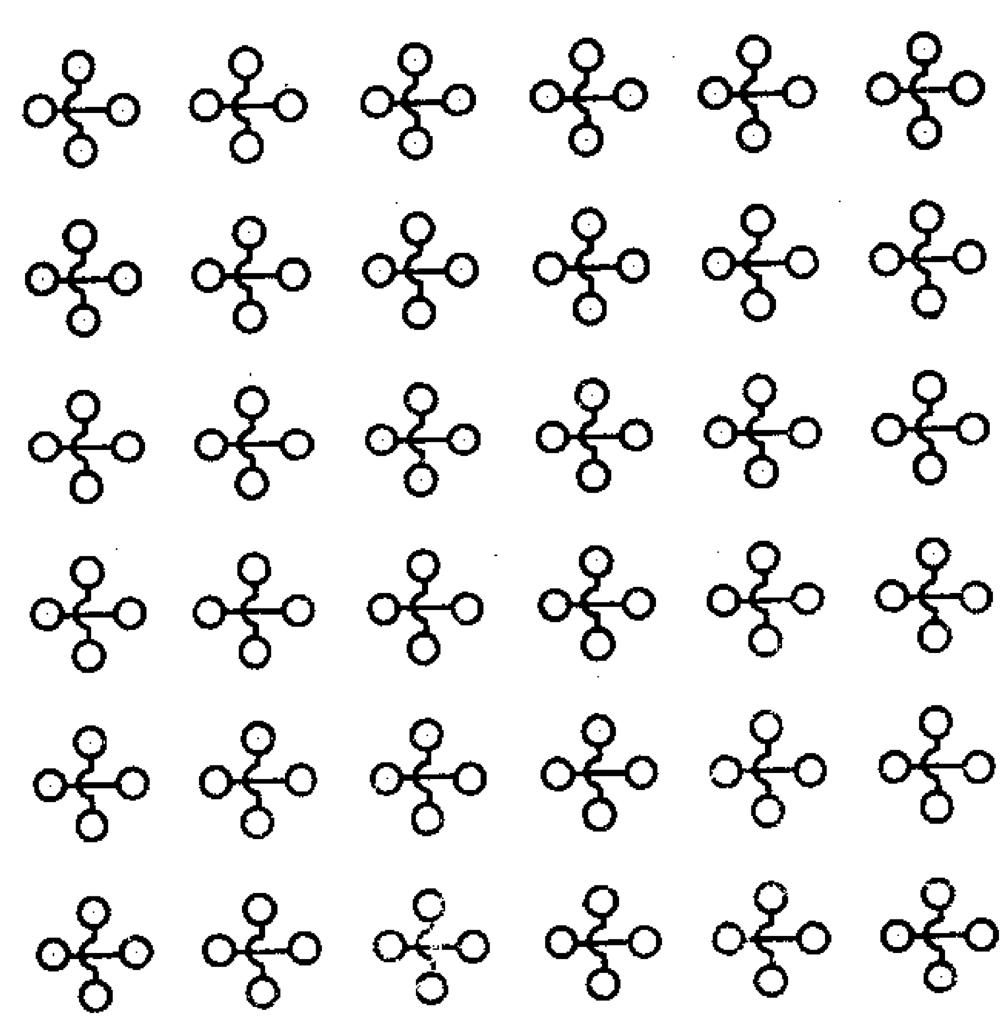

Fig. 6a

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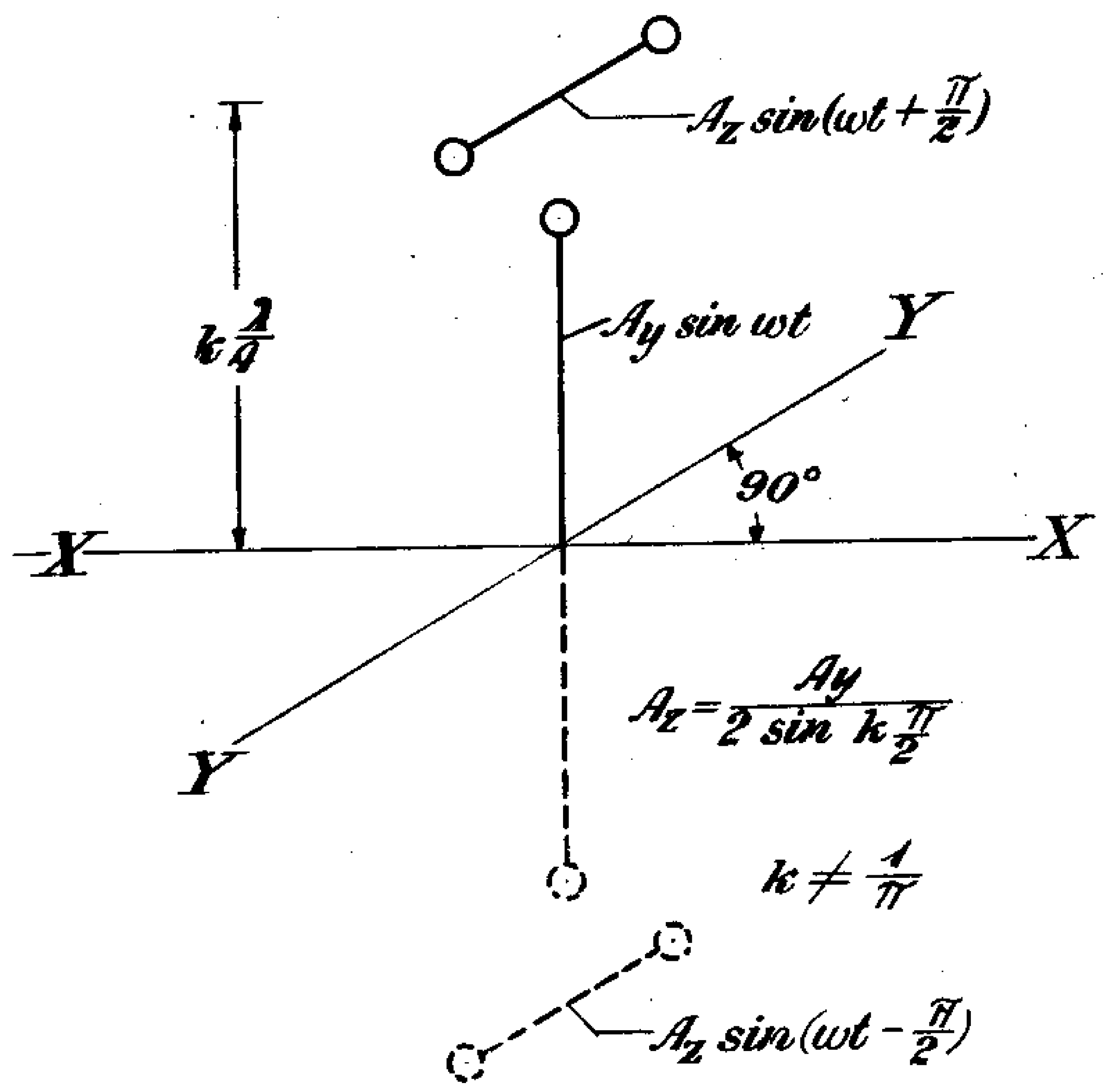

Fig. 7

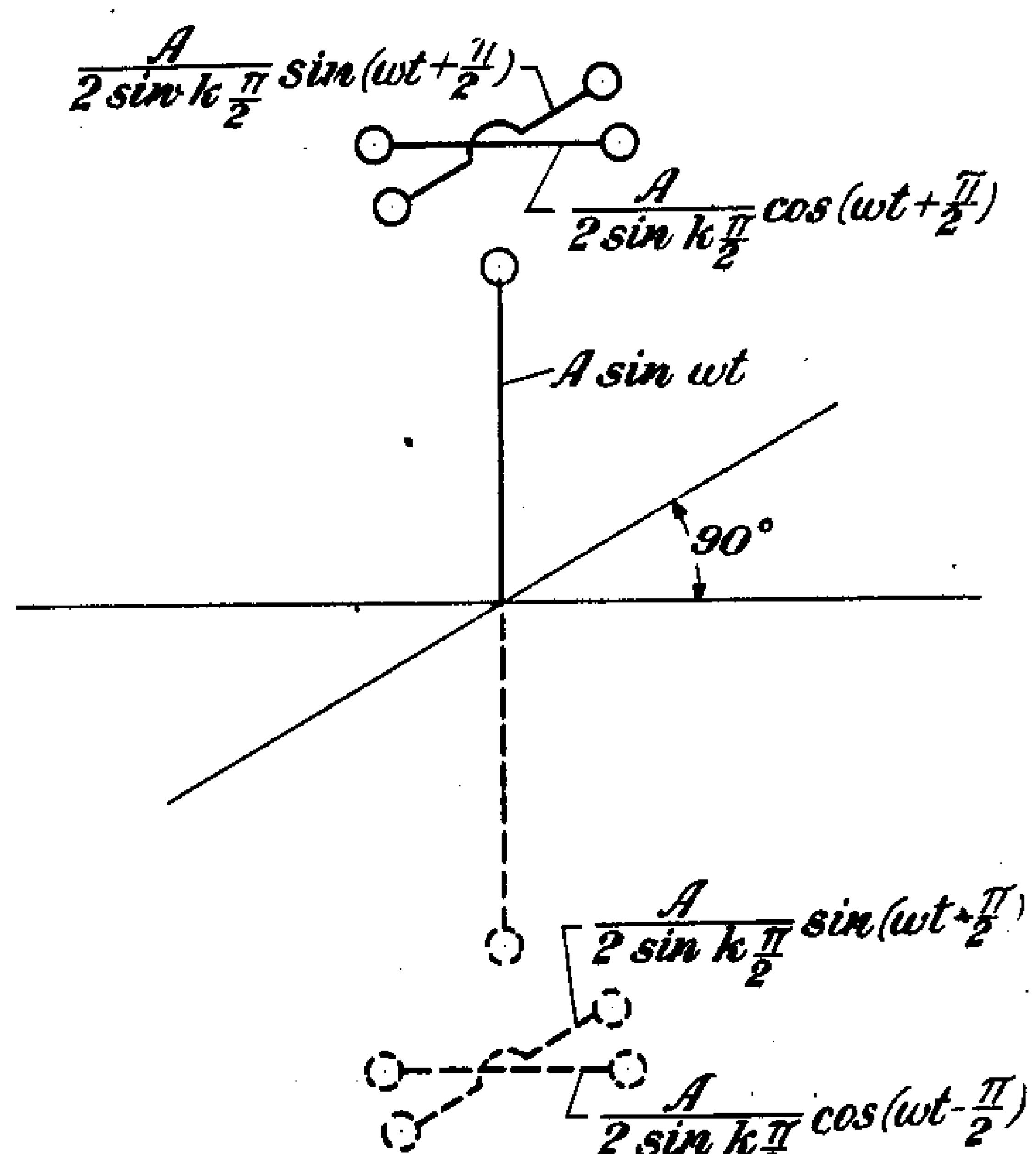

Fig. 8

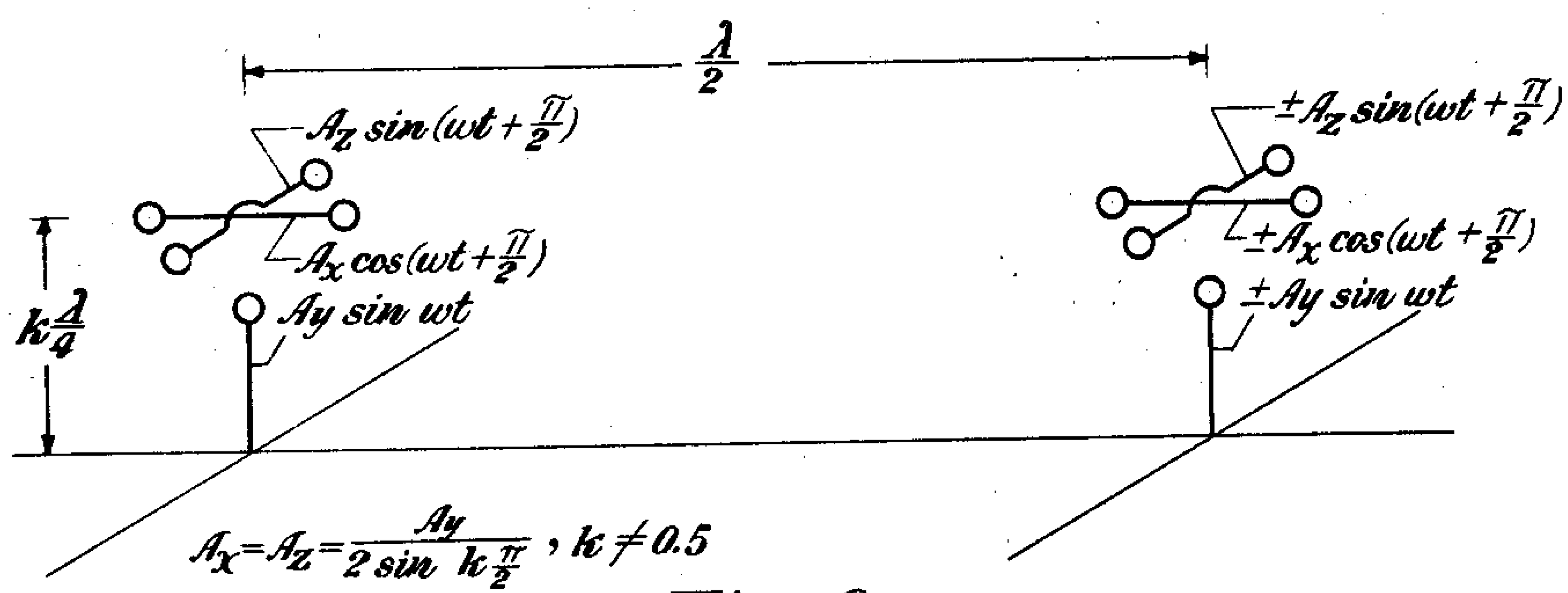

Fig. 9

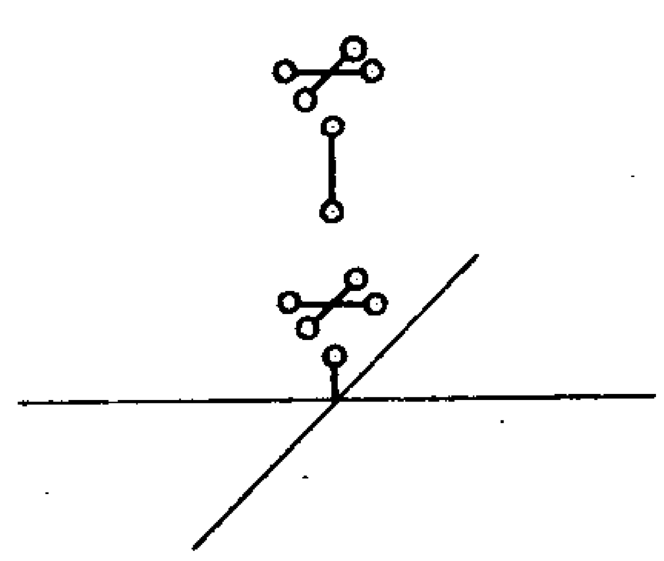

Fig. 10

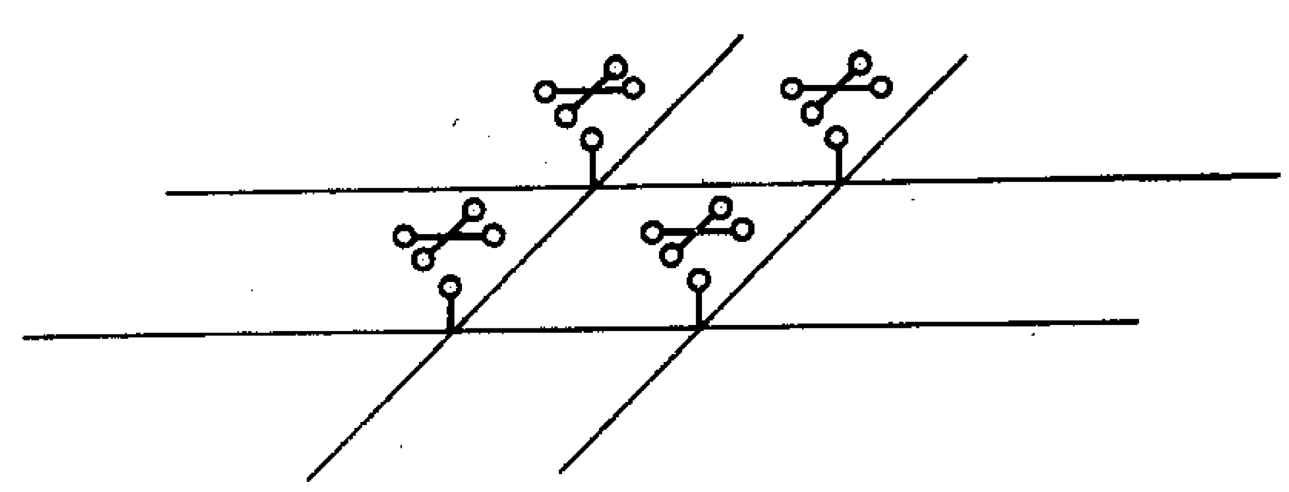

Fig. 11

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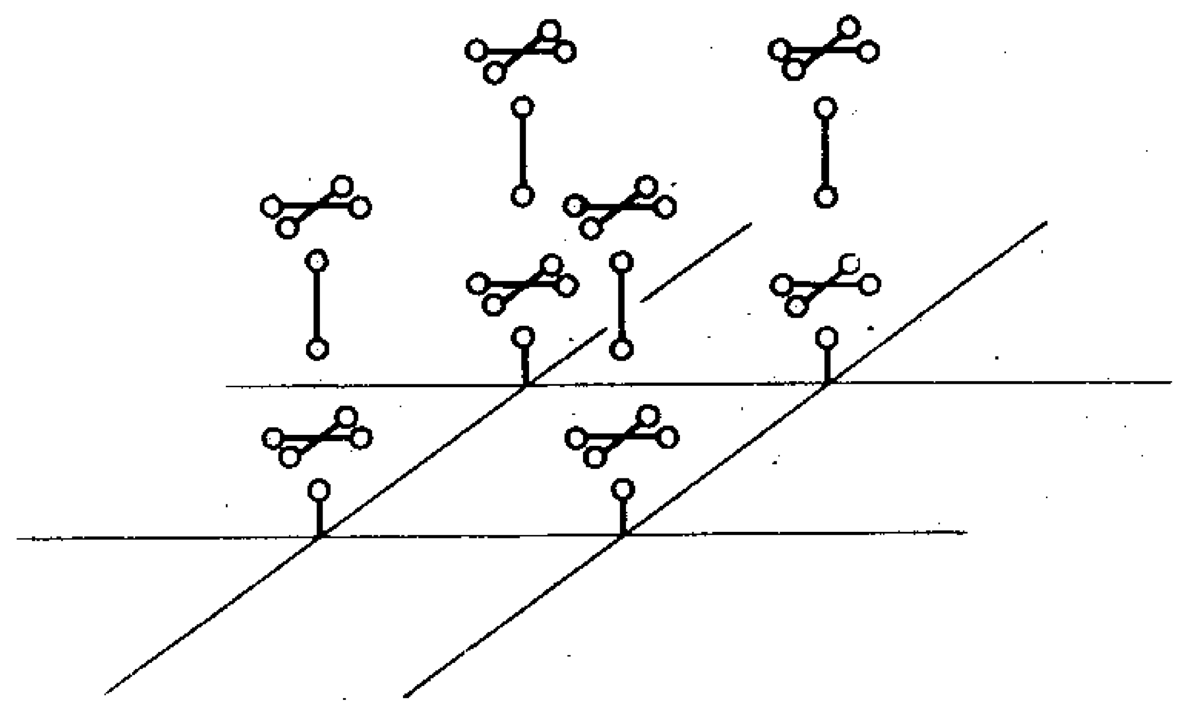

Fig. 12

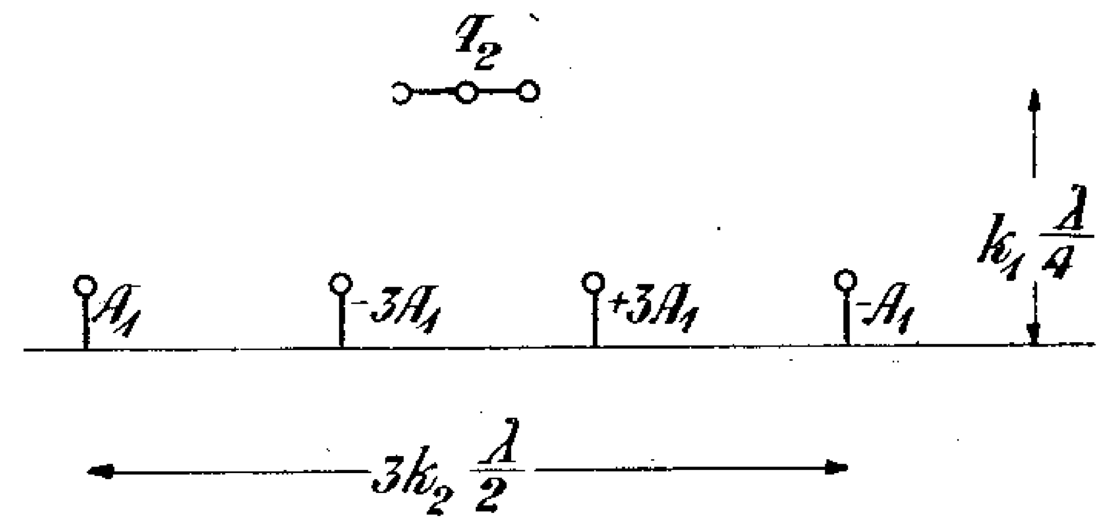

Fig. 14

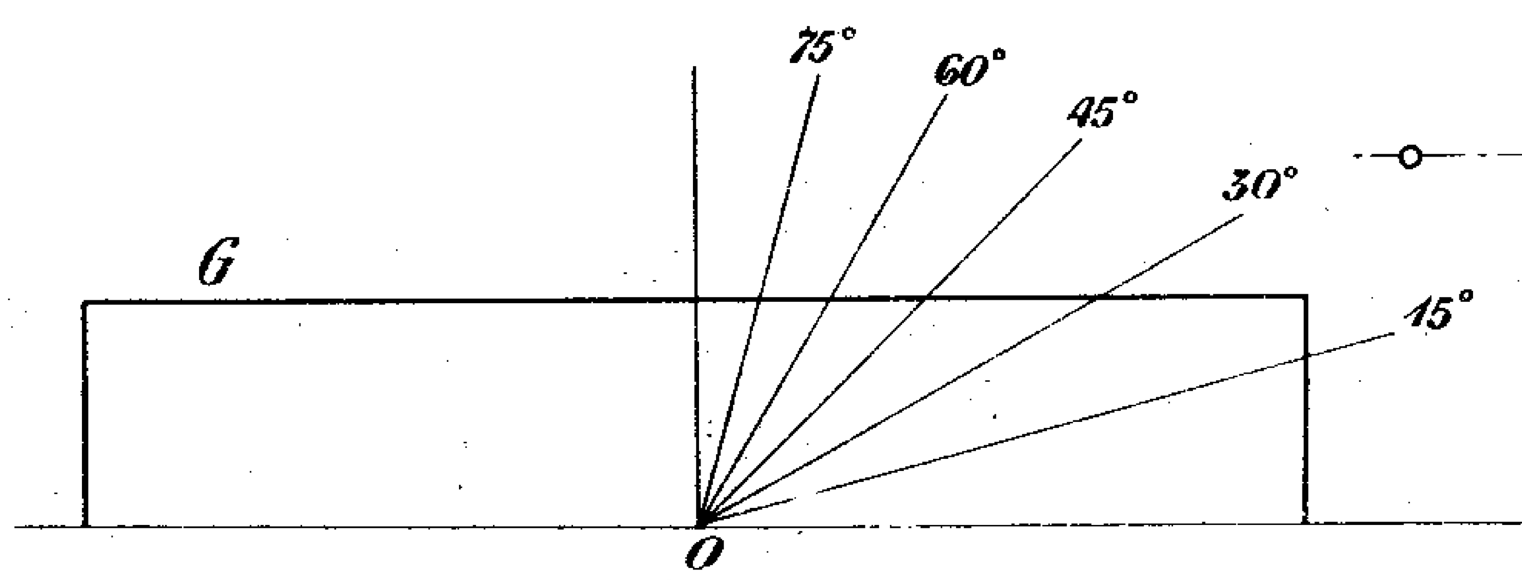

Fig. 13

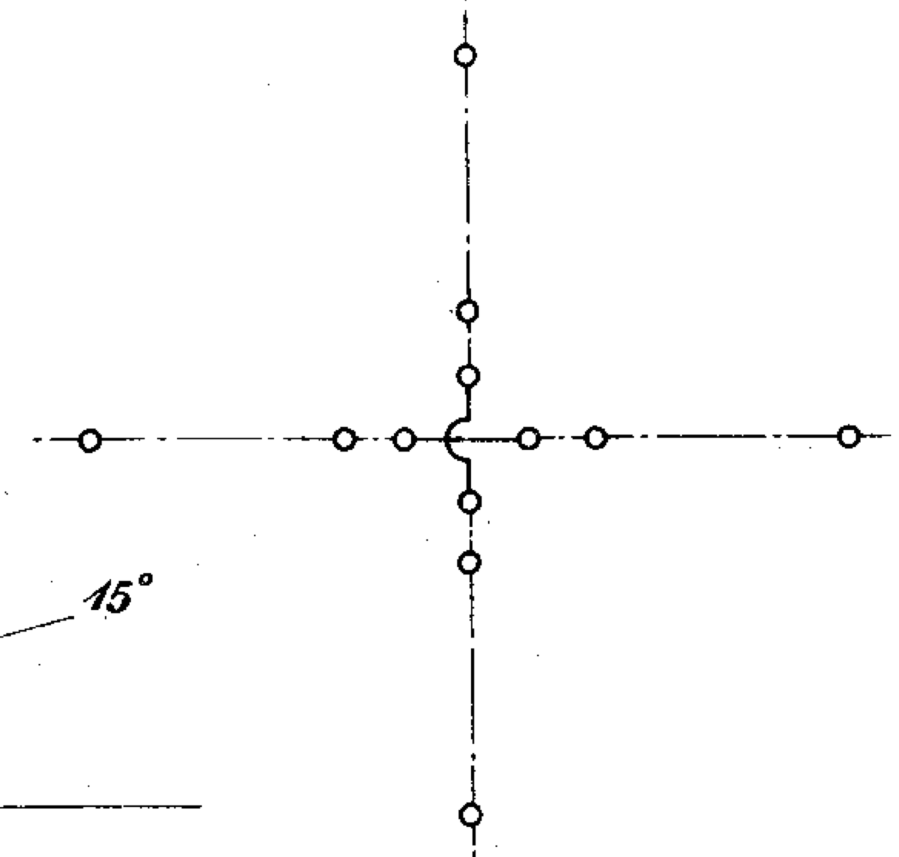

Fig. 14a

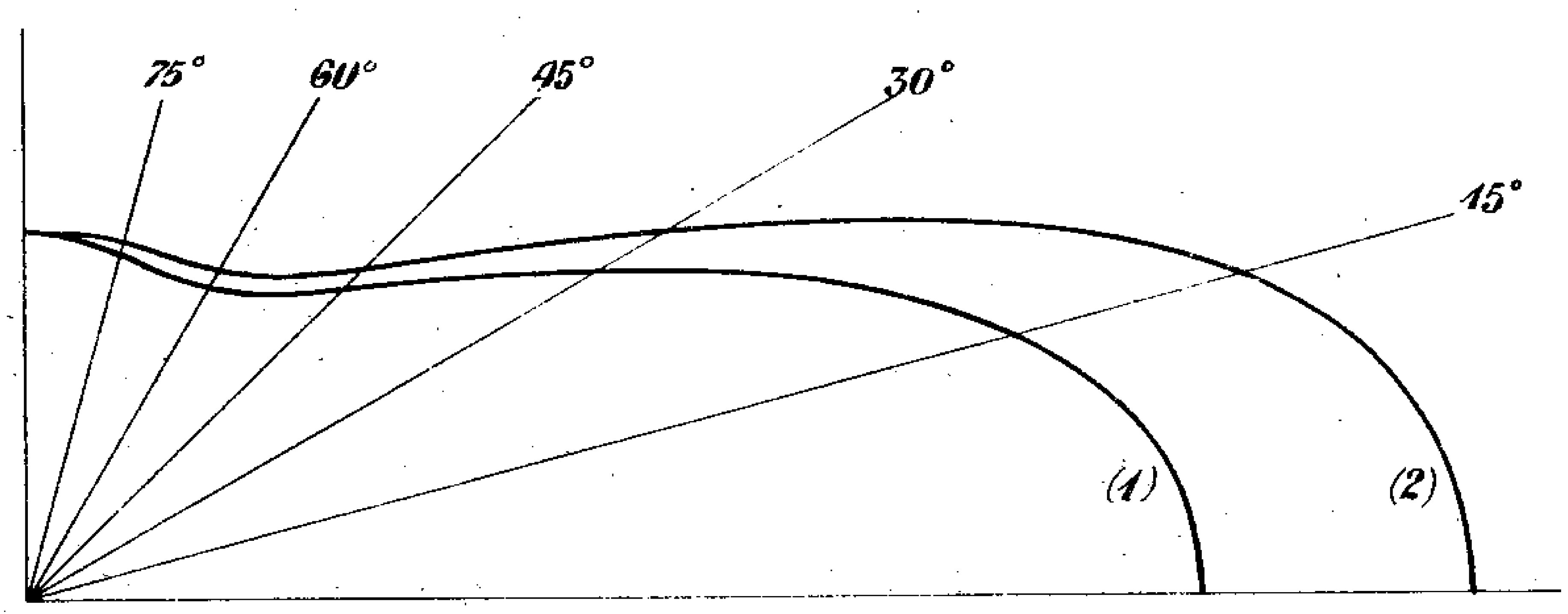

Fig. 14b

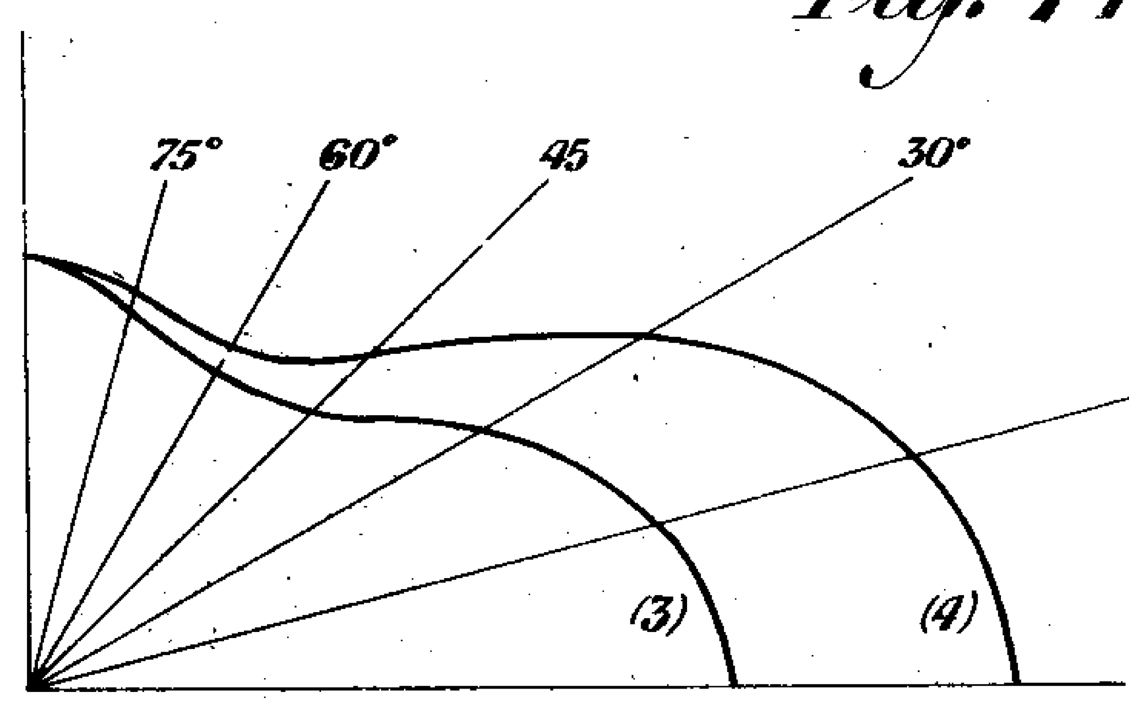

Fig. 14c

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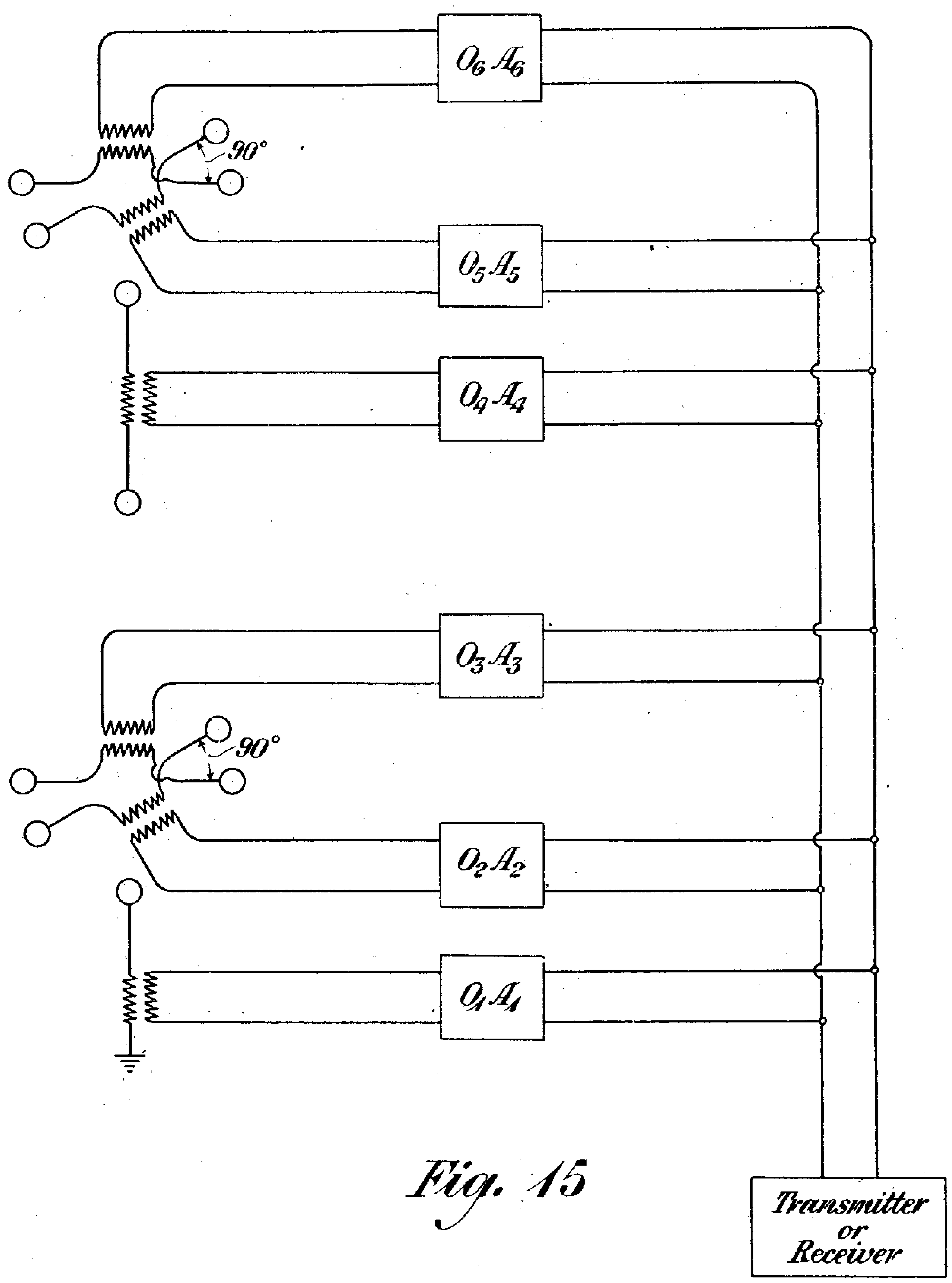

Fig. 15

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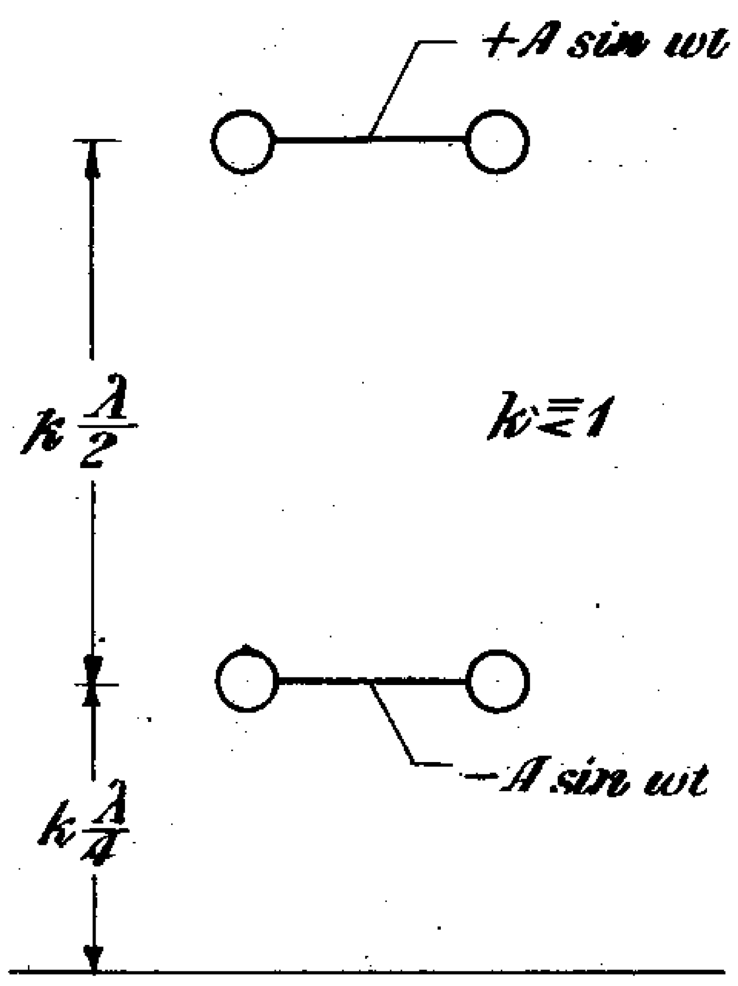

Fig. 16

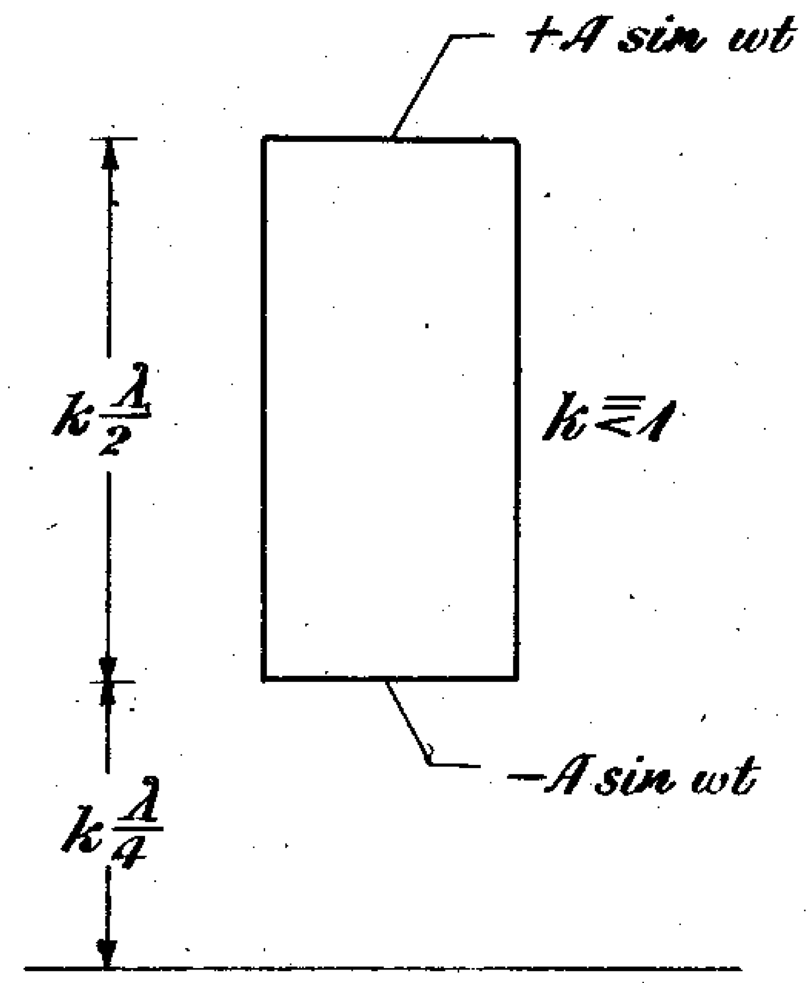

Fig. 17

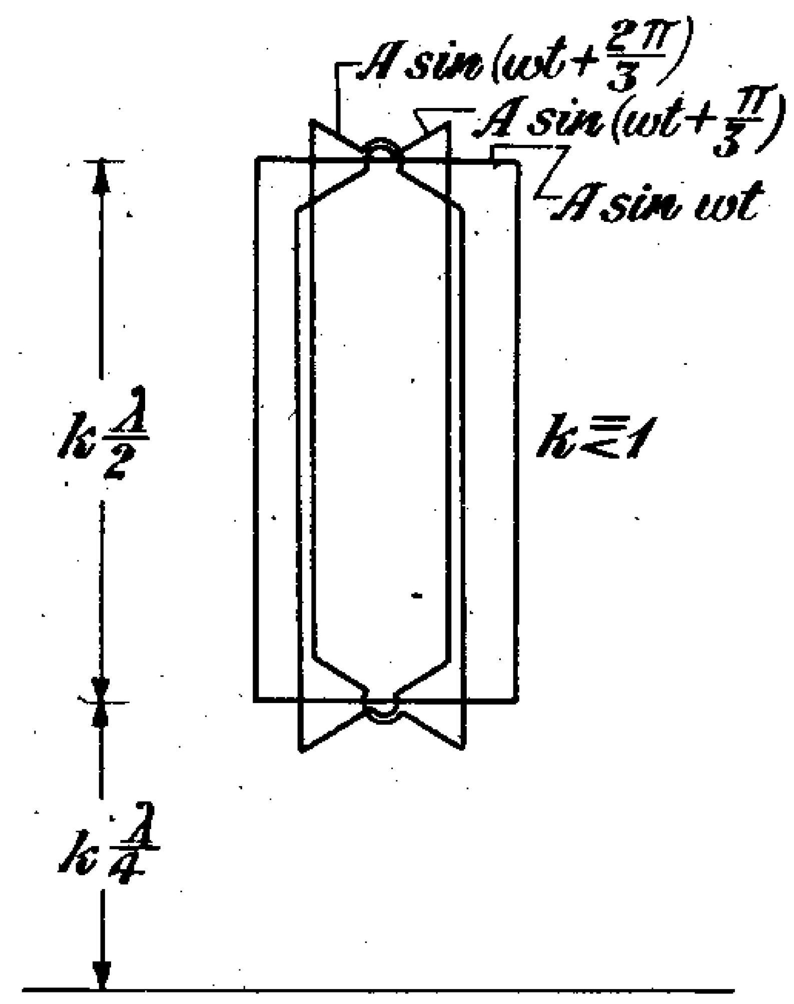

Fig. 18

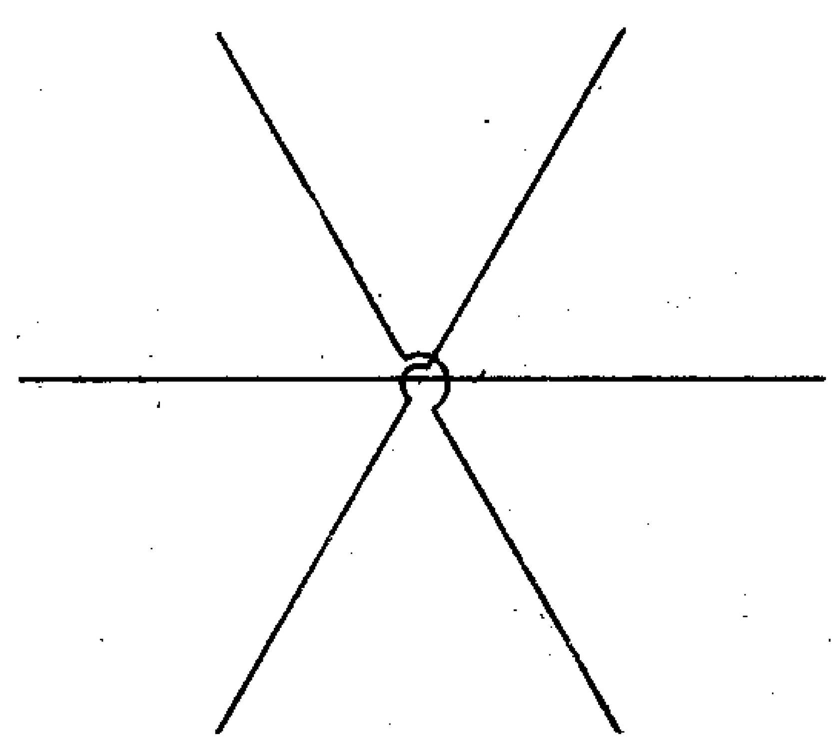

Fig. 18a

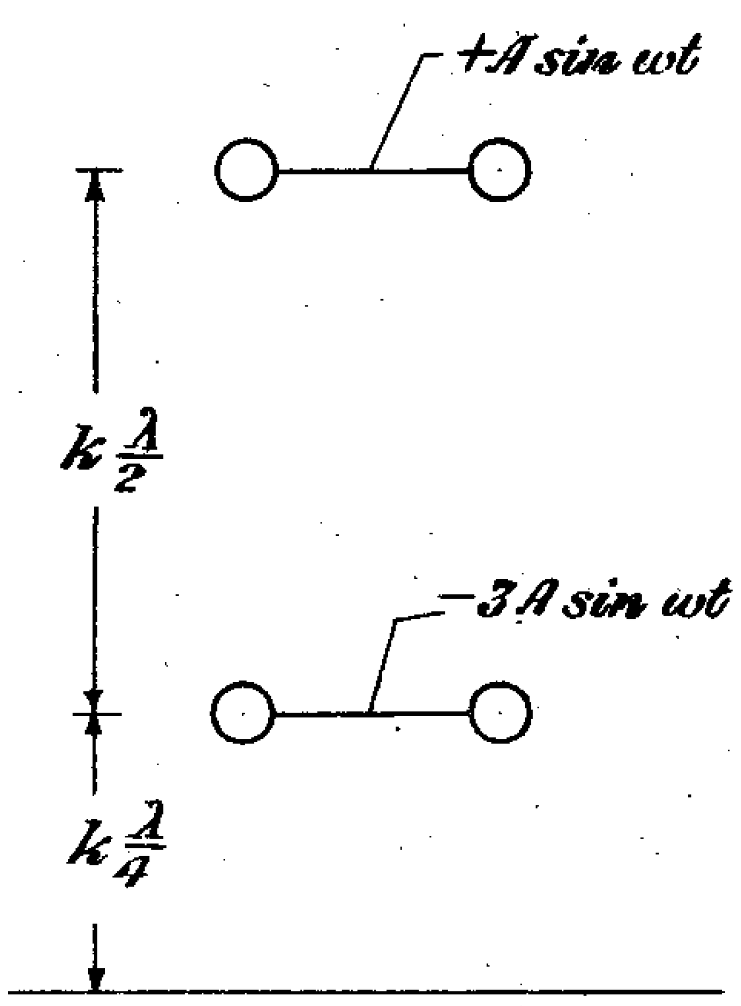

Fig. 19

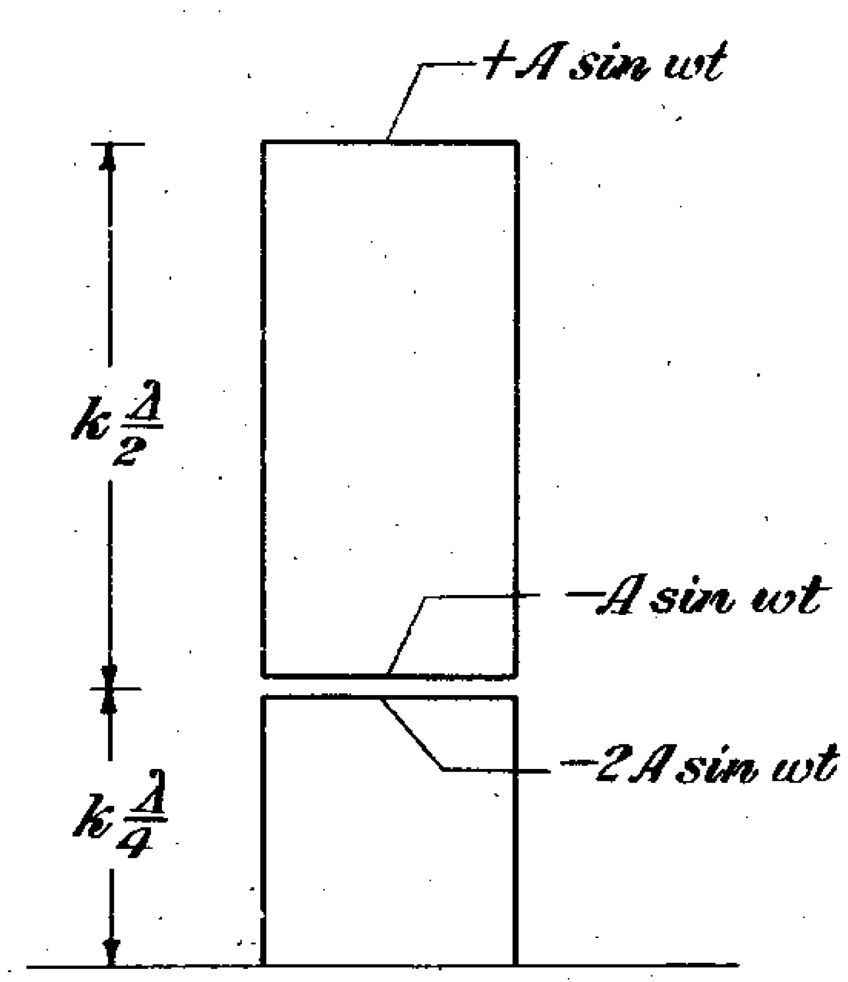

Fig. 20

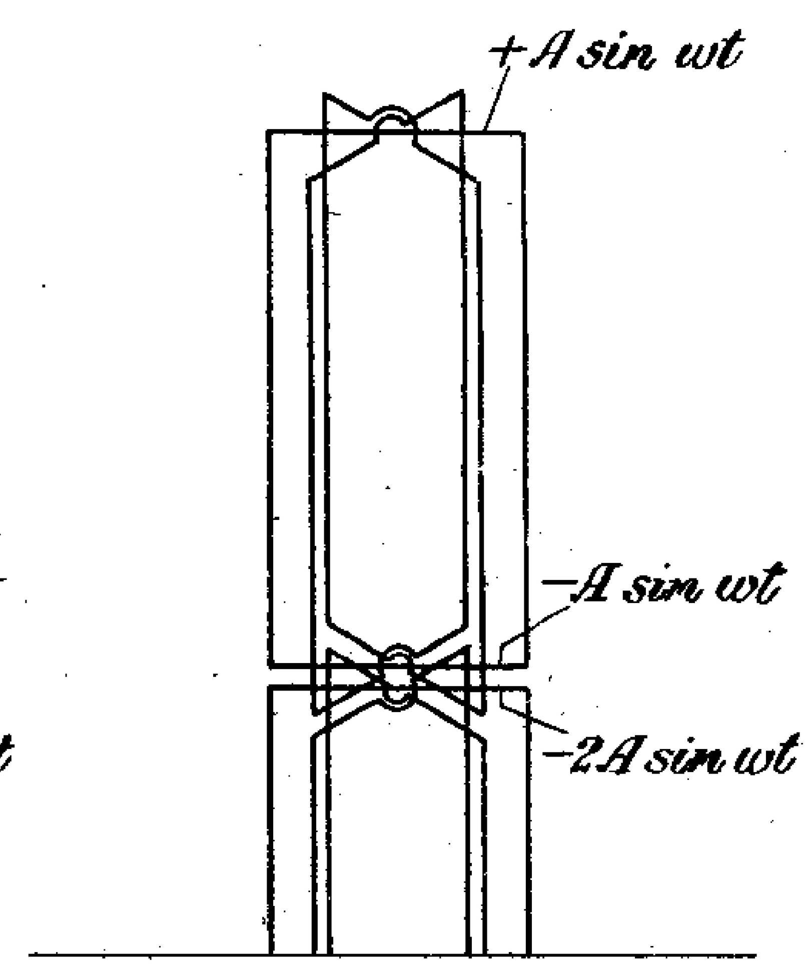

Fig. 21

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Patented June 4, 1929. **1,715,433**

UNITED STATES PATENT OFFICE.

JOHN STONE STONE, OF SAN DIEGO, CALIFORNIA, ASSIGNOR TO AMERICAN TELEPHONE AND TELEGRAPH COMPANY, A CORPORATION OF NEW YORK.

ANTENNA ARRAY.

Application filed August 29, 1922. Serial No. 584,972.

An object of my invention is to provide a system and method adapted for radio signaling between an earth station and an air-ship. Another object of my invention is to provide an antenna array adapted for selective transmission or reception at a desired angle of elevation with respect to the earth's surface. Another object of my invention relates to the generation and transmission of rotary progressive electromagnetic waves for signaling. Still another object of my invention relates to establishing a region or zone in the neighborhood of an earth station adapted for radio communication with an air-ship within that zone, but not adapted for communication with stations outside the zone. These and other objects of my invention will be made apparent in the following specification and claims, taken with the accompanying drawings, in which I have disclosed several embodiments of the invention by way of example. With the understanding that the invention will be defined in the appended claims, I now proceed to describe specifically the examples thereof shown in the drawings.

Figure 1 is an elevation diagram for a horizontal oscillator, looking in the direction of the arrow 1 in Fig. 1^b; Fig. 1^a is an elevation diagram looking in the direction of the arrow 1^a in Fig. 1^b; Fig. 1^b is a top plan diagram for the same oscillator; Fig. 2 is an elevation for a rotary oscillator; Fig. 2^a is a plan for the same; Fig. 2^b is a plan for a rotary oscillator having three linear oscillators as its elements; Fig. 3 is an elevation for a system of oscillators built up from two units like those shown in Fig. 2; Fig. 4 is a similar diagram built up from three units; Fig. 5 is an elevation of an antenna array built up from rotary units disposed in a horizontal plane; Fig. 5^a is a top plan view of the system shown in Fig. 5; Fig. 6 is an elevation of an array of rotary oscillators having three-dimensional extent; Fig. 6^a is a top plan view of the same; Fig. 7 is perspective view of the combination of a horizontal oscillator and a vertical oscillator; Fig. 8 is a perspective view of a combination adapted to transmit or receive with substantially equal intensity in all directions above the earth's surface; Fig. 9 shows a first step in combining the units of Fig. 8; Fig. 10 shows a further step, the units being disposed along a vertical line; Fig. 11 shows a horizontal rectangular array of such units; Fig. 12 shows an array of the units of Fig. 10 having three-dimensional extent; Fig. 13 is a diagram showing an ideal zone or region for radio communication between a station on the earth's surface and an air-ship; Fig. 14 is an elevation of a suitable antenna array corresponding to Fig. 13; Fig. 14^a is a top plan view corresponding to the elevation of Fig. 14; Figs. 14^b and 14^c give approximate curves of polar intensity with different choices of the constants for the array of Figs. 14 and 14^a; Fig. 15 is a diagram of a system for energizing the oscillator units in proper amplitude and phase relation; Fig. 16 is a diagram of a simple array of two equal oscillators; Fig. 17 is a diagram of an equivalent coil or loop; Fig. 18 shows in isometric projection three such coils or loops arranged to give a rotary resultant; Fig. 18^a is a plan view corresponding to Fig. 18; Fig. 19 shows those of the oscillators of Fig. 3 which lie in one vertical plane; Fig. 20 shows a coil system equivalent to Fig. 19; and Fig. 21 shows a plurality of sets like Fig. 20 arranged to give a rotary resultant.

In Fig. 1 there is shown a conventional representation of an oscillator A, consisting of two conductive spheres joined together by a direct conductive bar. This is disposed above the earth's surface with its axis horizontal. For convenience of reference, rectangular coordinate axes are indicated, OX on the earth's surface to the east, OY on the earth's surface to the north, and OZ extending vertically. The axis of the oscillator A is parallel to the coordinate axis OX.

It is assumed that the earth's surface is a perfect conductor. This will be substantially the fact in many situations, and in any case a metallic network laid on the earth's surface to form a surface ground will give a close enough approach to this ideal condition for practical purposes.

With the assumption that the earth's surface is a perfect conductor, the theory of radiation by the oscillator A, or reception thereby, may be advantageously worked out by means of the usual hypothesis which assumes an image at A′ whose electrical condition in all parts is always equal and opposite to that in the oscillator A.

Working from the image hypothesis, it can readily be shown that the intensity of the electric force at a distant point P in the XZ plane will be given by a vector PQ in that plane at a right angle to the radius vector OP and of a magnitude equal to OM, the corresponding radius vector of a curve E having approximately the shape shown in Fig. 1. In the XZ plane there is no magnetic force in any direction.

In the YZ plane (Fig. 1[a]), the magnetic force at a distant point R is given by the line RS in that plane and at a right angle to the radius vector OR and of magnitude equal to ON, the radius vector of the curve F. The electric force for a point R in the YZ plane is perpendicular to that plane at the point R and its magnitude is also represented by ON.

It will readily be appreciated that for other planes containing the vertical axis OZ there will be loci corresponding to those designated E and F for the XZ and YZ planes, respectively, and these plane loci collectively will form surface loci. Fig. 1[b] shows in dotted lines E_1 and F_1 the intersection of a horizontal plane VW with these loci.

In Figs. 2 and 2[a] two oscillators A and B are shown in the same horizontal plane with their axes respectively parallel to OX and OY. The hypothetical image oscillators are shown at A′ and B′ in Fig. 2. The oscillators A and B are operated a quarter-phase apart. Combining their radiation into one resultant, by combining the corresponding diagrams for each oscillator as shown in Figs. 1, 1[a] and 1[b], the result is reached that the radiation is substantially the same in any plane containing the vertical axis OZ. This substantial agreement in the intensity of radiation is indicated by the two curves in Fig. 2, approximating to the region in which the curve will lie for any angular position of the plane referred to. I call the combined oscillator AB of Figs. 2 and 2[a] a rotary oscillator. Inasmuch as the radius vector for the curves shown in Fig. 2 becomes zero when the radius vector is horizontal, it will be seen that the radiation from this rotary oscillator is entirely upward, though it extends over a wide angle.

A rotary oscillator may be made up from three or more component oscillators instead of two merely. For example, in Fig. 2[b] I have shown a rotary oscillator composed of three linear oscillators set 120° apart and differing in phase by 120°. The radiation produced in this case is more truly rotary than in the case of the two-element rotary oscillator of Fig. 2, but the earlier figure gives a sufficient approximation for most practical cases.

Letting the dot a in Fig. 3 represent one rotary oscillator with axis of rotation vertical, and letting the dot b represent a similar rotary oscillator with the same vertical axis of rotation and in the opposite phase, the cross designated c represents the pair ab considered as a unit. The distance between a and b should be equal to or less than a half-wave length for the purpose that I have in view and which I will point out presently. Another pair de is represented by the cross f. I call c or f a consequent source of the first order. These two consequent sources of the first order, c and f, taken together, are represented by the small circle g which I call a consequent source of the second order.

The primary sources hi and jk, giving consequent sources of the first order, combine to give a consequent source of the second order designated l. The two consequent sources of the second order, g and l are viewed as a unit consequent source of the third order, designated m. Reviewing the procedure by which this array of primary sources is built up, it will be seen that at four equally spaced vertical positions there will be, respectively, 1, 3, 3 and 1 primary sources as indicated by the numerals in parentheses in Fig. 3. The numerals are the coefficients of the binomial expansion, thus $(1+1)^3=1+3+3+1$. Evidently the procedure can be carried to any extent and the formula for a consequent source of the nth order is

$$(1+1)^n=1+n+\frac{n(n-1)}{2!}+\ \dots$$

I now assume that the earth's surface OX bisects the vertical range previously considered making the sources below that surface hypothetical, in accordance with the image theory. Thus I have, above the earth's surface as shown, two rotary oscillators, the lower one having three times the intensity of the upper one. This explains the first step in assembling the units of Figs. 2 and 2[a] in a vertical range. By taking two more steps, that is, by passing to a consequent source of the fifth order, the array of Fig. 4 is obtained. In any case, I arrive at a consequent source of odd order, that is I make "n" an odd number in the foregoing formula $(1+1)^n$.

The curve given in Fig. 4 exhibits the resultant intensity in various directions based on such curves as Fig. 2 for the elemental oscillators, it being assumed that the distance between these oscillators in the vertical direction is a suitable fraction of one-half wave length. The smaller this fraction is made, the narrower becomes the curve, and the more the range of oscillators is extended by adding units upwardly, the narrower the curve becomes. Thus it will be seen that with such a vertical range of rotary oscillators as shown in Fig. 4, it is possible to direct a beam of radiation only in directions which are principally vertical. A sort of inverted cone of radiation exists, with its vertex at the station on the earth's surface and its axis extending vertically upwardly.

The rotary oscillator units can also be combined in a rectangular horizontal array to get somewhat the same effect, as shown in Figs. 5 and 5ª. Here the oscillators are all in the same phase and they are arranged in a rectangular array one-quarter wave length apart along each of the principal dimensions. The polar curve for intensity of radiation in any plane containing the vertical axis is approximately that given in Fig. 5.

Figs. 6 and 6ª show an array of rotary oscillators having three-dimensional extent, thus combining the principles discussed for Figs. 4 and 5. In this particular case, the oscillators are only one-fifth wave length apart on each horizontal dimension, and less than one-half wave length apart in the vertical direction. The polar diagram for intensity is seen to be sharply selective for the vertical direction. This diagram has been calculated on the assumption that the vertical spacing is only one-eighth wave length.

The vertical ray station that I have disclosed in the foregoing part of this specification has the very useful characteristic of not interfering with stations engaged in intercommunication between points on the earth's surface, and such stations will not interfere with the vertical ray station. Moreover, the vertical ray station will be immune from interference by stray electromagnetic waves surging over the earth's surface, which are probably the cause of the greater part of "static" and other interference effects.

A vertical ray station will be adapted for communication with an air-plane in a comparatively limited region directly overhead. Thus, in time of war, it will be possible for an air-ship to communicate with a station on the earth's surface beneath it, without enemy air-ships and enemy land stations elsewhere being able to pick up messages. The zone above the earth's surface could be especially protected by anti-aircraft guns on the land, and thus made safe for co-operating air-ships desiring to communicate.

Vertical ray stations could be multiplied in great numbers over the earth's surface without causing interference, as will readily be apparent. Thus, air-ships passing over a designated route could establish communication at vertical points without developing troublesome interference. Such stations may serve as invisible beacons by which air-ships may get their bearings when vision is obscured or when the earth's surface lacks pronounced landmarks.

For cases in which it is desired to establish communication with an air-ship at various overhead points in its neighborhood without limitation to places directly overhead, I build up an array in the manner which I will now proceed to describe. Fig. 7 illustrates the first step; here an oscillator with its axis parallel to the X axis is combined with a vertical oscillator. This last oscillator is represented structurally by an antenna with an overhead capacity, the image theory being relied on to build up the hypothetical complete oscillator as shown in dotted lines. Then we may pass to the combination shown in Fig. 8, in which a rotary oscillator with axis of rotation vertical is combined with a vertical oscillator as shown. Letting the current in the vertical oscillator be represented by A sin ωt, then the currents in the two component oscillators of the rotary oscillator should be represented by

$$\frac{A}{2 \sin k\pi/2} \sin (\omega t + \pi/2) \text{ and }$$
$$\frac{A}{2 \sin k\pi/2} \cos (\omega t + \pi/2).$$

By taking k less than $1/\pi$ and putting the center of the rotary oscillator at a distance $k/4$ of a wave length from the center of the vertical oscillator, the result is secured that the radiation is substantially spherical or, remembering that all parts below the earth's surface are hypothetical, the radiation is hemispherical, with the center at O. I refer to the combination shown in Fig. 8 as a spherical source.

Such sources may be combined according to a method of building up consequent sources of first, second and higher orders corresponding to that which has already been disclosed for rotary sources. Fig. 9 shows two such spherical sources combined along the X axis; Fig. 10 shows several such spherical sources combined along the Z axis, and Fig. 11 shows a horizontal rectangular array formed of such spherical sources. In Fig. 12, a three-dimensional array of spherical sources is shown. By suitably proportioning the intensities, spherical sources can be combined to give aproximately any desired zone of radiation. For a specific example, suppose it is desired that the intensity of radiation from a station O shall be as shown by the line G in Fig. 13, which may be looked upon as a vertical section of the surface of a right cylinder whose axis is vertical. This would means that for a certain limiting intensity of transmission an air-ship could communicate with the station only from points within this cylindrical space. Thus the station could communicate with air-ships over a horizontal area of suitable width, but the component of the energy of the waves going upward would be made so low that not enough energy would reach an elevation of 35 miles from the earth's surface to call into play the disturbing effects of the ionized layer of the atmosphere. Moreover, this distribution shown in Fig. 13 would require a minimum amount of power for intercommunication with aircraft over a given vertical and horizontal range.

It will not be necessary here to go into details in working out an array to approximate the requirement indicated in Fig. 13. A suitable array is shown in elevation and plan in

Figs. 14 and 14^a. Figs. 14^b and 14^c show different curves that may be obtained as approximations toward the rectangle G of Fig. 13, by different choices of the constants. The height of the rotary oscillator above the earth's surface is one-quarter wave length for the curve 1, and one-sixteenth wave length for each of the curves 2, 3 and 4. The intensities or amplitudes in the various oscillators are indicated by the letters A_1 and A_2 with their numerical coefficients in Fig. 14, and the ratio of A_1 to A_2 is $\sqrt{8}$ for curve 1, $\sqrt{10}$ for curve 2, $\sqrt{2}$ for curve 3, and $\sqrt{4}$ for curve 4.

In the ordinary system of vertical antenna or antennæ the radiation is substantially all in a horizontal direction or directions, and there is a blind spot for the vertical direction so that in the very location in which communication may be most desired with an air-ship, it becomes impossible. With an array of Fig. 14, there is no blind spot overhead. Both directly overhead and for a considerable distance at the same height on every side, the reception will be of substantially the same intensity, but beyond that distance will fall off rather abruptly.

Fig. 15 represents either a transmitting or receiving system. Suitable phase shifters and amplifiers will be interposed in the branch circuits to the respective oscillators so as to establish the relations of phase and intensity set forth in the specification.

Thus far in the disclosure the elemental radiation generators have been shown conventionally like A in Fig. 1. each consisting of two conductor balls joined by a linear conductor. In an array made up of such units according to the principles herein disclosed, certain sets of units may be replaced by coils as will now be shown. Fig. 16 shows in elevation two simple conventional oscillators and Fig. 17 shows a simple rectangular closed loop or coil which is equivalent to the set of Fig. 16. In other words, an oscillatory current of the same frequency in the coil of Fig. 17 will produce the same radiation as the pair of conventional oscillators of Fig. 16.

Figs. 18 and 18^a with the attached legends show how three such loops can be combined to give a resultant substantially the same as would be given by two such sets one above the other as shown in Fig. 2^b.

In Fig. 19 two conventional oscillators are shown with amplitude $+A$ in the upper one and $-3A$ in the lower one, and equivalent loops are shown in Fig. 20. Combining units of Fig. 20, it is shown in Fig. 21 how a rotary radiation may be produced.

I claim:

1. An array of radiating antenna units spaced in two dimensions horizontally and also spaced vertically and positioned in relation to the earth's surface as a conductor to give a reenforced image effect, each unit consisting of a pair of horizontal oscillators at a right angle to each other and symmetrically disposed in relation to a vertical axis and a vertical oscillator in such axis, and means to energize the components of each unit in definite magnitude and phase relation and to energize the units in definite magnitude and phase relation so as to radiate energy from the array substantially alike in all horizontal directions and with a component of substantial magnitude directed vertically upward.

2. A rectangular array of rotary oscillators with the intensity along each dimension determined according to the coefficients of the binomial expansion.

3. A spherical radiator comprising three linear oscillators having their axes at right angles each to the others, and with means to energize them in differing phase relation.

4. A spherical oscillator comprising two linear oscillators with horizontal axes, a vertical grounded antenna and means to energize them in different phase relation.

5. An array of radiating antenna units spaced in two dimensions horizontally and positioned in relation to the earth's surface as a conductor to give a reenforced image effect, each unit comprising a pair of horizontal oscillators at a right angle to each other and symmetrically disposed in relation to a vertical axis, and means to energize the components of each unit in definite magnitude and phase relation and to energize the units in definite magnitude and phase relation so as to radiate energy from the array principally in a direction vertically upward.

6. The method of radio signaling between a ground station and an air-ship, comprising the step of producing oscillatory currents along different axial directions parallel to the ground surface and in different phase relation.

7. An array of radiating antenna units spaced in two dimensions horizontally and also spaced vertically and positioned in relation to the earth's surface as a conductor to give a reenforced image effect, each unit consisting of a pair of horizontal oscillators at a right angle to each other and symmetrically disposed in relation to a vertical axis, and means to energize the components of each unit in definite magnitude and phase relation and to energize the units in definite magnitude and phase relation so as to radiate energy in a direction principally vertically upward.

8. A directionally selective array of radiating antenna units spaced in two dimensions transverse to each other across the optimum direction of transmission, each unit comprising at least two oscillators in each of which two oscillators the oscillatory currents flow transversely to the optimum direction and transversely to each other, the said antenna

units being spaced along the respective dimensions so as to give selectivity in the optimum direction, and means to energize the respective oscillators in proper phase and amplitude relation to give selectivity in the optimum direction.

9. A directionally selective array of radiating antenna units spaced in three dimensions each dimension transverse to the others and two of them lying across the optimum direction of transmission, each unit comprising at least two oscillators in each of which two oscillators the oscillatory currents flow transversely to the optimum direction and transversely to each other, the said antenna units being spaced along the respective dimensions so as to give selectivity in the optimum direction, and means to energize the respective oscillators in proper phase and amplitude relation to give selectivity in the optimum direction.

In testimony whereof, I have signed my name to this specification this 17th day of August, 1922.

JOHN STONE STONE.