DIFFRACTION AND SECONDARY RADIATION WITH ELECTRIC WAVES OF SHORT WAVE-LENGTH.

BY A. D. COLE.

SEVERAL years ago the writer presented to the American Physical Society the results of a study of diffraction effects obtained with electric waves of short wave-length.[1] In that work, as has been the usual practice among experimenters with electromagnetic radiation of wave-length less than a meter, the radiating source was placed at the focus of a parabolic cylindrical mirror. With this arrangement the experiments find their optical analogy in diffraction phenomena of the type commonly called the "Fraunhofer class," where the light used has a plane wave-front. In the experiments about to be described, however, the exciter of electric waves was provided with no converging arrangement, either mirror or lens. Thus a "point source" (or more strictly a line source) was approximated, so that the results have their optical analogue in the "Fresnel class" of optical experiments. This present study differs from the earlier one also in this point; that the receiver also was unprovided with any arrangement for intensifying the effect of the radiation upon it. The usual parabolic mirror would be inadmissible in any study which attempts to compare intensities for points only a few centimeters apart, but in the earlier work a narrow reflecting strip about 1.5 cm. wide was placed behind the exciter at about one quarter wave-length distance, as suggested by Righi.[2] In the present experiments however, as it was desired to keep the conditions as simple as possible, both receiver and exciter were used alone.

The exciter used was of the modified Righi type described in earlier papers.[3] The oscillating system consisted of two cylinders of aluminium, each 2.4 cm. long and .32 cm. in diameter. They were placed with axis vertical and separated by a minute spark gap, whose length could be adjusted by a slow-motion screw pressing upon one limb of the glass frame, which served as a support for the two cylinders and the oil reservoir surrounding the spark gap. The two auxiliary spark gaps in air were from 2 to 3 mm. long. The receiver was of the Klemencic thermal type.

[1] Science, April 5, 1907 (Report of Meeting of Section B, A. A. A. S.).

[2] Righi, Die Optik der elektrischen Schwingungen, p. 36 (1898).

[3] PHYS. REV., 33, p. 241, 1906.

A thermal receiver was preferred because its indications are proportional to the energy received and it was desired to study the distribution of the energy and not simply locate maxima and minima. The receiver consisted of two brass cylinders, having in place of the spark gap a thermo-junction of fine iron and constantin wire of .02 mm. diameter. These cylinders were smaller and shorter than those of the exciter, but could be lengthened by fitting over them a pair of larger cylinders. These larger cylinders were of the same diameter at those of the exciter and had a hole bored axially in one end, of diameter equal to that of the small cylinders (.21 cm.). This end was also provided with a diametral slit to give springiness and range of adjustment. Special care was taken to insure a close fit and firm pressure of the sliding cylinders upon the smaller fixed cylinders. To adapt the same receiver for use with exciters of different period and to be able to tune to resonance conditions in each case, eleven pairs of sliding cylinders were prepared, varying in length from 5 to 44 mm.[1] In the present work however only the one exciter described was used; its length was 4.8 cm. and the receiver was found by a series of careful experiments to be in resonance with it—as will be shown presently—when its length was 3.9 cm.

Diffraction Experiments.

Exciter and receiver having been brought to the same vibration period by adjustment of the length of the receiver, some experiments were tried with such conditions as would produce diffraction if light radiation were used. Naturally it was found impracticable to imitate optical experiments in the relation existing between wave-length and distances travelled. Satisfactory intensity was obtained only when the total distance of travel was less than a meter, *i. e.*, only a few wave-lengths. Even at such distances the required intensity is not easy to get when no mirror or lens is used with either exciter or receiver unless one uses an interrupter of high frequency. In the present case a Wehnelt interrupter was used, in connection with an induction coil capable of giving a 12 cm. spark.

Fig. 1 shows the result of an experiment to measure the diffraction due to a thin edge of conducting material. Exciter and receiver were placed 60 cm. apart, with the axis of each vertical. Halfway between them was a flat sheet of zinc 47 cm. high by 37 wide, the center of one vertical edge being on the line *ER*. (The metal screens are not shown full size in the figures.) The receiver was mounted at *R* on a revolving arm which could swing horizontally about a center immediately below the refracting edge. The arm was swung about, step by step, through an angle of

[1] Phys. Rev., 20, p. 269, 1905.

55 degrees, from 15 degrees behind the screen edge to 40 degrees on the other side of the axial line. Readings were taken at each 5°, four in each position. Five times at approximately equal intervals during the readings the intensity was read with screen removed and receiver in the central position. There was a constant and gradual diminution of intensity during the series due to the gradual lengthening of the spark gap. The rate of this diminution is shown by the slope of the dotted line in the figure. To compare the readings for the several positions more fairly, the mean for each position was corrected to the value corresponding to the mean intensity for the series. From the figure we observe that along the line of the edge the intensity is reduced to one fifth that obtained when the screen is removed. It falls off gradually behind the edge, reaching value one tenth at about 8° and thereafter changing but little. On the other side of the axis it rises, more rapidly than it fell away on the protected side, and with increasing rapidity until at 27° from the center the same intensity is reached as with the screen away. Beyond this point the increase is less rapid, but the effect is everywhere greater than with the plate away (so that the word screen becomes a misnomer). A similar experiment was tried with the distance SR increased to 50 cm. (making ER 80 cm.), but no significant difference appeared with the made to changed distance. If with the greater distance the receiver had been travel along the tangent at R instead of along the arc, it might have been possible to get diffraction bands as in the corresponding optical experiment, for then two half period elements of the wave front would become exposed when R was removed about 50 cm. to one side of the axial line and the conditions for a minimum reached.

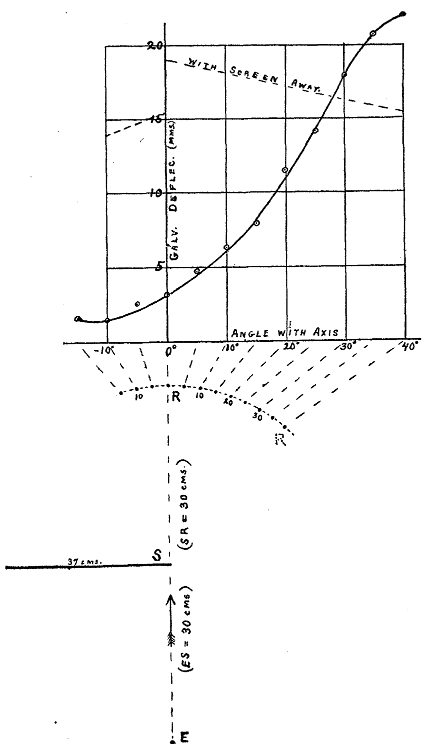


Fig. 1.

In Fig. 2 the results of an experiment are shown where two such plates were used, with their inner edges 20 cm. apart. In this case the radiation passed through an opening of 20 cm., or about 1.5 wave-lengths in width. The total distance of the receiver from the exciter was 80 cm., and from the plane of the plates was 50 cm. Readings were taken for positions 5° apart through an angle of 50° from the axis. The curve shows the

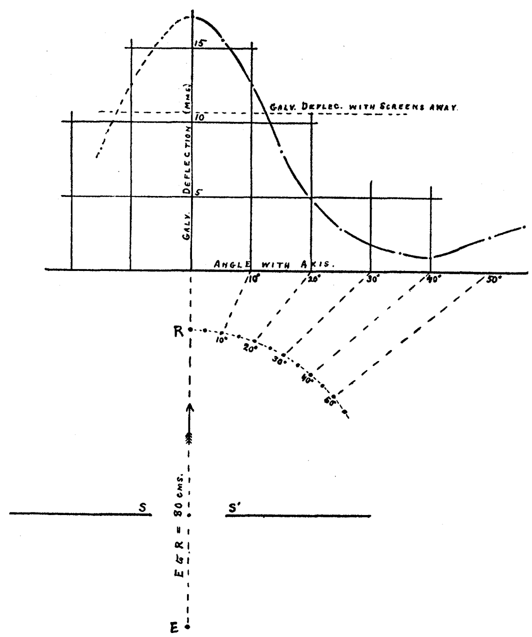
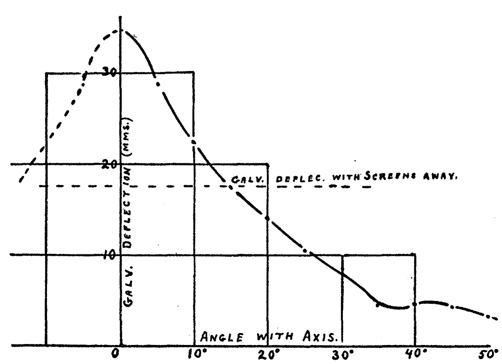


Fig. 2.

energy distribution found. It is seen that the effect of the plates was to increase the energy on the axial line by more than 50 per cent. above that shown when the plates were removed. As R is swung out to one side



Opening between Screens 25 cms.

Fig. 3.

the energy received decreases, slowly at first and then more rapidly. At 12° the same intensity is indicated as with the plates removed (shown on the curve by the horizontal dotted line). At 30° the geometrical shadow of the nearer plate is entered and the intensity is now about one sixth of that amount. At about 40° a minimum appears with intensity about 5 per cent. of that along the axis. (The readings here however were small and somewhat irregular and another comparison of the energies at 40° and 55° showed them nearly equal.)

A similar series was taken with a 25 cm. opening between the plates. The result is shown in Fig. 3. In this case the energy along the axis is twice that found when the plates are removed. The rate of falling off is somewhat more rapid than with the 20 cm. opening.

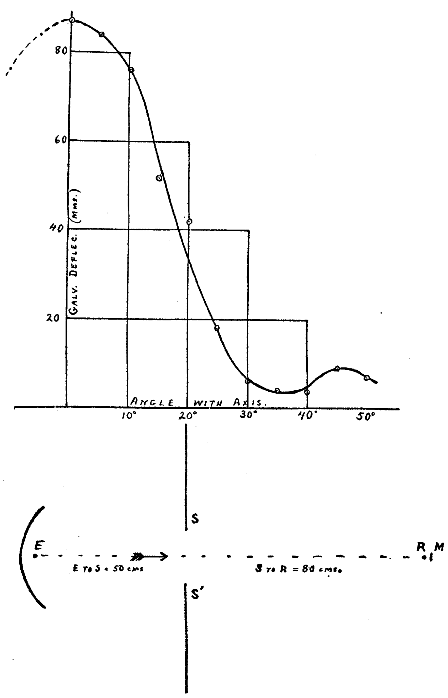


Fig. 4.

A clearer indication of maxima and minima ("fringes") is shown in the experiment which furnished the data for Fig. 4. This however was an experiment of the Fraunhofer class, since the exciter was placed at the focal point of a concave parabolic mirror (of 7.5 cm. focal length and 35 cm. width of aperture). A narrow reflecting strip of sheet metal was placed behind the receiver. Thus larger readings were secured. The distance between plates was also slightly different (17.6 cm. instead of 20). A minimum appears in the curve at about 37° and a second weak maximum shows beyond.

In Fig. 5 is shown the effect when the plates are located with reference to the exciter as shown in Fig. 2, but the receiver is placed successively at seven different points on the axis. Curve *A* shows the change in intensity as the receiver is moved from a position 40 cm. from the exciter by 10 cm. steps until it was 100 cm. away. Curve *B* shows the result of the same changes, when the plates were taken away. In every position of the receiver it is seen that the presence of the plates increases the amount of energy received. This increase is most marked when the receiver is 50 cm. distant where the ratio of ordinates of the two curves is greater than 2 : 1. The difference is not so great at 60 and 70 cm.

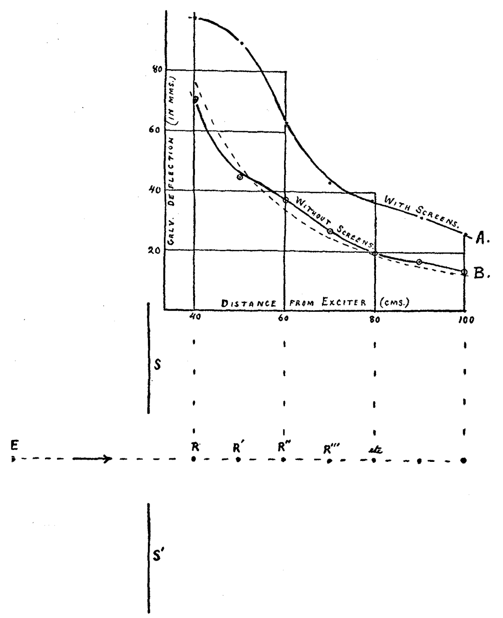


Fig. 5.

distance, but increases again beyond. Curve *B* shows that without the screens the decrease of energy with increase of distance approximately follows the inverse square law. The dotted curve is drawn so that its ordinates are inversely as the squares of the distances between exciter and receiver and this curve approximately coincides with curve *B*.

In another experiment the distance between exciter and receiver was kept fixed at 80 cm. but the plates were shifted along by steps of 20 cm., taking in succession the seven positions indicated in the lower part of Fig. 6. They were in each case 25 cm. apart, with the radiation axis half way between them. As before the effect of the plates is everywhere to increase the energy received at *R*, as shown in the upper part of Fig. 6, where the ordinates show the relative amounts of energy received for the several positions of the screens. The increase is most marked when the plates are 20 cm. from the exciter and is almost zero when the exciter is in the plane of the plates. For other positions the increase lies between 30 and 60 per cent.

Fig. 7. shows the results obtained when the positions of exciter and receiver and the plane of the plates are kept unchanged throughout the series, but the width of the opening between the plates is changed by short steps from 0 to 24 cm. The data for the full-line curve were obtained with the exciter and receiver 60 cm. apart and with the plates half way between them as shown in the lower part of the figure. The data for the dotted curve were obtained with R 20 cm. more distant, *i. e.*, 50 cm. beyond the plane of the plates. The form of the curve is about the same in each case. In both we notice that the radiation received at R is very small when the distance between the plates is less than one fourth the wave-length (3 cm.). Then it rises rapidly and nearly

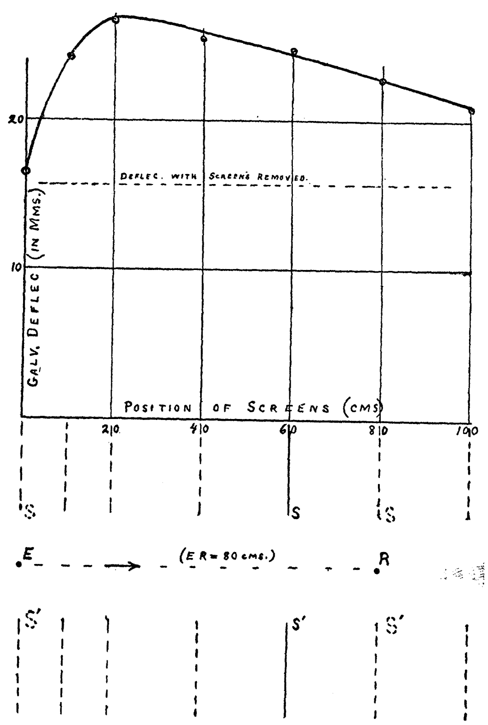


Fig. 6.

in proportion to the width of the opening up to about 1.5 λ (18 cm.). Then the increase is slower up to 24 cm. In the experiment where the total distance is 60 cm., an effect equal to that which we have with the plates removed is secured when the opening is about one wave-length in width. The largest effect is about 60 per cent. greater than this.

A few words about the relative dimensions of exciter and receiver and the wave-length used in these experiments. Early in the course of this work a paper was published by Dr. J. E. Ives[1] in which a different ratio of length of exciter to receiver was found for resonance than that which the author had named in a paper in PHYS. REV., 20, p. 268. In the

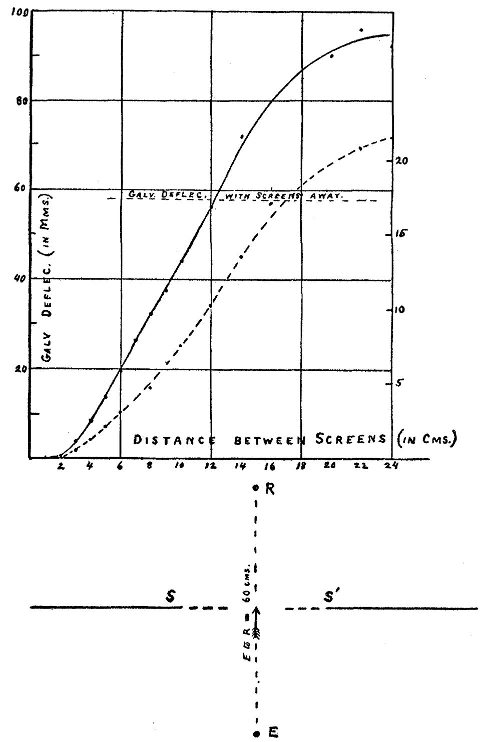


Fig. 7.

earlier experiments the adjustment of length of the receiver was secured by sliding slitted tubes of thin sheet copper over the copper cylinders of the receiver. Dr. Ives's results renewed a suspicion that these thin tubes did not fit as tightly as they ought and perhaps were too light in metal also. Therefore a new receiver was made provided with the set of heavier and better-fitting cylinders described early in this paper. These were adjusted as described in the earlier paper. The results are shown in the six curves of Fig. 8. These all show a decided and rather sharp maximum at about 40 mm.—perhaps the best mean value is 39 mm. The exciter length was 48 mm., and the ratio of lengths is therefore 1.23, which lies between the value previously found and that of Ives, although it is considerably nearer to Ives's value (1.43 for cylinders of 2.5 mm. diam.).

[1] PHYS. REV., 30, pp. 199–221, 1910.

I have not certainly located the cause of error in the early experiment, but it is very likely in the imperfect fit of the sliding cylinders. In the present work the good agreement of the several experiments was obtained

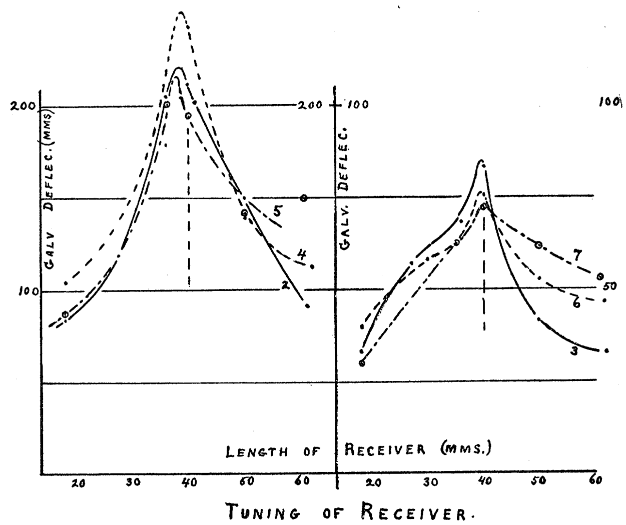


Fig. 8.

in spite of the fact that the conditions were purposely changed in the series shown by the different curves and one other not shown. Thus in one case both exciter and receiver were in concave mirrors, in another neither of them, in the others the exciter alone had a mirror; the distance between exciter and receiver was in one case 30 cm., in another 50 and in others 75; the length of the spark gap was also varied in different experiments.

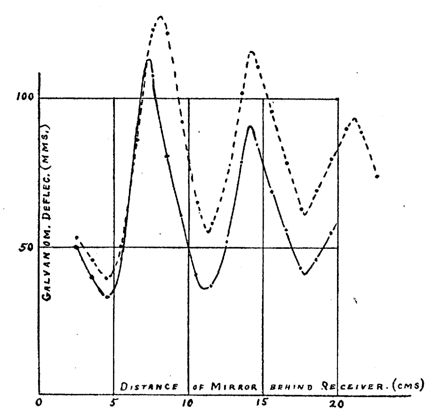


Fig. 9.

Exciter and receiver having been brought into resonance, the wavelength was determined from the interference curve secured by shifting the distance of a large plane sheet of zinc mounted behind the receiver. The data for two such series are shown in Fig. 9. In general each point on one of these curves is the mean of five readings. Thus the dotted curve shown involves over a hundred galvanometer deflections. The two curves shown were taken more than a week apart. The wave-length figured from the dotted curve is 13.1 cm. The curves seem satisfactory so far as regularity is concerned, also in the ratio of maxima to minima ordinates and in their agreement with each other. Many other curves were taken indicating the same wave-length. This wave-length is however larger than has been found for apparatus of about these dimensions by Ives and others using the interferometer method. If there is anything radically wrong in the method here used it would be desirable to know it, as it is essentially that used by Hertz in his classical interference-by-reflection experiments. It has been shown by the author[1] also that results by this method agree with those given by the Boltzmann two-mirror method and by the method of reflection from a single mirror behind the exciter.

Experiments with Interposed Rods.

Some measurements were made to find the magnitude of the screening effect of various conductors placed between exciter and receiver. First a thin brass rod was used, 40 cm. long and .32 cm. in diameter. It was placed in a vertical position on the line of exciter and receiver, which were 80 cm. apart. For each position along the line a series of readings was taken as follows: First three or four readings with no rod, then an equal number with the rod in position, again several readings with the rod removed, and so on until ten or twelve readings of each kind were obtained. The screening effect found was surprisingly large for any position, but differed considerably for different distances from the exciter as the following tabulation shows. The first column shows the distance of the rod from the receiver and the second the per cent. of radiation intercepted.

Rod from R, cm.	Intercepted by Rod, Per Cent.
2.4	77
5.	60
7.5	44
10.	37
15.	26
20.	27
25.	24
40.	32

One typical set of readings is shown, each of the eight positions tabulated having a similar set.

[1] Phys. Rev., 20, p. 271, 1905, and 23, p. 244, 1906.

Rod Away.		Rod 10 cm. from R.
		14.
		14.2
22.2	←	14.5
22.0		
25.0	→	15.0
		15.1
22.8	←	14.2
22.9		
23.7	→	14.2
		15.6
		14.0
22.0	←	14.4
21.5		
23.0		
25.0		
Means....23.0		14.5

$\frac{14.5}{23} = 63$ per cent. passing,

$\therefore$ 37 per cent. intercepted.

In the above experiments great care was taken to have the thin rod exactly on the line connecting exciter and receiver. But inasmuch as the diameter of the rod was only about one fortieth of a wave-length, it was difficult to think of so large a screening as a shadow or as a diffraction effect. The effect of moving the rod to one side was therefore tried. It was placed on the central line and half-way between E and R. Then it was moved 2 cm. to one side and a series of readings taken. So also at 4 and 6 cm to one side. In all three positions a large screening effect was found and nearly the same for each, about 25 per cent. Plainly this is no diffraction effect. Similar experiments with a thin wire are later described.

Effects of Lateral Shifting.

The thin rod was now replaced by a narrow strip of sheet metal, 3 cm. wide (and 34 cm. high). Its screening effect was measured on the central line, at the quarter, half and three quarter points (reckoning from R to E). It proved to be 49 per cent., 52 per cent. and 54 per cent. at the three points. The effect of moving this strip also to one side of the central position was tried, and with a surprising result. When 5 cm. from the central position, it cut down the effect at R more than when directly in line. The sidewise motion was continued, a series of readings being taken for each 5 cm. shift. The result is shown graphically in curve a of Fig. 10. At 15 cm. to one side it actually exerted a helpful influence, for the radiation received at R was greater than when the strip was removed.

Next a wider strip was tried in the same way. It was 7.5 cm. wide. The result is shown in curve b of Fig. 10. The effect is evidently of the same kind but greater. The maximum and minimum occur at the same points but they are more pronounced.

But the greatest surprise came when the last experiment was repeated with the thin edge turned toward the exciter. Almost the same curve as before was obtained, except that in the central position the obstructing power of the piece of metal was distinctly *greater* when it stood edgewise than when its broad side was presented. The results are shown graphically by the points surrounded by small squares in Fig. 10. It is seen that they all lie very close to the curve *b* except the one representing the deflection in the central position, whose height is scarcely two thirds of the ordinate of the curve at that point. The same experiment was then tried with the .32 cm. rod (used in the first test along the axis) The result appears in curve *c* of Fig. 10. It is of the same general character as the others, but the maximum and minimum are less pronounced.

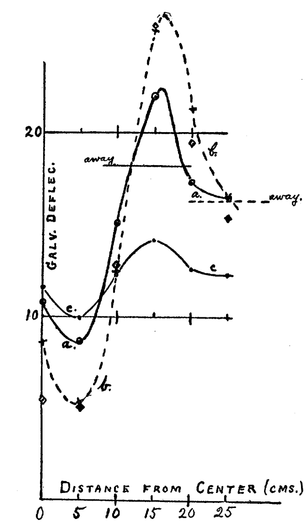


Fig. 10.

These phenomena seem hard to explain from the standpoint of the optical analogy, or if regarded as diffraction effects. A leading physicist suggested that the obstructing effect was proportional to the amount of metal present in the obstruction. This seems unlikely however, as any absorbed energy would doubtless take the form of alternating currents of a frequency so enormous that they would appear as "ultra-skin-currents" (as they have been aptly termed). Experimental evidence that it is not a question of mass of metal was obtained by some measurements on the obstructing effect of a vertical wire having a diameter of .72 mm., much smaller than the thin rod before used. It was found to absorb 19 per cent. of the energy when placed at the half way point and more than 40 per cent. when 5 cm. in front of the receiver. The absorbing power of the 3.2 mm. rod was 32 per cent. and 60 per cent. in the same positions, less than twice as much, while its mass was about twenty times that of the thin wire. That the result is not determined by the mass of metal is also seen by comparing curves *c* and *a*. The characteristic effect is much more marked in curve *a*, due to the thin strip, than it is in curve *c* due to the rod; yet the mass of the strip is smaller than that of an equal length of the rod in the ratio of 14.5 to 23.

The obstructing effect of the thin wire was so great when placed parallel to the electric force that it was tried in the horizontal position (perpendicular to the electric force), but no absorbing power could then be detected. A series of ten readings with wire horizontal at center—readings taken in groups as before described—gave a mean value of 14.8, while the companion series with the wire removed showed 14.7 mm. galvanometer deflection.

To explain such strong absorption effects optical analogies fail us, and it seems reasonable to refer them to the effects of radiation coming from oscillations induced in the obstructing conductors differing in phase something like a half period from that of the direct radiation. This has been called by Righi secondary radiation.[1] In the reference given he describes an experiment where another resonator similar in dimensions to the one used as receiver was placed at various distances to one side of the receiver and its influence upon the latter noted. This influence was found to vary with the distance, helping in some positions and opposing in others. At distance $= \lambda/2$ a maximum was obtained. This was tested in our apparatus by using a vertical strip of sheet metal whose length and width were equal to the length and diameter of the receiver. When this was placed 6.5 cm. ($= \lambda/2$) to one side of R on a line perpendicular to the axis, it was found to increase the energy received about 12 per cent. Trying non-resonant vertical conductors the long rod of .32 cm. diameter had no measurable influence, but a flat strip 7.5 cm. wide (with its width parallel to the radiation axis) gave a well-defined set of maxima and minima, but with distances between adjacent maxima and minima somewhat less than a half wave-length.

These later experiments and certain quantitative deviations of the diffraction phenomena from what is to be expected from optical analogy seem to find a possible explanation in the influence of secondary radiation from conductors in the vicinity. This suggested a more thorough and systematic study of the influence of neighboring conductors, which has since been made. A description of these experiments, a preliminary account of which has been presented to the Physical Society, will be given in a later paper.

SUMMARY.

1. A study was made of the distribution of radiant energy with several arrangements of electric wave apparatus likely to furnish diffraction effects. Among them were the following cases: radiation passing a thin edge of opaque material, radiation passing through openings of several widths, tested (a) for lateral distribution and (b) for variation along the

[1] Righi, Die Optik der elektrischen Schwingungen, Chap. II., 1898.

axis. The effect of the screens was to increase the energy received at certain points and some cases analogous to diffraction bands are described.

2. The effect of shifting a pair of "screens" along from one position to another along the radiation axis is described.

3. The effect of a gradual change in the width of an opening through which radiation passed was studied for two points on the axis. Very little energy passed when the opening was less than a quarter wave-length; with openings greater than one and a half wave-lengths more energy appeared beyond than when no screens at all were used.

4. Some resonance and interference results are shown by curves.

5. Large absorption or obstruction effects were found when either a thick or a thin wire was placed at any point along the radiation axis, if its length were parallel to the electric force. A flat strip reduced the intensity even more when placed edgewise than when broadside to the radiation.

6. When such a wire or strip was moved laterally by short steps from a central position strong maxima and minima were shown at the receiver.

7. One of Righi's "secondary radiation" experiments was repeated with the somewhat different apparatus used in this study and his result verified. The suggestion is made that many of the effects observed in these experiments can be explained by the interference of such secondary radiation with that directly received.

Ohio State University,
August, 1912.