VIII

ON ELECTROMAGNETIC WAVES IN AIR AND THEIR REFLECTION

(*Wiedemann's Ann.* **34**, p. 610, 1888.)

I HAVE recently endeavoured to prove by experiment that electromagnetic actions are propagated through air with finite velocity.[1] The inferences upon which that proof rested appear to me to be perfectly valid; but they are deduced in a complicated manner from complicated facts, and perhaps for this reason will not quite carry conviction to any one who is not already prepossessed in favour of the views therein adopted. In this respect the demonstration there given may be fitly supplemented by a consideration of the phenomena now to be described, for these exhibit the propagation of induction through the air by wave-motion in a visible and almost tangible form. These new phenomena also admit of a direct measurement of the wave-length in air. The fact that the wave-lengths thus obtained by direct measurement only differ slightly from the previous indirect determinations (using the same apparatus), may be regarded as an indication that the earlier demonstration was in the main correct.

In experimenting upon the action between a rectilinear oscillation and a secondary conductor I had often observed phenomena which seemed to point to a reflection of the induction action from the walls of the building. For example, feeble sparks frequently appeared when the secondary conductor was so situated that any direct action was quite impossible, as was evident from simple geometrical considera-

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[1] See VII., p. 107.

tions of symmetry; and this most frequently occurred in the neighbourhood of solid walls. In especial, I continually encountered the following phenomenon:—In examining the sparks in the secondary conductor at great distances from the primary conductor, when the sparks were already exceedingly feeble, I observed that in most positions of the secondary conductor the sparks became appreciably stronger when I approached a solid wall, but again disappeared almost suddenly close to the wall. It seemed to me that the simplest way of explaining this was to assume that the electromagnetic action, spreading outwards in the form of waves, was reflected from the walls, and that the reflected waves reinforced the advancing waves at certain distances, and weakened them at other distances, stationary waves in air being produced by the interference of the two systems. As I made the conditions more and more favourable for reflection the phenomenon appeared more and more distinct, and the explanation of it given above more probable. But without dwelling upon these preliminary trials I proceed at once to describe the principal experiments.

The physics lecture-room in which these experiments were carried out is about 15 metres long, 14 metres broad, and 6 metres high. Parallel to the two longer walls there are two rows of iron pillars, each of which rows behaves much like a solid wall towards the electromagnetic action, so that the parts of the room which lie outside these cannot be taken into consideration. Thus only the central space, 15 metres long, 8·5 metres broad, and 6 metres high, remained for the purpose of experiment. From this space I had the hanging parts of the gas-pipes and the chandeliers removed, so that it contained nothing except wooden tables and benches which could not well be removed. No objectionable effects were to be feared from these, and none were observed. The front wall of the room, from which the reflection was to take place, was a massive sandstone wall in which were two doorways, and a good many gas-pipes extended into it. In order to give the wall more of the nature of a conducting surface a sheet of zinc 4 metres high and 2 metres broad was fastened on to it; this was connected by wires with the gas-pipes and with a neighbouring water-pipe, and especial care was taken that any electricity that might accumulate at the upper and lower ends of the sheet should be able to flow away as freely as possible.

The primary conductor was set up opposite the middle of this wall at a distance of 13 metres from it, and was therefore 2 metres away from the opposite wall. It was the same conductor that had already been used in the experiments on the rate of propagation. The direction of the conducting wire was now vertical; hence the forces which have here to be considered oscillate up and down in a vertical direction. The middle point of the primary conductor was 2·5 metres above the level floor; the observations were also carried out at the same distance above the floor, a gangway for the observer being built up with tables and boards at a suitable height. We shall denote as the normal a straight line drawn from the centre of the primary conductor perpendicularly to the reflecting surface. Our experiments are restricted to the neighbourhood of this normal; experiments at greater angles of incidence would be complicated by having to take into consideration the varying polarisation of the waves. Any vertical plane parallel to the normal will be called a plane of oscillation, and any plane perpendicular to the normal will be called a wave-plane.

The secondary conductor was the circle of 35 cm. radius, which had also been used before. It was mounted so as to revolve about an axis passing through its centre and perpendicular to its plane. In the experiments the axis was horizontal; it was mounted in a wooden frame, so that both circle and axis could be rotated about a vertical axis. For the most part it does well enough for the observer to hold the circle, mounted in an insulating wooden frame, in his hand, and then to bring it as may be most convenient into the various positions. But, inasmuch as the body of the observer always exercises a slight influence, the observations thus obtained must be controlled by others obtained from greater distances. The sparks too are strong enough to be seen in the dark several metres off; but in a well-lit room practically nothing can be seen, even at close quarters, of the phenomena which are about to be described.

After we have made these preparations the most striking phenomenon that we encounter is the following:—We place the secondary circle with its centre on the normal and its plane in the plane of oscillation, and turn the spark-gap first towards the wall and then away from it. Generally the sparks differ greatly in the two positions. If the experiment is arranged at a distance of about 0·8 metre from the wall the sparks are much stronger when the spark-gap is turned towards the wall. The length of the sparks can be so regulated that a continuous stream of sparks passes over when the spark-gap is turned towards the wall, whereas no sparks whatever pass over in the opposite position. If we repeat the experiment at a distance of 3 metres from the wall we find, on the contrary, a continuous stream of sparks when the spark-gap is turned away from the wall, whereas the sparks disappear when the spark-gap is turned towards the wall. If we proceed further to a distance of 5·5 metres, a fresh reversal has taken place; the sparks on the side towards the wall are stronger than the sparks on the opposite side. Finally, at a distance of 8 metres from the wall, we find that another reversal has been executed; the sparking is stronger on the side remote from the wall, but the difference is no longer so noticeable. Nor does any further reversal occur; for it is prevented by the preponderating strength of the direct action and by the complicated forces which exist in the neighbourhood of the primary oscillation. Our figure (the scale in which indicates the distances from the wall) shows at I., II., III., IV., the secondary circle in those positions in which the sparks were most strongly developed. The alternating character of the conditions of the space is clearly exhibited.

At distances lying between those mentioned both sets of sparks under consideration were of equal strength, and in the immediate neighbourhood of the wall too the distinction between them diminishes. We may therefore denote these points—namely, the points *A, B, C, D* in the figure—as being nodal points in a certain sense. Still we must not consider the distance between any one of these points and the next as being the half wave-length. For if *all* the electrical disturbances change their direction in passing through one of these points, then the phenomena in the secondary circle should repeat themselves without reversal; for in the spark-length there is nothing which corresponds to a change of direction in the oscillation. We should rather conclude from these experiments that in passing through any one of these points one part of the action undergoes reversal, while another part does not. On the other hand, it is allowable to assume that double the distance between any two of the points corresponds to the half wave-length, so that these points each indicate the end of a quarter wave-length. And, indeed, on the basis of this assumption and of the fundamental view just expressed, we shall arrive at a complete explanation of the phenomenon.

For let us suppose that a vertical wave of electric force proceeds towards the wall, is reflected with slightly diminished intensity, and so gives rise to stationary waves. If the wall were a perfect conductor a node would form at its very surface. For inside a conductor or at its boundary the electric force must always be vanishingly small. Now our wall cannot be regarded as a perfect conductor. For, in the first place, it is only metallic in part, and the part which is metallic is not very extensive. Hence at its surface the force will still have a certain value, and this in the sense of the advancing wave. The node, which would be formed at the wall itself if it were perfectly conducting, must therefore lie really somewhat behind the surface of the wall, say at the point A in the figure. If double the distance $A\,B$, that is the distance $A\,C$, corresponds to the half wave-length, then the geometrical relations of the stationary wave are of the kind

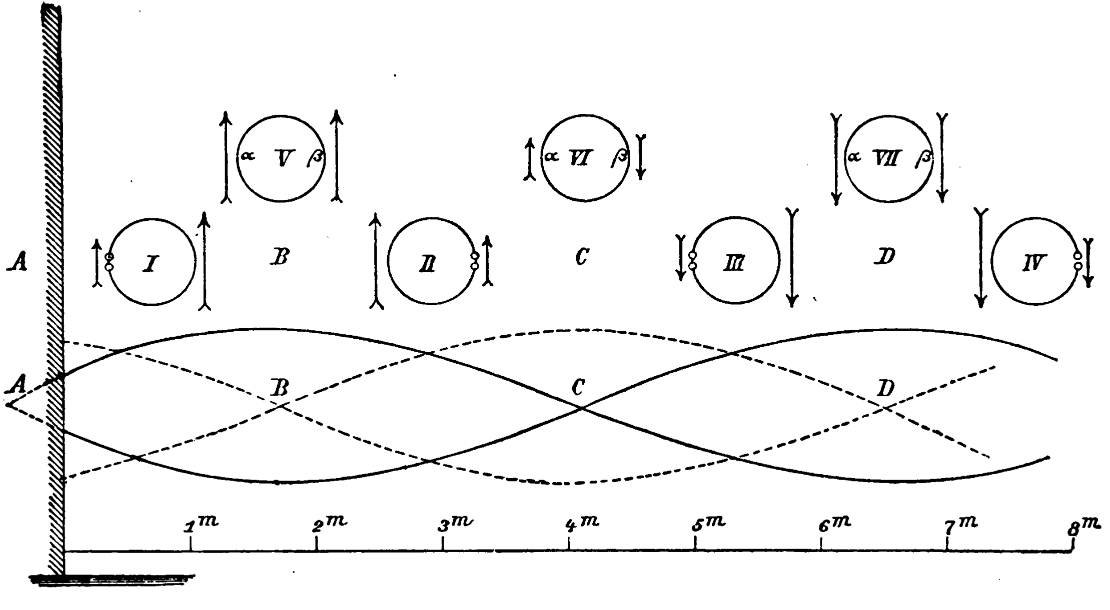

Fig. 26.

ch are represented in the usual symbolic fashion by the nuous wave-line in the figure. The forces acting on both of the circle in the positions *I*, *II*, *III*, and *IV* are ectly represented for any given instant in magnitude and rection by the arrows at the sides. If, then, in the neighbourhood of a node the spark-gap is turned towards the node, we have in the circle a stronger force acting under favourable conditions against a weaker force, which acts under unfavourable conditions. But if the spark-gap is turned away from the node, the stronger force now acts under unfavourable conditions against a weaker force, which in this case is acting under favourable conditions. And whether in this latter case the one preponderates or the other, the sparks must necessarily be weaker than in the former case. Thus the change of sign of our phenomenon every quarter wave-length is explained.

Our explanation carries with it a means of further testing its correctness. If it is correct, then the change of sign at the points B and D should occur in a manner quite different from the change of sign at C. At *V*, *VI*, and *VII* in the figure the circle and the acting forces in these positions are represented, and it is easily seen that if at B or D we transfer the spark-gap from the one position to the other by rotating the circle within itself, the oscillation changes its direction relatively to a fixed direction within the circle; during this rotation the sparks must therefore become zero either once or an uneven number of times. On the other hand, if the same operation is performed at C, the direction of the oscillation does not change; and therefore the sparks must either not disappear at all, or else they must disappear an even number of times. Now when we actually make the experiment, what we observe is this:—At B the intensity of the sparks diminishes as soon as we remove the spark-gap from a, becomes zero at the highest point, and again increases to its original value when we come to β. Similarly at D. At C, on the other hand, the sparks persist without change during the rotation, or, if anything, are somewhat stronger at the highest and lowest points than at those which we have been considering. Furthermore, it strikes the observer that the change of sign ensues after a much smaller displacement at C

than at *B* and *D*, so that in this respect also there is a contrast between the change at *C* and that at *B* and *D*.

The representation of the electric wave which we have thus sketched can be verified in yet another way, and a very direct one. Instead of placing the plane of our circle in the plane of oscillation, let us place it in the wave-plane; the electric force is now equally strong at all parts of the circle, and for similar positions of the sparks their intensity is simply proportional to this electric force. As might be expected, the sparks are now zero at the highest and lowest points of the circle at all distances, and are strongest at the points along the normal in a horizontal plane. Let us then bring the spark-gap into one of these latter positions, and move slowly away from the wall. This is what we observe:—Just at the conducting metallic surface there are no sparks, but they make their appearance at a very small distance from it; they increase rapidly, are comparatively strong at *B*, and then again diminish. At *C* again they are exceedingly feeble, but become stronger as we proceed further. They do not, however, again diminish, but continue to increase in strength, because we are now approaching the primary oscillation. If we were to illustrate the strength of the sparks along the interval *A D* by a curve carrying positive and negative signs, we should obtain almost exactly the curve which has been sketched. And perhaps it would have been better to start from this experiment. But it is not really so striking as the first one described; and furthermore, a periodic change of sign seems to be a clearer proof of wave-motion than a periodic waxing and waning.

We are now quite certain that we have recognised nodes of the electric wave at *A* and *C*, and antinodes at *B* and *D*. We might, however, in another sense call *B* and *D* nodes, for these points are nodes of a stationary wave of magnetic force, which, according to theory, accompanies the electric wave and is displaced a quarter wave-length relatively to it. This statement can be illustrated experimentally as follows:—We again place our circle in the plane of oscillation, but now bring the spark-gap to the highest point. In this position the electric force, if it were homogeneous over the whole extent of the secondary circle, could induce no sparks. It only produces an effect in so far as its magnitude varies in various parts of the circle, and its integral taken around the circle is not zero. This integral is proportional to the number of lines of magnetic force which flow backwards and forwards through the circle. In this sense, we may say that in this position, the sparks measure the magnetic force, which is perpendicular to the plane of the circle.[1] But now we find that in this position near the wall there is vigorous sparking which rapidly diminishes, disappears at *B*, increases again up to *C*, then again decreases to a marked minimum at *D*, after which it continuously increases as we approach the primary oscillation. Representing the strength of these sparks as ordinates with positive and negative signs, we obtain approximately the dotted line of our figure, which thus represents correctly the magnetic wave. The phenomenon which we first described can also be explained as resulting from the co-operation of the electric and the magnetic force. The former changes sign at the points *A* and *C*, the latter at the points *B* and *D*; thus one part of the action changes sign at each of these points while the other retains its sign; hence the resulting action (as the product) changes sign at each of the points. Clearly this explanation only differs in mode of expression, and not in meaning, from the one first given.

Hitherto we have only considered the phenomena in some of the more important positions of the circle. The number of transitions between these is in a threefold sense infinite. We shall therefore content ourselves with describing the transitions for the case in which the plane of the circle lies in the plane of oscillation. Near the wall the sparking is greatest on the side towards the wall, and least on the opposite side; on rotating the circle within itself the sparking changes from the one value to the other, attaining only intermediate values; there are no zero-points in the circle. As we move away from the wall the sparking on the side remote from it gradually diminishes and becomes zero when the centre of the circle is 1·08 metre distant from the wall; this distance can be ascertained within a few centimetres. As we proceed further, the sparks on the side remote from the wall reappear and at first are still weaker than on the side towards the wall; but

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[1] [See Note 18 at end of book.]

the strength of the sparks does not change from the one value to the other simply by passing through intermediate values; on rotating the circle within itself the sparking becomes zero once in the upper and once in the lower half of the circle. The two zero-points develop out of the one which was first formed and separate gradually more from each other, until at *B* they lie at the highest and lowest points of the circle. By this indication the point *B* can be determined with fair accuracy, but more exactly still by a further observation of the zero-points. On proceeding further, these zero-points slide over towards the side of the circle facing the wall, approach each other, and again coincide in a single zero-point at a certain distance from the wall which can be sharply determined. In this case the distance of the centre from the wall is 2·35 metres. The point *B* must lie exactly between this and the analogous point first observed, *i.e.* at a distance of 1·72 metres from the wall; this agrees within a few centimetres with the direct observation. If we proceed further towards *C* the sparks at all points of the circle tend to become of equal strength, and do become so at *C*. Beyond *C* the same performance begins over again. In this region there are no zero-points in the circle. In spite of this the position of the point *C* can be determined with fair accuracy, inasmuch as in its neighbourhood the phenomena first described alter very rapidly. In my experiments *C* was 4·10 to 4·15 metres, or say 4·12 metres from the wall. The point *D* could not be accurately determined for the phenomena had here become very feeble; only this much could be asserted, that its distance from the wall was between 6 and 7·5 metres. For an explanation of the details I may refer to a previous paper.[1] The mathematical developments therein indicated admit of being carried much further; but the experiments seem to be sufficiently intelligible without calculation.

According to our measurement, the distance between *B* and *C* is 2·4 metres. If we assume this to be the correct value, the nodal point *A* lies 0·68 metres behind the wall, the point *D* 6·52 metres in front of it, which agrees sufficiently well with the experiments. According to this, the half wave-length is 4·8 metres. By an indirect method I had obtained

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[1] See V., p. 80.

4·5 metres as the wave-length for the same apparatus. The difference is not so great as to prevent us from regarding the new measurement as confirming the earlier one.[1] If in our earlier measurements we substitute 2·9 for 2·8 metres as the wave-length in the wire, and 7·1 for 7·5 as the length of the coincidence (which will be found to agree with the observations), we can deduce the new value from the earlier observations. Perhaps, indeed, a mean value would be nearest to the truth; and I scarcely think it likely that the nodal point A should lie nearly 0·7 metre behind the metallic wall. Assuming a mean value for the wave-length, and a velocity of propagation equal to that of light, we get for the period of oscillation of our apparatus about 1·55 hundred-millionths of a second, instead of the 1·4 hundred-millionths obtained by calculation.

I have repeated the experiments with some alterations. Altering the distance of the primary oscillation from the reflecting wall did not result in much fresh information. If this distance could have been considerably extended, we might certainly have expected a distinct formation of a second and third wave-length; but there was not sufficient space for such extension. When the distance was diminished the phenomena simply became less interesting, for towards the primary oscillation they were more and more indistinct, and in the opposite direction the reversal of sign became lost. The experiments with an oscillation of different period are better worth describing, for they show that the points which have attracted our attention are determined, not by the form of the wall or of the room, but only by the dimensions of the primary and of the secondary oscillation. I, therefore, used for some experiments a secondary circle of 17·5 cm. radius, and a primary oscillation of the same periodic time as this circle. The primary oscillator was placed at a distance of 8-9 metres from the wall. It is, however, difficult to work with apparatus of such small dimensions. Not only are the sparks exceedingly minute but the phenomena of resonance, etc., are very feebly developed. I suspect that oscillations of such rapidity are very rapidly damped. Thus it was not possible here to make out as much detail as in the case of the larger circle; but the

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[1] [See Note 19 at end of book.]

main features, such as those first described above, could be plainly recognised. Near the wall, and at distances of 2·5 and 4·5 metres from it, the stronger sparks were on the side next the wall; at the intermediate positions (1·5 and 3·5 metres from the wall) the stronger sparks were on the side next the primary oscillation. A change of sign occurred about every metre; accordingly the half wave-length was here only 2 metres, and the oscillation was more than twice as rapid as that first used.

Finally, I may remark that as far as the above experiments are concerned, no great preparations are essential if one is content with more or less complete indications of the phenomena. After some practice one can find indications of reflection at any wall. Indeed, the action of the reflected waves can be quite well recognised between any one of the iron pillars above referred to and the primary oscillation; and similarly on the opposite side the eloctromagnetic shadow can be perceived.

Let us now extend our experiments in a new direction. Hitherto the secondary conductor has been placed between the reflecting wall and the primary oscillation—that is to say, in a space in which the direct and reflected waves travel in opposite directions and by interference produce stationary waves. If, on the contrary, we place the primary oscillation between the wall and the secondary conductor, the latter is situated in a space in which the direct and reflected waves travel in the same direction. Hence these must combine to produce a progressive wave, the intensity of which will, however, depend upon the difference of phase between the two interfering waves. If the phenomena are to be at all striking, the two waves must be of similar intensity; hence the distance of the primary oscillation from the wall must not be large compared with the dimensions of the latter, and must be small compared with the distance from the secondary oscillation. In order to test whether the corresponding phenomena could be observed under the working conditions, I arranged an experiment as follows:—The secondary circle was now set up at a distance of 14 metres from the reflecting wall, and therefore 1 metre away from the opposite wall. Its plane was parallel to what we have called the plane of oscillation, and its spark-gap was turned towards the nearer wall so that the conditions were specially favourable for the appearance of sparks in it. The primary conductor was set up parallel to its original position in front of the conducting wall, and at first at a very short distance—about 30 cm.—from it. The sparks in the secondary circle were extremely feeble. The spark-gap was now adjusted so that no sparks whatever passed over. The primary conductor was next shifted step by step away from the wall. Single sparks soon appeared in the secondary conductor, and these ran into an unbroken stream of sparks when the primary conductor arrived at a distance of 1·5-2 metres from the wall—that is to say, at the point *B*. This might be referred to the decrease in the distance between the two conductors. But when I now removed the primary conductor further away from the wall, and therefore nearer to the secondary, the sparks again diminished and disappeared when the primary arrived at *C*. On proceeding still further the sparks began to increase and did so now continuously. No exact measurement of the wave-length can be deduced from these experiments, but from what has been stated above it will be seen that the wave-lengths already obtained are in accordance with the phenomena. The experiments could be very well carried out with the smaller apparatus. The primary conductor was set up at a distance of 1 metre from the wall, and the corresponding secondary conductor 9 metres from the wall. The sparks in the latter were certainly small, but could be quite well observed. They disappeared when the primary conductor was moved out of its position, whether it was moved towards the wall or towards the secondary conductor. The sparks only reappeared when the distance from the wall was increased to 3 metres, and from there on they did not again disappear on approaching nearer to the secondary conductor. It is worthy of notice that at the same distance of 2 metres the presence of the wall proved to be of assistance in propagating the induction in the case of the slower oscillation, whereas it was a hindrance in the case of the more rapid one. This shows plainly that the position of the points to which we have drawn attention is determined by the dimensions of the oscillator, and not by those of the wall or room.

In acoustics there is an experiment analogous to those last described, in which it is shown that when a tuning-fork is brought near a wall the sound is strengthened at certain distances and weakened at others. The analagous experiment in optics is Lloyd's form of Fresnel's mirror-experiment.[1] In optics and acoustics these experiments count as arguments in favour of the wave-nature of light and sound; and so the phenomena here described may be regarded as arguments in favour of the propagation of the inductive action of an electric oscillation by wave-motion.

I have described the present set of experiments, as also the first set on the propagation of induction, without paying special regard to any particular theory; and, indeed, the demonstrative power of the experiments is independent of any particular theory. Nevertheless, it is clear that the experiments amount to so many reasons in favour of that theory of electromagnetic phenomena which was first developed by Maxwell from Faraday's views. It also appears to me that the hypothesis as to the nature of light which is connected with that theory now forces itself upon the mind with still stronger reason than heretofore. Certainly it is a fascinating idea that the processes in air which we have been investigating represent to us on a million-fold larger scale the same processes which go on in the neighbourhood of a Fresnel mirror or between the glass plates used for exhibiting Newton's rings.

That Maxwell's theory, in spite of all internal evidence of probability, cannot dispense with such confirmation as it has already received, and may yet receive, is proved—if indeed proof be needed—by the fact that electric action is not propagated along wires of good conductivity with approximately the same velocity as through air. Hitherto it has been inferred from all theories, Maxwell's included, that the velocity along wires should be the same as that of light. I hope in time to be able to investigate and report upon the causes of this conflict between theory and experiment.[2]

[1] [See Note 20 at end of book.]

[2] [See Note 21 at end of book.]