THE TRANSFORMATION INTO AN ELECTRIC CURRENT OF RADIATION INCIDENT ON A MOVING SURFACE.

BY BERGEN DAVIS.

A PLANE polarized beam of light is generally considered to consist of a train of waves in which the electrical component alternates in sign, but remains in the same plane perpendicular to the wave front. As the wave passes through a surface, a point on the surface would be subject to an alternating field of force.

It would be a matter of great importance to rectify the small currents that are set up in a conducting surface by such alternating fields of force. The detection of these currents would not only confirm the electro-magnetic theory of radiation, but would furnish a direct method for distinguishing the electric and magnetic components of the wave.

An account of some experiments by the late Professor A. Bartoli on the direct transformation of radiation into electric currents has recently been published.¹ The writer has lately repeated the experiments of Professor Bartoli, making such changes in the apparatus as our present knowledge of the electronic nature of electric conduction would warrant. Because of the importance of Bartoli's experiment, I think it advisable to give an outline of his reasons for expecting the effect and a translation of that part of his paper which describes his apparatus and the results obtained.

1. Professor Bartoli proceeds from his well-known thermo-dynamic proof of radiation pressure. He performed some experiments seeking to observe the expected radiation pressure, but failing to detect it, concludes that it does not exist. It occurs to him that perhaps his failure is due to the conversion of the incident energy into currents in the conducting surface. The experiment

¹ Su la trasformazione in correnti elettriche delle radiazioni incidenti Sopra una superficie riflettente in movimento. Accademia dei Lincei, 1903, 5th Series, 12.

described below was undertaken for the purpose of detecting these transformed currents.

It is, perhaps, worth while to give a translation of that part of his paper which describes his apparatus and the results obtained.

"Upon a disc H , of copper 4 mm. thick and 80 cm. in diameter, a copper band LPM , is firmly fixed and perfectly silvered, so that it will reflect at least 92 per cent. of the incident radiation. This band is insulated by means of well-dried pieces of wood, after they have been boiled in linseed oil, to which it is firmly attached by a great number of brass screws.

"The two extremities L and M of the band are joined by strips

Fig. 1.

of copper, l and m , to two rings of copper BB' , which are 3 mm. thick and insulated by two small ebonite wheels 4 cm. in diameter. The disc H , as well as the two small wheels BB' , are firmly fixed normally to the steel axis PS , which is 3 cm. in diameter but thicker in the middle. Above the two copper rings BB' , there are two insulated copper springs AA' , which by copper adjusting screws and thick copper wires, communicate with a mirror galvanometer of small resistance and of that type which is completely astatic.¹

"The axle PS , was resting on bronze bearings which were supported by a strong bed frame of a turning lathe of more than 1,000 kilograms and which was firmly fixed to the ground.

"It was possible to impress a very rapid rotation to the disc H by means of a belt passing over the iron pulley P 4.5 cm. in diameter. The motion was generated by two large wheels at each of which from six to eight men were working. A counting device simi-

¹ A two-needle mirror galvanometer of Magnus, constructed by Sauerwald, Berlin.

lar to Savart's toothed wheel made it possible to count the number of revolutions of the disc in a stated time. After a half-hour's work it was possible to impart to the disc *H* its maximum velocity which was about 100 to 150 revolutions per second. In that case the velocity of a point on the band *LPM* was about 240 to 410 meters per second.

"Before commencing the action, a pencil of solar rays concentrated upon the band *LPM* by means of plane and concave mirrors did not produce any thermo-electric current that made the galvanometer deviate more than two to three scale divisions. During the motion of the disc no thermo-electric current whatsoever (owing to the warming of the rings pressing against the springs, or owing to any other cause) made the galvanometer deviate while the moving disc was in the dark. While the galvanometer needle was motionless and the disc had attained its maximum velocity I let the solar pencil (by pulling up the diaphragm) fall upon the band *LPM* (at about its middle). I could then observe a deviation which at times attained 42 scale divisions. This deviation was always observed. It depended upon the direction of rotation. In fact revolving the disc in the opposite sense at the same speed produced a deviation of about 38 scale divisions in the opposite direction. This deviation was entirely dependent on the velocity of rotation; thus, with a rotatory velocity of about one half that of the maximum a deviation of 20 scale divisions was obtained, *i. e.*, about one half the preceding deviation. The deviation persisted as long as the solar pencil was striking the silvered band; when the rays were cut off by the diaphragm the galvanometer returned to zero; when the diaphragm was pulled up the galvanometer deviated anew.

"These experiments were made in the months of August and September, 1880, in the school of design which is situated on the ground floor of the Technical Institute of Florence. I was assisted in these experiments by Dr. Guido Alessandri, then my assistant, now professor in the Royal Lyceum of Potenza.

"For lack of sufficient motor and local conveniences, I could not continue the experiments which I have only indicated for the sake of recording them. I am satisfied however with the discovery of the fact. I reserve for some other time the repetition of these experi-

ments with improved means in order to determine the laws governing this phenomenon."

It is to be regretted that Professor Bartoli does not give the sensitiveness of his galvanometer. It is impossible to estimate the magnitude of the effect which he observed. It is not probable however that as early as 1880 he possessed an instrument so sensitive as those now at our disposal.

There are some conditions of the experiment just described that make it somewhat doubtful if the effect sought for was really observed. The silver surface was deposited on a copper band of considerable thickness. The light was reflected for the most part and certainly not at all transmitted through the strip. The disturbances produced in the strip would be confined entirely to the surface. The electro-motive force that may have been developed did not extend through the strip, consequently if a current were produced in the surface it would flow around through the back of the strip. The current would be completely closed locally and there could be no effective electro-motive force tending to send a current through the external circuit to the galvanometer.

There are other and more fundamental reasons for the improbability of the real existence of the effect described by Bartoli. Some of these objections will be considered in the second part of this paper.

II. It can be shown however that the alternating currents produced in a moving conductor by incident radiation will not be symmetrical, but during one half period will be of greater or less amplitude than the next half period provided the force acting on an electron is modified by its velocity in an electric field.

Suppose a plane polarized beam of light to pass through a thin conducting film in motion. The plane of the electric component is in the direction of motion. The electro-motive force of the light wave will act through the whole thickness of the film, but its intensity will decrease with the depth owing to absorption. The current produced will be proportional to the electro-motive force at any depth.

Let the sinusoidal form in Fig. 2 represent such a wave propagated downward through a conducting film *CD*. The electric component is in the plane of the paper. Consider that the carriers

of the current are free negative electrons. If the film is at rest as the train of waves passes through, the electrons will be subject to a symmetrically alternating force which will produce a symmetrical alternating current. If the film is in motion the alternating currents will be unsymmetrical or symmetrical according as the force acting on an electron is a function of its velocity in the field or not.

Assume the film to be in motion and the light wave at a given instant to occupy the position represented by case *A*, Fig. 2.

The electrons will have a motion relative to the field from left to right due to the motion of the film. This direction is opposite to that which the field of the wave tends to give them at this instant. The second case *B* represents the position of the wave a half period later than case *A*. The motion of the electrons relative to the field is here in the same direction as that which the field tends to produce. The relative motion of the electrons with

Fig. 2.

respect to the field will thus be a variable one. If the force acting on an electron moving parallel to and in an electric field depends on its velocity in the field, the currents in the film will no longer be symmetrical but will have a greater amplitude in one direction. The current will be alternating but unsymmetrical. Since the resistance is constant the effective electro-motive force will also be unsymmetrical.

I shall make the most simple assumption possible for the dependence of the force on the velocity, namely that it will be modified by a quantity proportional to $(u/v)^2$, where u is the velocity of the film and v is the velocity of light.

Then during the first half period (case *A*) the effective E.M.F. will be

$$E_1 = X \left[1 + \left(\frac{u}{v} \right)^2 \right] \sin pt.$$

The mean value of this is

$$E_1 = \frac{2}{\pi} \left[1 + \left(\frac{u}{v} \right)^2 \right] X.$$

During the next half period (case B) the effective E.M.F. will be

$$E_2 = X \left[1 - \left(\frac{u}{v} \right)^2 \right] \sin pt,$$

the mean value of which is

$$E_2 = \frac{2}{\pi} \left[1 - \left(\frac{u}{v} \right)^2 \right] X.$$

The effective E.M.F. tending to produce a current in one direction in the film is

$$E = (E_1 - E_2) = \frac{1}{2} \frac{4}{\pi} \left(\frac{u}{v} \right)^2 X = \frac{2}{\pi} \left(\frac{u}{v} \right)^2 X,$$

where X is the maximum electrical intensity of the sinusoidal light wave. This would be the mean electro-motive force for slow frequencies of vibration. The light wave, however, is of very high frequency, and it is well known that alternating currents of such frequencies cannot be propagated along conductors because of the impedance. Neglecting this impedance the theoretical value of E may be readily found.

Taking the solar constant as 3 gram-calories per minute the energy per cubic-centimeter of sunlight is 2.1×10^6 ergs and the value of X is found to be about 6.2 volts per centimeter.

If the linear velocity of the moving film is 10,000 cm. per second, the ratio $(u/v)^2$ becomes $-\frac{1}{9} \times 10^{-12}$.

Introducing the value of X and $(u/v)^2$ in (3) we have

$$X = 3.6 \times 10^{-11} \text{ volts per centimeter.}$$

If the sunlight is concentrated by a lens to 100 times its natural intensity, the electrical intensity becomes

$$X = 3.6 \times 10^{-10} \text{ volts.}$$

This is the electrical intensity at the upper surface of the film. At the lower surface the electrical intensity will be much less owing to reflection and absorption in the film. Much of the current developed at the upper surface would complete its circuit at the under

surface. The effective electrical intensity would thus be due to the intensity of the radiation that passed through the lower surface.

The electrical intensity (3.6×10^{-10}) is too small to be easily detected on account of the unavoidable disturbances produced by the high velocity of the film.

Also although the electrical intensity $2/\pi(u/v)^2 X$ is always in one direction in the film, yet it is not continuous but impulsive, and, as I have pointed out, impulses of the order of frequency of light vibrations can not be propagated along conductors.

In spite of these considerations which indicate an improbability of an effect in view of Bartoli's experiments I have thought it worth while to seek to test his observations by a modified method.

APPARATUS AND EXPERIMENT.

The method used was to move a semi-transparent film in a plane perpendicular to a concentrated beam of sunlight falling upon it.

The rotating device for giving a great linear velocity to the film (f) is shown in Fig. 3. An aluminium disc D is mounted on a

Fig. 3.

hollow steel axle A . The disc is recessed to firmly hold the glass plate g . The disc and plate are rotated by an air motor mm' . Air compressed to about 25 pounds pressure per square inch was directed by suitably constructed nozzles upon the toothed wheels mm' . By this device the glass plate could be given a speed of 200 revolutions per second and the direction of rotation could be quickly reversed.

A thin circular silver film (f) about 8 mm. broad was deposited

by the chemical method upon the glass plate. The strip of silver film formed nearly a closed ring. A radial silver strip extended from each end of the film toward the center and attached to aluminium wires by the small screw bolts pp' . These wires (insulated) were carried through the hollow axle to the ends of the shaft where they were attached to aluminium cones cc' . These cones were also insulated from the shaft. Aluminium springs ss' pressed against these conical points. The points of the cones were made to coincide as nearly as possible with the axis of rotation of the shaft. This reduced the motion between the points of the cones and the contact springs to a minimum.

The greater part of the glass disc was covered by an ebonite cover E . This was just large enough to cover nearly all the plate to the inner edge of the film. This cover prevented disturbances arising from the friction of the air against the radial parts of the film and the small bolts pp' . Great disturbances were always observed in the galvanometer when the apparatus was used without this cover.

The galvanometer was a D'Arsonval type recently constructed for our laboratory by the Weston Electric Instrument Company. Its resistance is 31.3 ohms. The volt sensitiveness is 81.6×10^{-10} volts per scale division, the scale being one meter from the instrument.

The sunlight was concentrated on the film (f) by means of a large lens. The films were of various thicknesses transmitting from .05 to .005 of the incident light. The sunlight could be admitted to or shut off from the film by a movable diaphragm. The greatest rate of rotation attained was about 180 revolutions per second, which gave a linear speed to the film of 6,000 cm. per second.

Very little disturbance was produced in the galvanometer by this rapid rotation. There was occasionally a slow drift, sometimes in one direction sometimes in the other.

A number of films of various thicknesses were experimented with but in no case was there a deflection of the galvanometer that could be traced to the act of admitting the light to the film or to suddenly shutting it off.

Three silver films and one platinum were tried. Their resistances were as follows :

- A. Resistances 150 ohms.
- B. " 500 ohms.
- C. " 200 ohms.
- D. This film was formed as follows :

The glass plate was silvered. This silver was coated with a thin film of gelatine. A platinum strip 8 mm. wide was then deposited on this gelatine by the cathode discharge. The platinum film was insulated from the silver by the gelatine. The resistance of the platinum film was 410 ohms.

The order of the effect that might have been expected had there been no impedance already referred to may be approximately calculated. The sunlight was concentrated to about 100 times its natural intensity. The maximum electrical intensity of the electrical component was about 600 volts, of which the resultant components parallel to the direction of motion was 300 volts. The thinnest film transmitted not more than five per cent. of the incident light. The electrical component at the back of the film was thus about 15 volts per centimeter. The velocity of the film was about 6,000 cm. per second. The mean impulsive electrical intensity was

$$x = \frac{2}{\pi} \left(\frac{u}{v} \right)^2 X = 4 \times 10^{-13} \text{ volts per cm.}$$

This was beyond detection by the galvanometer.

With a resistance of 531 ohms in the circuit, one scale division corresponded to an electro-motive force of 1.39×10^{-7} volts.

The effect if it exists was thus about three million times too small to be detected by this instrument.

CONCLUSION.

Professor Bartoli does not give the sensitiveness of his galvanometer. A direct comparison of the two experiments is consequently impossible. It may however be doubted if at that time (1880) he possessed an instrument of much greater sensitiveness than the one used by the writer. It is true that he attained a greater linear velocity of his conducting strip (40,000 cm. per second). But as I could certainly detect a throw of 4 scale division I should easily have observed an effect that gave him a throw of 42

scale divisions. If the galvanometers were equally sensitive this would allow for a peripheral speed one tenth that obtained by Professor Bartoli.

The fact that with my apparatus, which was on the whole probably as sensitive as that of Professor Bartoli, no effect was observed, and also that, if there was any partial rectification, the electrical intensity must have been impulsive and so destroyed by the impedance, leads at least to the conclusion that the existence of the effect described by Professor Bartoli is not established and must remain in doubt until again observed by other experimenters.

PHŒNIX PHYSICAL LABORATORY,

COLUMBIA UNIVERSITY,

October 27, 1906.