THE SELECTIVE REFLECTION OF HEAT WAVES BY LINEAR RESONATORS.

By E. C. Wente.

Synopsis.

Vacuum-thermocouple.—The construction of a vacuum-thermocouple of high sensitivity and quick action for measuring heat radiation is described.

Isolation of Long Heat Waves.—A method is given for isolating radiation of great purity and having a mean wave-length of 96 μ. This radiation is obtained by combining a quartz lens focal isolation apparatus with reflecting surfaces of potassium iodide.

The Reflection of Radiation by Linear Electric Resonators of Microscopic Dimensions.—Resonators were ruled from films of silver chemically deposited on glass plates. The reflecting power of such resonators was measured for the 96 μ waves. Square resonators, the length of whose sides are small compared with the wave-length reflect little more than bare glass, provided the resonators are separated sufficiently to prevent conduction between adjacent edges. Resonators of equal width and separated by a distance of approximately one half of a wave-length were found to produce a maximum of reflection when their length was equal to 0.3 of the wave-length. The metal strips, although microscopic in size, thus show electrical resonance when stimulated by long heat waves. The results are in every way comparable with those that have been obtained with the longer electric waves.

SINCE the work of Hertz on electric waves a large number of experiments[1] have been carried out on the transmission and reflection of such waves by groups of linear resonators.[2] It has been found that a maximum amount of radiation is reflected from a plane surface over which such resonators are distributed in parallel rows and columns when the wave-length is from two to three times the resonator length, the exact value depending principally upon the position of the individual resonators relative to each other, and upon the dielectric constant of the material with which they are in contact. Only a few experiments of this nature have been undertaken with radiation of shorter wave-lengths such as is emitted from hot bodies, chiefly on account of the difficulty of making resonators of microscopic dimensions. The first experiments

[1] A. Garbasso, Atti. Acc. di Torino, 28, 470 and 816 (1893), Garbasso and Aschkinass, Ann. d. Phys., 53, 534 (1894). Aschkinass and Schaefer, Ann. d. Phys., 5, 489 (1901). Cl. Schaefer, Ann. d. Phys., 16, 106 (1905). Blake and Fountain, Phys. Rev., 23, 257 (1906). M. Paetzold, Ann. d. Phys., 19, 116 (1906). Woodman and Webb, Phys. Rev., 30, 561 (1910). Nelms and Severinghaus, Phys. Rev., 1, 429 (1913).

[2] The term linear resonator as here used may be defined as any metallic rod or rectangular piece of metal foil whose length is at least twice its greatest width.

on reflection by groups of resonators in the field of infra-red spectrum were carried out by Rubens and Nichols[1] in 1897 with plane polarized residual rays from fluorite, which had a mean wave-length of 23.7 μ. Silver films, chemically deposited on glass, were ruled with a diamond on a dividing engine in such a way that the whole surface was left covered with regularly spaced, rectangular pieces of silver 5 μ wide and with separations of 5 μ. Four such surfaces were prepared, on each of which the resonators were of different lengths. When the residual rays were allowed to fall on these surfaces, it was found that a greater proportion of the incident radiation was reflected when the electric component was parallel than when it was perpendicular to the axis of the strips, and that in the former case the amount reflected was greatest when the resonators had a length approximately equal to an even multiple of a quarter of a wave-length. The results were hardly more than qualitative, however. Only four of a larger number of resonator plates that were ruled were deemed suitable for the experiments. On all the rejected plates 10 per cent. or more of the resonators were torn away during the difficult process of ruling. The spacing between the resonators was insufficient to produce a very sharp maximum in the reflecting power regarded as a function of the resonator length. Although the radiation as obtained by reflection from fluorite plates had a maximum at 23.7 μ, it was not as homogeneous nor as completely polarized as was desirable for these experiments.

In 1912[2] Wood performed experiments of a similar nature with the very long waves obtained from a Welsbach burner by the method of focal isolation. This investigator ruled the metal film of a "half-silvered" quartz plate into small squares. The film cut in this way was found to be entirely opaque to the long heat waves, although the linear dimensions of the squares were less than one tenth of a wave-length. Wood also performed some experiments with plates on which were deposited minute spherical metal particles, but found no indication of resonance.[3] Thus Wood failed to verify the results obtained by Rubens and Nichols.

The experiments described below were undertaken for the purpose of making a more complete study of the reflection of heat waves by linear resonators, particular attention being given to the highly important consideration of having the resonators well spaced in order to make the resonance as sharp as possible. The radiation with which Rubens and Nichols carried out their experiments had a mean wave-length of only 23.7 μ. Methods are now available for isolating radiation of much

[1] PHYS. REV., 5, 164 (1897), and also Ann. d. Phys., 60, 418 (1897).
[2] Phil. Mag., 25, 440 (1913).
[3] Phil. Mag., 25, 440–443 (1913).

longer wave-length,[1] so that the difficulty of making resonators of proper dimensions and spacings is considerably less.

Construction of Vacuum Thermo-couple.

In order to be able to rule metallic films into rectangles of the proper size it is advantageous to work with as long heat waves as possible. On the other hand, the amount of energy available decreases rapidly with the wave-length. For instance, in the case of the radiation obtained by Rubens and Wood by their quartz lens focal isolation method, the deflection of the radio-micrometer, even when the radiation was unpolarized, was only about 1 cm. A measuring instrument of the highest sensitivity is therefore necessary.

Of the various types of apparatus that have been used for radiometric measurements in the infra-red region, a vacuum thermo-couple with galvanometer seemed to be best adapted for use in this investigation. Recent experiments[2] have shown that the sensitivity of a thermo-couple is increased from four to seven times when used in a high vacuum; at the same time convection currents, which may cause fluctuations in the readings, are eliminated. In a theoretical paper on the design of vacuum thermo-couples Johansen[3] has discussed the values that must obtain for the dimensions of the lead wires and the area of the receiving surfaces at the junctions of a vacuum thermo-couple for maximum sensitivity. The thermo-couple here described was designed so as to conform to these values as nearly as possible.

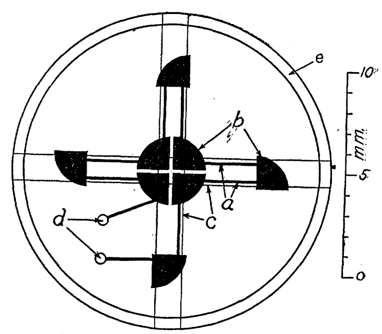

Fig. 1.
Front view of thermo-couple.

The general arrangement of the thermo-couple finally constructed is shown in Fig. 1. The leads are of bismuth and bismuth-tin alloy (Bi 95 per cent.; Sn 5 per cent.). Bismuth wire, made by Heraeus, was kindly supplied to the writer by Prof. H. M. Randall, of the University

[1] Rubens and Wood, Phil. Mag., 21, 249 (1911). Rubens and Hollnagel, Sitzber. der Preuss. Akad., Jan. 20, 1910.

[2] P. Lebedew, Ann. d, Phys., 9. 209 (1902).

W. H. J. Moll, Arch. Neerland des Sc. Ex. et Nat. (II), 100.

A. H. Pfund, Publ. Allegh. Obs., 3, p. 43 (1913); Phys. Zeit., 15, 876 (1913).

E. S. Johansen, Ann. d. Phys., 33, 517 (1910).

Reinkober, Ann. d. Phys., 34, 348.

W. Coblentz, Bull. Bur. of St., 11. 621 (1915).

[3] Loc. cit.

of Michigan. The alloy was made from commercial bismuth and tin. A junction formed from these materials gave a thermo-electric power of 135 microvolts per degree centigrade. The leads, *a*, are 2.5 mm. long and were all made of such a size that their resistance was 2.5 ohms each. In order to obtain leads of this size, small pieces of the material were pressed between glass plates and then cut into narrow strips with a razor blade. The resistance of each strip was measured separately, and those pieces not having the proper resistance were rejected. The ends of the leads were attached by a very small amount of solder of low melting point to the receivers, *b*, which consist of sectors of silver foil of 0.0005 cm. thickness and of 2 sq. mm. area.

Although a junction formed from bismuth and bismuth-tin alloy gives a high thermo-electric power, these materials have not been used extensively because the thermo-couples become easily broken, the alloy particularly being quite brittle. To avoid this difficulty the receivers were attached with a trace of shellac to the stretched quartz fibers, *c*, having a diameter of about 0.002 cm. The fibers are fastened to one end of a short piece of glass tubing, *e*. The heat conductivity of these fibers is quite negligible. The copper terminal leads, *d*, were attached by a glass seal to the other end of the glass tubing as shown in Fig. 2. A thermo-couple put together in this way will withstand a great deal of jarring without becoming broken.

The receiving surfaces, instead of being blackened on the front side in the usual way, were coated with a thin layer of water glass to which had been added a small amount of India ink. While unblackened surfaces are not good absorbers of ordinary light, Rubens and Wood[1] found water glass to be an especially good absorber of radiation of long wavelengths, whereas lampblack is almost perfectly transparent to these waves.

The thermo-couple was mounted in a glass container as shown in Fig. 2. The glass tube, *e*, on which the thermo-couple was mounted was placed inside of another glass tube, *c*, and attached to it with sealing wax in order to keep the receiving surfaces about a millimeter away from the quartz window, *a*. This quartz window, had a thickness of 1 mm. The vacuum was maintained by liquid air and charcoal. By means of a small discharge tube, attached as shown, the general state of the vacuum could be determined.

One of the chief disadvantages of a thermo-couple for use in radiation measurements has generally been considered to be its sluggishness. In order that a thermo-couple may respond quickly to variations in the

[1] Phi. Mag., 21, 249 (1911).

intensity of the radiation, the leads should be short and the junctions should have a small heat capacity. In the case of the couple just described, because of the high conductivity of silver, it was possible to make the receivers of silver foil of very small thickness. Supporting all the parts of the couple on quartz fibers eliminates the usual long lead wires going to the supporting frame.

Although the receiving surfaces of the couple were not entirely "black"

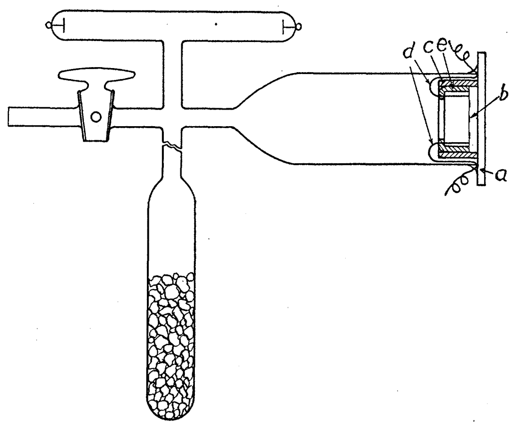

Fig. 2.

Mounting of thermocouple in evacuated tube.

for ordinary light, nevertheless, with the couple mounted as shown in Fig. 2, when connected to a galvanometer having a resistance of 25 ohms and a sensitivity of 1×10^{-10} amperes per mm., a deflection of 2,500 mm. per candle meter was obtained. This sensitivity compares favorably with that of any instrument heretofore described, having the same receiving area.

The Galvanometer.

The galvanometer used with the thermo-couple was identical in design with that described by Nichols and Williams[1] except for a slight modification of the shields. Instead of a cylinder of silicon steel, the intermediate shield consisted of 35 turns of 0.04 cm. transformer iron, wound spirally, the layers being separated from each other by paper 0.04 cm. thick. The efficacy of this type of shielding has been investigated both theoretically and experimentally by Esmarch.[2] The three shields combined were found to have a shielding ratio of about 40,000.

The zero position and sensitivity of moving magnet galvanometers

[1] Phys. Rev., 27, 250 (1908).

[2] Ann. d. Phys., 39, 1550 (1912).

have generally been controlled by means of a special magnet provided for that purpose. This has usually been necessary in order to overcome a certain amount of residual magnetism either in the shields or in some of the other parts in the immediate neighborhood of the moving magnets. With this arrangement slight variations in the strength of the residual field will cause a drift of the zero position, which may impair the accuracy of the readings. In the instrument here described this residual magnetism was reduced practically to zero by very carefully demagnetizing the inner shield and by winding the galvanometer field coils with non-magnetic copper wire. No control magnet was necessary, as the moving system followed almost exactly any angle through which the upper end of the quartz fiber suspension was turned. The quartz fiber was selected of a thickness to give the desired sensitivity, which in most of the work was 5×10^{-11} amps. per mm., with the scale at a distance of one meter. With this sensitivity the galvanometer had a period of about 12 sec. for a complete oscillation.

The galvanometer was supported by a Julius suspension, and to prevent disturbances from air currents and temperature changes the frame of the Julius suspension together with the galvanometer was surrounded by a box. Heavy copper leads were used to connect the thermocouple to the galvanometer. Soldered connections were used throughout, and all junctions were protected as much as possible from circulating air currents. In spite of all these precautions, during certain hours of the day the galvanometer zero reading varied several millimeters; these fluctuations were apparently caused by earth currents as during other periods the zero reading was constant to a small fraction of a millimeter.

Method of Isolating Radiation of Long Wave-length.

In order to make satisfactory resonators on glass by ruling silvered surfaces, it is desirable to work with the longest wave-lengths possible. The method of focal isolation with a Welsbach burner as a source, according to the experiments of Rubens and Wood,[1] gives radiation which is distributed over a fairly wide spectral region, but has quite a distinct maximum of energy at about 100 μ wave-length. A modification of this method was adopted for this investigation.

The general arrangement of the apparatus is shown in Fig. 3. a and a' are quartz lenses having a thickness of 0.7 cm. at the center and 0.35 cm. at the edge, a diameter of 4.4 cm. and a focal length for ordinary light of 13.5 cm. c shows the position of the surface whose reflecting power is to be studied. The opening, O and the reflecting surface at C

[1] Loc. cit.

have diameters of 0.5 and 1.0 cm. respectively. The lens a' is placed in a position such that the radiation of long wave-length is brought to a focus at c. Coming from c, it is reflected from plane surfaces at e and f and then again brought to a focus on the central junctions, h, of the thermo-couple by the lens, a. The short waves, which would otherwise pass through the central parts of the lenses, are stopped by the metal

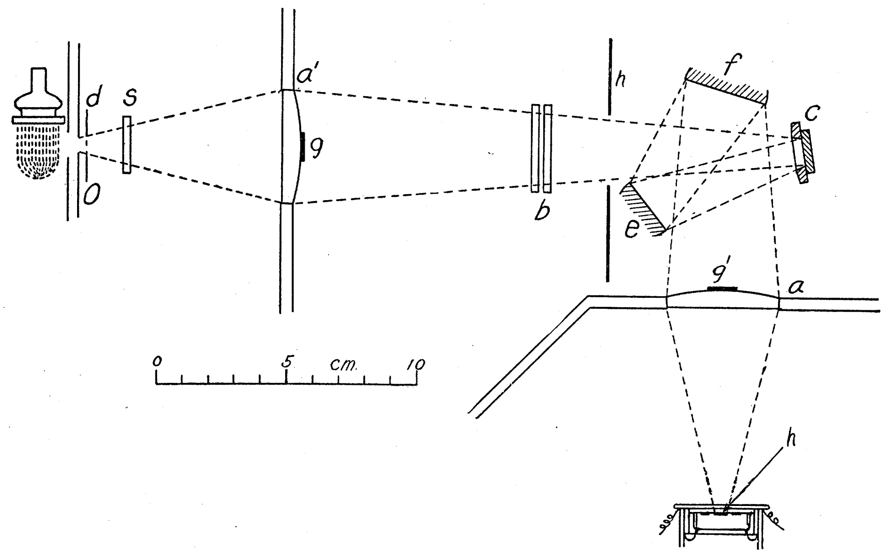

Fig. 3.

discs g and g'. The shutter, s, is made of a plate of rock salt 3 mm. thick. Rock salt is almost perfectly transparent up to the point where quartz is a total absorber, and is opaque to radiation beyond 80 μ, where the quartz begins to transmit freely. At b is placed a Fabry and Perot interferometer such as was first used by Rubens and Hollnagel[1] for measurements of wave-lengths in the infra-red region. The plates are made of quartz 3 mm. thick the inner surfaces of which are plane to within a few wave-lengths of sodium light.

At d is a polarizer which consists of a plane grating made of platinum wires 0.025 mm. in diameter separated by a distance of 0.025 mm. A grating of this type has been investigated by DuBois and Rubens,[2] who found that for long heat waves the transmitted radiation was almost completely polarized. The grating, which had a diameter of only 1 cm., was easily made by winding the wires on a metal frame and spacing them

[1] Phil. Mag., 19, 761 (1911).

[2] Ber. der D. Phys. Gesell., 9, 431 (1911).

by means of a guide fastened to the carriage of a dividing engine. The wires were then soldered to the frame and those on one side of the frame, removed. In this manner little difficulty was experienced in making sufficiently good gratings of the small size required.

The apparatus as described above is very similar to that used by Rubens and Wood,[1] who found that the radiation reaching the thermocouple, when a Welsbach burner was used as a source, had a mean wave-length of approximately 100 μ, but the energy was distributed over a rather wide spectral region. For this investigation it is highly desirable that the radiation should be as nearly monochromatic as possible. The radiation was therefore purified further by introducing reflecting surfaces of potassiums iodide at *e* and *f*. The residual rays from potassium iodide have a wave-length somewhat less than 100 μ[2]. This value coincides very nearly with the mean wave-length of the radiation obtained by the focal isolation method with a Welsbach burner.

These reflecting surfaces of potassium iodide were prepared by grinding the salt to a powder, and forcing it against a piece of heavy plate glass with a pressure of about 450 kilograms per square cm. When the pressure was relieved, the salt was left in a solid mass, which could easily be removed from the glass plate, the surface adjacent to the glass being left in a perfectly smooth condition, so that no grinding or polishing was required.[3]

Fig. 4 shows an interferometer curve which was taken with the apparatus arranged as described but with silver instead of potassium iodide surfaces at *e* and *f*. The ordinates represent deflections of the galvanometer resulting from the opening of the shutter, *s*. The abscissæ give the separation of the interferometer plates, except for an additive constant, as no special pains were taken to determine the exact distance between the plates for the smallest separation.

If the energy distribution with respect to wave-length had but one maximum, the curve obtained in this way should have a form similar to that of a damped sine-wave, that is, the amplitudes of the periodic variations in the galvanometer deflections should decrease gradually with the separation of the interferometer plates. In the curve shown, these amplitudes first decrease and then increase and finally decrease gradually. This fact shows that the spectral distribution curve of the radiation has more than one maximum.[4] The radiation so obtained

[1] Loc. cit.

[2] Rubens and Hollnagel, loc. cit.

[3] This method of preparing reflecting plates appears to have been used first by Miss G. Langford, PHYS. REV., 33, 137 (1911).

[4] Rubens and Hollnagel, loc. cit.

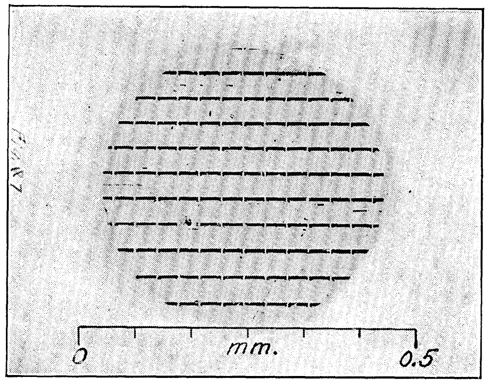

Fig. 7.

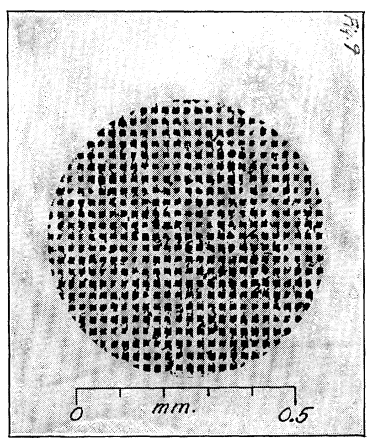

Fig. 9.

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is therefore quite unsuited for investigating the reflecting power of resonators. Rubens and Wood concluded from the curve obtained by them with apparatus of the same type that the spectral distribution curve had only one maximum; but apparently they did not continue

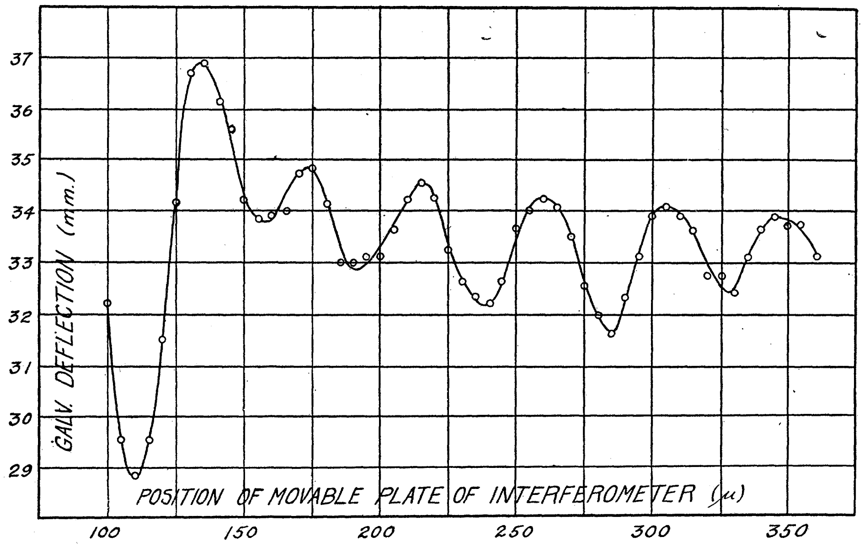

Fig 4

their observations to sufficiently large separations of the interferometer plates to determine the real character of the energy distribution of the radiation. The fact that there are several maxima is probably due to absorption bands of water vapor.[1]

The curve of Fig. 5 corresponds to that shown in Fig. 4 except that the

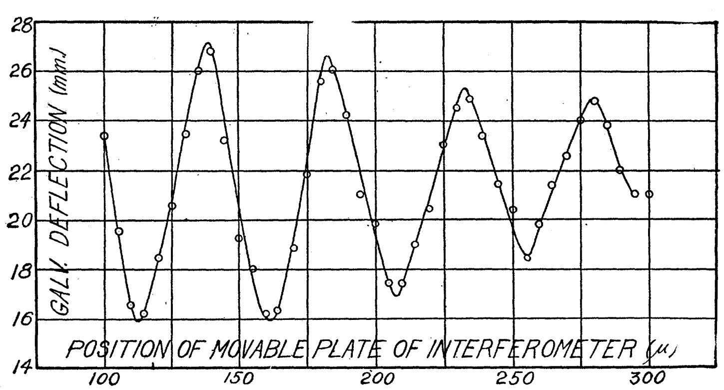

Fig. 5.

[1] H. Rubens, Sitzber. der Preuss. Akad. der Wiss., 28, p. 513 (1913).

silver plates at e and f were replaced by the potassium iodide surfaces. This curve, being very similar to a damped sine-wave, indicates that the energy of the radiation reaching the thermo-couple is grouped principally about a single wave-length. This wave-length may be calculated from the distances the interferometer plates were moved between successive maxima or minima. The mean of all these distances is $47.9\,\mu$ from which we determine the principal wave-length as 2×47.9 or $95.8\,\mu$. An approximate idea of the energy distribution curve in this case may be obtained, if, following the method adopted by Rubens and Hollnagel, we assume that this has the form of a resonance curve when plotted as a function of the wave-length, *i.e.*,

$$\Phi_\lambda = \Phi_0 \frac{\delta^2}{\delta^2 + 4\pi^2(\lambda - \lambda_0/\lambda)^2},$$

where λ_0 is the wave-length for which the energy of the radiation has a maximum value, Φ_0, which in this case we assume to be $95.8\,\mu$. δ is the logarithmic decrement, as obtained from the interferometer curve. δ,

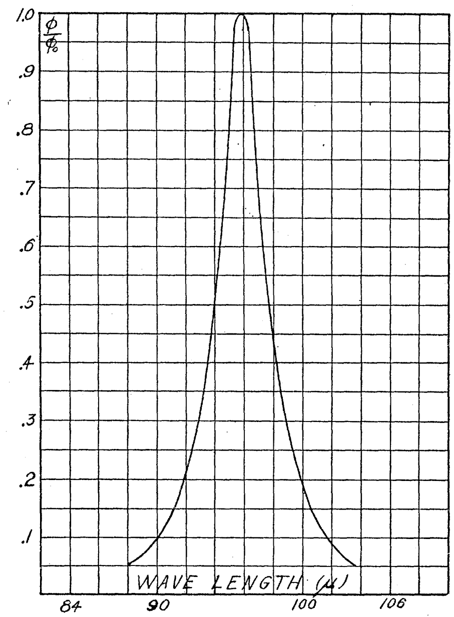

Fig. 6.

Distribution of the energy of the radiation as a function of the wave-length.

as determined from the curve of Fig. 5, assumed as a damped sine-wave, has an approximate value of 0.25. With these values of λ_0 and δ Φ_λ, plotted as a function of λ, gives the curve shown in Fig. 6. This curve shows that the greater part of the radiation lies within a narrow band of wave-lengths.

All the preceding measurements were made with a Welsbach burner as source. A quartz mercury vapor lamp was tried but apparently gave less radiation of the desired wave-lengths even when operated at very high voltages.

Construction of Resonators.

In order to make resonators of the small size required for these experiments silver was chemically deposited on pieces of plate glass 0.4 cm. thick and the fresh deposit ruled into rectangles of the proper size with a diamond on a dividing engine. For this method to work satisfactorily the silver deposit should be uniform in thickness and adhere firmly to the glass. These conditions seemed to be best satisfied by the use of the formaldehyde silvering process.[1] Best results were obtained only when the glass plates were first immersed in a hot solution of chromic acid. The silvering process was so regulated as to give coatings of practically the same thickness for all of the plates. This thickness was such that the silvered surfaces reflected the 96 μ radiation as completely as a plate of silver several millimeters thick, although they were not entirely opaque to light in the blue region of the visible spectrum.

In order to obtain resonators that are widely separated it is necessary to remove the silver deposit in wide strips. If an attempt is made to make wide cuts with a diamond, a large proportion of the resonators will be carried away, whereas clean cuts result, if the diamond is set so as to rule a fine line by having one of its natural edges parallel to the direction of the cut. To remove the silver in wide strips it was found most

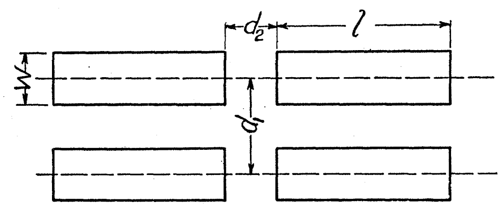

Fig. 8.

satisfactory therefore to rule fine lines but so close together that no metal remained between adjacent rulings. In this way it was possible to leave very narrow strips of silver and separated by as wide a space as desired. Light watch oil, flowed over the surface during the ruling, carried away the chips of silver removed by the diamond and so prevented

[1] Wood, Physical Optics, p. 281, 1914 edition.

their accumulation under the cutting edge. Fig. 7 is a photomicrograph of a part of a set of resonators ruled in this way. This particular photomicrograph was taken of the plate listed as No. 7 in the table below. It shows the character of the resonators on all the plates numbered from 1 to 8. The following table gives the dimensions and spacings of the resonators of all the plates that were used in this study. Fig. 8 will make clear the meanings of the terms used in the table.

In the experiments of Wood[1] on the reflection of long heat waves by

No. of Plate.	l (μ).	w (μ).	d_1 (μ).	d_2 (μ).
1	13.0	8	44.5	4
2	17.2	"	"	"
3	21.35	"	"	"
4	25.5	"	"	"
5	29.7	"	"	"
6	33.85	"	"	"
7	38.0	"	"	"
8	42.2	"	"	"
9	15.0	15.0	17.0	2
10	15.0	15.0	27.0	12

ruled silvered surfaces it was found that single narrow cuts made by the diamond did not alter the resistance of the film appreciably. This result was verified. A single fine cut of the diamond increased the resistance of the film only slightly, although as far as could be determined from the image given by the microscope the silver had been removed completely. When several adjacent cuts were made so that the gap was 2 or 3 μ wide the resistance was increased, but only after the total width of the space was roughly 5 μ did the resistance become practically infinite. Apparently when the diamond makes a narrow single cut, the silver is not completely removed from the gap, although it does appear so when observed with a microscope. However, if the surface was ruled so as to leave widely spaced strips of metal 5 or 10 μ wide, a single cross cut made the resistance along the strips practically infinite. In this case the diamond undoubtedly removes the silver in its path completely.

Experimental Results.

Wood[2] found that when a silvered surface was ruled into regularly spaced squares, the reflecting power of the surface was the same as before the rulings were made, even if the width of the squares was only a small fraction of the wave-length of the incident ray. As one would expect

[1] Loc. cit.

[2] Loc. cit.

such a surface to reflect scarcely more than the bare glass it was thought worth while to make a further test of this point. Two silvered surfaces were therefore ruled into squares 15 μ wide. In the first of these the cuts were about 2 μ wide and the resistance across each cut was approximately 100 ohms per cm.; in the second set the cuts were made wide enough to make the resistance between the squares practically infinite. A photomicrograph of this plate is shown in Fig. 9. When these plates were used in turn as reflectors at c (Fig. 5), the former was found to reflect 70 per cent. of the incident radiation, whereas the latter reflected only 30 per cent., the reflecting power of a plate of silver being assumed as 100 per cent. A glass surface without any metallic deposit reflected 20 per cent. The surface with the wide cuts, before being cross-ruled, reflected only 34 per cent. of the radiation when the electric component of the incident waves was perpendicular to the strips, but 86 per cent. was reflected when it was parallel to the strips.[1] From these data it appears that the negative result obtained by Wood was very probably due to the fact that the squares were not separated completely from each other.

The ideal method of stuyding the selective reflection of waves by a group of linear resonators is to determine the reflecting power of such a group for monochromatic radiation of varied wave-length. However, this method is impracticable because of the difficulty of obtaining pure radiation of the different wave-lengths required. A method virtually equivalent to this is to keep the wave-length of the radiation constant and to measure the reflecting power of a number of groups of resonators of different dimensions, but in each of which the quantities, w, l, d_1, d_2 (Fig. 8), bear the same relation to each other. It is rather difficult to rule sets of resonators of different sizes with a fixed relation between all the dimensions on account of the many different settings that have to be made on the dividing engine. However, experiments on electric waves have shown that the quantities, d_2 and w (Fig. 8), affect the sharpness of resonance but little, provided l is

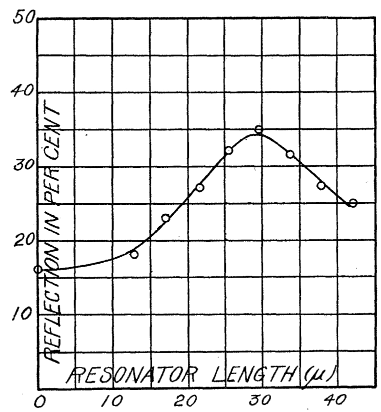

Fig. 10.

[1] These particular measurements were made with the radiation obtained without the use of the KI reflecting surfaces. The radiation was therefore not as pure as is indicated by the curve in Fig. 6.

at least four times as great as w.[1] The plates numbered from 1 to 8 in the table were therefore ruled so that all the dimensions except l were the same in each case.

The percentage reflection of each of these plates was measured for the radiation obtained by the combination of the quartz lenses and potassium iodide reflecting surfaces (Fig. 3). These values, plotted as a function of the resonator length, 1, are shown in Fig. 10.

Concluding Remarks.

The curve shown in Fig. 10 has a distinct maximum for a resonator length of about 29 μ. Although this maximum is not very sharp, it is sufficiently pronounced to show that the microscopic metal strips on the plates function as electrical resonators when stimulated by the heat waves 95.8 μ in length emitted by a Welsbach burner.

It may be of interest to compare the results here given with those obtained by other experimenters using electric waves and linear resonators made from tinfoil. Most of the work with electric waves was done with resonators in air. For this case the theoretical value[2] for the ratio of wave-length to the resonator length for resonance is given by some investigators as 2 and by others as 2.5. The ratio found by different experimenters varies between these values. Perhaps the most recent experimental investigation of this point is that of Nelms and Severinghans,[3] who found that this ratio was a function of the axial separation of the resonators, but when the separation was greater than twice the resonator length, it approached the value 2.5. The curve shown in Fig. 10 incidates that for resonance the wave-length (95.8 μ) is 3.3 times the resonator length. Because of the high dielectric constant of glass the electrostatic capacity of the individual resonators is greater than is the case when they are completely surrounded by air, and for this reason it is to be expected that the ratio of wave-length to resonator length for resonance should be somewhat greater than 2.5. A similar result was found by Blake and Fountain[4] for electric waves having a wave-length of 10 cm. and resonators made from strips of tinfoil. These investigators found that when resonators attached to a glass plate were separated axially a distance equal to 0.5 of a wave-length the ratio of resonator

[1] Nelms and Severinghous, loc. cit.

[2] MacDonald Electric Waves, p. 111.

M. Abraham, Ann. der Physik, 66, 435 (1898).

Rayleigh, Phil. Mag., 8, 105 (1914).

Oseen, Mat. Astron. Och Fysik (Stockholm), 9, 30, p. 1 (1914).

[3] Loc. cit.

[4] Loc. cit.

length to wave-length for resonance was 3.5. It is not possible to make any accurate comparison between the values found for resonators on glass for electric waves and for the long heat waves used in the investigation described in this paper; the dielectric constant, even if the same kind of glass were used, might be very different in the two cases because of the difference in frequency. The composition of the glass is undoubtedly also an important factor. In spite of these different conditions the agreement between the value as found in this investigation and that given by Blake and Fountain for the ratio of wave-length to resonator length for resonance is very close.

It would be very desirable to separate the amount of energy reflected by the resonators from the amount reflected by the glass. Rubens and Nichols[1] assumed that the resonators and the glass reflected independently. It does not appear that this assumption is altogether legitimate, as the experiments of Blake and Fountain show. They found that for certain resonator lengths less energy was reflected by a glass plate covered with resonators than from a plate of bare glass. There appeared to be no simple way of separating these two quantities so that the results are here given only for the composite structure.

In the experiments of Rubens and Nichols it was found that a much larger percentage of the energy was reflected by linear resonators when the wave-length was equal to twice the resonator length. Not a sufficient number of resonators of different lengths were tried, however, to show the exact position of the maximum. The distance between the resonators which they used was a small fraction of a wave-length. Now, experiments[2] on electric waves have shown that as the separation between the resonators is decreased the length of the resonators for resonance is increased. For this reason it is probable that a resonator length equal to one half the wave-length was very nearly the proper length. It is therefore more than probable that the phenomenon observed by them was due to electrical resonance. The maximum reflection observed by Rubens and Nichols was 66 per cent. as compared with 35 per cent., the value found in the experiments here described; this difference is probably due to the fact that the number of resonators per unit area was much greater. The latter value agrees more closely with the value obtained by Blake and Fountain with electric waves.

Although the results obtained in these experiments do not indicate that metallic resonators of the type considered reflect highly selectively, yet the reflection is so much greater within a certain region that the use

[1] Loc. cit.

[2] Blake and Fountain, loc. cit.

of such plates of resonators for isolating heat waves of a certain wave-length by multiple reflection does not seem altogether impracticable. Severinghans and Nelms[1] used a similar method for obtaining electrical waves of much greater purity than was otherwise possible. Although the measurements of Rubens and Von Baeyer[2] on the radiation obtained from a quartz mercury vapor lamp indicate the presence of wave-lengths as great as 600 μ, by far the larger proportion of the radiation was of much shorter wave-lengths. If this radiation were reflected a number of times from plates of resonators of proper dimensions the longer wave-lengths would be isolated more definitely. The outstanding difficulty in the use of such reflecting plates is that the energy finally obtained would be very small, perhaps too small, for accurate measurement with apparatus at present available

In conclusion the writer wishes to acknowledge his indebtedness to Professor E. F. Nichols, who suggested the foregoing investigation, for his kindly encouragement and very helpful suggestions.

SLOANE LABORATORY,
YALE UNIVERSITY.

[1] Loc. cit.

[2] Sitzber. der Berl. Akad., 1, 666 (1911).

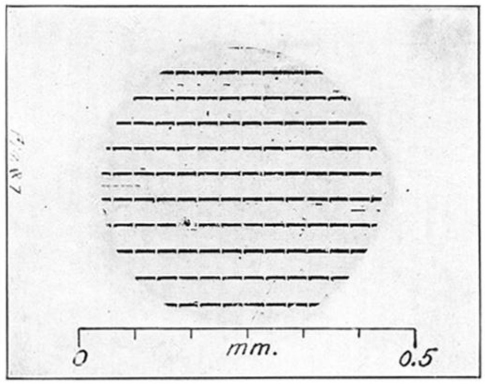

Fig. 7.

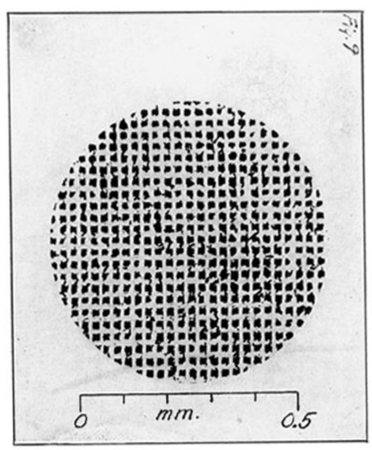

Fig. 9.