SOME PECULIARITIES OF POLARIZATION AND ENERGY DISTRIBUTION BY SPECULUM GRATINGS.

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SYNOPSIS.

Intensity Minima in Spectra of Speculum Gratings.—A series of intensity minima, resembling absorption lines, are to be found in the continuous spectrum of a speculum grating at such wave-lengths as are being tangentially diffracted in other orders. They are limited to the azimuth of polarization with electric vector perpendicular to the rulings and appear best in such gratings as show strong spectra in several orders. While they appear in the visible spectrum for a deeply ruled grating, in general they may be observed only for longer wave-lengths—say between .8 μ and 2 μ. Although simple energy considerations furnish a fairly satisfactory explanation of the phenomena, it is highly desirable that the Rayleigh-Voigt grating theory be modified and extended to fit these and similar facts or else that a new theory be developed.

Practical Importance to the Spectroscopist.—It is highly desirable that work on the Zeeman effect or other polarization phenomena with speculum gratings be arranged—as may be easily done—so as to avoid this effect. The same may be said of infra-red absorption measurements.

IT is a well-known fact that grating spectra show certain peculiarities not exhibited by prismatic spectra, such as ghosts, abnormalities of polarization and some others. To these there may now be added—for speculum gratings—another peculiarity in the form of a series of marked minima of intensity in the continuous spectrum, superficially resembling absorption lines. These are confined to the azimuth of polarization in which the vibration (electric vector) is perpendicular to the rulings, and are as a rule much more prominent in the early infra-red region—wave-length from .8 μ to 2 μ—than in the visible spectrum. This probably accounts for their not having been generally observed before.[1] Another reason is that the effect is not likely to show very well in a grating of the sort which would ordinarily be chosen for spectroscopic work, *i.e.*, one having, among other properties, that of concentrating its energy in one spectrum, while it is marked in gratings which give bright second and higher orders as well as the first.

The phenomenon was not wholly unlooked for when the problem was

[1] The dark bands observed by Wood (Phil. Mag. (6), 4, 396, 1902, and 23, 310, 1912) for an abnormal speculum grating and particularly for gratings ruled on silver, while unquestionably closely related to these minima cannot, from the description, be certainly identified with them.

taken up, but was not just what was expected. In a previous paper[1] the writer has described experiments which show that the directly reflected light or central image from a speculum grating is markedly deficient in light of such wave-length as is, in the first or higher order spectrum, emerging tangentially from the grating. The effect is confined to the azimuth of polarization already mentioned, viz., with electric vector perpendicular to the rulings, and is in general accord with the Rayleigh-Voigt grating theory.[2] This theory goes on to predict that, for this same azimuth of polarization one should find in the first order spectrum, say, at such wave-lengths as are being tangentially diffracted in the second or higher order spectra, sharp *maxima* of energy. Wood[3] has found such an effect in the case of a special grating ruled on silver. The phenomena noted here are, with one exception, just the reverse of this, viz., *minima* instead of maxima.

A rather simple spectro-bolometric apparatus served very well in the measurement of this effect. Light from a special tungsten strip filament lamp[4] was focused by a concave mirror (of approximately 30 cm. focal length and 8 cm. aperture) on a slit at the principal focus of another mirror, from which the light then fell in a parallel beam on the grating. The diffracted light passed through a large (5 cm. aperture) Wollaston double image prism of calcite, which separated the beam into the two azimuths of polarization, perpendicular and parallel to the rulings, respectively. These spectra were focused by another mirror on the two strips of a special bolometer so that in this way the energy in each state of polarization could be investigated independently. A sensitive 8-coil Thomson galvanometer at a distance of approximately 3 meters served in connection with the bolometer to measure the energy at any given wave-length, which energy is expressed, in this paper, in terms of the galvanometer deflections. To avoid the effect of overlapping spectra a 25° glass prism was placed between the lamp and first concave mirror. The latter was adjustable so that the slit could be illuminated by a block of radiation, perhaps .2 μ wide in wave-length, taken from any part of the resulting (impure) spectrum.

The illuminating system of lamp, prism, two mirrors, and slit, was rigidly mounted and arranged so that it could be rotated with the grating about the axis of the spectrometer. In studying the energy distribution the incidence was fixed at any desired angle, and the whole system then

[1] Astrophys. Jour., 51, 129, 1920.

[2] Proc. Roy. Soc. (A), 79, 399, 1907. Gött. Nachr. Math. Phys. Kl. (1911), p. 40.

[3] Phil. Mag. (6), 23, 310, 1912.

[4] These lamps are now obtainable from the Nela Laboratory. They are invaluable in spectroscopic work where an intense constant source of this nature is desired.

rotated so that the angle of diffraction of the radiation falling on the bolometer could have, in turn, any value up to 90°.

Gratings.—Through the kindness of Professor Michelson and Professor Gale four gratings were specially ruled by Mr. Fred Pearson of Ryerson Laboratory and furnished for this investigation. They all had ruled surfaces approximately five centimeters square, and were of the following spacings: No. 1, 8709 lines to the inch—$S = 2.916\ \mu$; No. 2, 7620 lines per inch—$S = 3.333\ \mu$; No. 3, 10160 lines per inch—$S = 2.500\ \mu$; No. 4, same spacing but ruled with at least ten times the pressure, giving a comparatively very deep cut. No. 5 was a Hopkins grating of 15,000 lines per inch ($S = 1.693\ \mu$), with a quite extraordinary concentration of energy in one spectrum.

The results are shown graphically in Figs. 1 to 4. These are in reality energy curves plotted with angle of diffraction as abscissa instead of

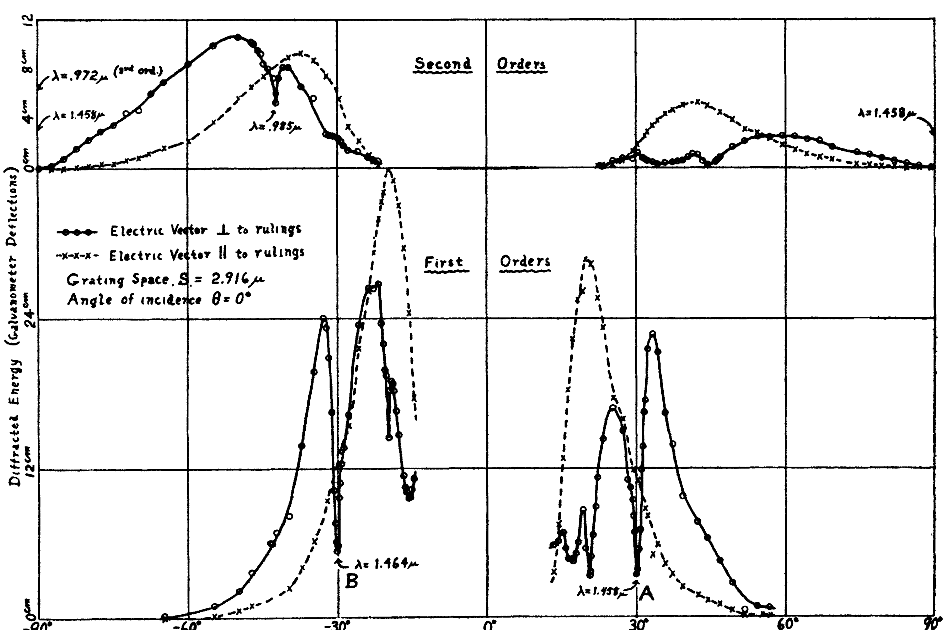

Fig. 1.

Energy curves (of a tungsten filament) for both azimuths of polarization, as determined with a speculum grating (No. 1) of 8,709 lines per inch. Light incident normally.

wave-length, as in the ordinary case. No correction of any sort has been applied. The plus and minus signs in connection with the angle of incidence or diffraction are used to indicate the two sides of the grating normal.

The minima at or very near angle 30° in Fig. 1 are very marked. Now since sin 30° = 1/2, the same wave-length occurs here in the first order as is emerging tangentially in the second: how closely these wave-lengths check is indicated. There are also secondary minima in the neighborhood of 20° and 15° for wave-lengths which are tangential in the third and fourth orders respectively, though the agreement is not so good in this case.

Referring now to the upper part of the figure, showing the second order, it will be remarked that there is a considerable amount of energy in this order and it is particularly to be noted that as the angle of emergence approaches 90° the proportion of radiation of perpendicular polarization to parallel becomes larger and larger. This is in accordance with the Rayleigh theory and is a fact which can be readily observed with almost any speculum grating by examining the tangentially emergent light with a nicol prism.

A simple and fairly satisfactory explanation of these minima may be based on this last mentioned fact, viz., the relatively large amount of perpendicularly polarized radiation coming obliquely from the grating (although to account for the excess of energy of this state of polarization we must, for the present, rely entirely on the Rayleigh theory; no purely physical reason can, as yet, be adduced). For this excess must be made up by a deficiency at this same wave-length region in other spectra and since the dispersion at nearly tangential emergence is very great—the change in the sine of the angle between 80° and 90° is only one eighth that between 40° and 50°—the obliquely diffracted radiation comes from a very limited spectral region. This accounts for the (usually) narrow minima found at this wave-length in other orders.[1]

A rather critical test of this reasoning was applied by tilting the grating slightly so that the incidence was about 2 1/2° instead of zero. The wave-length tangential in the second order on one side would then be somewhat shorter and on the other, somewhat longer than before. The minimum in the first order should then appear split into two, neither as pronounced as the original one, and the two might furthermore be expected to be of different intensities, corresponding to the difference between the two second order spectra. These predictions are all seen to be amply verified in Fig. 2.

[1] It might be thought that this point could be made more evident by plotting energy in terms of wave-length rather than angle of diffraction, in which case there should appear a sharp maximum at tangential emergence which would correspond exactly to the minimum in some other order at the same wave-length. This does not show satisfactorily, however, because there is so much loss of energy at or near tangential emergence. That is to say, at 70° light may come from all parts of a furrow, whereas at 89° the shielding of one furrow by another is such that the only light emerging comes from the tips.

At other angles of incidence and for other gratings the minima may have markedly different shapes, as Fig. 3 shows. A casual study of these curves will show the correspondence between the wave-lengths of the minima and the radiation tangentially emergent in some other order. While in most cases this order is higher than the one under investigation,

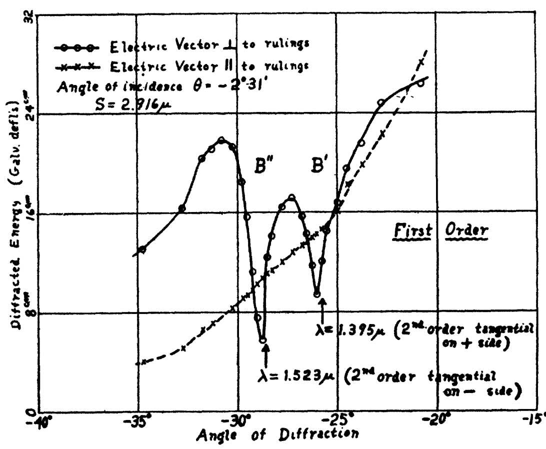

Fig. 2.

Detailed study of minimum *B* (Fig. 1) for an incidence of −2°31′.

a number of instances have been found in which the minimum in the first order on one side corresponds to tangential emergence in the first order on the other. It will be noted that a characteristic of all the minima is a sharp and rapid rise of intensity on the side of longer wave-lengths (*i.e.*, when this wave-length in the second order, say, has passed entirely from the grating) while the rise on the short wave-length side may be very much delayed. In some cases indeed it does not occur at all and the minimum degenerates into a sharp change in intensity.

A rather remarkable case of this is shown in Fig. 4. At first sight it would be thought that this is conclusive evidence for the Rayleigh theory, but a little closer investigation causes one to doubt this and indeed to consider it as merely a special case of the preceding phenomena. It will be noted that the detailed study of this small maximum, for the three angles of incidence, shows that the *sharp side*, and not the peak of the minimum, corresponds exactly to the above theory. Why the energy should fall off rapidly on the right-hand side as it does, giving to the whole the appearance of a fairly sharp maximum, cannot be explained save by remarking that it is undoubtedly due to the groove form, which doubtless accounts in turn for the extraordinary concentrating power of this grating.[1]

Visual Observations.—As already remarked, most gratings show this effect very much better in the infra-red than in the visible spectrum. An exception, however, is grating No. 4 which has very deep furrows and which gives visible dark bands in excellent agreement with the above

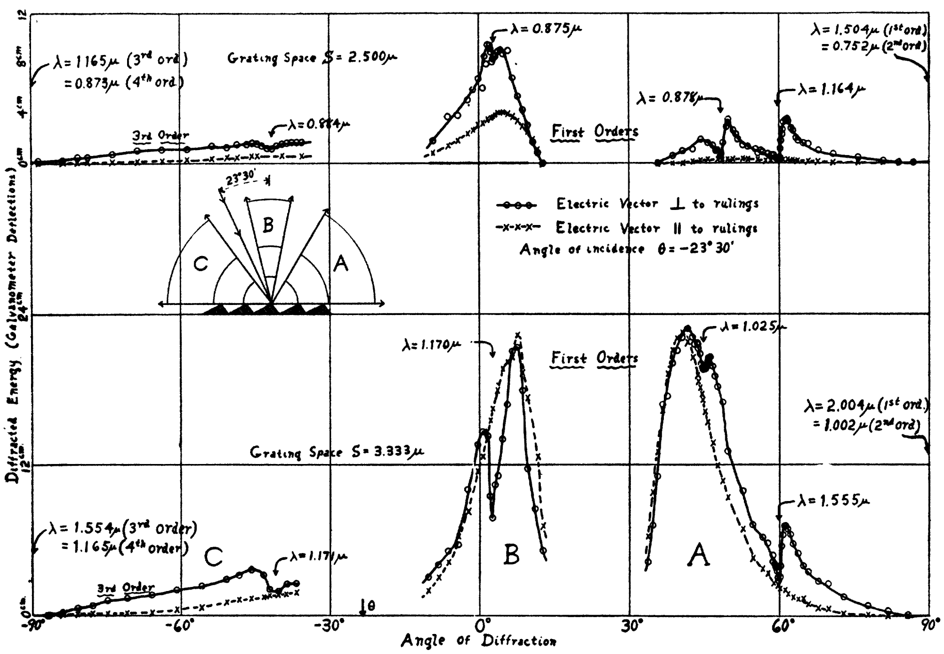

Fig. 3.

Energy curves (of tungsten filament) for both azimuths of polarization, as determined with speculum gratings (Nos. 2 and 3) of 7,620 and 10,160 lines per inch. Angle of incidence, −23°30′.

reasoning. As a matter of fact the agreement is very much better than in the case of the infra-red minima for this same grating. The dark bands observed by Wood, as already mentioned, are doubtless also manifestations of this same general phenomenon and may indeed be identical with the minima found here, although his data does not afford a quantitative check in this case.

[1] It is perhaps a fair question to ask if the phenomena observed by Wood (Phil. Mag. (6), 23, 315, 1912) were not identical with this, a fact which, of course, could only be cleared up by careful investigation, if possible, as to whether the *center* or *edge* of the sharp maximum he observed checks with the theory.

Discrepancies.—While the foregoing explanation of the phenomena as described seems fairly satisfactory, at least to the writer, there are certain other effects observed in this connection which must at present remain totally inexplicable. It will be noted in the curves that in some

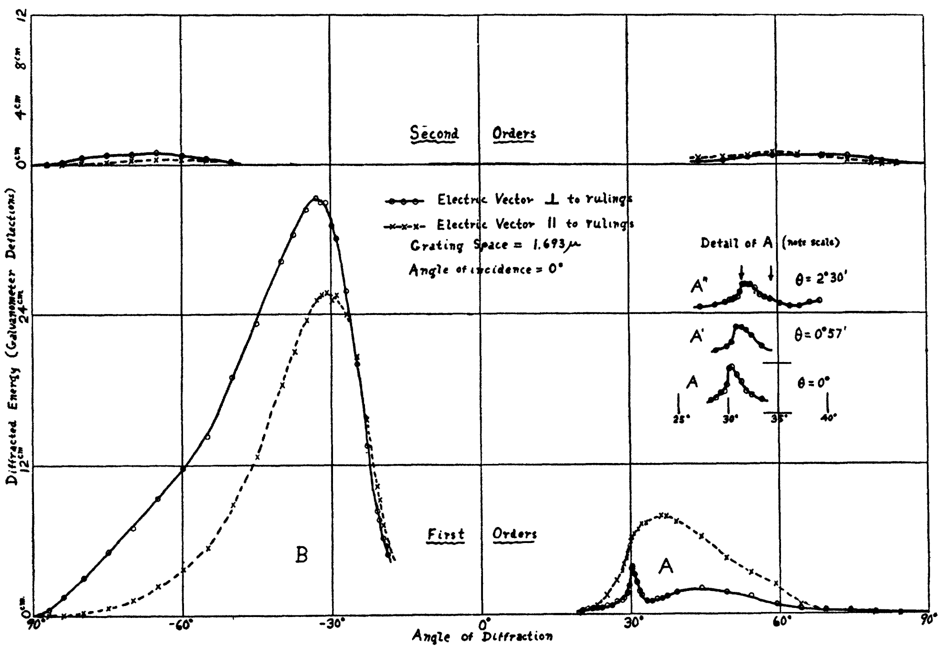

Fig. 4.

Energy curves for a grating (No. 5) of 15,000 lines per inch. Light incident normally.

cases the wave-length at the point of the minimum is slightly longer than that tangentially emergent in the other order. While in the figures shown the discrepancy does not exceed 2 per cent., there are cases in which this is even more.

Considerable study and discussion[1] of this point has failed to yield any very satisfactory explanation, but the outstanding phenomena will be briefly described in order to aid anyone in fitting an explanation to the facts. They are: (*a*) The discrepancies are, when they exist, always in the same sense, *e.g.*, the wave-length at the minimum is always *longer*

[1] Professor Sparrow suggests in explanation of this, an interaction between the light vibrations and the conduction currents they occasion in the furrowed metal on reflection. Professor Wood believes that this is another point of evidence to be added to his results (Phil. Mag., July, 1919) on reflection from films of granular or furrowed surfaces which seem to demand for explanation some new principle in optics. It is probable that the best method to clear this up is to use either very long infra-red wave-lengths or short electromagnetic waves with gratings which can be ruled on a correspondingly large scale.

than that tangentially emerging in the other order. If it were shorter it could be easily explained. (*b*) The disagreement is greater, as a rule, when the light is incident normally or nearly so. In some cases a grating which shows a discrepancy of 2 or 3 per cent., at normal incidence will give results checking to a small fraction of a per cent., when the incidence is increased to 30° or so. (*c*) The discrepancy is most prominent in deeply furrowed gratings. (*d*) In the one grating No. 4 which shows both infra-red and visual minima the discrepancy is as already remarked, much greater in the infra-red than in visual measurements,—the agreement indeed, in the latter case, frequently reaching one part in a thousand.

It may be remarked on this latter point that the phenomena in the infra-red region under investigation doubtless depends on the furrow as a whole, whereas in the visual results probably only corresponding facets of the furrows, or possibly the thin edges, come into account. Wood found that the slightest rubbing of the gratings ruled on silver fundamentally altered the polarization effects he observed visually, while the writer in investigating for longer wave-lengths the phenomena for the central image found that they were changed in no way, even when the grating was polished with Vienna lime or rouge. We may accordingly then believe that when the furrow exceeds a certain depth or degree of roughness, as in grating No. 4, it can no longer act as a whole even on the longer wave-lengths and hence the results in this region are somewhat confused. The visual results, however, if concerned with only some small but similar part of each furrow may be quite distinct and regular and this seems to be the case. It may be added that for this deeply cut grating some trace of these polarization abnormalities are observable in the other azimuth of polarization.

Conclusion.—The minima of intensity for polarization (electric vector) perpendicular to the rulings which occur either in the central image or in any spectrum at such wave-lengths as are tangentially emergent in some other spectrum are probably characteristic of all speculum gratings. They are, however, prominent only in gratings cut with a poor diamond point so that considerable light is diffracted in all of the orders. While simple conservation-of-energy reasoning will account for the effects in a general way, a new grating theory, or substantial modification of the Rayleigh-Voigt theory, is undoubtedly needed to explain comprehensively these and similar phenomena. From a practical standpoint it is eminently desirable in working on polarization phenomena, *e.g.*, the Zeeman effect, with a speculum grating, to avoid the region of such wave-lengths as might show the effect described here. In studying infra-red absorption spectra it would also be well to have this point in mind, for while the minima would be only half as prominent with unpolarized light they might still give rise to false absorption observations. A slight change in the angle of the grating would, of course, at once show such measurements as spurious.

In conclusion the writer wishes to express his indebtedness to the Rumford Fund for assistance in conducting this investigation.

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January, 5 1921.