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INFRARED STUDIES AND DIFFRACTION-GRATING MEASUREMENTS

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OUTLINE OF THE WORK

I. Microwave measurements of transmission gratings having a grating space smaller than the wavelength; attempts to produce such gratings for use as infrared polarizers.

II. Microwave measurements of the intensity distribution among the spectral orders for reflection echelette gratings; several similar measurements on infrared gratings.

III. Search for superior surfaces on which to rule infrared gratings.

IV. Thick films for interference filters in the far infrared.

V. Considerations regarding the design of spectrometers.

VI. Construction and performance of a far-infrared grating spectrometer.

I. TRANSMISSION GRATINGS

A study was made of the transmission of metal wire and strip gratings having a grating spacing less than the wavelength of the radiation. The measurements were made with microwaves of 3-cm wavelength. The dependence upon (a) the direction of polarization of the radiation, (b) the grating space, (c) the angle of incidence of the radiation, and (d) the elements of the gratings being wires, thin strips, or thick strips. A detailed account of the work may be found in the first report of this project, but it may be briefly summarized as follows.

The transmission is generally larger for radiation having its electric field perpendicular to the direction of the grating elements (wires) than for the parallel orientation. This difference increases as the wavelength increases - the perpendicular approaching 100 percent transmission and the parallel 0 percent (i.e., completely reflected). As the wires are moved closer together the transmission of both components decreases. For sufficiently small grating spaces, the transmission of the perpendicular component becomes quite small; but, peculiarly, wire gratings show a transmission band when the wavelength is some 25 percent greater than the grating space.

It was intended to adapt these transmission gratings to the polarization of far-infrared radiation. Several attempts were made, none of which were very successful. For example, an opaque coating of silver was evaporated upon a KRS5 window. Lines spaced at 0.001 inch were then cut through this coating with a diamond, using the ruling engine here. Measurements were made on a Perkin Elmer Spectrometer with a CsBr prism and a selenium polarizer. There was no transmission of the parallel polarization in the 30- to 35-micron region, as expected, but there was only 10 to 15 percent transmission of the perpendicular polarization. Microscopic examination of the films showed that the trouble probably was due to the diamond's not cutting away the silver, but only plowing a furrow through it, and the actual gap between the metal strips was a very small region at the bottom of the furrow. Next it was planned to shadow-coat aluminum or silver onto a polyethylene replica of a coarse echelette grating, and thereby obtain a set of parallel metal strips. This work was never undertaken, principally because Mr. Lawrence Mertz of Baird Associates was successful in producing effective transmission polarizers by a ruling process.

II. Echelette Reflection Gratings

A. Review of Measurements

The major effort of this project has been on the problem of the intensity distribution of radiation reflected from a diffraction grating. By the use of 3-cm wavelength microwaves and model gratings of considerable precision with respect to this wavelength, it was though possible to eliminate most of the vagaries that had beset measurements with visible light. The preliminary results on a pair of echelette gratings is the subject of the second report of this project, which describes the apparatus and procedures. The third report covers the measurements made on several sets of gratings having blaze angles of 25°, 35°, and 45°, with the grating space (D) ranging from 0.7 to 2.5 wavelengths (λ), the percent of the incident energy present in each spectral order having been determined for angles of incidence between +60° and -60° for the parallel and perpendicular polarization. As an example, one may refer to Figs. 6 and 7 for the parallel and perpendicular polarization of a 25° grating with D = 1.2λ. No simpler interpretation can be given for the observed distributions; and there are no calculations on this subject currently available.

B. Performance in a Littrow Spectrometer

The influence of these distributions on the performance of a typical grating spectrometer can be shown to better advantage by replotting the data. As a typical case, if one considers a Littrow type mounting in which the collimating lens or mirror also serves as the telescope, imaging the spectrum close by the entrance slit, then one is concerned with the percentage of the incident light in the particular order that is returned to the exit slit as the grating is rotated so as to vary the emergent wavelength. As in common practice, we have selected the 1^{st} order spectrum as the one to be passed by the exit slit, and Figs. 1 and 2 show the concentration of radiation that could be expected for a near-perfect grating for various wavelengths with a grating blazed at a 25° angle: Fig. 1 for the electric field parallel to the direction of the grooves of the grating, Fig. 2 for the electric field perpendicular. The curve for the $+1^{st}$ order is the efficiency of the grating as a function of wavelength; the values of the other orders indicate where the balance of the incident energy has gone. For example, with $\lambda = 0.5D$, for the parallel polarization, the efficiency would be 55 percent (i.e., that fraction of the incident radiation would be reflected to the exit slit), 33 percent would be lost into the $+2^{nd}$ order off to one side, and 12 percent lost to the central image off to the other side. The most noteworthy features shown are the nearly complete concentration of the energy of the perpendicular component into the 1^{st} order for wavelengths equal to or greater than the wavelength corresponding to the blaze (i.e., at $\lambda = .84D$), and the maximum in the concentration of the parallel component into the 1st order at a wavelength shorter than the blaze. Such extremely high efficiencies are of great importance in connection with spectrometers using multiple reflections or "passing" of a grating, for with n reflections from the grating, the transmission factor is given by the n^{th} power of the efficiency at a single reflection. As can be seen from the curves, one will generally find the emergent radiation to be highly polarized. The same remarks also apply to gratings of other blaze angles. For unpolarized radiation, there is a rather broad range of wavelengths for which the efficiency is greater than 50 percent: from $\lambda_{short} = 0.53D$ to $\lambda_{long} = 1.4D$.

In Figs. 3 and 4, similar curves are given for the parallel and perpendicular polarization, respectively, in the case of a grating having a 35° blaze angle. The wavelength in the blaze occurs at $\lambda = 1.05D$. Although similar to the previous case of a 25° grating, there is now complete concentration of energy polarized perpendicularly for $\lambda > 0.9D$, but a somewhat increased concentration for the parallel component also. The range of wavelengths over which the efficiency would be 50 percent or greater for unpolarized radiations is $\lambda > 0.7D$ up to $\lambda = 1.4D$ and possibly further.

In Fig. 5, the comparable results are shown for a 45° blaze angle. The blaze wavelength is $\lambda = 1.4D$. The parallel component is considerably weakened over the whole range, but for $\lambda > 1.1D$, the perpendicular component is reflected entirely into the +1st order. The range for 50 percent efficiency using unpolarized radiation is from $\lambda = 0.85D$ to $\lambda = 1.5D$ and beyond (the limit of these observations).

C. Special Gratings

A number of variations of a particular grating were tried to gain additional information on the factors that determine the diffraction pattern.

1. Continuous metal surface grating. A possible objection to the work previously reported concerns the fact that the diffraction elements are separate metal-covered strips that are pressed together as tightly as possible. The contact between strips is far from perfect, although the electrical resistance across the grating is practically zero. At any rate, it was decided to paste a continuous sheet of aluminum foil over the surface of such a grating to see if there would be any change. This was done, but the results were identical within the 1- to 2 percent reproducibility of the measurements. One may then conclude that such gaps that are a small fraction of a wavelength are unimportant in this diffraction problem.

2. Measurements with 1-cm Microwaves. A second cause for alarm concerns the small number of grooves present in the gratings studied: somewhere between 12 and 40, depending upon the grating space. To infer that visible and infrared gratings with a 100,000 lines or so behave similarly is quite a step. However, when one examines the Fraunhofer diffraction pattern of multiple slits as the number of slits is increased from 1 up to 10, one is impressed by the fact that the biggest change in the diffraction pattern occurs in going from 1 to 2 slits, a smaller change from 2 to 3 slits, but an almost imperceptible difference between 9 and 10 slits.

By using microwaves of 1-cm wavelength rather than 3 cm the grating would be scaled down proportionately, so that there would be a threefold increase in the number of grooves. There were several practical difficulties encountered: the output of the 1-cm klystron was not as stable as that of the 3-cm model, and the tolerance on the perfection of the gratings, being increased threefold, was difficult to attain without a great deal of trouble. The results, however, were quite similar (nearly identical) to those obtained with 3-cm waves. Shown in Figs. 6 and 7 are the curves for 3-cm waves, parallel and perpendicularly polarized, diffracted by a 25° grating with $D = 1.2\lambda$. In Figs. 8 and 9 are the comparable curves for the 1-cm wavelength microwaves. In this latter grating the grooves were sawed into a wood sheet and then covered with aluminum foil, but the grating space was not quite properly selected to match that of the 3-cm grating. Actually, for it, $D = 1.3\lambda$, and the angles of incidence at which orders appear and disappear are not quite the same as previously. Otherwise there is no appreciable difference. There is also some supporting evidence on this point from measurements in near-infrared gratings mentioned later in this report.

It is noteworthy in the results with the 1-cm waves that for the perpendicular component, the angular range of the transition from one order to another has been reduced to about $1^1/_4$ degrees. This is just about $^1/_3$ the width of the transition for the 3-cm waves, and corresponds to the reduction in the size of the diffraction pattern (or image) formed by the spectrometer system. This diffraction then masks what would otherwise be a discontinuous change in the energy distribution between the orders. This is a most striking circumstance, for such a discontinuity has never been found in any other diffraction phenomena.

3. Imperfect Groove Form. The disparity between this microwave data and previous data in the visible region has been attributed to the nonperfect triangular groove form and its variation across the surface of the fine gratings necessary for short wavelengths. An attempt was made to see the effect of an irregularity on a facet of the grating by attaching a small aluminum strip to the edge of each large facet, again on the standard grating shown in Figs. 6 and 7. The strips were $^3/_{16}$ inch wide and $^1/_8$ inch high; with respect to the wavelength of 1.25 inches, they were only 0.1λ high. The data is plotted on

Figs. 10 and 11 for the two polarizations. A sizeable increase is shown in the concentration into the +1st order for the parallel polarization, and a noticeable decrease for the perpendicular component. The grating still hardly shows that it is an echelette, that is, it concentrates radiation just as well when reflected principally from the small facets at negative angles of incidence as when reflected completely from the large facets at positive angles. The overall performance of the grating has been considerably improved, then, by making it worse. By word of mouth, it has been heard that a similar effect has been noticed in the final polishing of an echelle grating; too high a polish (or too regular facets) cuts down its efficiency. This could lead to endless speculation about how poor to make a grating to get the best performance, but the matter was not pursued further. It does substantiate the statement made above that measurements of fine gratings cannot be expected to shown the true nature of the diffraction pattern by reason of the irregularities in their grooves.

4. Venetian-Blind Gratings. The peculiarities in the intensity distribution shown by these echelette gratings leads one to the conclusion that there are probably large surface currents flowing on the surface of the gratings, currents that carry no energy but contribute fields that permit the satisfaction of the electric and magnetic boundary conditions at the surface of the grating. A possible clue to their existence could be obtained from the examination of a grating with a discontinuous surface. Such a grating was made by assembling 2-inch-wide strips of $^1/_{16}$-inch-thick aluminum in a wood frame; or, one might say, the small facet of the echelette was removed. In reality, this grating is only discontinuous with respect to the perpendicular electric field, for currents can still freely move vertically along the strips if induced by the parallel field. Again, this was the standard grating, blaze angle 25° and D = 1.2λ. The measurements are displayed in Figs. 12 and 13. The parallel polarization hardly recognizes the absence of the small facet, except to increase somewhat its concentration into the 1st order. This is true even for negative angles of incidence where the radiation sees predominately the open space between metal strips. The perpendicular component is affected only slightly at positive angles of incidence, but passes nearly completely through the openings at negative angles. A strong resemblance exists between this phenomena and that of the Hertz effect in the transmission of wire gratings. Returning to the starting proposition, however, one would hesitantly conclude from the small change in the perpendicular component at positive angles of incidence that the surface currents do not exert too great an influence.

A second grating of this type was made, having narrower metal strips that were half the ordinary width of the large facet of a groove. The results for angles of incidence of +25 and -25° are:

Angle of Incidence		⊥	∥
+25°	+1st order	51%	43%
	0th order	14%	19%
-25°	-1st order	2%	9%
	0th order	13%	16%

These percentages are taken relative to reflection from a plane mirror, the balance of the energy presumably being transmitted through the open spaces of the grating. It is surprising that the reflectivity of the parallel component is not considerably higher than that of the perpendicular. But rather the fall off of intensity to 62 to 65 percent is close to the geometrical factor of 50 percent for both polarizations.

5. Sinusoidal Groove Form. A sheet of corrugated roofing in which the ripple was moderately close to a sine curve was also measured. Unfortunately, the grating space was rather large D = 2.14λ, so that no real comparison can be made with the data for echelette gratings. The depth of the corrugation or groove was 2/3 λ. Figures 14 and 15 show that the polarization effects are quite large for this type of groove as well as for triangular grooves. The results on this grating are subject to a much greater probable error than others, from lack of care, for it was felt that they would only serve as an indication of the distribution for a different groove shape.

D. Infrared Grating Measurements

Measurements were taken on several gratings available for use in the infrared region in order to see if there might be some agreement with the microwave data. The instrument used was a double monochromator consisting of a thermocouple detector, a grating spectrometer, a prism spectrometer to separate the overlapping orders possible with the grating, and a Nernst glower source. Added to this array now was a third grating spectrometer of the Littrow type using an off-axis paraboloidal mirror as the collimator and telescope. Only the percentage of the incident radiation diffracted into the +1st order was determined; and this was done relative to an aluminized flat mirror that could be inserted in place of the grating. The radiation was polarized by a multiple film selenium transmission polarizer, but no check was made of it to determine the completeness of polarization. The overall response of the detecting system was not linear, but it was calibrated by standard signals, and the deflections corrected accordingly. Measurements were only made at the blaze of each grating. Three such sets of measurements were taken:

1. On a 7620-line-per-inch aluminized replica made by Bausch and Lomb, blaze angle about 23°.

2. On a 1200-line-per-inch grating ruled on solder at the University of Michigan, blaze angle about 24°.

3. This 1200 line per inch grating was then aluminized and remeasured.

The results are given in the following table as a function of the direction of polarization of the radiation, with the microwave data of Figs. 6 and 7 at an angle of incidence of +25° included for comparison purposes.

	Parallel	Perpendicular
Bausch and Lomb 7620	72%	95%
Michigan 1200	39%	82%
Michigan 1200 aluminized	42%	88%
Microwave results	65%	100%

Qualitatively, all the gratings show the same higher reflectivity for the perpendicular component as did the microwave data. Individually, the Bausch and Lomb grating was of excellent quality, judging from visual examination and resolving power tests, and the disparity between it and the microwave case is the least. One might conjecture that even this difference could be interpreted as due to a small edge on the facet. This would have changed the values in the proper direction as shown by Figs. 10 and 11. Time, as well as spectral energy limitations, prevented the examination of this grating (and also the others) over an extended wavelength scale, but it should be done before too much is said about correspondences.

The 1200-line-per-inch grating was quite dull for visible light, and showed crystal formation of the solder. The groove form appeared to be quite regular when examined by a microscope, but it is easy to be deceived in the process. Again, the higher reflectivity for the perpendicular component over the parallel is similar to the microwave data. There was no way to determine what happened to the missing energy though.

In the event that the loss was due to a poor reflectivity of the solder surface in the 17-micron region, an opaque film of aluminum was evaporated over the grating. This brought about a slight increase in reflectivity, but really left the question unsolved. The most likely cause would be that of incomplete ruling, with a flat region of the original surface left between each groove, in which case a considerable amount of radiation would go into the 0^{th} order.

III. SEARCH FOR BETTER SURFACES FOR RULINGS

Initially, it was planned to make a survey of the ruling properties of different substances in order to find a better material than the solder surface currently used for coarse echelette rulings at the University of Michigan. These solder surfaces are time consuming in preparation, show a considerable amount of crystal granularity, and tarnish with age. To their advantage, they can be ruled easily and well with little wear on the ruling tool and the shaping (or shaving) process leaves them moderately flat (order of 5 fringes of Na light on an 8-inch square).

Several experimental rulings were tried on thick evaporated aluminum coatings on glass and on plastic films on glass. No conspicuous success was scored on either, although it was felt that the aluminum would be best for moderately fine gratings, and that the plastic films showed promise for coarser rulings. It became apparent that a good deal of time would have to be spent on the job to produce something worthwhile; but other portions of the program seemed more valuable, and further work on these surfaces was postponed.

IV. THICK FILMS FOR INTERFERENCE FILTERS IN THE FAR INFRARED

A Fabry-Pérot etalon, consisting of a pair of parallel, highly reflecting surfaces separated by a small distance, t, possesses the unusual characteristic of transmitting narrow wavelength regions and reflecting the balance. The properties of a Fabry-Perot etalon are well known and can be found in most works on optics, or reference can be made to Tolansky's monograph.[2] The feature of their behavior that makes an interference filter so valuable is the high angular dispersion that it produces in the vicinity of the first-order interference maximum. This permits the acceptance of radiation over a considerable range of angles of incidence with no variation in the wavelength transmitted. The first-order transmitted wavelength is equal to twice the separation of the plates. Then, by varying the separation of the plates, the spectrum can be scanned.

The major problem lies in producing highly reflecting films that have a low absorption loss. There appeared to be several possibilities -- metal films, wire transmission gratings, and an interference film obtained from alternate high and low refractive index materials. The metal films have far too great an absorption to be satisfactory. Metal-strip transmission gratings should be satisfactory, but it was decided that it would be simpler to prepare the dielectric interference films. An estimate of the transparency of the film to far-infrared radiation was made with a quartz-lens focal isolation system having an H-4 mercury-lamp source and a Golay cell detector. A number of possibly suitable materials were selected on this basis, but it was apparent that the spectral characteristics of the film should be determined more accurately. Further work was postponed until a far-infrared spectrometer could be built.

V. ON THE DESIGN OF INFRARED SPECTROMETERS

Much has been written on the performance of infrared spectrometers and the design characteristics of them. One may cite, for example, Daly and Sutherland,[3] John Strong,[4] and S. Brodersen.[5] The problem might be stated as how to build a spectrometer so as to get the optimum performance as regards resolution and signal-to-noise ratio from it. The literature apparently contains no complete answer to the problem, and the missing link, so to speak, is in connecting the detector to the optical system. It is not so much a matter of how much energy leaves the exit slit of the spectrometer as it is how to make the most efficient use of the detector, and what detector is most effective.

One begins with a source at the entrance slit of the spectrometer and calculates how much power from it in a particular frequency range finally gets to the detector. Dividing this quantity by the sensitivity of the detector, i.e., the equivalent noise power input, one obtains the signal-to-noise ratio for the particular frequency range.

The power from the source of emissivity, e, located at an entrance slit of length l_s and width w_s which is accepted by a square collimator is

$$e \, E_\nu \, d\nu \, l_s \, w_s \, \frac{W^2}{f^2} \qquad ,$$

where W is the width and f is the focal length of the collimator (the collimator is assumed to be square to obtain the maximum energy as well as best use of a rectangular grating). Many other frequencies are also entering the entrance slit, but there is a dispersing system in the spectrometer that bends all others out of the path to the exit slit, and only those in the interval $d\nu$ are passed through it. Hence the same expression, multiplied by the efficiency (or percent transmission) of the spectrometer, suffices for the power passed by the exit slit of identical dimensions to the entrance slit. This assumes that the telescope system imaging the radiation at the exit slit has the same focal length as the collimating system, a simple and common arrangement, as in a Littrow or an Ebert system. Other cases can be considered, but they do not affect the outcome and only produce a complication of the argument. One then has for the power out of the exit slit:

$$e\ E_\nu\ d\nu\ l_s\ w_s\ \frac{W^2}{f^2}\ T$$

Next there is an imaging system, an ellipsoidal mirror, to focus this radiation onto the detector. This will be a demagnifying optical system of ratio M that will give an image size $l_i = l_s/M$ by $w_i = w_s/M$, but converging in a greater solid angle. This solid angle can be more easily expressed in terms of the F number of the system. The ellipsoidal mirror should be of such a width B that it accepts the solid angle of radiation leaving the exit slit. In terms of its object and image distances, p and q,

$$M = p/q,$$

$$F_s = p/B = f/W ,$$

$$F_d = q/B .$$

From the last two relations one finds

$$F_d = F_s/M .$$

The power falling onto the detectorthen is

$$e\ E_\nu\ d\nu\ \frac{M\ l_i\ M\ w_i\ T}{M^2\ F_d^2}$$

or

$$e\ E_\nu\ d\nu\ \frac{l_i\ w_i}{F_d^2}\ T$$

The length will be a certain fraction, g_1, of the length of the detector:

$$l_i = g_1\ l_d$$

and similarly

$$w_i = g_2\ w_d .$$

Then the power abosrbed by the detector is, taking the absorptivity of its surface as a constant,

$$\frac{a\ e\ E_{\nu}\ d\nu\ g_1\ g_2\ A_d\ T}{F_d^2} ,$$

where A_d is the area of the detector. This is just the result to be expected from a consideration of the energy received from a black-body source by the detector, with the limitation of source emissivity, e, transmission factor T, solid angle subtended by source F_d^{-2}, and area illuminated $g_1 g_2 A_d$.

Given the noise level of the detector, N, in terms of the equivalent power, the signal-to-noise ratio for the spectrometer is

$$\frac{a\ e\ E_{\nu}\ d\nu\ g_1 g_2\ A_d\ T}{N\ F_d^2} .$$

The nature of the dispersing element of the spectrometer does not enter explicitly, but its dispersive power as well as the focal lengths of the optical system are implicit in the fraction of the area of the detector illuminated (g_1 and g_2). Also the resolution of the dispersive element must be sufficient to isolate the $d\nu$ involved.

The first use made of this equation was to calculate the effective transmission factor for several of the spectrometers here at the University of Michigan using the known values of A_d, F_d, $d\nu$, g_1, and g_2, and making reasonable assumptions as to values of a and e and the source temperature (so as to calculate E_{ν}). For both the near- and far-infrared grating spectrometers, the transmission factor calculated was only several percent. This seemed abysmally small; losses estimated from mirror and window reflections, grating efficiency, etc. would indicate that a transmission factor of 10 to 20 percent should be expected. Tests have been started, but not completed, as to the reason for this poor transmission. A check on a Perkin Elmer prism spectrometer showed a reasonable agreement between the transmission factor calculated from its performance and one estimated from the losses in the individual components, both lying between 10 and 20 percent.

Next the equation can be used to evaluate the optimum performance of a spectrometer and shows what factors are significant to that performance. Given a particular detector of known area, noise level, etc., then a spectrometer should be designed to make g_1 and g_2 as large as possible, and the biggest solid angle possible, as seen from the detector, should be filled with radiation

Conversely, given a particular spectrometer, the detector and the demagnifier should be selected so as to give the greatest value for

$$\frac{g_1 g_2 A_d}{N F_d^2} .$$

The following discussion will be limited to the use of a diffraction grating as the dispersing element in the spectrometer although similar reasoning holds for the case of a prism, or of an interference filter. Except for the extreme far-infrared region, all grating spectrometers have a common characteristic of only illuminating a small fraction of the width of the detector, be it a thermocouple with a receiver several tenths of a millimeter wide, or, even worse, a Golay cell 2 or so mm wide.

A number of methods of improving this have been proposed. The use of an image slicer was developed by Strong, Rupert, and Benesch[6,7] in which an extra long exit slit on the spectrometer is imaged as shorter but wider.

Another device is one involving multiple reflections from the same grating as suggested by Hulthén and Lind,[8] Walsh,[9] Fastie and Sinton,[10] and Jenkins and Alvarez.[11] In this case, the angular dispersion produced by the grating is proportional to the number, n, of traversals or reflections, and hence slits that are wider by the same factor, n, may be used and still pass the same frequency band. The chief disadvantage of this method is in the loss in energy from the transmission of the spectrometer. With T as the fraction transmitted on one traversal, then T^n is transmitted after n traversals.

Third, the focal length of the optics of the spectrometer could be increased, thereby increasing the linear dispersion at the slit. At the same time, to gain any advantage in energy the aperture would have to be held constant, so that a grating of a proportionately larger area would be necessary (and such are not always available). The instrument would also rapidly become enormous in size.

A fourth method which has not as yet been fully exploited lies in another manner of increasing the dispersion of a grating. Given a Littrow type mounting, the grating equation is

$$m\lambda = 2D \sin i .$$

From this the angular dispersion may be calculated as

$$\frac{d\theta}{d\lambda} = \frac{2 \tan i}{\lambda} .$$

Then it follows that the width of the exit slit for a particular dλ, or the linear dispersion, is

$$W = f\,d\theta = \frac{2\,f\,\tan i}{\lambda}\,d\lambda = \frac{2\,f\,\tan i}{R} \quad .$$

Hence this factor can be greatly increased by the use of the grating at large angles. Since gratings are customarily used for angles of incidence in the range of 15° to 35°, the tangent is generally $^1/_2$ or less. Adel and Barker[12] pointed out that by operating at large angles of incidence, there would be a gain in resolution. However, there was a loss of energy because of the decrease in the projected width of the grating, and a decrease in the efficiency of the grating itself at large angles of incidence. By a proper choice of focal length relative to the grating size, the first factor may be eliminated. The microwave measurements on echelettes show that the latter factor may not be too serious, as the perpendicular component still has a very high efficiency at angles up to 60°.

Operation at even larger angles, say 80°, where the tangent of the angle of incidence is 5 or more, is possible, however, through the use of an echelon grating with an actual increase in grating efficiency. The echelon may be considered as a very coarse echelette used in a high spectral order. Because of the larger size of the facets relative to the wave length, Fraunhofer's diffraction theory may be used to calculate the intensity distribution. The prediction for such a grating is 100 percent efficiency when used at the blaze angle, as is shown by Candler.[13]

The high spectral order demands that there be another dispersive element to separate out one spectral order. This may be accomplished with an ordinary echelette. In effect then, one is adding a third monochromator to the present prism-grating monochromator used in high-resolution infrared work. Calculations on a sample case of an echelon of 40 grooves, with facets 1.25 cm and 0.25 cm wide and 10 cm long, show that a resolution of between 0.02 and 0.01 wave numbers should be attainable in the 10-micron region. This compares to present values some ten times larger. Again it should be pointed out that this results from obtaining higher dispersion from a grating at oblique angles of incidence, so that wider slits are used, and consequently a larger fraction of the sensitive area of the detector.

Echelons have been made for use in the visible and ultraviolet, and a review of the methods may be found in Candler.[13] The same procedure would be used for the larger size needed for the infrared, but with less tolerance necessary because of the increased wavelength. Briefly, a parallel-sided flat of fused quartz whose thickness is the size of the large facet is cut into strips, and these strips are pressed together into optical contact with the offset of one strip from the next being the small facet. Then the assembled strips are aluminized. One would no longer be dependent upon a ruling engine, the size and perfection of the grating would be set by the skill and patience of an optician in preparing some 40 or 50 items.

A fine scanning of a limited region of the spectrum could be accomplished best by varying the pressure (and index of refraction) of a nonabsorbing atmosphere surrounding the gratings. This gives rise to a change in wavelength of $\Delta\lambda = \lambda\Delta n$, where Δn is the change in refractive index of the gas resulting from its change in pressure. A change of wavelength sufficient to scan from one spectral order to the next may be obtained with a one- or two-atmosphere pressure variation, if the order number is in the thousands. This is the case, since

$$\Delta m = m \frac{\Delta\lambda}{\lambda} = m \, \Delta n,$$

and with Δn per atmosphere of air being 3×10^{-4}, m must be several thousand in order to have $\Delta m = 1$. Such a scanning mechanism would be more sensitive and less costly than a rotation of the grating, and permits the echelon to be used in the blaze at any wavelength. The coarse scanning would be done through a rotation of the echelette grating in a conventional manner.

The main advantages of such a system would be greater energy, higher resolution, moderate size, less concern with accuracy of imaging or aberrations of the optical components and perfection of slits (because of the increased size of the slits), a fairly simple scanning mechanism, and the use of a single echelon over the entire spectral range. No experimental work has been done on this as yet, but it is planned for the immediate future.

VI. A FAR-INFRARED GRATING SPECTROMETER

At the present time, there are only three far-infrared spectrometers with an appreciable resolution that have been built -- those of Randall at Michigan,[14] McCubbin at Johns Hopkins,[15] and Oetjen at Ohio State.[16] Since Randall's spectrometer was designed primarily for the 20- to 100-micron region and moreover was in continuous use, it was decided to build a new, small, simple spectrometer.

This new grating spectrometer for use at wavelengths greater than 80 microns was assembled as indicated in Fig. 16. An H-4 mercury arc enclosed by a water-cooled brass jacket was the source of the radiation. A spherical mirror, M_1, focused this light onto the slit S_1, a $^3/_8$-inch-diameter hole.

Next is a focal isolation section in which a crystal quartz lens images the far-infrared wavelengths on the slit, S_2, but does not focus near-infrared and visible wavelengths because of its different index of refraction (2.2 in the far-infrared, 1.6 in the visible). A 0.75-inch-diameter aluminum disc was pasted on the center of the lens to eliminate the central rays. The crystal quartz also absorbs rather completely wavelengths between 2.5 and 75 microns. The radiation passes through a chopper with glass blades so that only the wavelengths absorbed by the glass are interrupted -- in this case, the far-infrared. The grating spectrometer proper was an Ebert type with a 8-inch-diameter spherical mirror of 35-cm focal length. A grating 3 inches wide was located on a turntable next to S_2. The diffracted rays were collected by M_2 and focused at the exit slit S_3. A tapered cone with a paraffin lens[17] concentrated the energy onto the entrance window of a Golay cell. After several attempts, it was found that a suitable cone could be made by winding a sheet of aluminized mylar on a mandrel. The high-melting-point paraffin was shaped into a lens whose focal length equaled the length of the cone by molding and scraping against the concave face of a glass lens. The only item not indicated was a copper sheet extending from the grating to the first mirror to shield the Golay cell from extraneous light. The grating used was a 200-line-per-inch echelette made by Mr. P. A. Weyrich on the University's ruling engine.

Figure 17 is a typical spectral scan on an average summer day and shows the tremendous absorption from rotation transitions in atmospheric water vapor. It is not possible to indicate the point of 100-percent transparency, or the envelope of the radiation curve. Changes in humidity altered the height of the maxima by a factor of 2 or more. A dry box or vacuum chamber is consequently a necessity and may well give a sizeable gain in energy. The slits S_2 and S_3 were 0.5 cm wide and, with the grating at an angle of about 25°, should allow a spectral resolution ($\lambda/\Delta\lambda$ or $\nu/\Delta\nu$) of about 70. That such is obtained is shown nicely by the separation of the absorption lines at 69.2 cm^{-1} and 68.1 cm^{-1}.

It is not possible to make calculations on the energy performance of the spectrometer, as the effective radiating temperature of the source is not known. However, from the known characteristics of the spectrometer and the detector, predictions can be made of improvements. The chief item is the noise level of the Golay cell. A check against a lamp calibrated by the Bureau of Standards indicated its noise level to be 10^{-10} watts with a 30-second response time. This is a factor ten worse than the advertised performance. More recently, matters have been improved three- or fourfold, with an equivalent change in the appearance of the spectrum. Also, the cone gives a demagnification ratio of 10, converting the F:5 beam of the spectrometer to a F:0.5 beam at its apex. Consequently, the 3-mm-diameter window of the Golay cell could "see" any radiation from a 3-cm-diameter exit slit. Such a slit width would be possible by increasing the linear dispersion, either by an increase in focal length or by a more oblique angle of the grating. If one made complete use of the effective receiving area of the Golay cell in this manner, there would result a gain of a factor of 8 in signal strength. An evacuated path would also contribute appreciably. Hence, from an optimistic viewpoint, one might consider as possible a hundredfold increase in signal strength, which might be extracted immediately as a tenfold increase in resolution (yielding about 0.1 cm^{-1}). Future work will verify or repudiate this possibility.

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% OF ENERGY IN SPECTRAL ORDERS FOR A LITTROW MOUNT SET FOR THE +1st ORDER

BLAZE ∠ 25° E⊥TO GROOVES

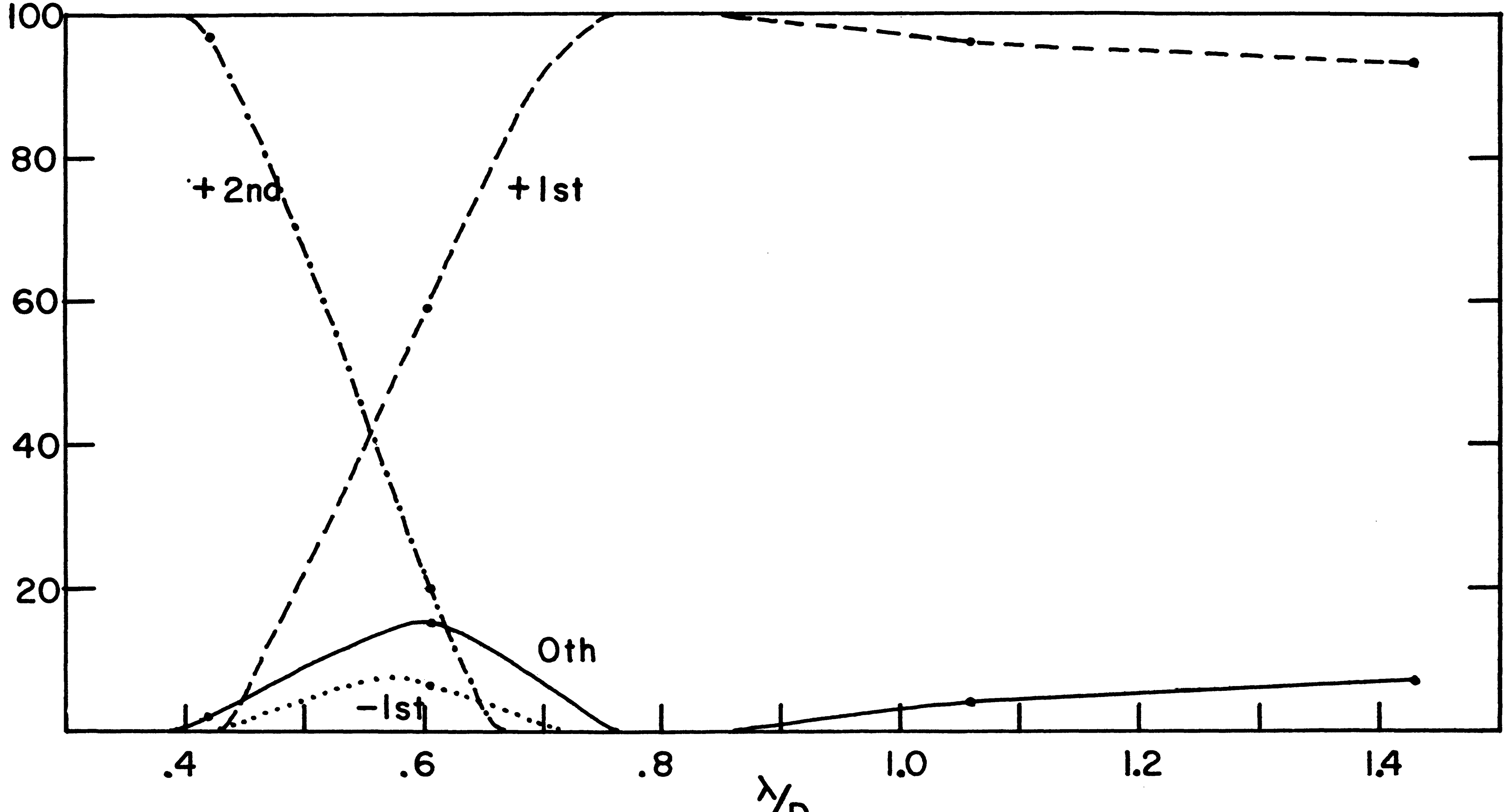


FIGURE 1

% OF ENERGY IN SPECTRAL ORDERS FOR A LITTROW MOUNT SET FOR THE +1st ORDER

BLAZE ∠ 25° E ∥ TO GROOVES

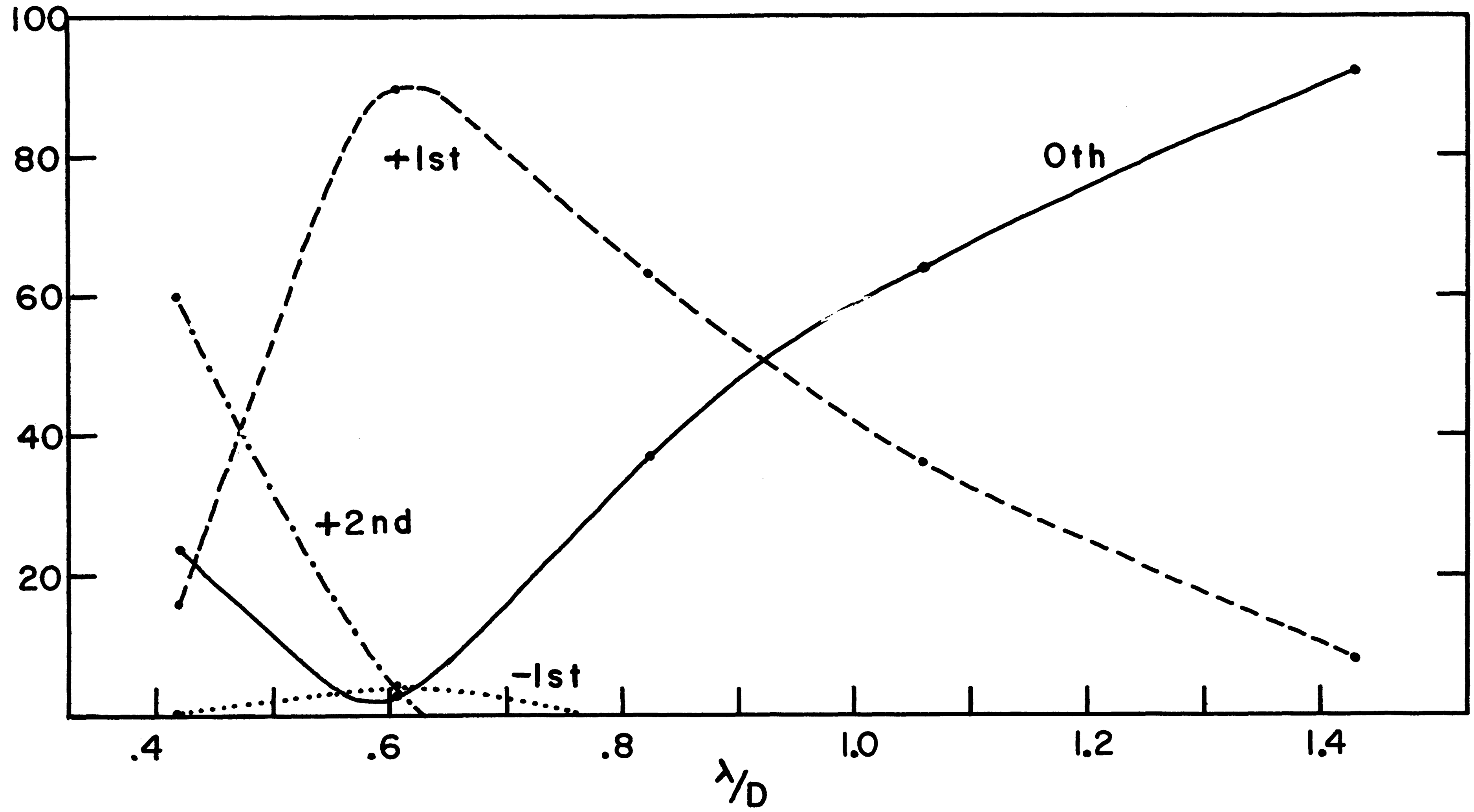


FIGURE 2

% OF ENERGY IN SPECTRAL ORDERS FOR A
LITTROW MOUNT SET FOR THE +1st ORDER
BLAZE ∠ 35° E ⊥ TO GROOVES

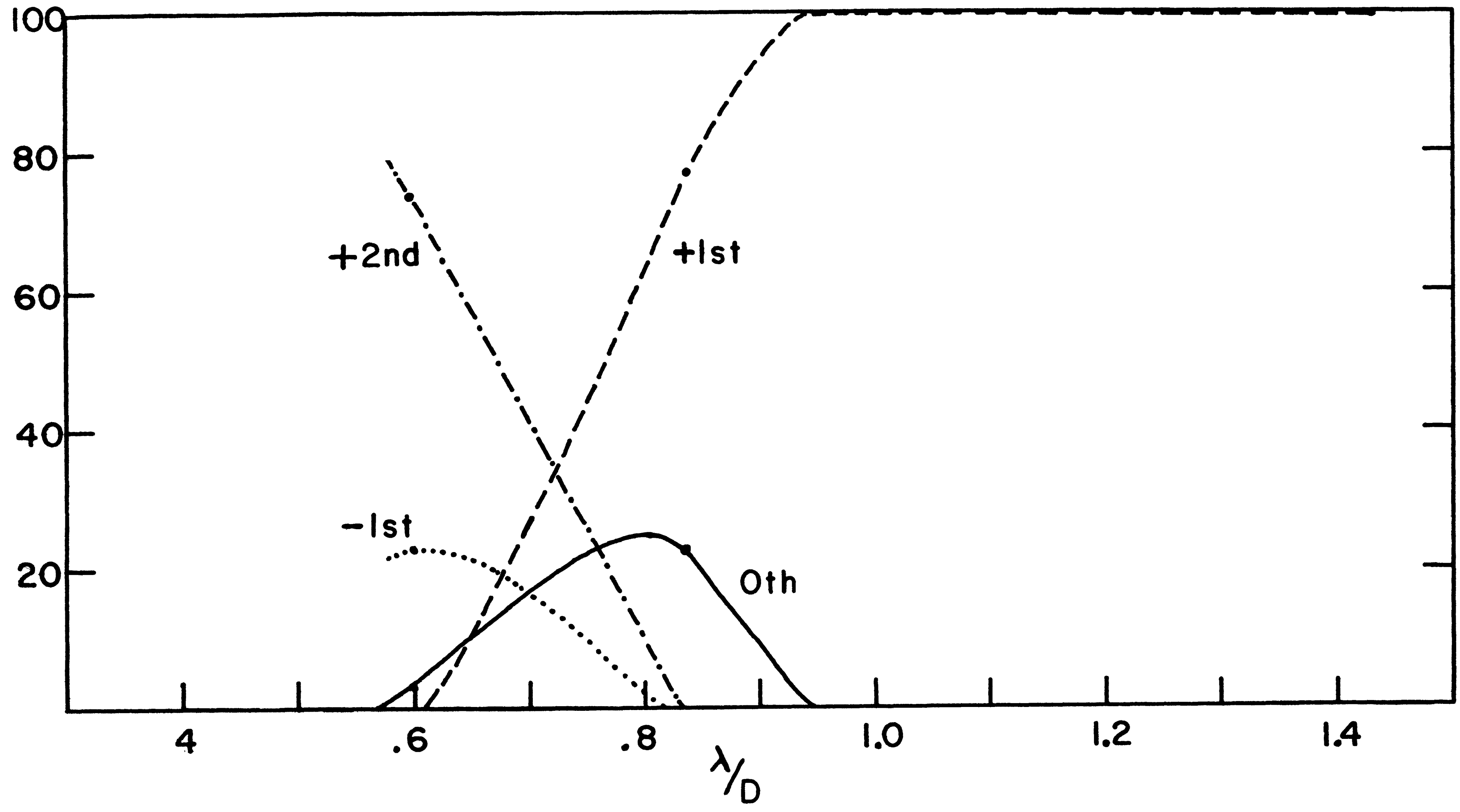


FIGURE 3

% OF ENERGY IN SPECTRAL ORDERS FOR A LITTROW MOUNT SET FOR THE +1st ORDER

BLAZE ∠ 35° E ॥ TO GROOVES

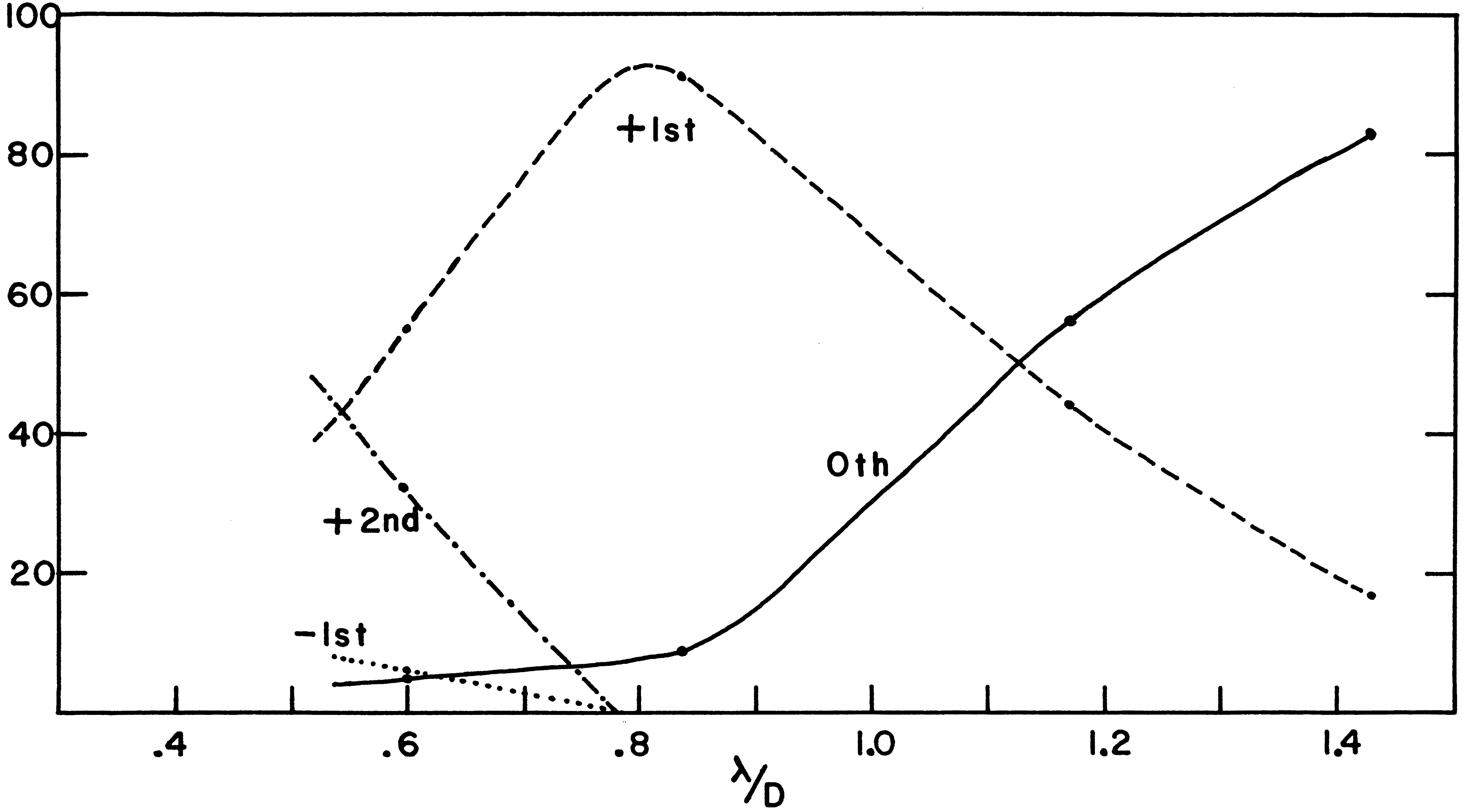


FIGURE 4

% OF ENERGY IN SPECTRAL ORDERS FOR A LITTROW MOUNT SET FOR THE +1st ORDER BLAZE ∠ 45°

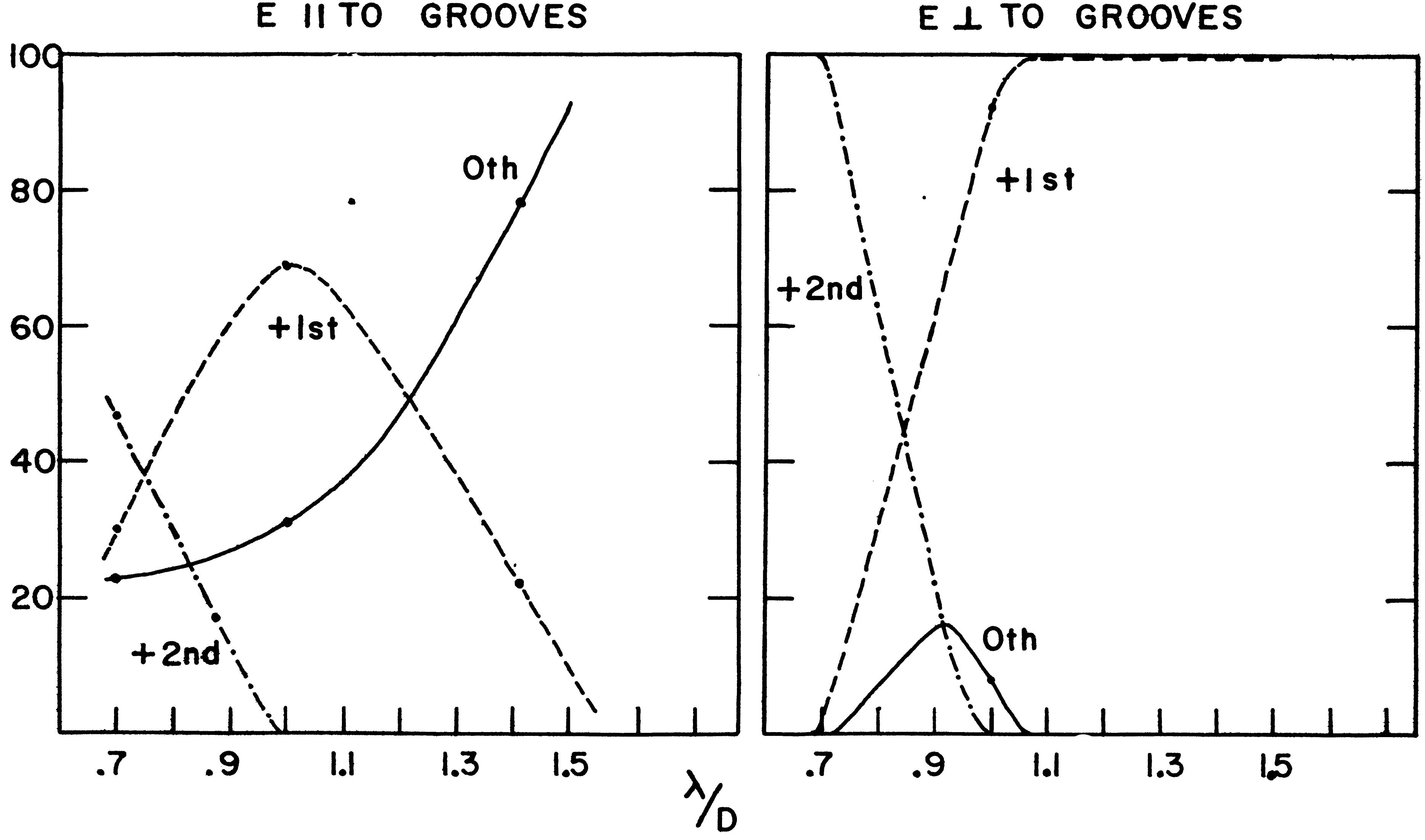


FIGURE 5

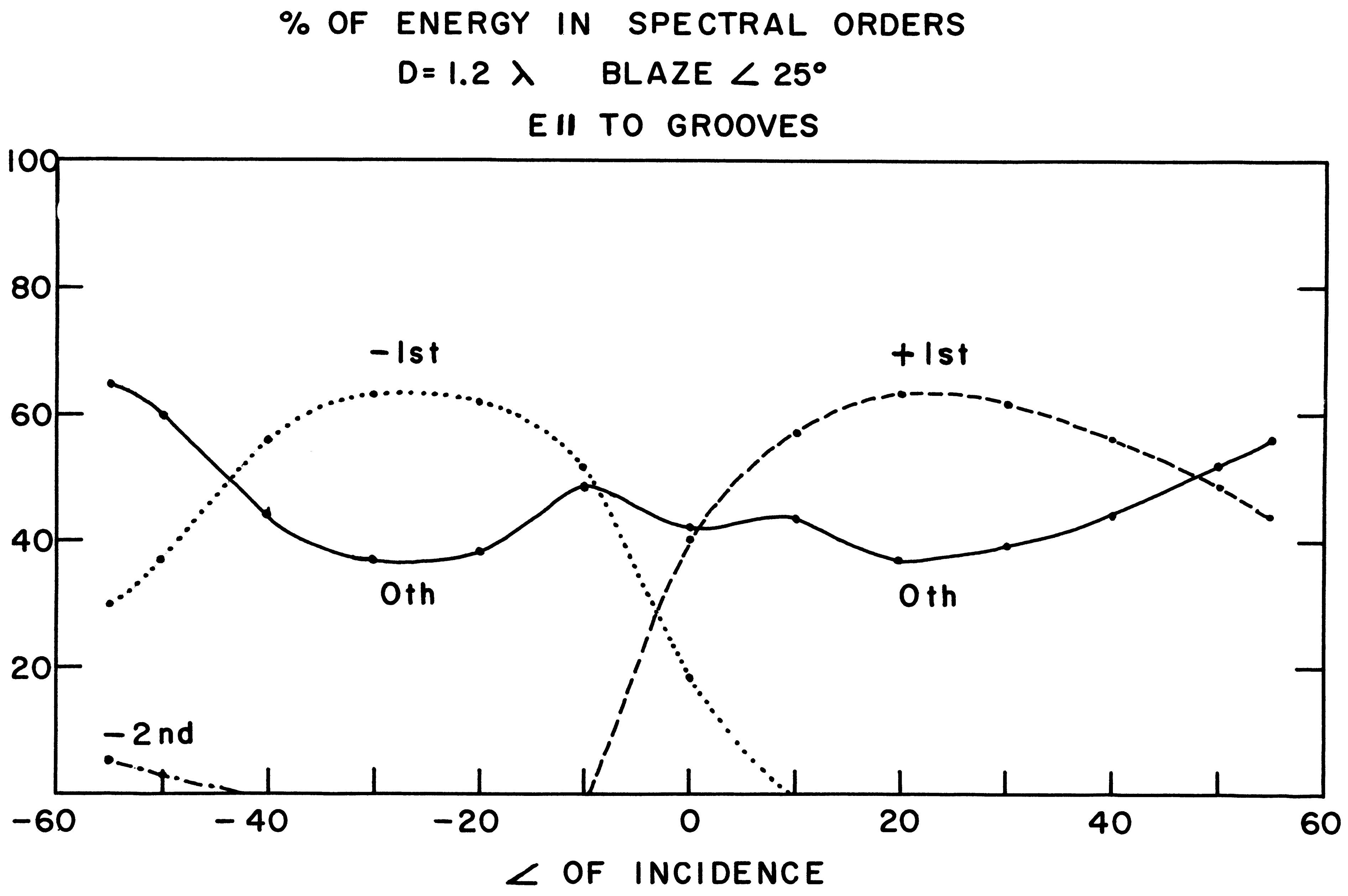

% OF ENERGY IN SPECTRAL ORDERS
D= 1.2 λ BLAZE ∠ 25°
E ll TO GROOVES
100
80
60
40
20
-1st
+1st
0th
0th
-2nd
-60
-40
-20
0
20
40
60
∠ OF INCIDENCE

FIGURE 6

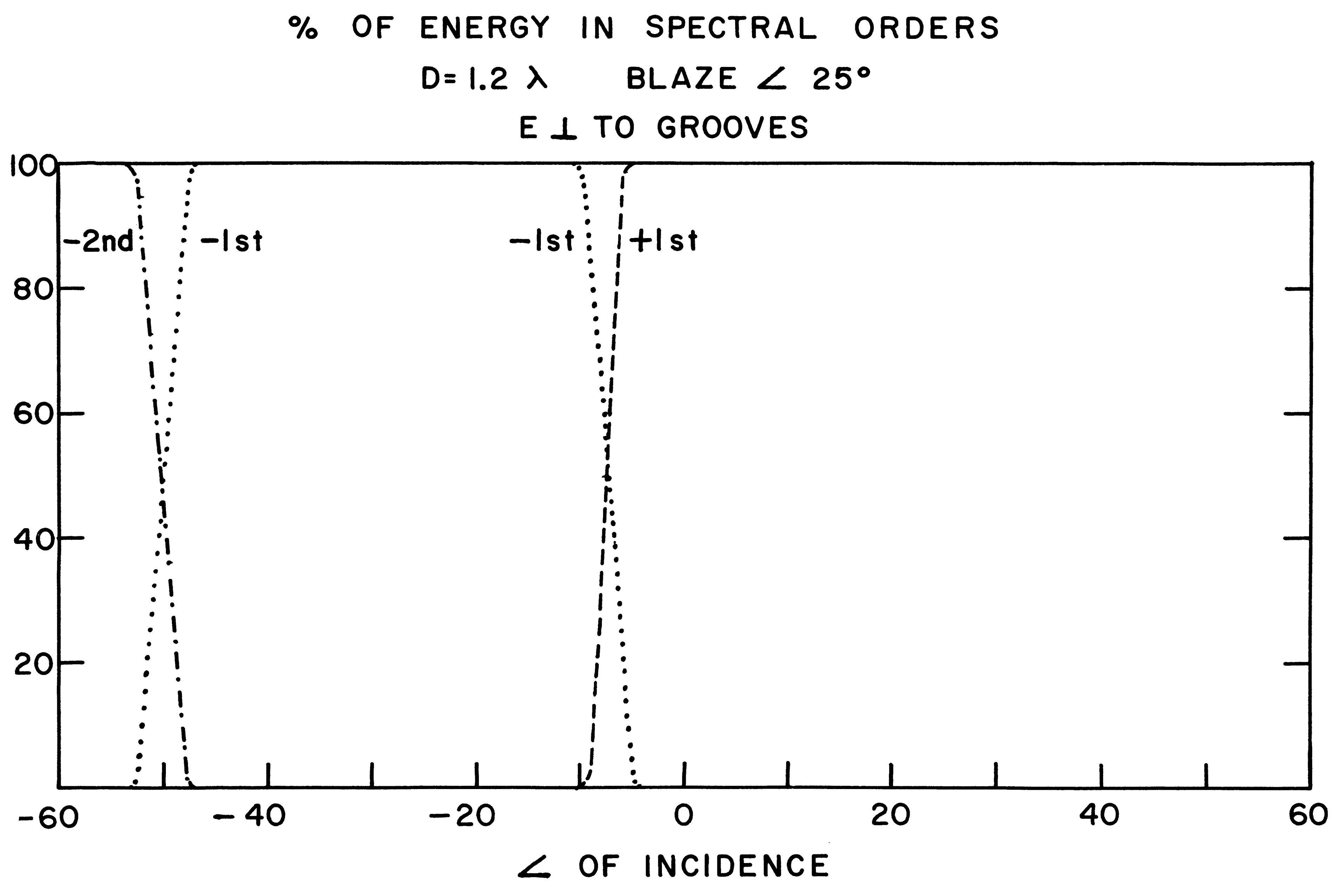

% OF ENERGY IN SPECTRAL ORDERS
D= 1.2 λ BLAZE ∠ 25°
E ⊥ TO GROOVES
100
80
60
40
20
-2nd
-1st
-1st
+1st
-60
-40
-20
0
20
40
60
∠ OF INCIDENCE

FIGURE 7

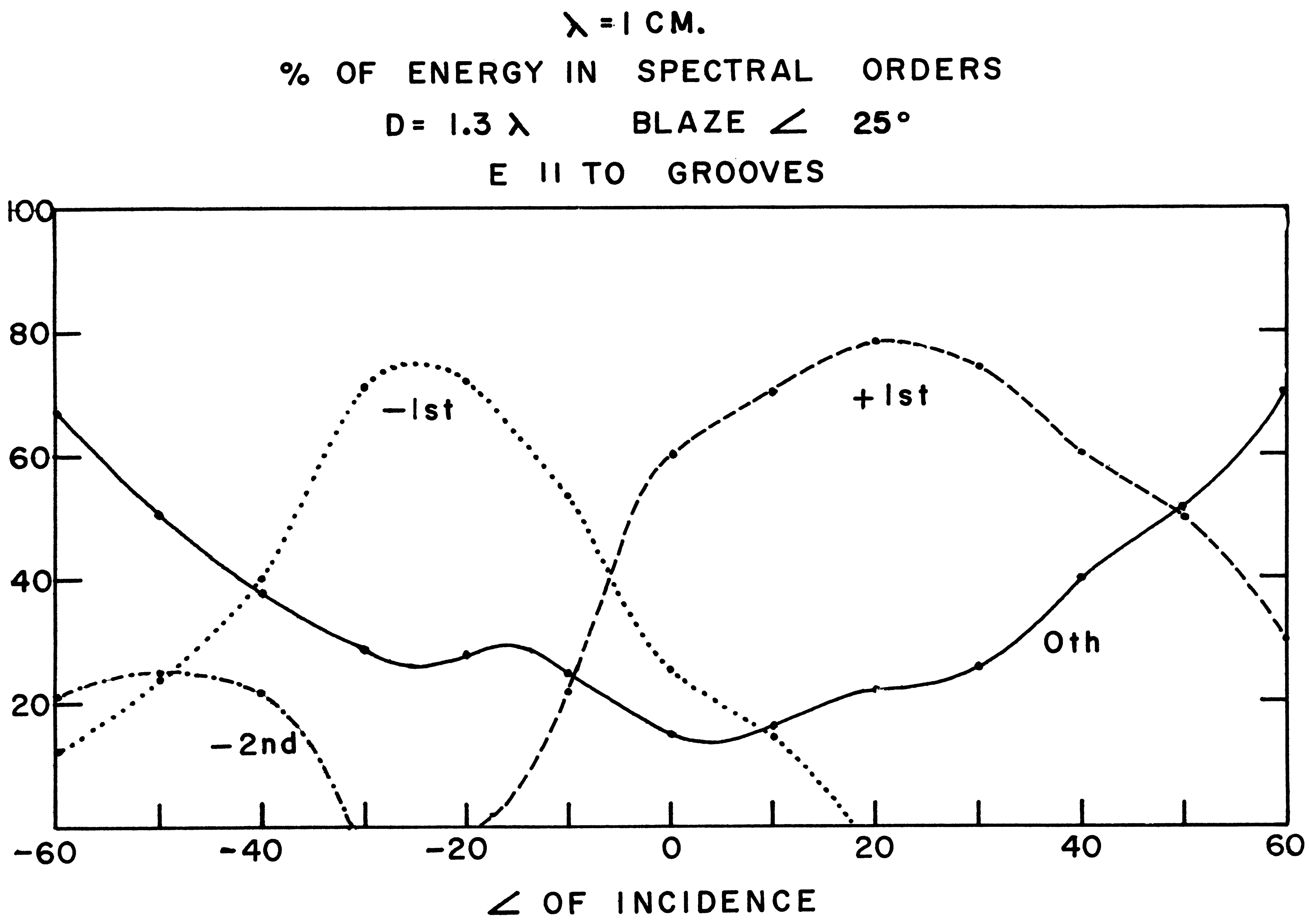

λ = 1 CM.
% OF ENERGY IN SPECTRAL ORDERS
D= 1.3 λ BLAZE ∠ 25°
E ll TO GROOVES
100
80
60
40
20
-60
-40
-20
0
20
40
60
-1st
+1st
0th
-2nd
∠ OF INCIDENCE

FIGURE 8

λ = 1 CM.

% OF ENERGY IN SPECTRAL ORDERS

D= 1.3 λ BLAZE ∠ 25°

E ⊥ TO GROOVES

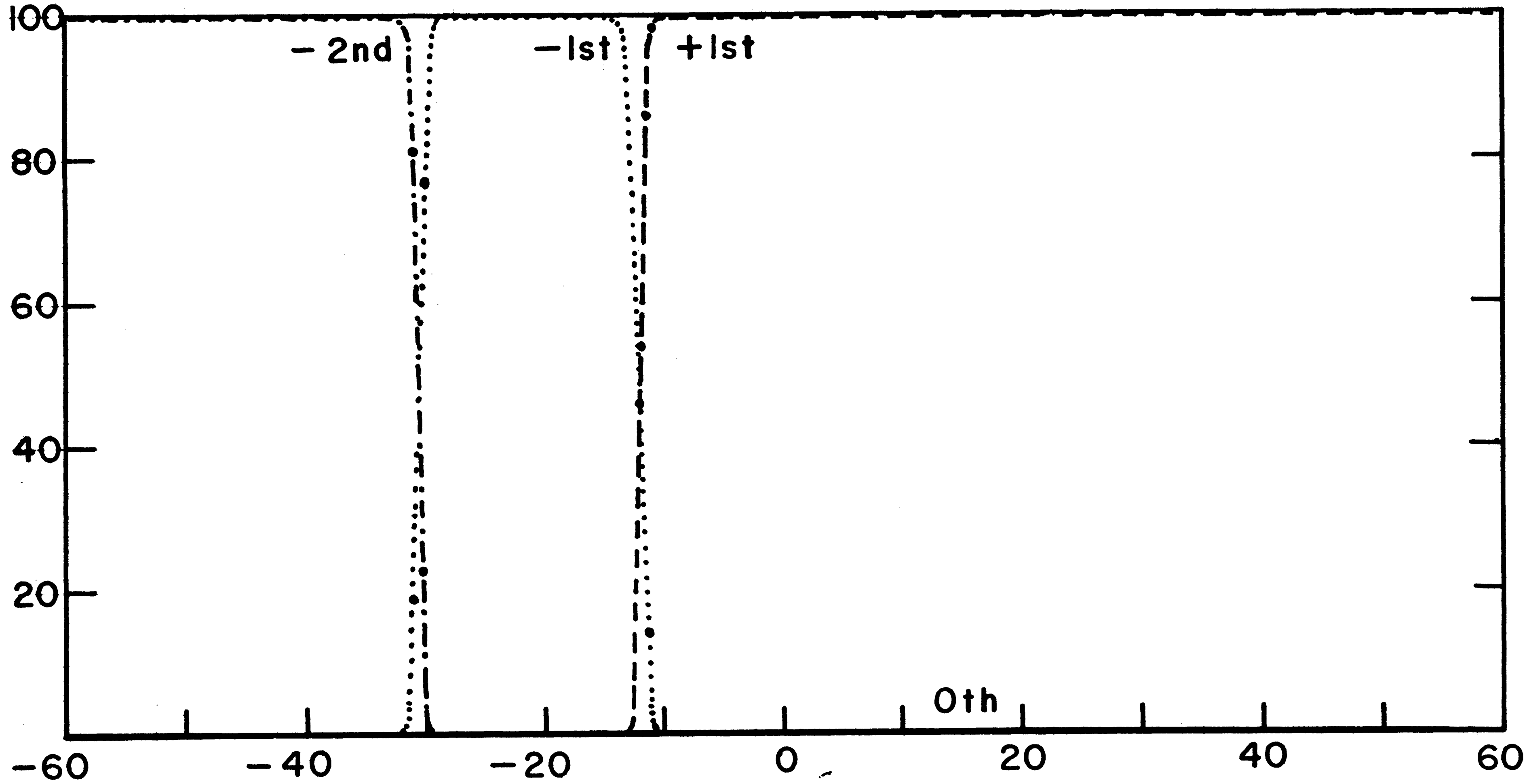


FIGURE 9

IMPERFECT GROOVE FORM

% OF ENERGY IN SPECTRAL ORDERS

D = 1.2 λ BLAZE ∠ 25°

E ∥ TO GROOVES

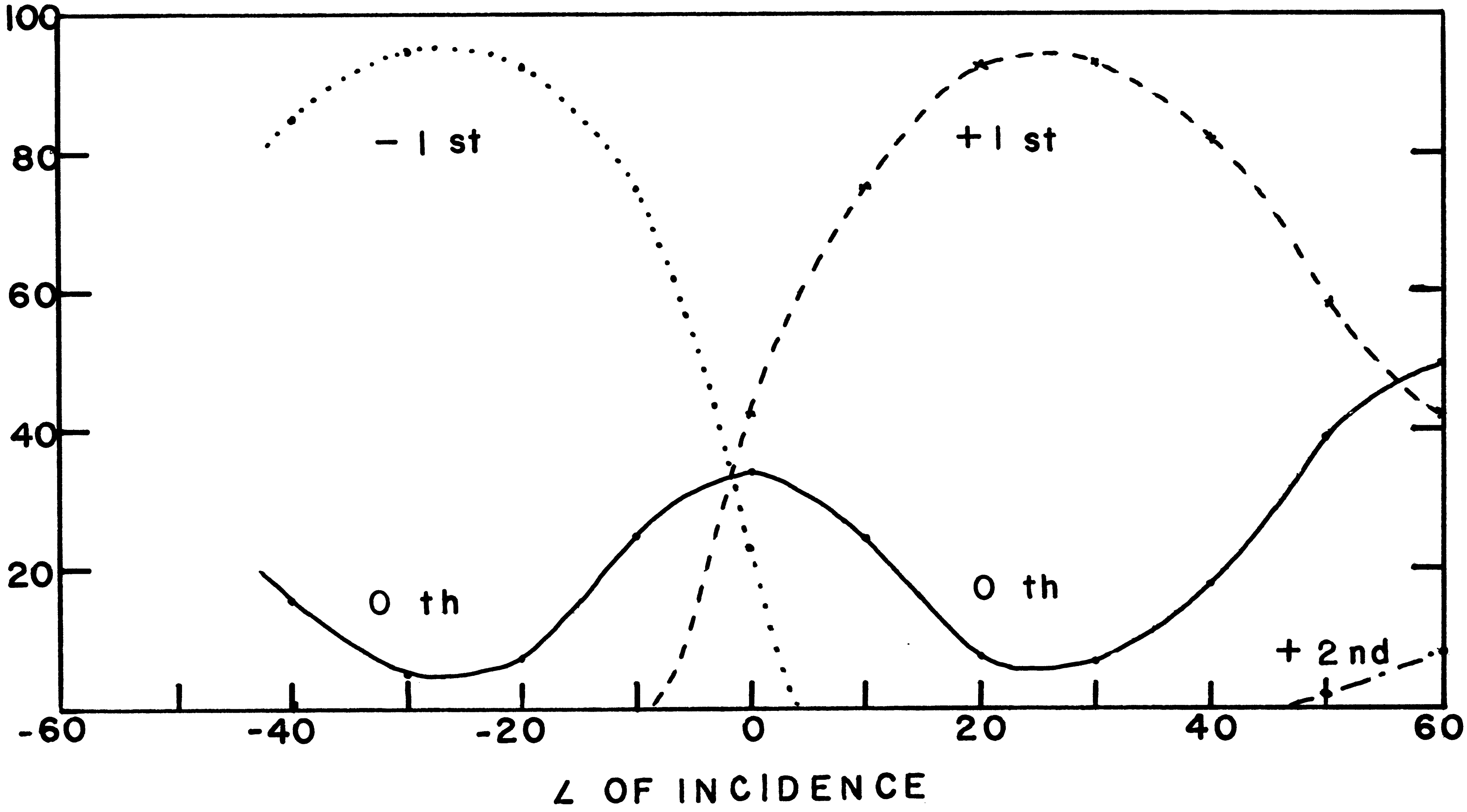


FIGURE 10

IMPERFECT GROOVE FORM

% OF ENERGY IN SPECTRAL ORDERS

D = 1.2 λ BLAZE ∠ 25°

E ⊥ TO GROOVES

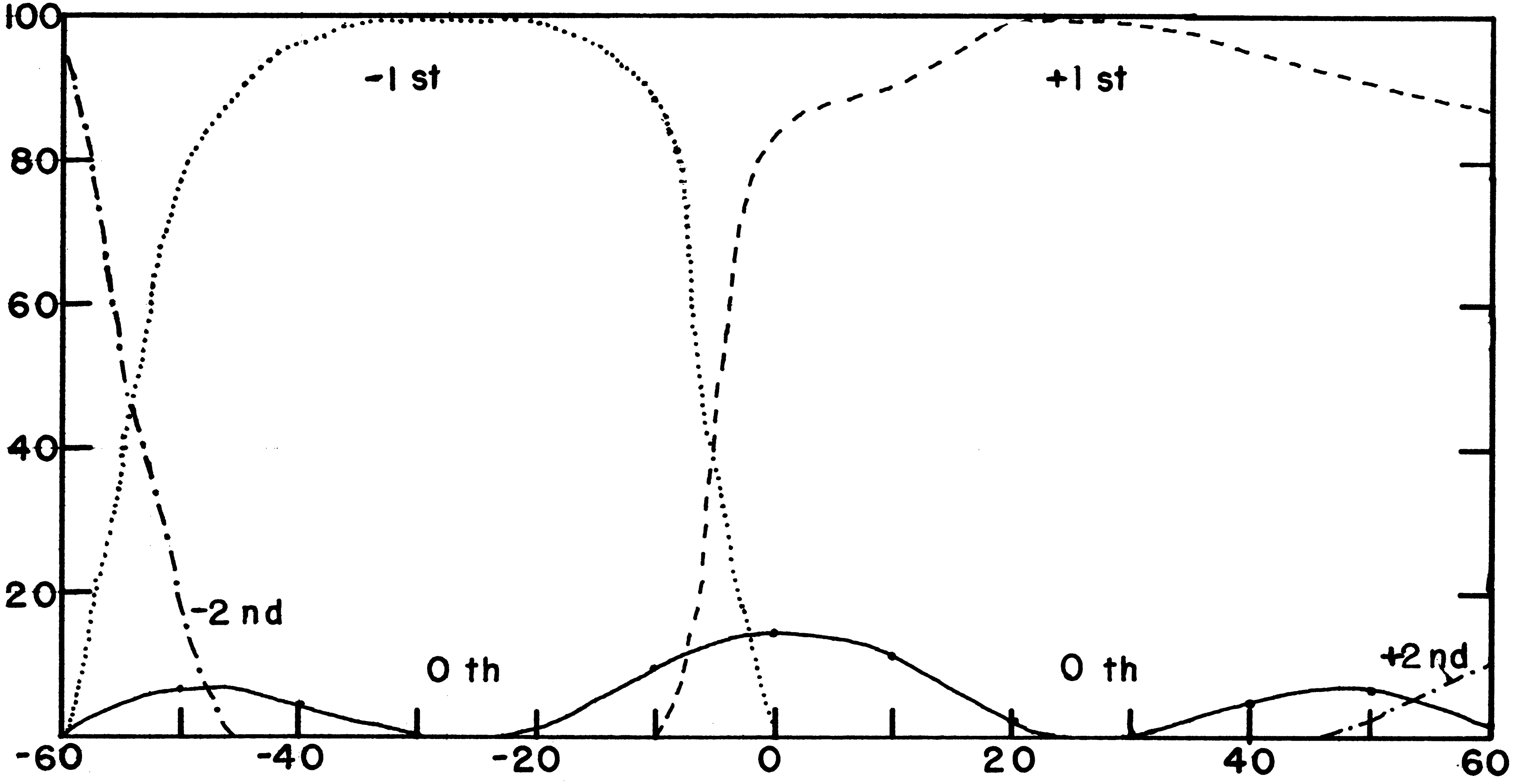


FIGURE II

VENETIAN BLIND GRATING

% OF ENERGY IN SPECTRAL ORDERS

D=1.2 λ BLAZE ∠ 25°

E ∥ TO GROOVES

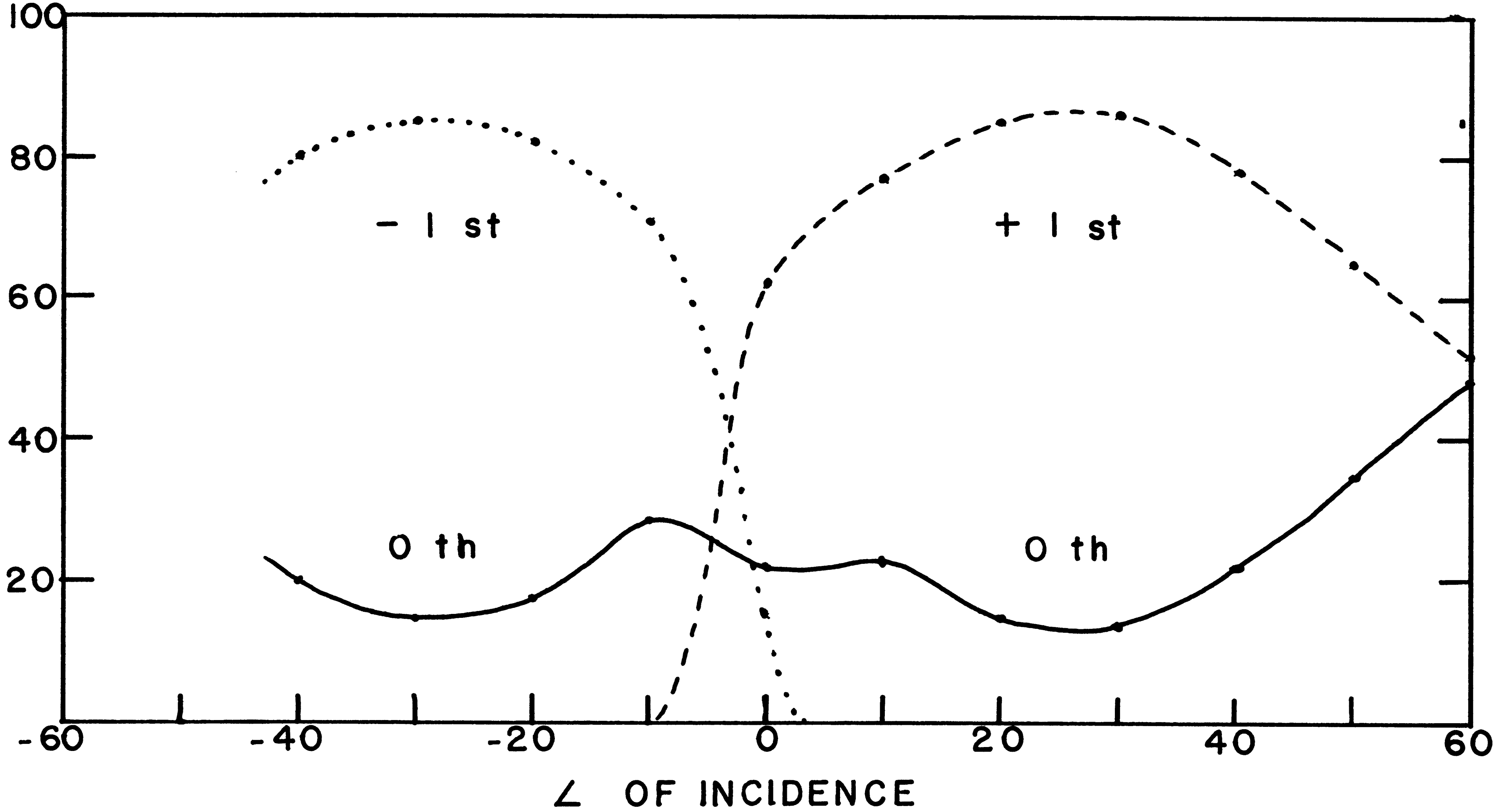


FIGURE 12

VENETIAN BLIND GRATING

% OF ENERGY IN SPECTRAL ORDERS

D = 1.2 λ   BLAZE ∠ 25°

E ⊥ TO GROOVES

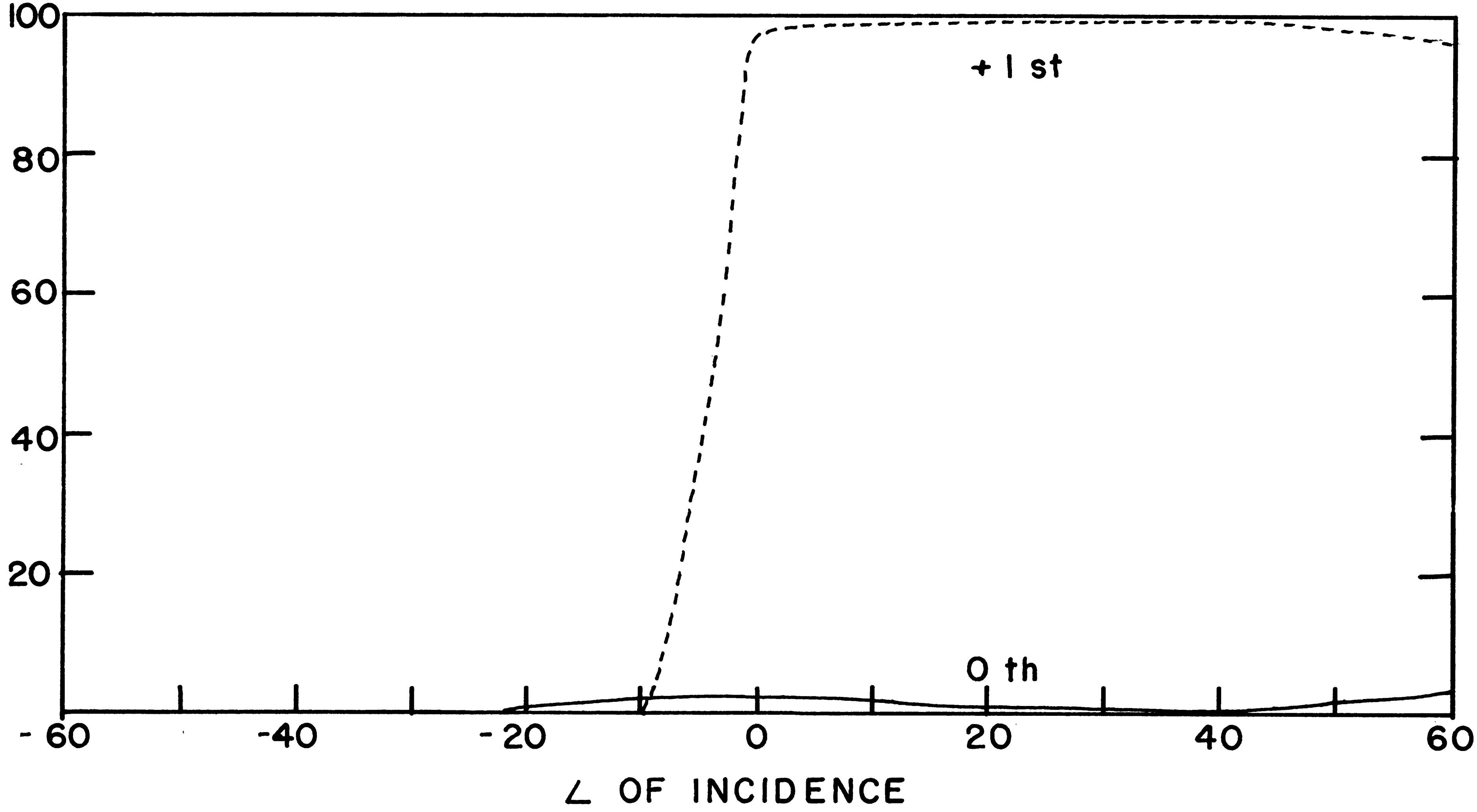


FIGURE 13

SINUSOIDAL GROOVE GRATING

% OF ENERGY IN SPECTRAL ORDERS

D = 2.67 λ DEPTH OF GROOVE = 0.67 λ

E ∥ TO GROOVES

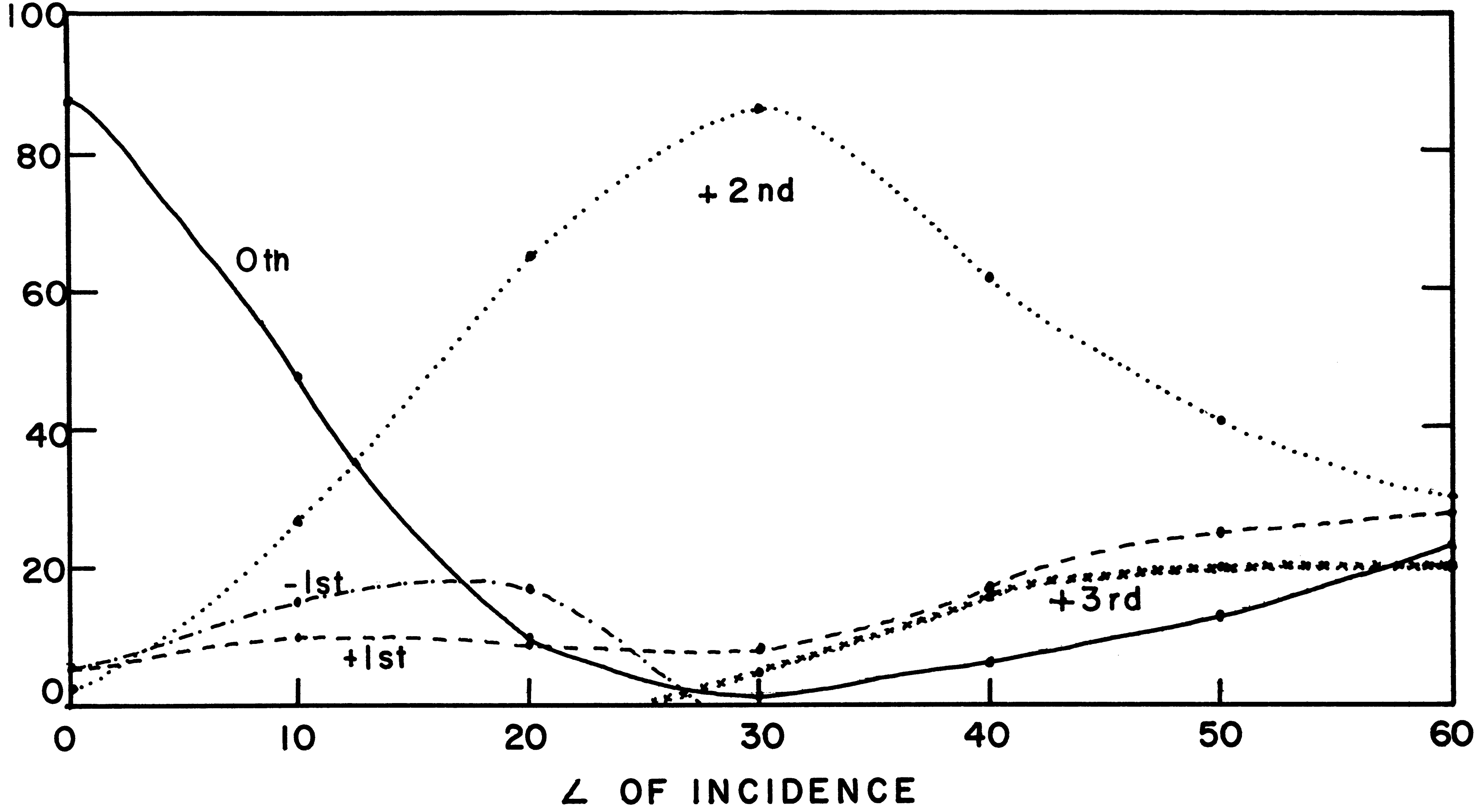


FIGURE 14

SINUSOIDAL GROOVE GRATING

% OF ENERGY IN SPECTRAL ORDERS

D = 2.67 λ DEPTH OF GROOVES = 0.67 λ

E ⊥ TO GROOVES

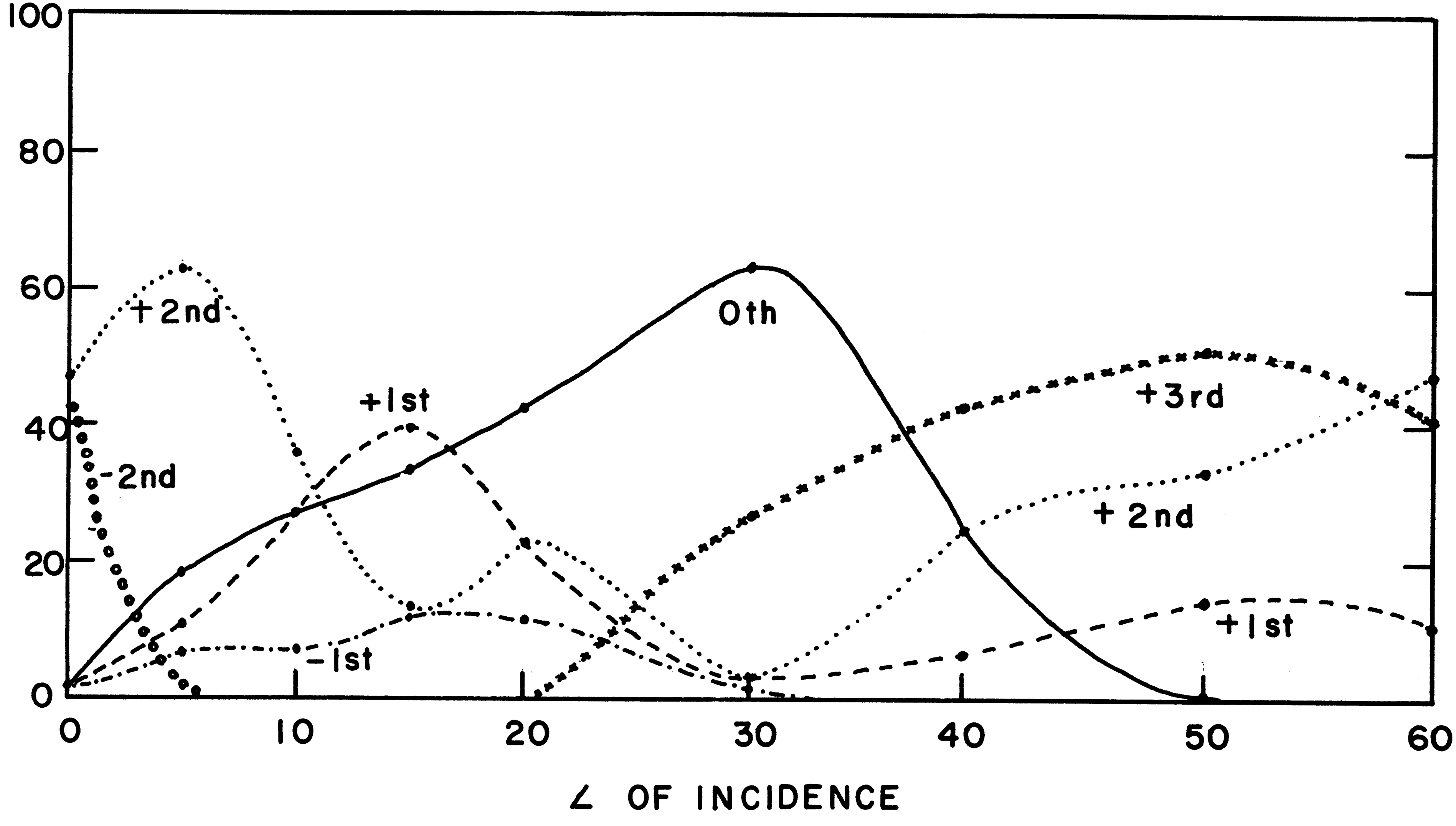
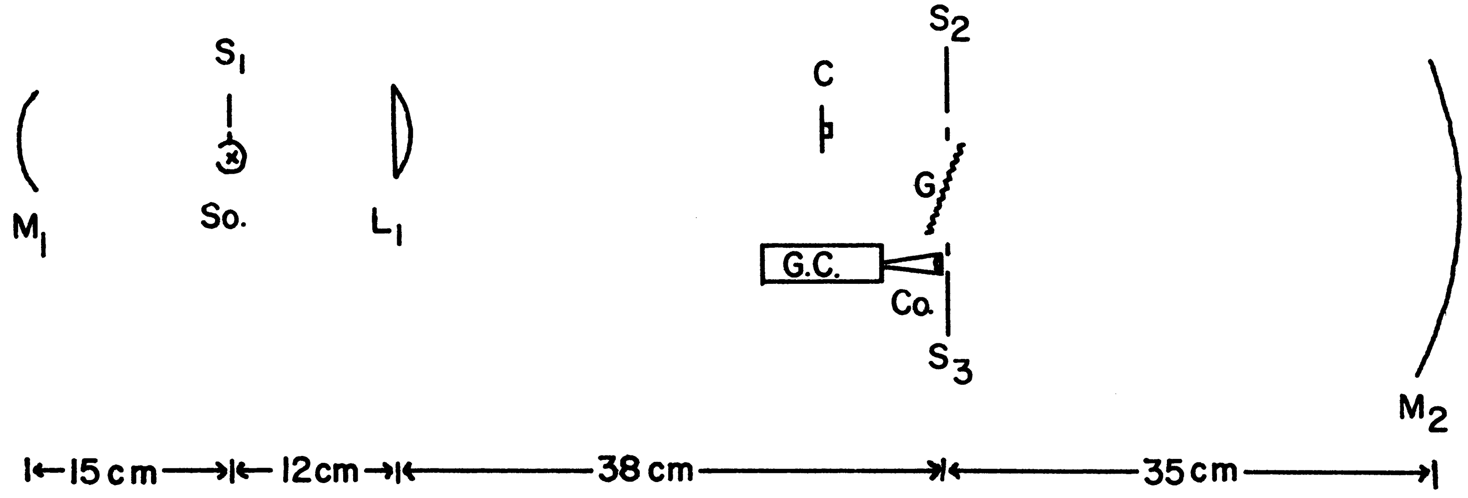


FIGURE 15



M_1, M_2 : Spherical Mirrors
S_1, S_2, S_3 : Slits
L_1 : Quartz Lens
C : Chopper

G : Grating
G.C. : Golay Cell
Co. : Condensing Cone
Paraffin Lens
So. : H-4 Hg. Lamp

FIGURE 16

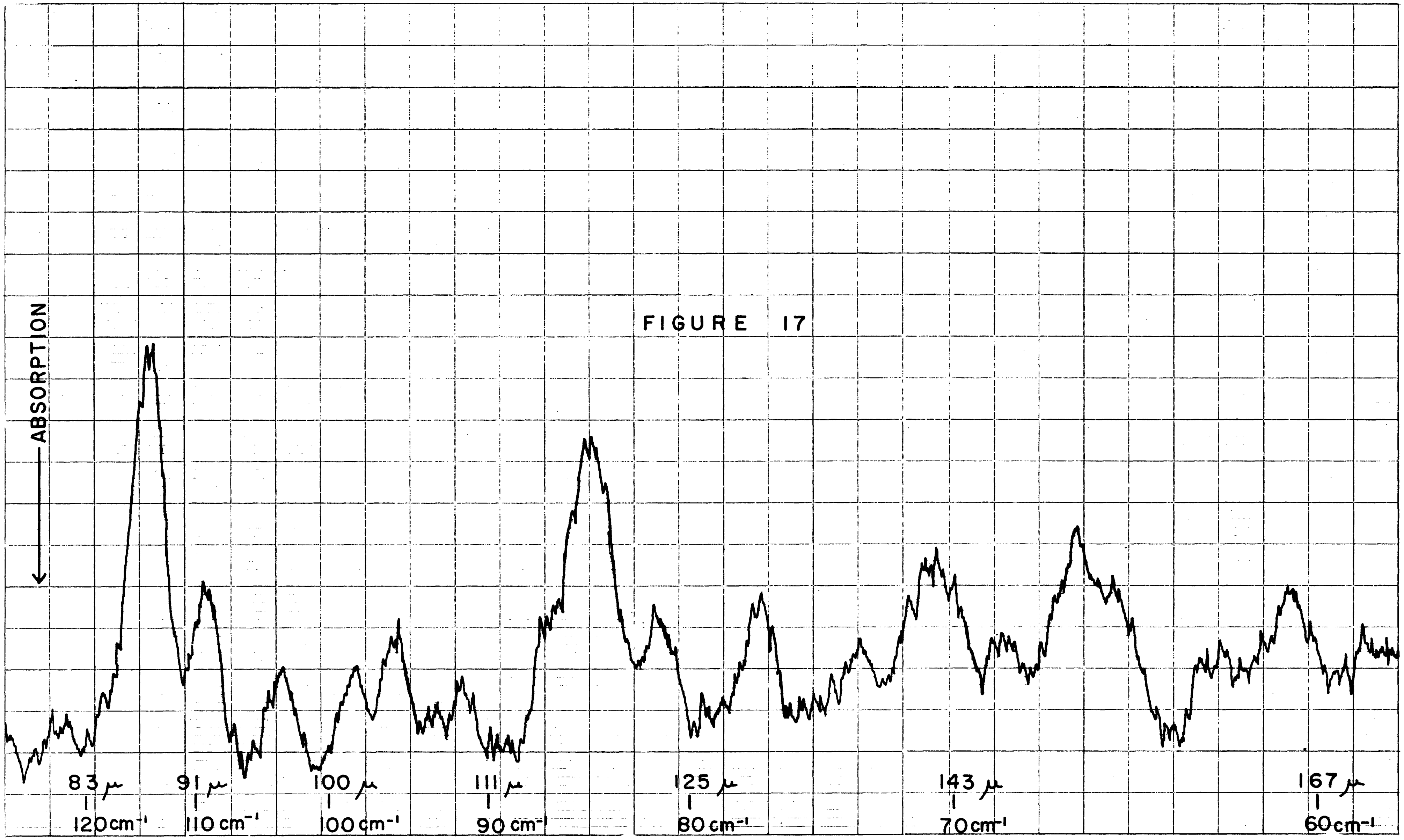

ABSORPTION
83 μ
120 cm⁻¹
91 μ
110 cm⁻¹
100 μ
100 cm⁻¹
111 μ
90 cm⁻¹
125 μ
80 cm⁻¹
143 μ
70 cm⁻¹
167 μ
60 cm⁻¹

FIGURE 17