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MICROWAVE MEASUREMENTS OF THE INTENSITY DISTRIBUTION OF ECHELETTE DIFFRACTION GRATINGS

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SUMMARY AND CONCLUSIONS

Apparatus has been assembled to measure the energy distribution among the spectral orders of model echelette diffraction gratings with 3-cm microwaves. Results for two gratings representative of those used in infrared spectroscopy show a strong dependence upon the direction of polarization of the incident radiation, as well as upon the angle of its incidence upon the grating. In the vicinity of the blaze of the grating, radiation polarized with the electric field perpendicular to the grooves goes completely into the 1^{st} order (or it could be said that the grating is 100 percent efficient). The parallel component , however, is only partly reflected into the 1^{st} order (for these particular gratings, some 60 or 80 percent) the balance going into the 0^{th} order. A second point of considerable interest is the discontinuous nature of the change in energy distribution of the perpendicular component when a spectral order reaches grazing angles of emergence.

The remarkable behavior of these gratings and their complete divergence from previous measurements indicates value of further work on the problem.

INTRODUCTION

The distribution of energy among the spectra of different orders formed by a diffraction grating is a problem of considerable interest, both as a problem in diffraction theory and as a practical consideration in the operation of a grating spectrograph. The latter is especially true for the infrared region as a consequence of the limited amount of available energy from sources and relatively insensitive thermal detectors. A sizeable gain in performance can be achieved if the radiation is concentrated in one particular spectral order of the grating. This was done by R. W. Wood [1] with an "echelette" grating--one in which the grooves were ruled with flat facets at a particular angle. In this manner, as much as 80 percent of the incident energy could be blazed into one order. At the present time, it would be helpful to know how high these efficiencies can be made, especially in connection with spectrographs using multiple reflections or passes of a grating.

Perhaps the most complete set of measurements to date was reported by Wood [2] in which the intensity distribution for several gratings was determined for different angles of incidence with unpolarized visible light. The imperfections that exist in the grooves of gratings with comparable spacing have been shown by Heidenreich and Matheson [3] with the aid of an electron microscope. Such imperfections would be expected to alter appreciably the performance of the grating. In addition, the dependence of the "Wood Anomalies" upon the direction of polarization of the radiation, as discussed by Palmer [4], indicates that the performance will also vary significantly with the direction of polarization. One may justifiably conclude that the experimental work is far from complete and also may well not be a reliable guide to the optimum performance of a diffraction grating.

A theory for the echelette grating was developed by Rowland [5] in which he derived general equations for the intensity distribution from a grating with a triangular groove shape. From this work, Stamm and Whalen [6] have calculated a number of specific cases, but there is only qualitative agreement with previously reported values. Rowland used the scalar method of Kirchoff and Huygens which ignores any possible effect of the polarization direction. Twersky [7] has used multiple scattering theory to calculate the diffraction patterns for gratings of several types other than the echelette, and does predict that there should be a noticeable influence of the polarization upon the results. Meecham [8] quite recently has developed a new method for the calculation of diffraction patterns from periodic structures and has made several calculations for the parallel polarization reflected from echelette gratings. The fundamental difficulty with the theoretical treatment of gratings of practical interest lies in the fact that these gratings have a grating space that is of the same size as the wavelength of the radiation. It is in this range that the methods of Kirchoff and Huygens used by Rowland become invalid, and for the other methods there is the difficulty of obtaining convergent solutions to the equations.

OUTLINE OF THE WORK

There appeared to be some hope of obtaining a great deal more information on the behavior of gratings through the use of microwaves. Since the size of the grating space would be increased in proportion to the wavelength (in this case, 3 cm), essentially perfect gratings of known contour could easily be made. Further advantages stem from the fact that the radiation would be both monochromatic and completely polarized, and also available at high power levels.

Apparatus was finally arranged as in Fig. 1. The source was a 723 AB klystron whose output was modulated at 2000 cps by the application of an a-c voltage of that frequency to the repeller electrode of the klystron. The wave guide from it was terminated at the focus of a paraboloidal seachlight mirror 90 cm in diameter and 35-cm focal length. The parallel beam of rays from this mirror was inclined downward at 8° to the horizontal and fell upon the diffraction grating 9 meters away. The grating could be rotated about a vertical axis and its angular position measured. A second searchlight mirror similar to the first served as the telescope and collected the radiation reflected downward from the grating. This mirror was mounted on an arm, that could be turned about the same vertical axis as the grating so as to scan through the energy in the several spectral orders emerging at different angles from the grating.

A crystal was placed at the focus of this mirror. The crystal was connected to an untuned a-c amplifier, and the amplified signal was rectified and read from a microammeter. An attenuator in the wave guide near the source served to limit the signal to the range over which the response of the crystal was linear. This was verified by rotating the crystal and observing that the response was proportional to the square of the cosine of the angle, which would be expected for the fraction of a linearly polarized beam transmitted by an analyzer as a function of angle.

The gratings were made from wooden boards that had been covered with aluminum foil. These were then mounted in a wooden frame and set at a particular angle and spacing. On the opposite side of the mount was placed a piece of plate glass covered with aluminum foil. This flat mirror was useful in aligning the components and also provided a measurement of the total energy in the beam.

The procedure adopted in the measurements was, first, to get the signal from the mirror set at the same angle at which the grating was to be used. Then the grating was rotated into position and the telescope rotated through the spectral orders. The images of the different spectral orders varied in width, because for each order at its particular angle the grating presented a different aperture (its projected width in that direction). Consequently, it was necessary to take the readings through the image of each spectral order at half-degree intervals. The areas under these curves of intensity versus angle of the telescope for each order were determined with a planimeter, and these areas taken as proportional to the signal. Generally there was reasonable agreement (5 percent) between the sum of these areas for all orders and the area under the curve for the mirror. Consequently, the percentage of incident energy in a particular order was taken as the ratio of the area under the intensity curve for that order to the sum of the areas of all orders.

The direction of polarization was varied by rotating both the source and crystal through 90°.

RESULTS

The first grating tested was an echelette of 25° blaze angle as indicated in Fig. 2. The grating space was 1.5 inches, the wavelength 1.25 inches, the boards 5/8-inch thick--the short face of the 90° groove being one-half of a wavelength. The results are plotted in Fig. 3 for the electric field of the radiation parallel to the direction of the grooves, with the percentage of the incident energy in each spectral order as a function of the angle of the incident beam with the normal to the grating. The angle of incidence is designated as positive if it is on the side of the normal to the grating as indicated in Fig. 2. The angle of emergence "r" for each spectral order is determined from the grating equation

$$m\lambda = D(\sin i \pm \sin r)$$

and the sign of each order is designated by whether the + or - sign is used in the equation.

The distribution among the orders with the electric field perpendicular to the grooves is plotted in Fig. 4 for the same 25° blaze-angle grating. There was generally no detectable energy at the position in which the 0^{th} order (or specularly reflected image) should fall. The angular width of the transition for the +1st to the -1st order, and also from the -1st to the -2nd order corresponded to the width of the diffraction pattern of the order that was just disappearing or appearing at a grazing angle to the grating.

In Figs. 5 and 6 the results are plotted for a 15° grating, a grating space twice the wavelength, and the short face one-half the wavelength.

DISCUSSION

The results for both gratings show a higher concentration of energy in a particular order for the perpendicular component than for the parallel. In the direction of the blaze, i.e., at an angle of incidence of +25° for the 25° grating and an angle of +15° for the 15° grating, the efficiency of the perpendicular component is 100 percent. A consideration of the boundary-value conditions on the large facet of each groove for electric fields indicates that this might be expected for the 25° grating. Assuming the metal to be a perfect reflector, the fields in it are zero and hence $\Sigma E_{normal} = 0$ and $\Sigma E_{tang} = 0$. But at the blaze angle, the only fields allowed are those of the incident beam, the +1st order, and the 0th order. Both the incident and 1st order fields are entirely tangential (since both beams are perpendicular to the large facet). If there were a 0th order field, it would contain a normal component and hence violate the condition that $\Sigma E_{normal} = 0$.

For the parallel polarization, the fields are completely tangential for all beams, so that the restriction indicated above does not apply.

As indicated in the introduction, there are no theoretical predictions for such gratings at the present time.

It is difficult to place a probable error on the measurements. For small angles we feel confident that the figures are reliable to better than 5 percent. At angles of incidence greater than 40°, the measurements become somewhat more uncertain. The reproducibility has been within 1 or 2 percent generally.

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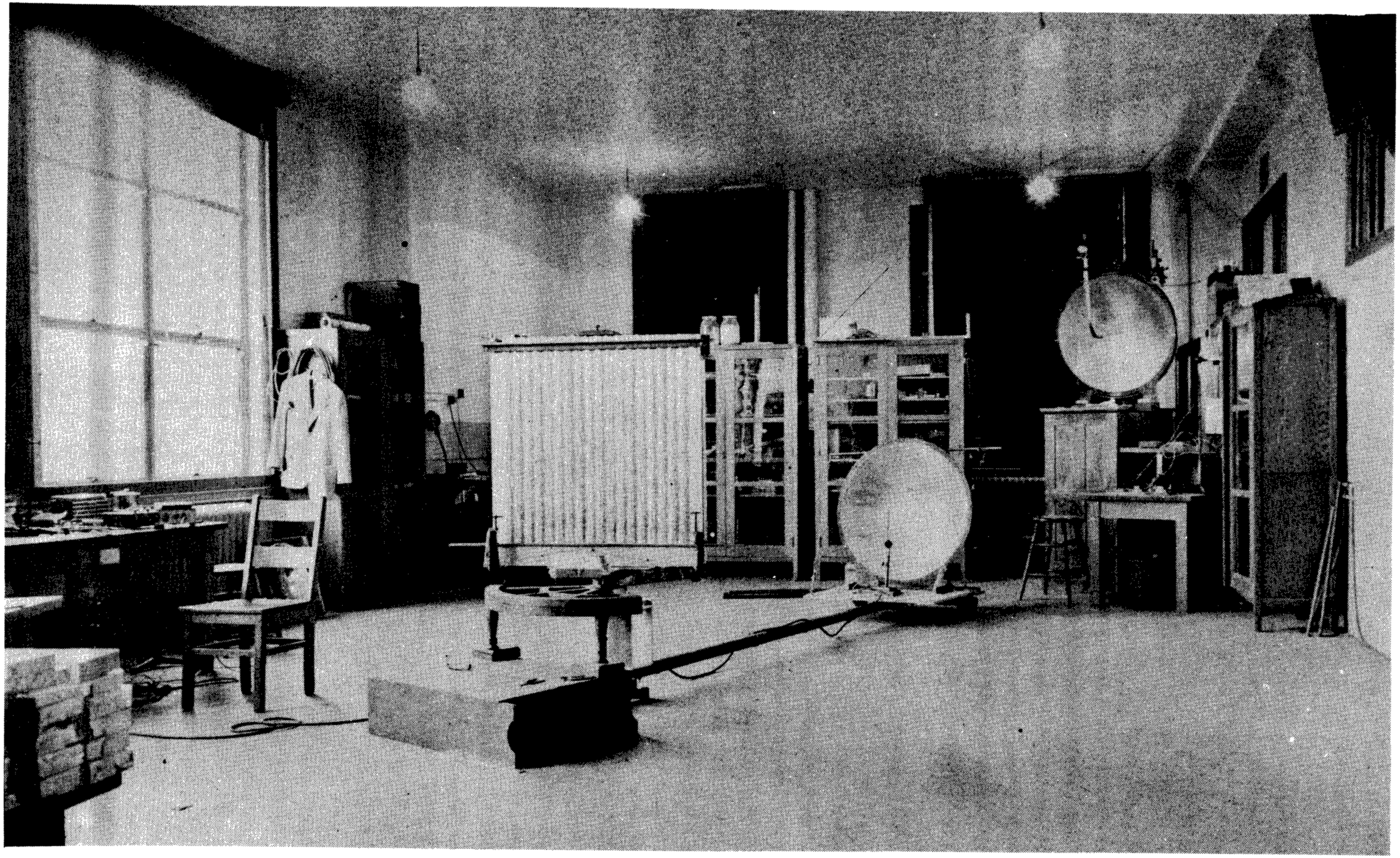
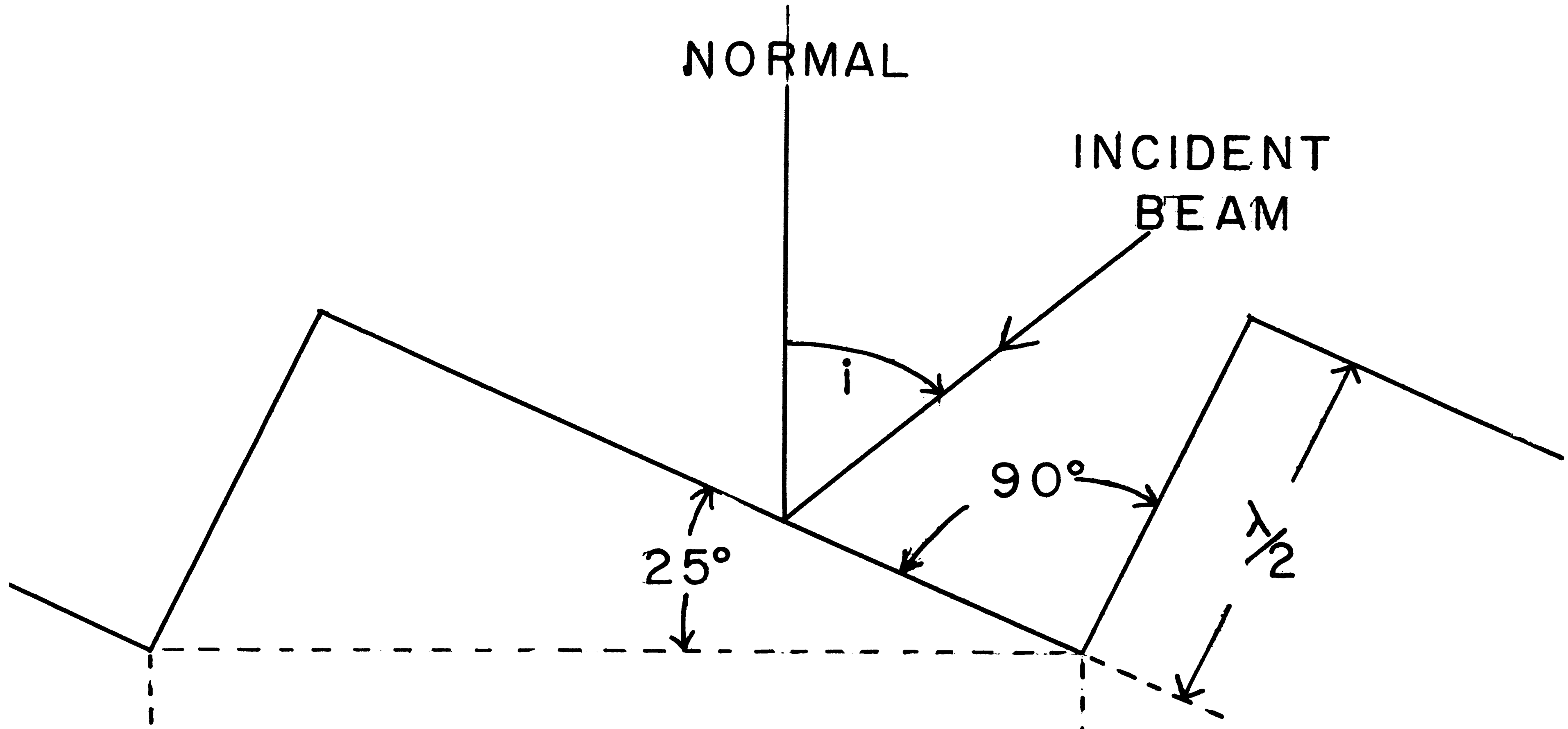


FIG. I



$D = 1.2\,\lambda$

$$m\lambda = D(\sin i \pm \sin r)$$

FIG. 2

% OF ENERGY IN ORDERS
D = 1.2 λ BLAZE ∡ 25°
E ∥ TO GROOVES

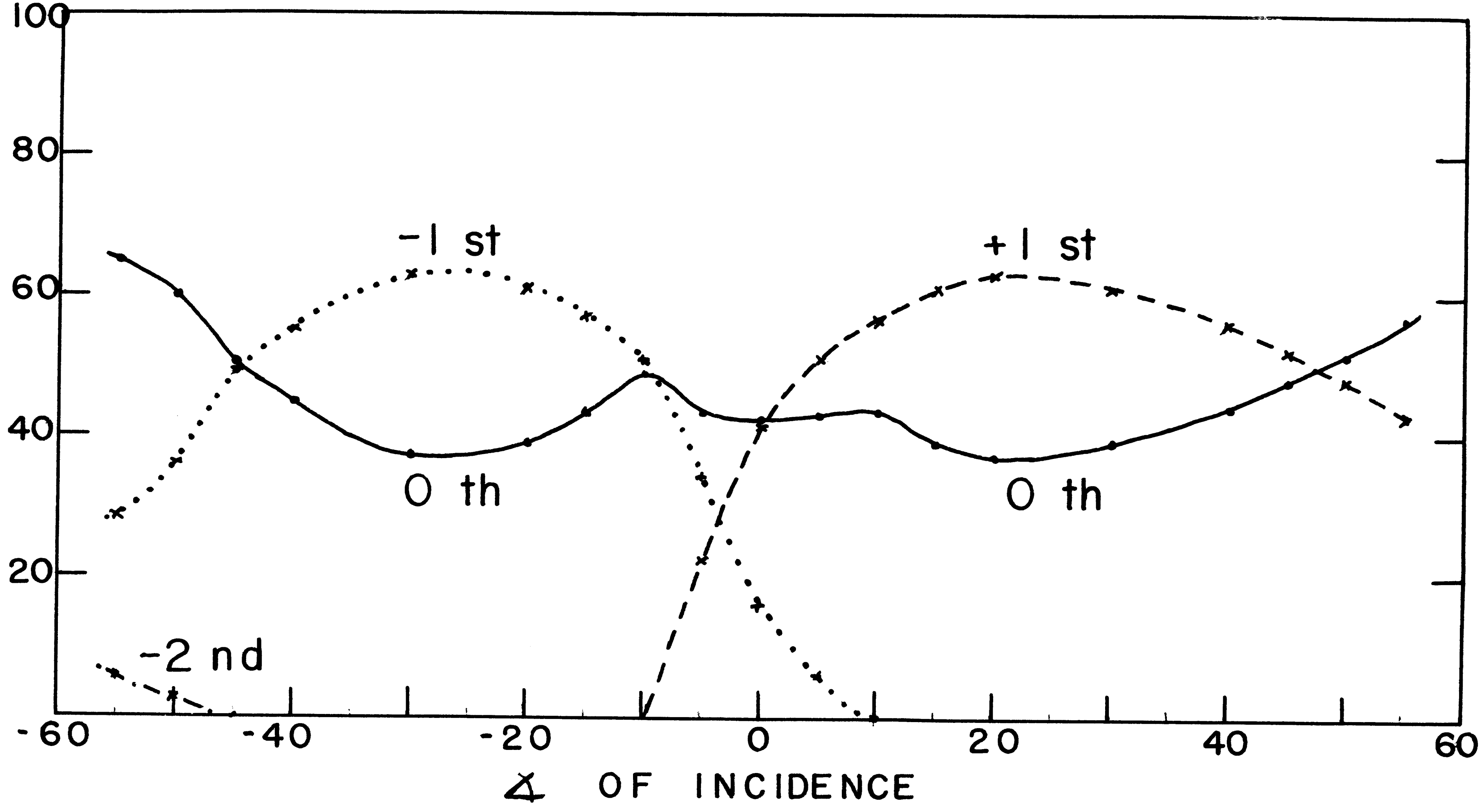
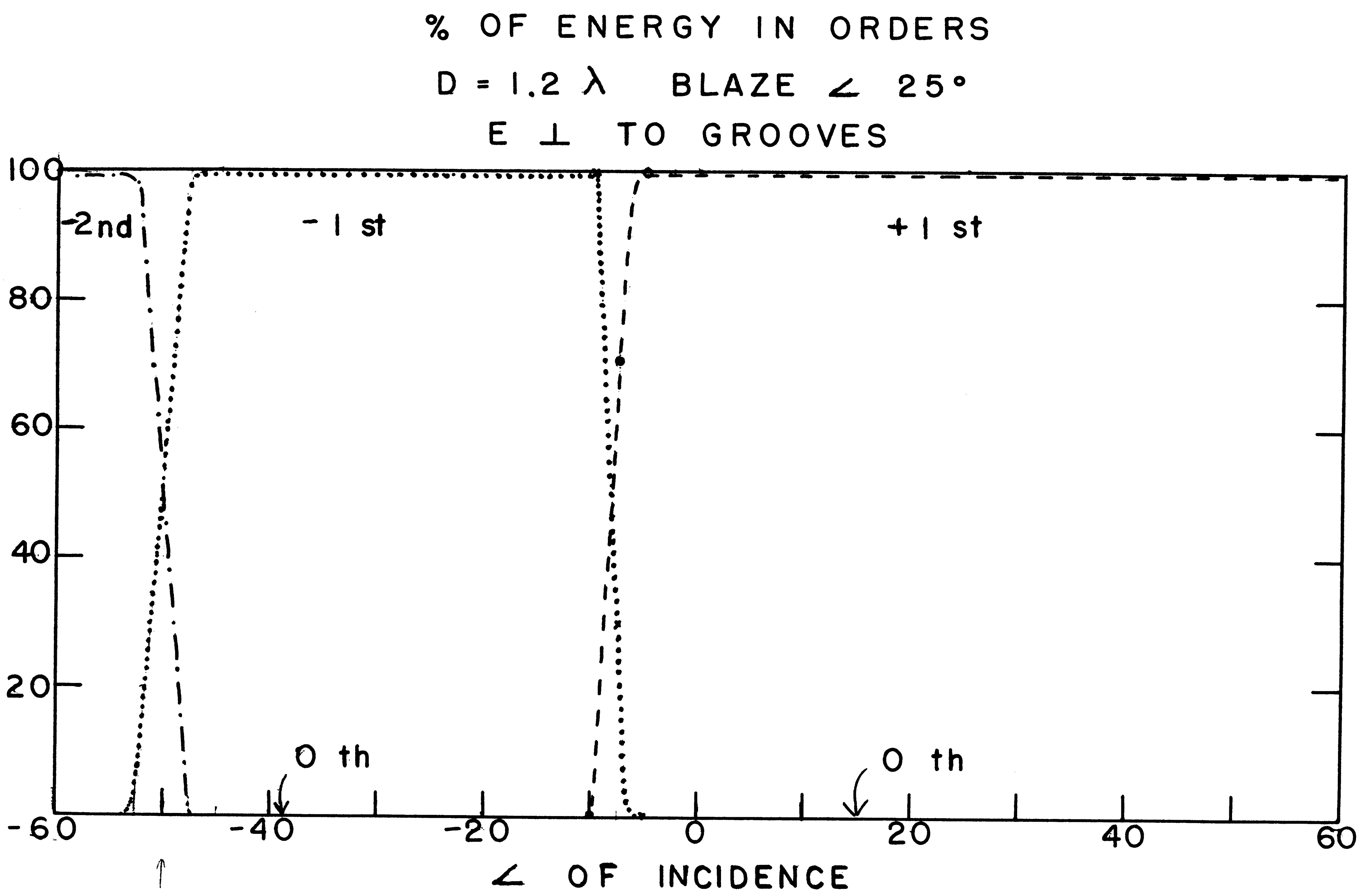
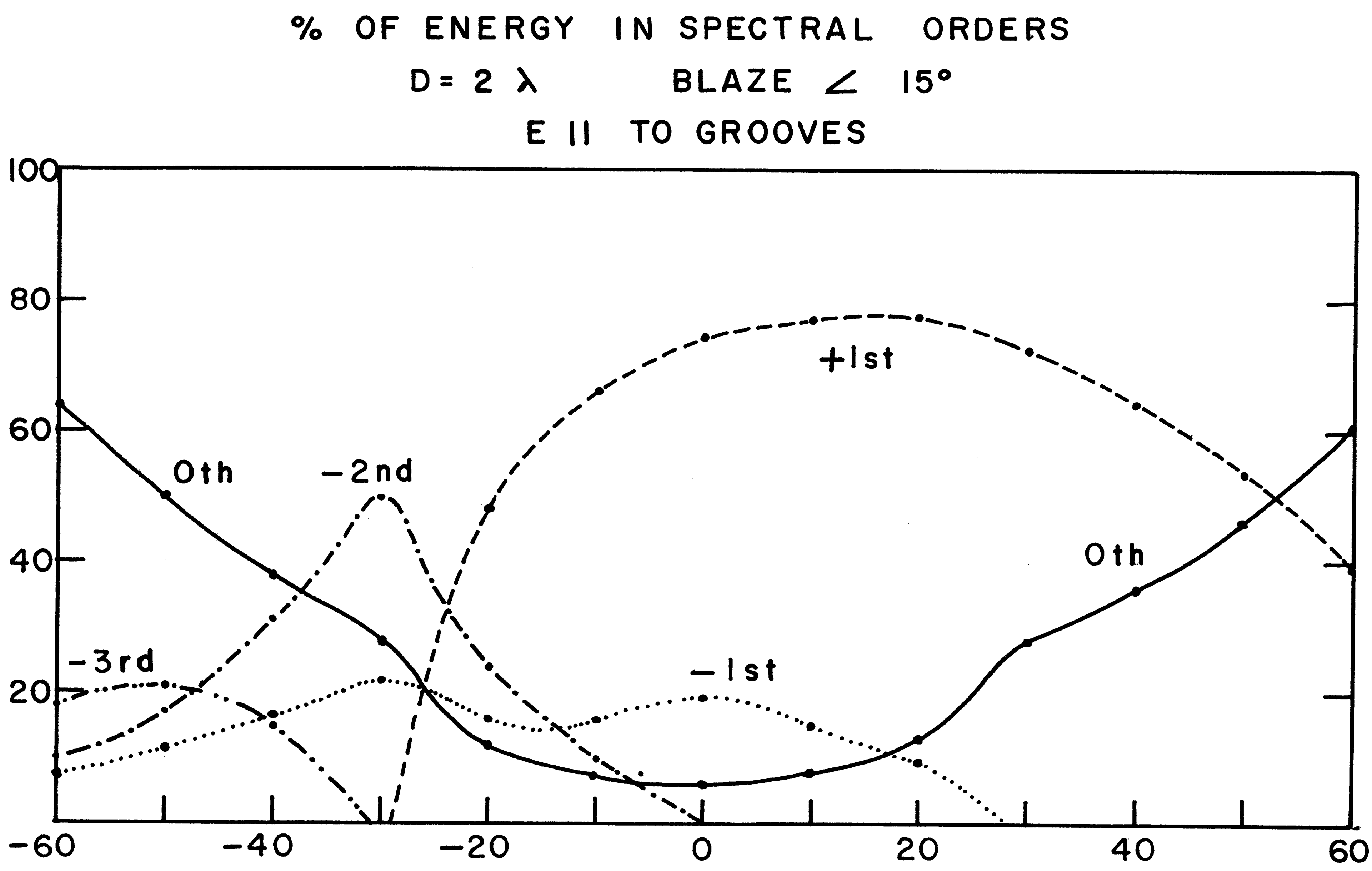


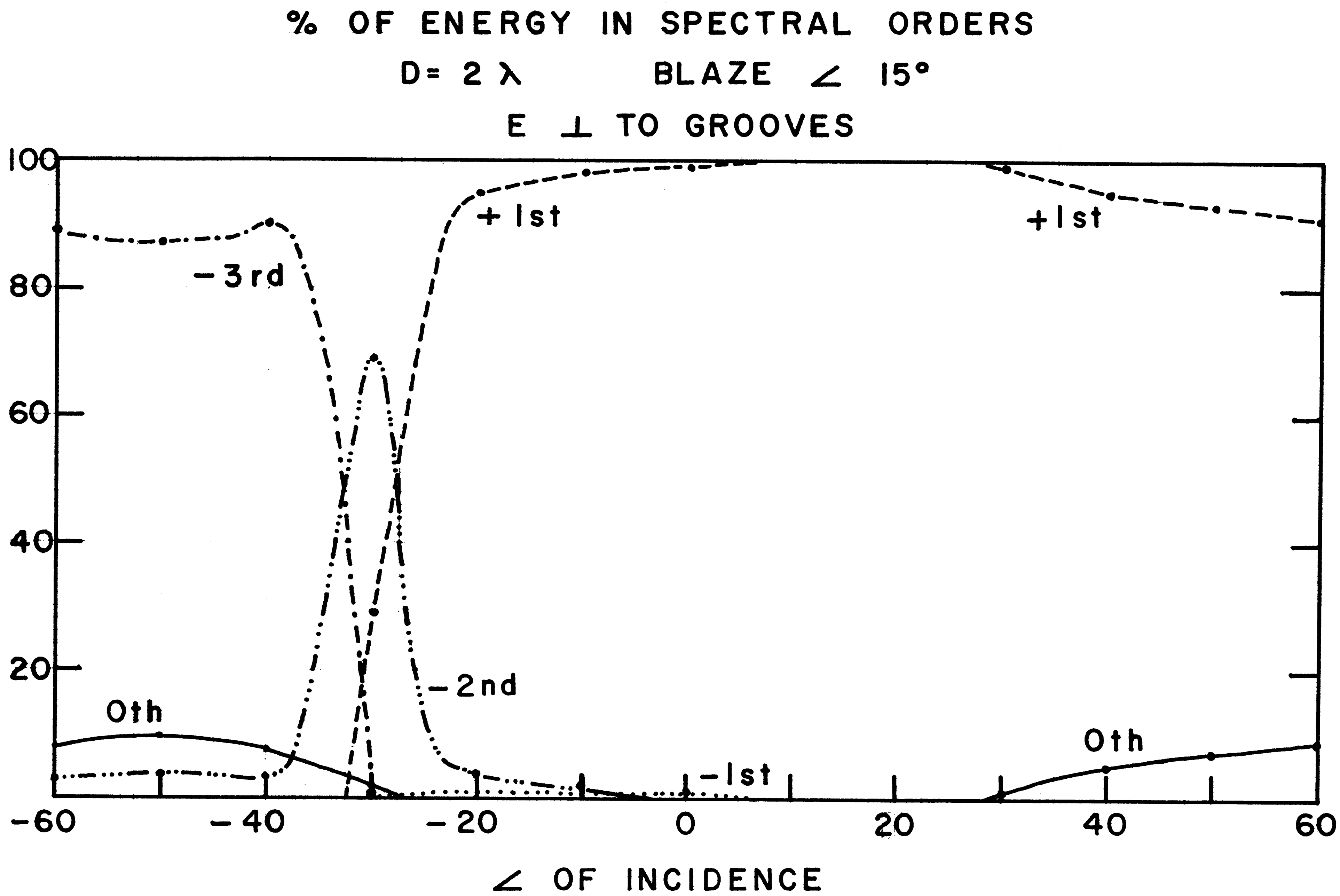
FIG. 3



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

FIG. 4


% OF ENERGY IN SPECTRAL ORDERS
D= 2 λ BLAZE ∠ 15°
E || TO GROOVES
100
80
60
40
20
-60
-40
-20
0
20
40
60
0th
-2nd
+1st
-3rd
-1st
0th
∠ OF INCIDENCE
FIG. 5


% OF ENERGY IN SPECTRAL ORDERS
D= 2 λ BLAZE ∠ 15°
E ⊥ TO GROOVES
100
80
60
40
20
−3rd
+1st
+1st
−2nd
0th
0th
−1st
−60
−40
−20
0
20
40
60
∠ OF INCIDENCE
FIG. 6