A Simple Grating System for Millimeter and Submillimeter Wavelength Separation*

In the course of a series of tests on a harmonic generator[1] which multiplied a 10-Gc fundamental to frequencies as high as 700 Gc (0.4 mm wavelength), it was necessary to separate and identify the various harmonics that were generated simultaneously. A device to serve the function of a filter was required. High accuracy of wavelength measurement was not essential since the fundamental frequency was known to one part in 10^4. It was necessary only to identify which harmonic was being selected. In order to obtain high efficiency, an echelette grating spectrometer was constructed, in emulation of many, thus working with millimeter waves and the infrared. A spectrometer similar to that of Coates[2] was considered, but expediency dictated a simpler system. The final design emphasized convenience in use by separating input and output paths, and simplicity of construction by having but one moving part. In Figs. 1 and 2 it may be seen that the grating merely rotates on fixed bushings; no other optical parts are moved.

Two horn-fed parabolic reflectors were mounted with their axes intersecting at an angle of 60°. The axis of rotation of the grating was co-planar with the parabola axes and was parallel to the rulings of the grating. As the grating was tilted to select the desired wavelength, unwanted wavelengths were diverted out of the principal plane of the spectrometer as shown in Fig. 2(a); only the desired wavelength was reflected to the receiving horn where it was detected by a crystal or a bolometer.

The angular separation of the input and output waves, shown in Fig. 2(b), was the most novel feature of the spectrometer. The input and output axes were co-planar with the grating axis. The only effect on the diffraction pattern was to reduce slightly the effective width of the rulings. As a result, the spectrometer combined the advantages of the wide bandwidth of a spectrometer with parallel input and output and the advantages of the separation of input and output for experiments obtained with other types of grating systems. It also allowed the spectrometer itself to be built as a compact package, occupying less than two square feet of bench space.

The heart of the spectrometer was an echelette grating, which has rectangular facets set at a constant angle (the blaze angle) to the surface of the grating. The effect of the facets is to reflect virtually 100 per cent of the incident energy into that spectral order most nearly corresponding to specular reflection in the individual facets.

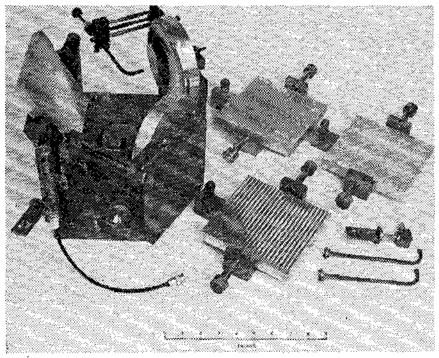

Fig. 1—The grating spectrometer and accessories.

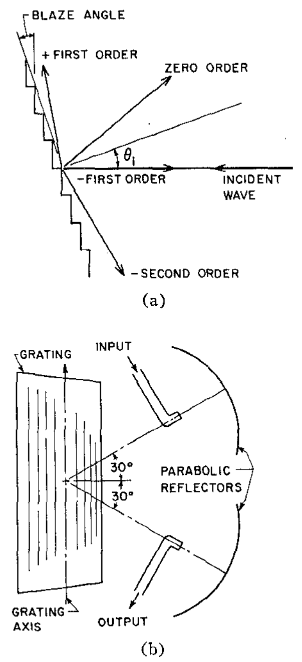

Fig. 2—(a) Side view of spectrometer. (b) Plan view of spectrometer.

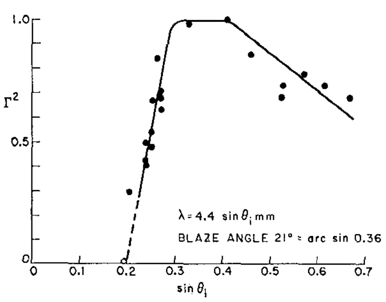

Fig. 3—Power efficiency of echelette grating.

It is readily shown that if the incident wave has the electric field perpendicular to the rulings and the wavelength is chosen so that the incident wave and a reflected order can both be perpendicular to the facets, the boundary conditions on the grating surface can be exactly satisfied by these two waves. No energy can be given to the other spectral orders. This is in marked contrast to transmission gratings or wire gratings in which some energy is delivered to each possible order of the grating. There exists a wavelength range of almost two to one about this central wavelength for which such high efficiency is obtained. Peters[3] has made a series of measurements at 3-cm wavelength, demonstrating this property of the echelette grating.

In Fig. 3 are shown the results of measurements of grating efficiency for first-order reflections in a wavelength range of 0.9 to 2.4 mm. It can be seen that the power reflectivity Γ of this grating was greater than 85 per cent over a 2:1 bandwidth. This particular grating was cut to reflect 1.5 mm wavelength at its blaze angle, with sin $\theta_i = 0.35$. The drop in reflectivity for large angles is due to zero-order reflection; the sharp drop at sin $\theta_i = 0.2$ occurs where the second-order reflection becomes predominant. The measurements were made by measuring the change of Q of a parallel-plate resonator when the grating was substituted for one of the end-plates. This technique has already been described elsewhere.[4]

The gratings were fabricated on a shaper, using a rectangular tool bit tilted at the blaze angle. One line of the grating was cut on each stroke of the shaper, using the standard 0.02 inch, 0.03 inch, etc. feeds of the shaper for cutting the various gratings. Four gratings were made, covering the wavelength range from 6 mm to 0.3 mm. It was found that replicas made of aluminum foil formed into the rulings of another grating and reinforced with casting epoxy were almost as efficient as the mechanical gratings. A sine-bar with rack and pinion drive was used to tilt the grating. The sine-bar was adjusted so that sin θ_i was read directly off the drive knob.

The same feed horns were used for all wavelengths throughout our experiments. The fixed horn aperture held the resolution to about 0.2 mm for all wavelengths.[5] Had the appropriate size horn been used for each wavelength, the resolution would theoretically be about 1 Gc over the entire range of the instrument.

Frequently the feed system was separated so that quasi-optical experiments could be performed. Occasionally two gratings were used in tandem. This could serve either of two functions. With two gratings, the resolution of the system could, of course, be increased. A more useful function, however, was to arrange the extra grating as a low-pass filter. A grating too fine to affect

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[1] P. A. Szente, R. H. Miller, and K. B. Mallory, "Production of Submillimeter Waves by Bunched, Relativistic Electrons," presented at the Millimeter and Submillimeter Wave Conference, Orlando, Fla.; January 7–10, 1963.

[2] R. J. Coates, "A grating spectrometer for millimeter waves," *Rev. Sci. Instr.*, vol. 19, pp. 586–590; September, 1948.

[3] C. W. Peters, R. H. Hunt, W. K. Pursley, and T. F. Zipf, "Microwave Measurements of the Intensity Distribution of Echelette Diffraction Gratings," Engineering Research Institute, University of Michigan, Ann Arbor, Project 203, Rept. No. 3; 1954.

[4] D. A. Johnson, K. B. Mallory, R. H. Miller, R. H. Pantell and P. A. Szente, "Small signal characteristics of ferroelectric ceramics at millimeter wavelengths," Proc. IEEE, vol. 51, pp. 332–339; February, 1963.

[5] The "feed horns" were the cut ends of sections of RG-99 waveguide, with no flare. It would appear that the cone of illumination should decrease in proportion to the wavelength and that the area of grating in use would also be proportional to wavelength. With fixed blaze angle, and therefore approximately constant angle of incidence, one would expect the resolution to be $\Delta\lambda/\lambda \approx \lambda/A$, where A is the illuminated width of the grating. This would predict a constant resolution of, say, 4 per cent. Using geometric optics, however, one decides that an image of the feed horn is formed at the receiving horn; no matter how good the focusing, the resolution is limited by the width of the apertures. Since the experiments covered a range of more than three octaves and the waveguide was over-moded over most of this range, the latter argument was taken as a sufficient explanation of the observed performance.

the desired wavelength was placed in tandem so that the zero-order reflection (the only one existing for the desired wavelength) reached the detector. Submultiples of this wavelength, which would normally also be transmitted through the spectrometer, were now diverted into other orders with the usual high efficiency of the echelette grating. It was possible, therefore, to make measurements at, say, the 10th harmonic without serious interference from the 20th harmonic.

The over-all insertion loss of the spectrometer ranged from 5 to 3 db and from 5.4 to 1.0 mm, mainly due to horn and waveguide losses. This instrument proved to be very convenient for harmonic identification and separation, and certainly could not be replaced by conventional types of microwave wavemeters at these wavelengths.

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Submillimeter Photon Counting in Ruby*

A microwave detection process very similar to Bloembergen's quantum counting[1] has been observed in the vicinity of 500 Gc using the fluorescence of ion pairs in red ruby. The detector which has been realized is quite sensitive and particularly simple because it uses polychromatic light for pumping. The results reported here are preliminary, and the apparatus is not refined for detection beyond the stage at which feasibility has been shown.

The quantum systems responsible for submillimeter photon counting are the ion pairs which exist in significant numbers in red ruby. The fourth neighbors and those closer have a large spin-exchange interaction which modifies the pair spectra in such a way that the ground state of the Cr^{+++} pair is split into four energy levels of total spin 3, 2, 1 and 0 since each ion has a spin of 3/2.[2] The transition frequencies among the spin levels of the fourth and second neighbor pairs are in the range of 300 to 3000 Gc.[3]

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[1] N. Bloembergen, "Solid state infrared quantum counters," *Phys. Rev. Lett.*, vol. 2, pp. 84–85; February 1959.

[2] A. L. Schawlow, D. L. Wood, and A. M. Clogston, "Electronic spectra of exchange-coupled ion pairs in crystals," *Phys. Rev. Lett.*, vol. 3, pp. 271–273; September, 1959.

[3] P. Kisliuk, A. L. Schawlow, and M. D. Sturge, "Energy levels in concentrated ruby," *Bull. Am. Phys. Soc.*, Ser. II, vol. 7, p. 616; December, 1962.

An approximate energy level diagram of the fourth neighbor pairs is shown in Fig. 1, and on it is the simplified photon counting cycle. This cycle does not depend upon the use of monochromatic pumping light to sense changes in the populations of the ground state levels; instead it utilizes the indigenous selection rules in the normal fluorescence cycle of the red ruby crystal. This is evident in the following description of the counting cycle:

1) In a ruby crystal at 4.2°K, only the lowest energy level of the pair system ($S=3$) is significantly occupied. If it is assumed that the intensities of transitions from this level to the U band are relatively low, when the crystal is pumped with green light the resulting fluorescence from the fourth neighbor pairs is small.
2) When a microwave signal at the proper frequency (615 Gc) is incident on the crystal, there will be absorption, and this will cause an increase in the population of the $S=2$ level.
3) If the $S=2$ level has a strong transition to the U band, the increase in its population will cause an increase in the total fluorescence from the crystal.

Monitoring the fluorescence from the crystal completes the photon counting detection scheme.

One factor, perhaps a critical factor, has been neglected in the preceding discussion; nonradiative energy transfer from isolated ions to pairs makes a major contribution to the fluorescence, and it is very likely that this transfer is sharply frequency selective, particularly at low temperatures. With the information available, it is impossible to discriminate between effects due to this transfer and the simpler effects discussed above.

The apparatus which was used to observe detection is shown in Fig. 2. All the active elements are placed within the insulating space of a specially constructed helium cryostat. The ruby crystal, about 0.3 mm³ of dark ruby, is cooled by conduction through the copper bottom of the helium vessel. This copper plane also acts as one end of the bisected-confocal microwave cavity; the other end is an evaporated silver coating on the polystyrene lens. The lens end is tunable, by means of a micrometer and lever system, over a 2 mm range about the mean cavity length of 1 cm. Pumping light enters the cryostat assembly vertically through a fused quartz window, and, after being deflected by the front surface mirror, it reaches the ruby at a 45° angle. The fluorescence is detected by a commercial thin-film Ge bolometer, and the radiation reaching it is limited by a sharp cutoff red filter, which passes wavelengths greater than 6500 A.

The pumping light source is a 500 watt, Hg-Xe compact arc lamp, and the arc is imaged on the ruby by an $f/2.5$ lens. The light is mechanically chopped at 50 cps to allow the use of a lock-in amplifier.

The microwave signal is thermal radiation, and it enters the cavity by means of

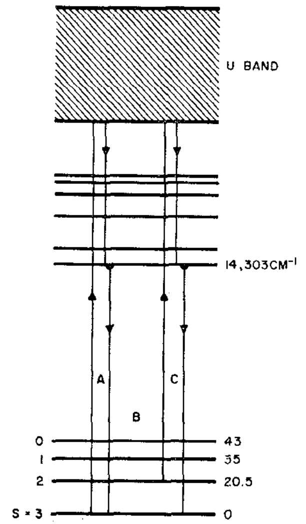

Fig. 1—Partial energy level diagram (from Kisliuk, Schawlow, Sturge[3]) of the fourth neighbor pairs of Cr^{+++} in ruby, showing the simplified photon-counting cycle.

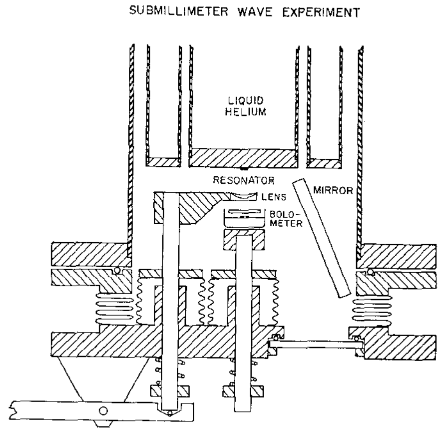

Fig. 2—A cross-section view of the basic assembly used to observe the submillimeter detection.

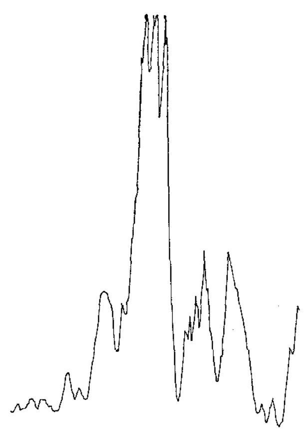

Fig. 3—A recorder trace of the bolometer output as the cavity frequency passes through the 612 Gc ruby resonance. The principal peak is 480 Mc wide.