Proposal: The Generation of Coherent Infrared Radiation from a Diffraction Grating*

The generation of optical radiation from a diffraction grating has been described by Smith and Purcell[1] and by Salisbury.[2] This communication will report a set of improvements on their method which can lead to coherent radiation. Simple calculations have been performed for two special cases to obtain estimates of the output power available. It appears that such a device could give powers from a microwatt to 0.2 mw in the region of 0.1 to 0.5 mm wavelength. Output power levels of this order are entirely adequate for experiments in high resolution spectroscopy and related problems.

All previous experiments in this field have involved a ribbon beam of relativistic electrons streaming along the face of the grating perpendicular to the ruling lines. An oscillating dipole is set up between an individual electron and its image charge in the grating, and radiation is generated. This method leads to shot noise radiation. The radiant output appears over the full hemisphere above the grating, with a spectrum of wavelengths generated according to the equation $\lambda(\theta)=d(c/v-\cos\theta)$.

The coherence quality of this radiation can be improved by a series of steps; the first of these being a complete change in the method of electronic excitation. A ribbon beam of electrons is used, but is aimed perpendicular to the grating and focused to impact on a single element. This beam is then swept by a high frequency field so that the point of impact moves at a substantial fraction of the velocity of light.[3] The point of impact must advance uniformly in time. To do this requires that one use the central portion of a sinusoidal sweep and introduce odd harmonics to linearize the central portion.

The easiest way to visualize this excitation is to consider a diffraction grating of separated metal bands rather like a partially opened venetian blind. Such gratings can be made with even optical dimensions.[4] This particular geometry permits a very simple estimate of power radiated, for one has only to calculate the energy stored between a charged and an uncharged element and to assume that this energy is radiated as the charging sweep progresses down the grating. Such an estimate for the electrostatic case is given in Table I. The radiation is still polychromatic, as described by (1), but is coherent in two senses; it is radiated in a cylindrical ribbon about the grating rather than a hemisphere, and all of the different wavelengths emitted can be described by equations with a common phase factor. This suggests that further improvements in coherence may be obtained. A partial concentration of this polychromatic radiation can be obtained by backing the grating with a reflector or by using a more complicated electron gun with a series of parallel filaments so arranged that the electron images impinge simultaneously on alternate elements of the grating.

TABLE I

POLYCHROMATIC RADIATION FROM A DIFFRACTION GRATING WITH SEPARATE, INSULATED ELEMENTS, END-GROUNDED

Grating:	2-cm high $\times$10-cm long $\times$0.04-cm period
Beam·	2 cm $\times$0 03 cm cross section, 200-ma current
Sweep Rate:	0.47 c (This is a severe requirement. For 10-kv acceleration and 0 2-c forward velocity, peak amplitudes of 1000–2000 v must be used to produce this sweep rate.)
Duty Cycle.	$D=0.167$, neglecting return sweep
Charge per element:	2.8×10^{-13} coulombs $=1.75\times10^{6}$ electrons per sweep
$C_{MN}\leq1.1$	mmf interelement capacitance
$V_{MN}\geq0.5$	volts = instantaneous interelement field
$W_{MN}\geq1.5\times10^{-14}$	joules = instantaneous interelement field energy
$P=W_{MN}\cdot N.f.$	$=(1.5\times10^{-11})$ (250 elements) 225 $\times10^{8}$ sweeps per sec) $=8.4\times10^{-3}$ watts
0.045 cm $<\lambda<0.125$ cm.	Range of wavelengths radiated

Total coherence and monochromatic output can be obtained by setting up an interaction between the radiation field near the grating and the on-coming electron beam. This interaction is effective only within a fraction of a wavelength of the grating, and the grating may be viewed as producing a coherent interruption of the electron beam. The grating must be enclosed in a resonant structure in this steady-state case, and the obvious structure to be considered is a folded Fabry-Perot interferometer, as shown in Fig. 1. The most severe limitation on the Q of this resonator is set by diffraction losses, as calculated by Fox and Li.[5,6] A solid metallic grating is used in this case, and either single or multiple electron beams may be used, since only the total beam current is significant. A simple estimate of the monochromatic, coherent radiation output is obtained by specifying that a field exists on the grating, calculating from this field the work done by the electron beam over a distance somewhat smaller than one period of the grating, and equating this input power with the power dissipated in the resonator and radiated outward to become available for practical use. Such a calculation is given in Table II. This calculation leads to an output power of roughly 0.2 mw at 0.5 mm wavelength. To carry this estimation of power to shorter wavelengths, one must state the lengths to which he is willing to go to preserve beam current. For single element excitation with beam area decreasing in proportion to the grating period and with constant current density, power will decrease as about the third power of wavelength to roughly one microwatt at 0.1 mm. For constant total beam current obtained by increasingly elaborate electron optics and simultaneous excitations at multiple points on the grating, power will decrease roughly as the first power of wavelength. In any event, these are useful power levels in a region heretofore penetrated only on a millimicrowatt level, so this device is suggested as a laboratory generator for this region.

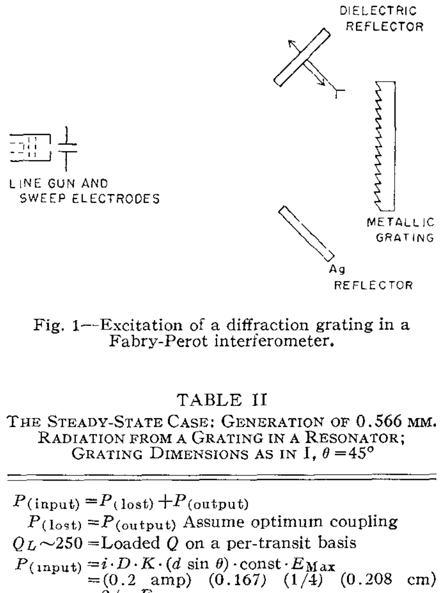

Fig. 1—Excitation of a diffraction grating in a Fabry-Perot interferometer.

TABLE II

THE STEADY-STATE CASE: GENERATION OF 0.566 MM. RADIATION FROM A GRATING IN A RESONATOR; GRATING DIMENSIONS AS IN I, $\theta=45°$

$P_{(input)}$	$=P_{(lost)}+P_{(output)}$
$P_{(lost)}$	$=P_{(output)}$ Assume optimum coupling
$Q_L\sim250$	= Loaded Q on a per-transit basis
$P_{(input)}$	$=i\cdot D\cdot K\cdot(d\sin\theta)\cdot\text{const}\cdot E_{Max}$ $=(0.2\text{ amp})\ (0.167)\ (1/4)\ (0.208\text{ cm})\ 2/\pi\cdot E_{Max}$
	$0<K>1$ is an estimate of the effective interaction between the beam and the fringing field near the grating.
	$=4.5\times10^{-2}E_{Max}$ [P in watts, E in statvolts/cm]
P_{output}	$=\dfrac{2\cdot10^{-5}}{32\tau Q}E_{Max}^2=2.65(E_{Max})^2$ τ = resonator transit time
P_{output}	$=\text{const}\cdot\tau Q\cdot(iDKd\sin\theta)^2=1.9\times10^{-4}$ watts at 0.566 mm.

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[1] S. J. Smith and E. M. Purcell, "Visible light from localized surface charges moving across a grating," *Phys. Rev.*, vol. 92, p. 1096; November 15, 1953.
S. J. Smith, "Visible Light from Localized Surface Charges Moving Across a Grating," Doctoral thesis, Harvard University, Cambridge, Mass.; 1953.

[2] W. W. Salisbury, U. S. Patents Nos. 2,634,372, 1953; 2,688,107, 1954; 2,866,917, 1958; and 2,939,998, 1960. Also, "Emission of visual radiation from free electrons," *J. Opt. Soc. Am.*, vol. 52, p. 1315; November, 1962.

[3] This device is in the general class of sweep-modulated generators. Several of these were discussed at the Orlando meeting: J. R. Baird and P. D. Coleman, "Bunching of an Electron Beam by Deflection Modulation," Paper 5.5; and G. T. Flesher, "Harmonic Generation by Electron Beam Virtual Bunching with Sweep Modulation," Paper 7.4. In particular, Baird and Coleman described a closely related device designed to multiply from 10 Gc to 160 Gc with 10 watts output. Their design did not include a resonator for the harmonic output, but Baird indicated that this was under consideration (private conversation).

[4] G. R. Bird and M. Parrish, Jr., "The wire grid as a near-infrared polarizer," *J. Opt. Soc. Am.*, vol. 50, pp. 886–891; September, 1960.

[5] A. G. Fox and T. Li, "Resonant modes in a maser interferometer," *Bell Sys. Tech. J.*, vol. 40, pp. 453–488; March, 1961.

[6] The dielectric plate can introduce prohibitive losses if a poor choice of material is made. Ordinary dielectrics (Al_2O_3, TiO_2, LiF, Teflon, etc.) are strong absorbers in this region. These absorptions are associated with "reststrahlen" phenomena. See S. Roberts and D. D. Coon, "Far infrared properties of quartz and sapphire," *J. Opt. Soc. Am.*, vol. 52, pp. 1023–1039, September, 1962; or L. Genzel, and M. Klier, "Spektraluntersuchungen im Gebiet um 1 mm. Wellenlange III Dispersionsmessungen am Lif," *Z. Phys.*, vol. 44, pp. 25–30; 1956, for representative data. *The extension of maser-laser technology into this region is greatly hindered by these optically active lattice vibrations.* Ultrapure silicon is a material of choice for a dielectric reflector.