MONDAY, MAY 15, 1961
SESSION 1: MILLIMETER WAVES

10:45 AM - 12 NOON
CHAIRMAN: R. O. STONE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D. C.

1.2 A MILLIMETER WAVE FABRY-PEROT MASER

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So far a major limitation to the development of millimeter, and sub-millimeter wavelength beam masers[1], has been the lack of a suitable high Q resonant structure of adequate dimensions for these wavelengths. This is necessary so that a sufficient number of state-selected molecules can be injected into the resonant structure, for the weak molecular stimulated power emission to exceed losses, and give maser oscillation or detectable amplification. Recent developments in Fabry-Perot interferometers, or resonators for millimeter research, appear very significant for such maser applications, and indicate the possibility of operating such devices at shorter wavelengths, utilizing rotational transitions in molecules such as HCN, and NH_3.

Suitable interferometer designs have been described[2, 3], and Fig. 1 shows the sharp fringes obtained at $\lambda = 6.3$ mm. Basically the resonator consists of two parallel metal plates with an array of suitably spaced coupling holes over the entire plate area. This utilizes the full radiating apertures of the reflectors, and reduces the effects of diffraction, such as leakage of energy from between the plates. Neglecting such effects the unloaded Q of such a resonator is given by:

$$Q_o = (2\pi d)/[\lambda(1 - R)], \qquad (1)$$

where d is the spacing between the plates, and R is the power reflection coefficient of the metal. Thus Q_o varies as $\lambda^{-\frac{1}{2}}$ for a given plate separation, in contrast to conventional microwave cavities. Measurements at $\lambda = 6.3$ mm show that Q values in excess of 50,000 are possible[3], and indicate that diffraction effects can be kept small, particularly for small plate separations.

Figure 2 shows the transmission type millimeter wave maser with the molecular guns and focussers injecting molecules between the metal plates of the resonator. This allows considerable flexibility, and a number of such molecular injectors can be used. The equivalent circuit of the interferometer section is shown in Fig. 3. Values of the susceptances may be deduced[4, 5], and hence the degree of coupling determined. Thus if $Z_m = R_m + jX_m$ is the intrinsic impedance of the metal, and $Z = R + jX$ represents the impedance transformed into the resonator, then

$$Q_{ext} / Q_o = 2R_m / R, \qquad (2)$$

and values of insertion loss and loaded Q values may be determined. Since the reflector plates must be quite flat, the use of thin perforated films on optical flats appears desirable.

Conventional gaseous masers employ static electric field state selectors[1] to produce inhomogenous electric fields, which exert different dipole forces on molecules in different energy states. The force on the molecules may be written as

$$\underline{F} = -\nabla V = -\frac{\partial V}{\partial E}\nabla E = \mu_{eff}\nabla E, \qquad (3)$$

where V is the potential energy of the molecules in the static electric field of magnitude E, and μ_{eff} is the effective dipole moment of the molecule in a given state. Usually $\partial E/\partial r$ is positive, and molecules having μ_{eff} negative are focused towards the axis of the state selector. The value of μ_{eff} also depends on the magnitude of the electric field in general. A plot of μ_{eff}/μ versus $P = \mu E 8\pi^2 I_B/h^2$, is shown in Fig. 4. Here I_B is the moment of inertia of the linear type molecule and h is Planck's constant. It follows that for linear and symmetric top molecules, the potential on the state selector electrodes must be set to specific values to focus desired states. This is quite unlike the situation for ammonia.

Maser oscillations occur when the power given up by the molecular beam to the resonator exceeds the total power losses. The threshold of oscillation may then be deduced as

$$N_{min} = \frac{3h\bar{v}^2 (1 - R)}{8\pi^3 \mu_{21}^2} \qquad (4)$$

where $\bar{v}$ is the average molecular velocity in the beam, μ_{12} is the matrix element between states 1 and 2, and N is the number of molecules per second entering the resonator. For HCN we have $\bar{v} = 4.85 \times 10^4$ cm/sec, $\lambda = 3.38$ mm, $\mu_{21}^2 = 3 \times 10^{-36}$ stat. coul. cm^2, and $1 - R = 8.3 \times 10^{-4}$. Thus an HCN maser will have its threshold of oscillation when

$$N_{min} = 1.76 \times 10^{13} \text{ mols/sec.}$$

Similarly the minimum number of molecules required for detectable amplification with a given receiver sensitivity may be deduced. In general the hyperfine structure of the transitions must be considered when computing the number of molecules in a given state available from the source. Figure 5 shows such hyperfine structure in the HCN $J = 0 \rightarrow 1$ transition. In these calculations hyper fine structure has been neglected.

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[1] J. P. Gordon, H. J. Zieger, and C. H. Townes, "The Maser—New Type of Microwave Amplifier, Frequency Standard and Spectrometer," Phys. Rev. vol. 99, pp. 1264–1274.

[2] W. Culshaw, "Reflectors for a Microwave Fabry-Perot Interferometer," IRE Trans. on Microwave Theory and Techniques, vol. MTT-7, pp. 221–228; April 1959.

[3] W. Culshaw, "High Resolution Millimeter Wave Fabry-Perot Interferometer," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 182–189; March 1960.

[4] J. Munushian, "Electromagnetic Propagation Characteristics of Space Arrays of Aperture-In-Metal Discontinuities and Complementary Structures," University of California, Berkeley, Electronics Res. Lab. Rep., Ser. No. 60, Issue 126; September, 1954.

[5] N. Marcuvitz, "Waveguide Handbook," MIT Rad. Lab. Ser., McGraw-Hill Book Co., New York, pp 408–412; 1951.

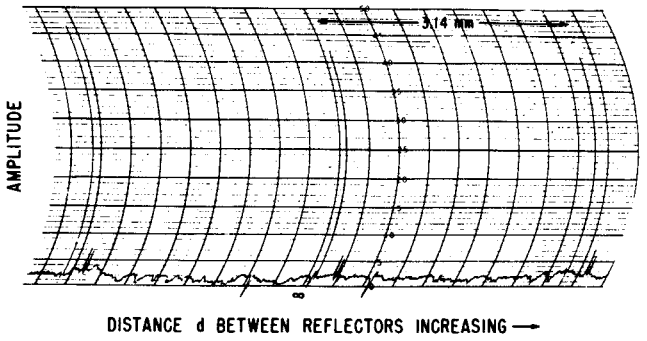

Figure 1 - Fringes Recorded on Microwave Fabry-Perot Interferometer Using Perforated Brass Plates as Reflectors

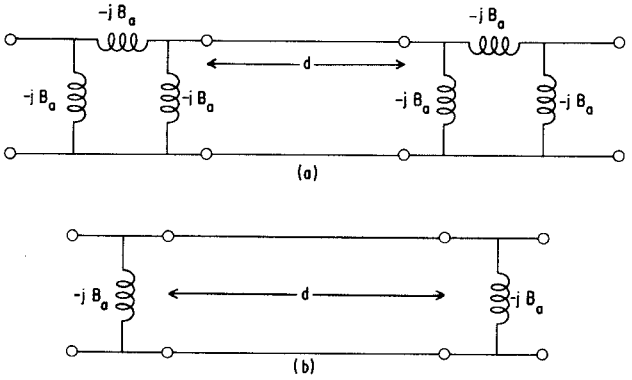

Figure 3 - Equivalent Circuits for Fabry-Perot Interferometer.
(a) Holes In A Thick Metal Plate
(b) Holes In A Thin Metallic Film

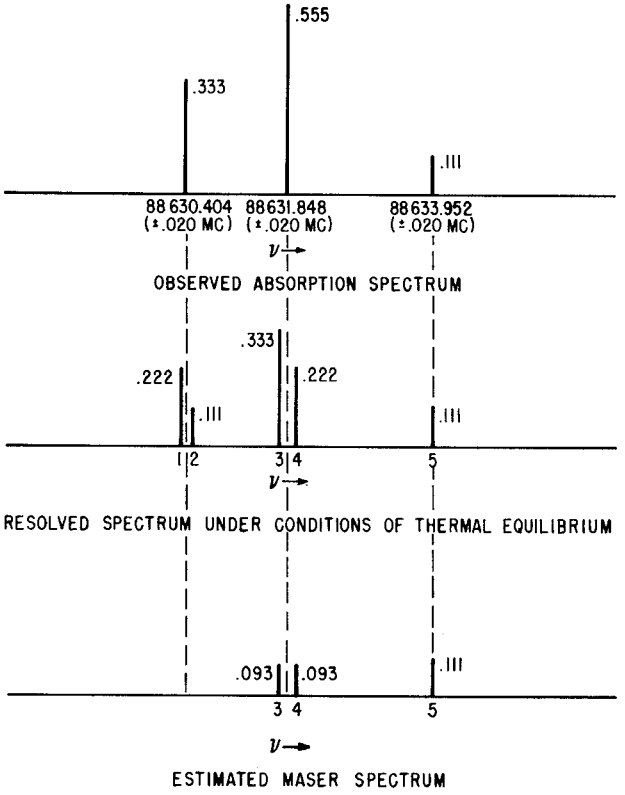

Figure 5 - $H^1\ C^{12}\ N^{14}$ J = 0→1 Transition Hyperfine Structure.

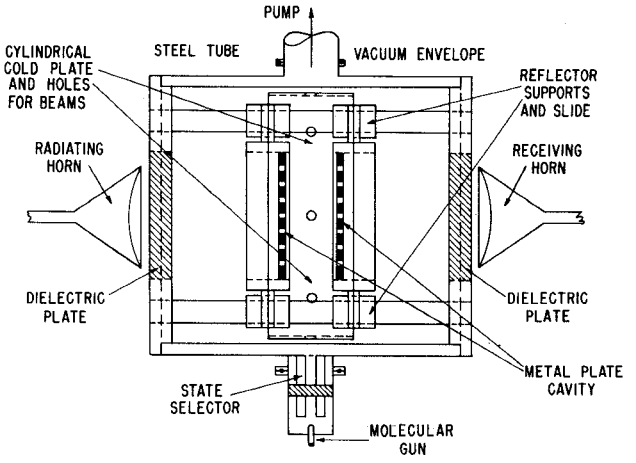

Figure 2 - Proposed Millimeter Wave Fabry-Perot Maser.

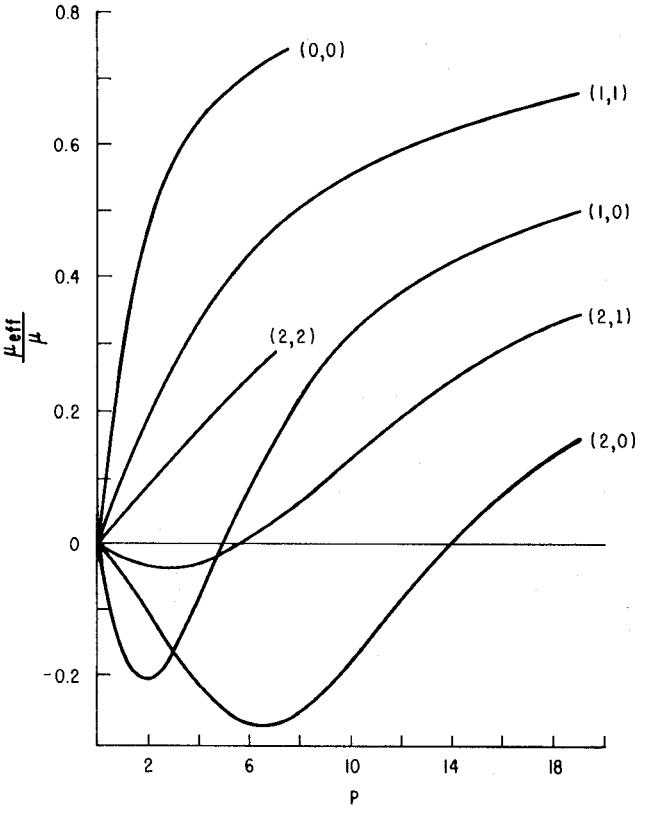

Figure 4 - Effective Electric Dipole Moment of A Rotating Linear Molecule In An Electric Field for States J = 1 and J = 0 . Hyperfine Interactions are Neglected.