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A 4-mm FABRY-PEROT MASER

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The shape of the experimental spectral line from a beam of active molecules is explained qualitatively for different oscillation modes by studying the field structure in a Fabry-Perot cavity resonator. A maximal excitation parameter is obtained when the mirror separation is $\lambda/2$ and the mode has a single maximum of the field E. The $1_{01} - 0_{00}$ transition of the CH_2O molecule was used for generation. The Stark effect for this transition is characterized by the fact that the application of an electric field only shifts the line frequency, without splitting or change of intensity. On this basis a maser can be designed which is tunable by the Stark effect to within $\sim 10^7$ cps.

BEAM-type masers with Fabry-Perot cavity resonators have appeared in recent years.[1-3] It is of interest to study the properties of these masers. We have investigated a 4-mm wavelength maser employing the $1_{01} - 0_{00}$ transition of the CH_2O molecule.

1. INVESTIGATION OF A FABRY-PEROT CAVITY RESONATOR

We used the Fabry-Perot cavity resonator that was described in [3]. The separation of the parallel mirrors was varied without affecting their parallelism. With separations close to $m\lambda/2$ (m is an integer) groups of resonances were observed, corresponding to different cavity modes. It is very important to know the mode in the resonator of a beam-type maser. We therefore developed a procedure for monitoring the mode.

The best instrument for investigating the microwave field structure in a cavity was found to be a half-wave dipole (~ 2 mm long) made of copper wire cemented to a hair stretched across a frame. With a klystron as the signal source and with the cavity coupled for transmission, the output signal was detected and a resonance curve was observed on an oscilloscope screen when the klystron frequency was varied. The dipole was inserted into the cavity and the induced changes were observed. The resonance pattern is not affected when the dipole is perpendicular to the electric field **E** in the cavity. When the dipole is parallel to E the resonance Q is reduced and the resonant frequency is shifted to an extent which increases with the strength of **E** at the location of the dipole. We can thus determine the number and locations of the field maxima in the cavity and the polarization of the oscillations.

The procedure for tuning the cavity was as follows. The mirrors were first brought close together and the gap between them was used to establish geometric parallelism. The separation was then increased to $\lambda/2$, and the resonances were used for further tuning. The electric paral-

lelism does not coincide with the geometric parallelism because of the disturbance introduced by the coupling elements, for example. The positions of the mirrors were adjusted by moving them apart in such a way that a large resonance maximum would appear without any preceding small resonances. The absence of preceding resonances was monitored accurately to within 1% of the magnitude of the first large resonance, which possesses the highest Q. When these conditions were fulfilled, this resonance for the smallest mirror separation corresponded to the simplest mode with a single maximum of E at the center between the mirrors. In this cavity mode E is polarized like the coupled waveguides (along the line connecting the waveguides).

The next resonance (at a greater separation) corresponds to two maxima of **E** on the diameter etc. An increase of the mirror separation by $m\lambda/2$ does not change the field structure and relative locations of the resonances, but only adds maxima in the direction perpendicular to the mirrors. These results correspond in general to the results obtained with another type of Fabry-Perot resonator, investigated in [4].

The Q of the simplest mode was ~ 2000, and the field was concentrated within a region of 3—4 cm. The Q of the resonances remained almost unchanged as the separation increased from $\lambda/2$ to 2λ. For the first three resonances Q was of a single order of magnitude. The type of coupling indicated above was found to be better than two other types which were tested. In one case coupling was effected by coupling waveguides to the side of the cavity with their broad sides parallel to the planes of the mirrors. This type of coupling was poor because of the large field distortion introduced by the waveguides (the mirrors had to be misaligned for the purpose of tuning), and also because coupling with our needed simplest mode could only be brought about through uncontrollable parasitic effects. The other type of coupling employed a single waveguide opening into the cavity at the center of a mirror. Because of the unavoidable asymmetry, this waveguide excited simultaneously the simplest mode of appropriate polarization and a degenerate mode with polarization differing by $\pi/2$.

By means of a dipole inserted into the cavity the displacement of the microwave maximum was observed. When the parallelism of the reflectors was imperfect within certain limits the mode and Q were not affected, but the position of the field maximum was shifted to correspond with the largest mirror separation. This also affected the coupling, because the microwave field strength at the waveguide aperture had changed. A change in the position of the field maximum within the cavity changes the location where maximum energy is transferred by molecules to the field when the cavity is used in a beam-type maser. This in turn changes the Doppler frequency shift due to the existence of microwave energy flow from the site of molecular energy transfer to the coupling hole. This effect must be taken into account whenever a maser is used as a frequency standard.

2. SPECTRAL LINE SHAPE WITH DIFFERENT CAVITY MODES

The interaction of the beam of active molecules with the cavity field in the cases of different modes was studied by means of the graphical method developed in [5],[1)] where it was shown that the state of a two-level molecule with the dipole moment μ, interacting with the field $E_0 \cos \omega t$, is described by the equation*

$$d\mathbf{r}/dt = [\Omega \mathbf{r}].$$

This equation represents the precession of the vector **r** about the direction of the vector Ω in a space having three coordinate axes labeled I, II, and III. The projection of **r** on axis III denotes the difference of the level populations. The projections of Ω on the axes are $\Omega_I = \mu_{12} E_0/\hbar$, $\Omega_{II} = 0$, and $\Omega_{III} = \omega_{12} - \omega$, where μ_{12} is the matrix element of the transition dipole moment and ω_{12} is the frequency of transition between the molecular levels.

At the instant when a molecule begins to interact with the field (upon entering the cavity) it is in its upper state; therefore at this instant **r** is parallel to axis III. If the field has a single maximum, the probability of a transition from the upper state to the lower state during the transit time τ through the cavity will obviously be greatest for $\omega = \omega_{12}$, with **r** rotating through the angle $\Omega_I \tau$ around axis I. If the field has two maxima differing in phase by π, at the instant when a molecule passes from one maximum to the other the projection Ω_I is reversed because E is then reversed. In this case, with $\omega = \omega_{12}$, in the time required for a molecule to traverse the first maximum the vector **r** rotates through the angle $\Omega_I \tau/2$ around the axis I, while during the transit of the second maximum it returns to its original

[1)] The present authors have calculated the spectral line shape in [6].

*$[\Omega \mathbf{r}] = \Omega \times \mathbf{r}$.

position. Therefore, when the signal frequency equals the transition frequency ω_{12}, the molecule will not radiate.

However, if the signal frequency differs somewhat from ω_{12}, r will not return exactly to its initial position, and the probability of a transition to the lower level during the transit time will not be zero. If $\Omega_{III} = \omega_1 - \omega$ is of such magnitude that during the time required for a molecule to traverse the first maximum r goes into the I—III plane, i.e., $\Omega\tau/2 = \pm\pi$, then during the transit of the second maximum the projection r_{III} will decrease and the probability of a molecular transition to its lower level during the transit time τ will reach its maximum. For a low signal strength the condition $\Omega\tau/2 = \pm\pi$ can be replaced by $(\tau/2)(\omega_{12} - \omega) = \pm\pi$; hence, $\omega = \omega_{12} \pm 2\pi/\tau$. Thus in this case we should observe splitting of the line into two components with the frequency separation $\Delta f = 2/\tau$. These components should be resolved, because the width of each one depends on the total time of interaction between a molecule and the field, and is of the order $1/\tau$. With an increasing number of field maxima in the cavity the separation of components will increase as n/τ, where n is the number of field maxima. It should be noted that for odd n a component having the frequency ω_{12} of the molecular transition will be observed, because in this case at the instant when the molecule leaves the cavity the vector r is inclined at the angle $\Omega_I\tau/n$ with respect to the axis III. With increasing n this effect will clearly diminish. A component having the frequency ω_{12} can also be induced by asymmetry of the field maxima or by a change of molecular beam intensity in passing from one field maximum to another.

Figure 1 shows photographs, on a single scale, of emission lines for different cavity modes. The line for the simplest mode, in Fig. 1a, has a width of about 15 kc, which agrees well with the size of the microwave field region. The split line in Fig. 1b corresponds to the mode with two field maxima. This type of line splitting evidently accounts for the "biharmonic" generation mode in a maser with a Fabry-Perot cavity, which was observed in [7]. We observed simultaneous increase of the excitation parameter for both components. With a sufficient number of active molecules generation of each of the split line components can evidently occur.

The interaction of a molecule with the microwave field in the traversal of two phase-related field regions in the cavity is essentially equivalent to the interaction in Ramsey's spaced field method [8], with the single difference that the length of the transit space is of the same order as the length of the region in which the microwave field is active. Indeed, with a suitable amplitude and phase distribution of the microwave field in the cavity along the molecular trajectory we can obtain the "interference" pattern of a spectral line (Fig. 1c) with a narrowed central maximum, which is characteristic of Ramsey's method. Calculated line shapes for different field phases have been thoroughly discussed in Ramsey's book. [8]

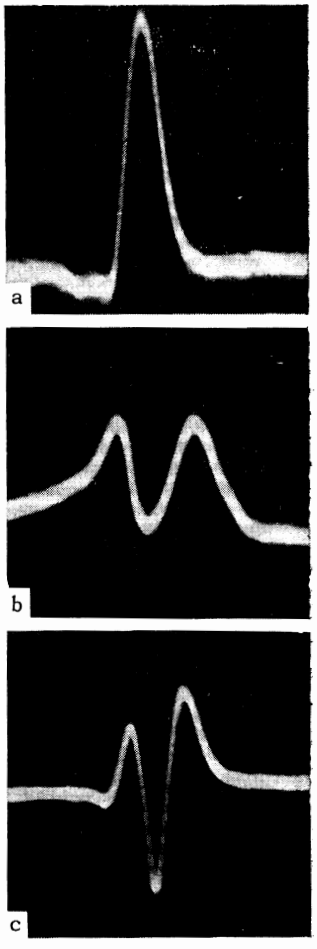

FIG. 1.

It is also of interest to consider the inverse problem—to determine the amplitude and phase distributions of the microwave field in the cavity from the shape of the spectral line observed when a molecular beam passes through the cavity. The direction of the beam in the cavity can be varied. This method of investigation could be useful in the millimeter wavelength range, where a direct investigation of the field by means of a probe, for example, could introduce unacceptable distortions.

3. STARK EFFECT IN THE $1_{01}-0_{00}$ TRANSITION

As we have already noted in [9], the Stark effect for the $1_{01}-0_{00}$ transition resembles the Stark effect in the J transition 1 – 0 of a linear molecule with $B_e = (B + C)/2$, where B_e, B, and C are, respectively, the rotational constants of the equivalent linear molecule and of the CH_2O molecule. It is thus possible to simplify the consideration of the corresponding theory. In the present work we find fulfillment of the condition $\chi = \mu E_d/hB_e \ll 1$, where μ is the dipole moment and E_d is the constant electric field. The levels here experience the quadratic Stark effect [10] shown in Fig. 2. The energy levels of a linear molecule in a field E_d are given by

$$\begin{aligned} \varepsilon &= -{}^1/_6\chi^2 + \ldots \quad \text{for } J = 0, M = 0, \\ \varepsilon &= 2 + {}^1/_{10}\chi^2 - \ldots \quad \text{for } J = 1, M = 0, \\ \varepsilon &= 2 - {}^1/_{20}\chi^2 + \ldots \quad \text{for } J = 1, M = \pm 1, \end{aligned} \tag{1}$$

where $\epsilon = W/hB_e$ and W is the energy level. When the asymmetry of the CH_2O molecule is taken into account, without changing the form of the dependence, only the coefficients of χ^2 are changed slightly.

Figure 2 shows that only a single Stark component corresponds to each of the transitions $\Delta M = 0$ and $\Delta M = +1$. When, moreover, we consider the total absence of fine structure in the $1_{01} - 0_{00}$ line, [9] we find that in a homogeneous field E_d the Stark effect in both types of transitions, $\Delta M = 0$ and $\Delta M = \pm 1$, results only in a frequency shift without change in the shape or intensity of the line.

The simplest mode was excited in the cavity with a single maximum of E on the diameter, the vector E being parallel to the mirror planes. The mirrors were insulated from each other and a constant voltage was applied between them. The separation was $\lambda/2 \sim 0.207$ cm and the field E_d was very homogeneous in the microwave field region. The field E_d was perpendicular to the microwave-field electric vector E and only transitions involving changes of the magnetic quantum number, $\Delta M = \pm 1$, were allowed. When the field E_d is applied the energy of the lower participating level with J = 0, M = 0 decreases more rapidly than that of the upper level with J = 1, M = ±1, and the frequency of the transition is shifted upward. The frequency change calculated from (1) as a function of the voltage applied to the cavity was $\Delta\nu = 104\ U^2$, with $\Delta\nu$ given in cps and U in volts. The dipole moment μ was taken to be 2.31 debye; [5] also, $(B + C)/2 = 36\,419$ Mc.

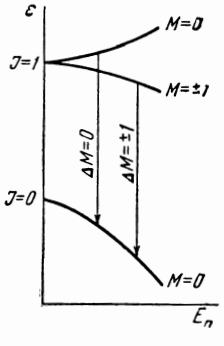

FIG. 2.

Upon application of the dc voltage the frequency of the line increased, without splitting and with almost no change of intensity. The experimental results are represented approximately by $\Delta\nu = 85\ U^2$, which agrees with the calculation to within 20%. With a voltage ~ 170 V, corresponding to ~ 3 Mc frequency shift, the line intensity decreased about 30% due to broadening resulting from inhomogeneity of the field E_d.

It is of interest to estimate the possible range of tunability of a line in a carefully designed cavity resonator. It is reasonable to require that the difference between the Stark frequency shifts in different parts of the cavity should not exceed the line width. Assuming the mirror separation to be accurate within 5×10^{-5} cm (possible in practice with sufficiently plane mirrors adjusted for parallelism directly from the line shape) along with other data from the present experiment, we obtain the maximum tuning range ~ 30 Mc.

The Stark effect is ordinarily employed to determine the dipole moments of molecules [11] or, if the dipole moment is known, to measure the voltage. We can expect that by using the properties of the Stark effect for the two participating levels to tune the maser frequency the accuracy of these measurements will be enhanced because the frequency change can be calculated more accurately.

4. OPTIMUM CONDITIONS FOR SELF-EXCITATION

In observing the emission line as a signal we used the ninth harmonic of the klystron, which was stabilized with a quartz oscillator and an automatic phase-control circuit. The crystal oscillator was modulated with a 50-cps frequency and the relative deviation $\Delta f/f \sim 10^{-6}$ in order to observe the spectral line. A 50-cps potential was also applied to the klystron reflector, leading to a periodic interruption of the automatic phase-control

circuit stabilization. The klystron frequency changed very abruptly; this was equivalent to a periodic switching-off of the signal. The spectral line on the oscilloscope screen was then accompanied by a step indicating the magnitude of the signal. A photograph of the oscilloscope screen is shown in [12]. In this way it was possible to monitor continuously the amplification coefficient K of an underexcited maser, i.e., the excitation parameter η [2)] related to K by the familiar formula $\eta = 1 - 1/K$.[13,14]

The experimentally measured excitation parameter for the simplest cavity mode with $\lambda/2$ mirror separation was about twice as large as for the next mode with two field maxima. Upon proceeding to higher modes the excitation parameter diminished until the line disappeared in noise. Using the same beam of active molecules, we measured the excitation parameter for the simplest mode with mirror separations $\lambda/2$ and λ. Doubling of the cavity volume reduced the excitation parameter one-half.

The foregoing results made possible the design of a maser with a Fabry-Perot resonator that possessed the highest excitation parameter. The mirror separation was $\lambda/2$, and the cavity was tuned to the simplest mode with a single field maximum. We used the sorting system previously proposed by one of the present authors,[15] which yielded a plane beam of active molecules. Generation was obtained with a single molecular beam source in the form of a tube of 0.6-mm diameter. It should be noted that the authors used the much weaker $1_{01} - 0_{00}$ transition of the CH_2O molecule, for which the product of the working level population by the squared matrix element of the transition dipole moment is about 35-40 times smaller than in the case of the $J = 1 \rightarrow 0$ transition of HCN and $J = 3$, $K = 3$ of NH_3, which were previously employed in masers with Fabry-Perot cavities.[1,2]

[2)] The conditon $\eta \geqslant 1$ governs the self-excitation regime of the maser.

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