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UDC 621.378.33

We report the frequency characteristics of a formaldehyde maser [1]. The experimental part of this research was completed during 1965-1966.

1. DEPENDENCE OF FREQUENCY OF THE H_2CO MASER ON ITS PARAMETERS

Two masers, using the $1_{01}-0_{00}$ transition in H_2CO (wavelength $\lambda \sim 4.1$ mm), were constructed. They can operate either in the single-beam or double-beam mode. A photograph of the apparatus with the vacuum chamber removed is shown in Fig. 1. The resonators can be tuned mechanically with the aid of a rod, and are thermostated to within 0.01° . A detailed description of formaldehyde masers is given, e.g., in [2]. The usual procedure was used to investigate the frequency characteristics of the masers (see e.g., [3]). The output of the two generators, decoupled by ferrite isolators and a waveguide T-junction, was fed into a superheterodyne receiver, and the difference frequency after the IFA was measured by a digital frequency meter. The parameters of one of the generators, regarded as the reference generator, were kept constant, whereas the parameters of the second could be varied and investigated. The frequency of the klystron heterodyne for the 4-mm range was stabilized against a quartz oscillator.

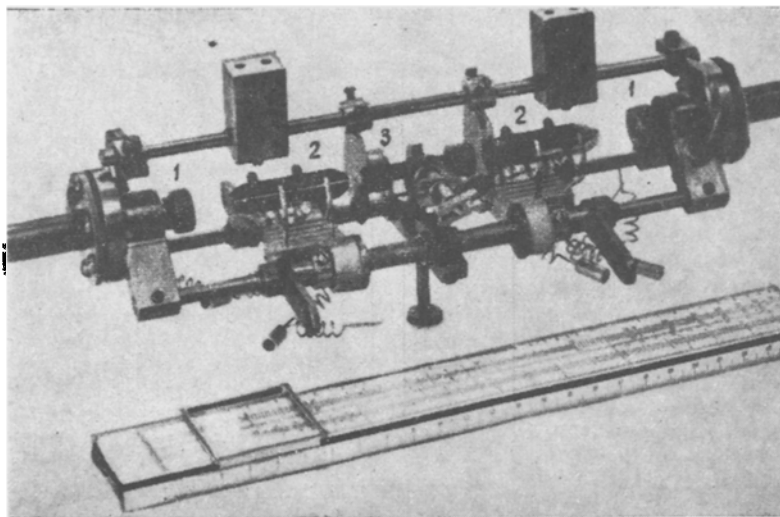


Fig. 1. Double-beam formaldehyde maser with vacuum system removed: 1) beam sources cooled down to $-60^\circ C$; 2) sorting quadrupoles; 3) E_{010} resonator.

Scientific-Research Radiophysical Institute, Gor'kii University. Translated from *Izvestiya VUZ. Radiofizika*, Vol. 12, No. 2, pp. 224-235, February, 1969. Original article submitted April 16, 1968.

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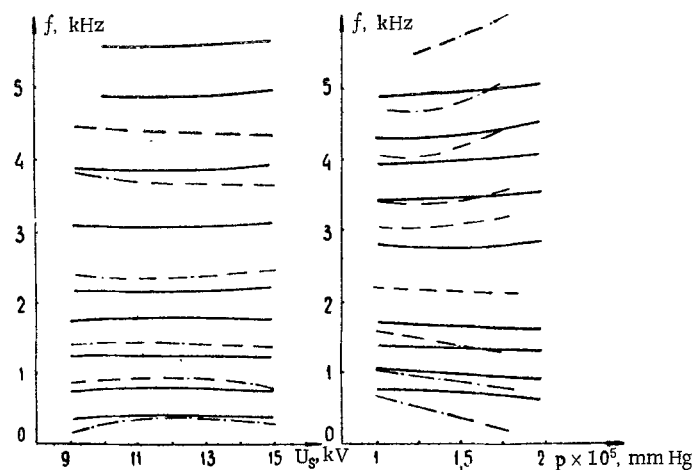


Fig. 2. Formaldehyde maser frequency as a function of the parameters. The continuous lines are for the double beam; the discontinuous lines denote the single beam.

To investigate the properties of the formaldehyde maser as a frequency standard, we measured the frequency of its oscillations as a function of the most important parameters, namely, the sorting field and the molecular-beam intensity (for different resonator settings). The frequency of the reference maser was kept constant to within 10–15 Hz during the measurements. The frequency characteristics were therefore recorded for a relatively large detuning of the resonator in order to ensure that the measured frequency shift was substantially greater than 10–15 Hz. The frequency was measured as a function of the beam intensity with a sorting field of 13 kV. The pressure in the working volume of the maser was used as a measure of the beam intensity.

The results shown in Fig. 2 are similar to the analogous results for ammonia masers using $J = 3$, $K = 2$, $N^{14}H_3$, or $J = 3$, $K = 3$, $N^{15}H_3$. In particular, there is no evidence for the complicated relations which are characteristic for masers using lines with unresolved fine structure ($J = 3$, $K = 3$, $N^{14}H_3$) [3].

The use of the double-beam system reduces the dependence of frequency on instrumental parameters because it tends to compensate the effect associated with nonuniform emission by molecules in the resonator. However, we then have the difficulty of balancing the beam intensities, which is greater than in the case of ammonia and is connected with the particular method used to produce the working material by thermal decomposition of the formaldehyde polymer. The decomposition process is not stable enough, and changes in the beam intensity which are effected by heating the polymer container are subject to considerable delay. In view of these difficulties, all the subsequent characteristics were determined under single-beam conditions. It follows that when we discuss the overall form of the characteristics we are really concerned only with the upper limit for the frequency instability of the formaldehyde maser.

The $1_{01}-0_{00}$ transition in H_2CO is characterized by the absence of fine structure and the fact that the maximum Stark energy of the upper level occurs for sorting fields that can readily be produced (~ 150 kV/cm). It follows that the dependence of frequency on the parameters, and especially on the sorting field, should be smaller than in the case of the ammonia maser [1, 2]. In fact, the experimental dependence of frequency on the sorting voltage has a flat region beginning at about 13 kV. With the resonator tuned to maximum power, the frequency of the oscillations is found to remain constant to within ± 10 Hz when the sorting voltage is varied from 12 to 14 kV.

For comparison, we recorded the characteristics of single-beam masers based on the $1_{01}-0_{00}$ and $J = 3$, $K = 3$ transitions in $N^{14}H_3$, using the same method. The H_2CO maser had a quadrupole and the NH_3 oscillator a sextupole sorting system. The beam source was a single capillary. Generation in H_2CO was produced with 5 kV across the sorting system, while in the case of NH_3 the voltage used was 10 kV. Generation in H_2CO was observed at pressures of $8 \cdot 10^{-6}$ – $4 \cdot 10^{-5}$ mm Hg and in NH_3 at pressures of $4 \cdot 10^{-6}$ – $8 \cdot 10^{-5}$ mm Hg. Maximum power was reached at $1.7 \cdot 10^{-5}$ and $2 \cdot 10^{-5}$ mm Hg, respectively.

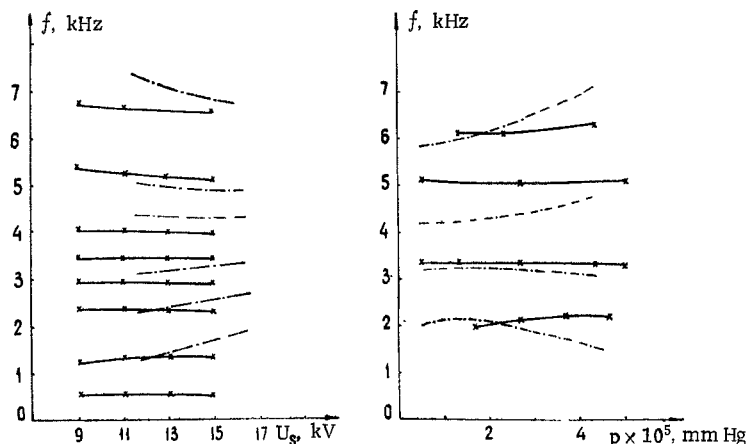


Fig. 3. Dependence of frequency on sorting voltage and pressure for the formaldehyde and ammonia masers. The continuous lines denote H_2CO ; the discontinuous lines denote NH_3 .

TABLE 1

	σ_p	σ_U
H_2CO	$3 \cdot 10^{-10}$	$7 \cdot 10^{-11}$
NH_3	$2 \cdot 10^{-10}$	$6 \cdot 10^{-10}$

The characteristics of the ammonia and formaldehyde masers were normalized to the same value at the point corresponding to maximum resonator power. The absolute value of the frequency deviation of the ammonia maser was multiplied by 3 (in accordance with the frequency difference between the generators) to retain the relative magnitude of the shift. The resulting families of characteristics are shown in Fig. 3 and indicate that the dependence of frequency on the parameters (especially the sorting voltage) is much less pronounced in the case of the formaldehyde maser.

We have also investigated the frequency reproducibility of both masers. Table 1 shows the root mean square variations in frequency for equal pressures in the vacuum chamber (σ_p) and equal voltages across the sorting system (σ_U). It is clear from the table that the frequency reproducibility when the voltage is varied is much better in the case of formaldehyde. The somewhat lower reproducibility of frequency with pressure is probably due to the difficulties mentioned above in producing given beam intensities.

2. MEASUREMENT OF THE FREQUENCY OF THE $1_{01}-0_{00}$ LINE OF H_2CO

The frequency corresponding to the $1_{01}-0_{00}$ transition in formaldehyde had been measured previously by various researchers, using a gas-cell spectroscope and a relatively broad spectral line, to an accuracy of the order of a few hundred kHz. According to [4], $\nu(1_{01}-0_{00}) = 72838.14$ MHz. In the case of the molecular-beam generator, the spectral line is very narrow and, by tuning the frequency of the self-oscillations of the generator to the center of the spectral line, we can increase the accuracy very substantially. During the frequency measurements the resonator of the molecular-beam generator was tuned to the center of the spectral line, using the maximum generator power, the molecular beam intensity also corresponded to the maximum generation power, and the voltage across the sorting system was 13 kV to within 1%.

During the measurements, the frequency of the reference quartz oscillator was kept at 1 MHz by comparing it with a standard frequency signal transmitted by radio. The frequency of the stabilized heterodyne klystron was equal to the 72,810th harmonic of the quartz oscillator. The oscillations of the tuned molecular generator were fed into a mixer together with the oscillations from the heterodyne. The difference frequency between the molecular generator and the heterodyne (~ 28 MHz) was measured by a counting frequency meter after preliminary amplification.

Measurements performed in this way showed that the transition frequency (on the UT-2, 1966, scale) was

$$\nu(1_{01}-0_{00}) = 72\,838\,338\,860 \text{ Hz} \quad (1)$$

to within a root mean square error of 290 Hz (this is an average over several dozen measurements). When the resultant error was calculated, we took into account the root mean square variation in frequency ($\sigma_f = 3.44 \cdot 10^{-9}$) connected with the detuning of the resonator, the uncertainty in the determination of the true value of the frequency ($\sigma_H = 2 \cdot 10^{-9}$), and the measurement uncertainty ($\sigma_m = 7 \cdot 10^{-10}$), as well as the root mean square variations in the frequency as a function of pressure and sorting voltage, mentioned above.

The final value for the transition frequency stated above enables us to improve the values for the rotational constants of formaldehyde. The rotational energy of the ground vibrational state of formaldehyde for a level J_{mn} , taking into account the centrifugal distortion, can be written in frequency units as follows [5, 8]:

$$W(J_{mn}) = \frac{1}{2} (A_0 + C_0) J(J+1) + \frac{1}{2} (A_0 - C_0) E_{mn}(\kappa) + \frac{1}{4} \sum_a \tau_{aaaa} P_a^4 + \frac{1}{4} \sum_{\alpha\beta} \tau_{\alpha\alpha\beta\beta} (P_\alpha^2 P_\beta^2 + P_\beta^2 P_\alpha^2) + \frac{1}{2} \tau_{baba} (P_b^2 P_a^2 + P_a^2 P_b^2), \quad (2)$$

where A_0 , B_0 , and C_0 are the rotational constants; a , b , and c are axes connected with the molecule; J is the rotational quantum number;

$$E_{mn}(\kappa) = \begin{cases} 0 & \text{for the } 0_{00} \text{ level,} \\ \kappa - 1 & \text{for the } 1_{01} \text{ level;} \end{cases} \quad (3)$$

$$\kappa = \frac{2B_0 - A_0 - C_0}{A_0 - C_0} \quad (4)$$

is the Ray asymmetry parameter; τ represents the components of the tensor characterizing the centrifugal distortion; P_q^2 is the square of the angular momentum along the q -axis and is given by

$$P_q^2 \simeq \frac{\partial W^0(J_{mn})}{\partial Q}, \quad (5)$$

and Q is the corresponding rotational constant. The quantity $E_{mn}(\kappa)$ is tabulated in [8].

For the transition $1_{01} - 0_{00}$ the above equations yield

$$\nu(1_{01} - 0_{00}) = B_0 + C_0 + \frac{1}{4} (\tau_{bbbb} + 2\tau_{bbcc} + \tau_{cccc}). \quad (6)$$

The values of the components of the tensor τ are as follows: $\tau_{bbbb} = -0.40331$ MHz, $\tau_{bbcc} = -0.29166$ MHz, $\tau_{cccc} = -0.23114$ MHz [6]. Unfortunately, the accuracy to which these quantities were determined is not indicated in [6]. However, these constants were used in [7] (for the transition $1_{10} - 1_{11}$) to show that

$$B_0 - C_0 = 4,832.13 \text{ MHz}, \quad (7)$$

to within ± 0.01 MHz, which gives an idea about the possible uncertainty.

Our measurements thus yield

$$B_0 + C_0 = 72,838.642 \text{ MHz}, \quad (8)$$

and if we combine Eqs. (7) and (8), we find that

$$\begin{aligned} B_0 &= 38,835.38 \text{ MHz,} \\ C_0 &= 34,003.26 \text{ MHz.} \end{aligned} \quad (9)$$

3. TUNING OF THE FORMALDEHYDE MASER

1. The frequency of the molecular generator is given by [3]

$$\nu = \nu_L \left[1 - \frac{Q_R}{Q_L} \frac{\nu_R - \nu_L}{\nu_L} G(U, \gamma_0) + \sum_i \Delta_i(U, \gamma_0) \right], \quad (10)$$

where ν_L , ν_R , Q_L , and Q_R are the frequency and Q factor of the line and the resonator, respectively, and $G(U, \gamma_0)$ and $\Delta(U, \gamma_0)$ are functions of the sorting voltage and the saturation parameter γ_0 , i.e., the generation power. The molecular generator is usually tuned until the frequency becomes independent of any particular parameter. This is achieved by modulating Q_L or $G(U, \gamma_0)$.

We have investigated the possibility of tuning the resonator of the formaldehyde maser by modulating the spectral-line Q with the magnetic field and by modulating the excitation parameter, i.e., $G(U, \gamma_0)$, by reorientation of the molecules in front of the resonator (the tuning properties can be judged from Figs. 2 and 3; it is clear that, because the frequency is not very dependent on the sorting voltage, this is not an effective tuning procedure).

2. Transitions involving reorientation of the molecules with $J = 0$, $|\Delta M| = 1$ have been used in radiospectroscopy in the electric resonance method [16]. In the formaldehyde maser with a sorted beam (occupying the upper level $J = 1$) the molecules can have a magnetic quantum number (component of J along the chosen axis) of $M = 0$ or $|M| = 1$. Only one of these groups can interact with the resonator field, i.e., radiate energy [11]. Reorientation of the molecules in the weak fields in front of the resonator may lead to a change in the statistical weights of molecules interacting and not interacting with the microwave field, and this may lead to a change in the excitation parameter at constant beam intensity. We emphasize that in the case of H_2CO , this effect will occur only for transitions with reorientation which correspond to $|\Delta M| = 1$ and, if the transition intensities corresponding to $M = +1$ and $M = -1$ are different, there will be a similar relation for the linear slope of the magnetic characteristics (see below).

The matrix element for transitions with reorientation $\Delta J = 0$, $|\Delta M| = 1$ is zero in this case if there is no electric field, i.e., for unperturbed wave functions. The electric field perturbs the wave functions, mixes them, and leads to the appearance of a matrix element for transitions between sublevels with different M.

Let us find the matrix element for the dipole moment of transitions between sublevels $M = 0$, $M = +1$, and $M = 0$, $M = -1$ of the level 1_{01} ($J = 1$, $K_{-1} = 0$, $K_{+1} = 1$; the index K_{-1} for H_2CO is very close to the number K for a symmetric top). Let us take the z axis along the constant field \vec{E}_z , which perturbs the levels and seek the perturbed wave functions in the form

$$\psi'(JM) = \sum_{ij} c(ij) \psi(ij), \quad (11)$$

where $\psi(ij)$ are the unperturbed wave functions and the coefficients $c(ij)$ are given by (to within second-order quantities) [12]

$$c(ij) = \frac{\langle ij | \hat{V} | JM \rangle}{W^0(JM) - W^0(ij)} \quad \text{for } ij \neq JM, \quad (12)$$

$$c(JM) = 1.$$

In these expressions the W^0 are the unperturbed level energies, and the perturbation $V = -d_z E_z$ is expressed in terms of the unperturbed matrix elements corresponding to $\Delta M = 0$. The unperturbed matrix elements of the dipole moment of the $JKM \rightarrow J'K'M'$ transition are given by

$$\langle JKM | \hat{d} | J'K'M' \rangle = d \Phi_{JJ'} \Phi_{JKJ'K'} \Phi_{JMM'}, \quad (13)$$

where d is the dipole moment of the molecule and the Φ are the matrix elements of the direction cosines. The values of these matrix elements are given in [13], Table 1.

TABLE 2

	$\Delta J = 0$ $M = 0 \leftrightarrow +1$	$\Delta J = 0$ $M = 0 \leftrightarrow -1$
d^+	0	$-i \frac{3\sqrt{2}}{10} \frac{d^2 E_-}{h(B_0 + C_0)}$
d^-	$-i \frac{3\sqrt{2}}{10} \frac{d^2 E_-}{h(B_0 + C_0)}$	0

Let us find the perturbed wave function for the level $J = 1$, $M = 0$. The nonzero matrix elements for the perturbation will be those between the level $J = 1$, $M = 0$ and the levels $J = 0$, $M = 0$ and $J = 2$, $M = 0$. Since

$$\begin{aligned} W^0(1_{01}) - W^0(0_{00}) &= h(B_0 + C_0), \\ W^0(2_{02}) - W^0(1_{01}) &\simeq 2h(B_0 + C_0), \end{aligned} \quad (14)$$

where h is Planck's constant, we obtain

$$\psi'(10) = \psi(10) - \frac{1}{\sqrt{3}} \frac{dE_-}{h(B_0 + C_0)} \psi(00) + \frac{1}{\sqrt{15}} \frac{dE_-}{h(B_0 + C_0)} \psi(20). \quad (15)$$

The state $J = 1$, $M = 1$ is connected through the transition $\Delta M = 0$ only with the state $J = 2$, $M = 1$. The corresponding perturbed wave function is

$$\psi'(11) = \psi(11) + \frac{1}{2\sqrt{5}} \frac{dE_-}{h(B_0 + C_0)} \psi(21). \quad (16)$$

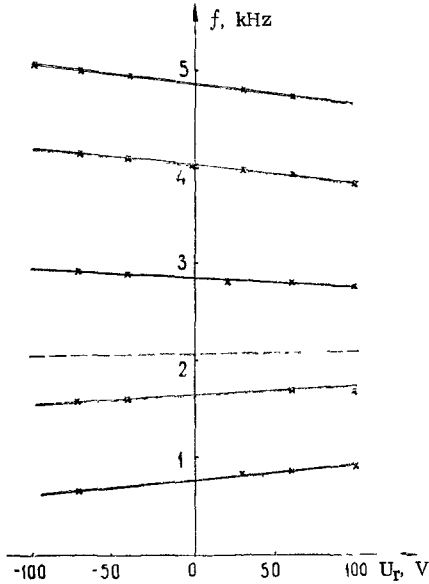


Fig. 4. Formaldehyde maser frequency as a function of the reorienting voltage U_r for different methods of tuning.

Using the definition of the matrix element and remembering that all the matrix elements in Eqs. (15) and (16) are real numbers, we find for the transition $J = 1$, $M = 0 \leftrightarrow J = 1$, $M = 1$ that

$$\begin{aligned} \langle 10 | \hat{d}_y | 11 \rangle &= \int \psi'^*(10) \hat{d}_y \psi'(11) dv \\ &= \frac{1}{2\sqrt{5}} \frac{dE_-}{h(B_0 + C_0)} \langle 10 | \hat{d}_y | 21 \rangle - \frac{1}{\sqrt{3}} \frac{dE_-}{h(B_0 + C_0)} \langle 00 | \hat{d}_y | 11 \rangle \\ &\quad + \frac{1}{\sqrt{15}} \frac{dE_-}{h(B_0 + C_0)} \langle 20 | \hat{d}_y | 11 \rangle. \end{aligned} \quad (17)$$

The matrix elements for the transitions $|\Delta J| = 1$, $|\Delta M| = 1$ are also given in [13], Table 1. Finally, substituting for the matrix elements in Eq. (17), we obtain

$$\langle 10 | \hat{d}_y | 11 \rangle = i \langle 10 | \hat{d}_x | 11 \rangle = \frac{3\sqrt{2} d^2 E_-}{20 h(B_0 + C_0)}, \quad (18)$$

which is identical with the results reported in [14] for $B_0 = C_0$ (linear molecule). For the transition $J = 1$, $M = 0 \leftrightarrow J = 1$, $M = -1$,

$$\langle 10 | \hat{d}_y | 1-1 \rangle = -i \langle 10 | \hat{d}_x | 1-1 \rangle = -\frac{3\sqrt{2} d^2 E_-}{20 h(B_0 + C_0)}. \quad (19)$$

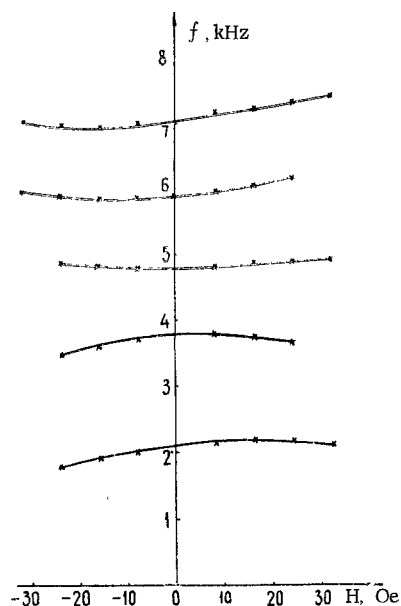


Fig. 5. Formaldehyde maser frequency as a function of the magnetic field H , applied at right angles to the resonator for different resonator settings.

The matrix elements for the corresponding transitions in the case of ammonia can be obtained in a similar way and have a similar structure. Such transitions will be induced by an alternating electric field E_{\perp} which oscillates or rotates in the xy plane, where the oscillating field (which can be represented by the sum of two fields of half the amplitude rotating in opposite directions) will induce both types of transition given by Eqs. (18) and (19) to an equal extent. Interaction with the rotating field can be described by a perturbation of the form

$$V = -\frac{1}{2} (d^{+} E_{\perp}^{-} + d^{-} E_{\perp}^{+}), \quad (20)$$

where $d^{\pm} = d_x \pm i d_y$; $E_{\perp}^{\pm} = E_{\perp x} \pm i E_{\perp y}$; and the terms $d^{+} E_{\perp}^{-}$ and $d^{-} E_{\perp}^{+}$ correspond to the interaction with fields rotating in opposite directions [12]. The matrix elements d^{\pm} obtained from Eqs. (18) and (19) are shown in Table 2.

It is clear from this table that a field rotating in a given direction will induce only one type of transition with reorientation of the molecules.

In our experiments E_{\perp} was the leakage field of the sorting system, whereas the field inducing the transitions was produced by a charged wire ring surrounding the sorted beam in front of the resonator [10]. The dependence of the generation frequency on the ring voltage for different settings of the resonator is shown in Fig. 4.

The characteristics shown in Fig. 4 indicate that this is a satisfactory method of tuning the formaldehyde maser. According to existing data on the ammonia maser, the frequency of the maser depends on the method used to tune it. This is also the case for the formaldehyde maser: the resonance point obtained by pressure tuning lies 1000 Hz below the frequency obtained by the reorientation method which, in turn, lies 300 Hz below the point obtained by the sorting voltage method (the position of these points is determined to within ± 150 Hz). We recall that the absolute width of the spectral line is greater by a factor of three as compared with the case of the ammonia maser and amounts to about 15-20 kHz [1].

3. The possibility of magnetic tuning in the formaldehyde maser is due to the fact that even the molecules in the $^1\Sigma$ state have a magnetic moment of the order of the nuclear magneton $\mu_J = \mu_n g_J J$ because of rotation [8]. Therefore, even for a resultant nuclear spin equal to zero, which occurs in the $1_{01} - 0_{00}$ case of H_2CO , the molecules still interact with the magnetic field. Let us determine the magnitude of this interaction. The Zeeman energy is

$$W_Z = -\mu_n g_J (JH) = \begin{cases} 0 & \text{for the } 0_{00} \text{ level,} \\ -\mu_n g_J M H & \text{for the } 1_{01} \text{ level,} \end{cases} \quad (21)$$

where $\mu_n = 762.3$ Hz/G is the nuclear magneton, M is the component of J in the direction of the magnetic field H , and g_J is the effective g factor in the rotational state under consideration and can be expressed in terms of the components of the g tensor as follows:

$$g_J = \frac{1}{2} \left\{ 1 + \frac{1}{J(J+1)} \left[E_{mn}(x) - (x+1) \frac{dE_{mn}(x)}{dx} \right] \right\} g_{aa} + \frac{1}{J(J+1)} \frac{dE_{mn}(x)}{dx} g_{bb} \\ + \frac{1}{2} \left\{ 1 - \frac{1}{J(J+1)} \left[E_{mn}(x) - (x-1) \frac{dE_{mn}(x)}{dx} \right] \right\} g_{cc}, \quad (22)$$

where $g_{aa} = -2.90$; $g_{bb} = -0.14$; $g_{cc} = -0.14$ [9, 19]. Using Eqs. (3) and (22) for the 1_{01} level, we obtain

$$g_J = \frac{1}{2} (g_{bb} + g_{cc}) = -0.14. \quad (23)$$

To modulate the linewidth, the magnetic field was applied, as usual, at right angles to the microwave electric field in the resonator, i.e., at right angles to the axis of the resonator in which the E_{010} oscillations were excited. By taking the z axis in the direction of the magnetic field, i.e., by characterizing the molecules by the projection M of J along the magnetic field, we find from the usual selection rules that the microwave line corresponding to the $1_{01}-0_{00}$ transition in H_2CO is split by the magnetic field into two Zeeman components which correspond to the transitions $J = 1, M = 1 \rightarrow J = 0, M = 0$, and $J = 1, M = -1 \rightarrow J = 0, M = 0$. The frequencies of these transitions are shifted by

$$\Delta\nu_Z = \pm 107 H \text{ Hz}, \quad (24)$$

where H is in oersteds. This relation is much weaker (relative deviation of the frequency is smaller by about an order of magnitude) than in the case of ammonia, for which $g \sim 0.5$. The experimental magnetic characteristics are shown in Fig. 5 and confirm our conclusions. In fact, fields up to 30 Oe have to be used for modulating the line Q , whereas, in the case of ammonia, fields of the order of a few oersteds are sufficient.

4. EFFECT OF REORIENTATION OF THE MOLECULES ON THE MAGNETIC TUNING OF MASERS

A maser using the $1_{01}-0_{00}$ transition in formaldehyde is a very convenient instrument for elucidating a number of general problems in maser physics because of the very exceptional simplicity of the transition. For example, this device has been used to elucidate beam-sorting processes and molecular orientation in the sorted beam [11]. We describe below one further investigation which has been carried out with the aid of this maser.

It is clear from Fig. 5 that the magnetic tuning curves have both a quadratic and a linear dependence of frequency on the magnetic field applied to the resonator, just as in the case of ammonia [17, 18]. The presence of the linear dependence reduces the tuning accuracy and, consequently, the stability of the maser since the position of the line center is then uncertain. The quadratic dependence is obtained as a result of the increase in the spectral linewidth in the resonator [3] for equal Zeeman component intensity. The linear dependence, on the other hand, indicates that the Zeeman component intensities are unequal, i.e., the center of gravity of the line has been shifted by the magnetic field.

Unequal intensity of the Zeeman components may be due to unequal population of the $J = 1, M = +1$, and $J = 1, M = -1$ levels at entry into the resonator. Again, unequal population of levels differing by the sign of M may be a result of a reorientation of the molecules in the sorted beam which, in principle, can produce separate induction of transitions from levels differing by the sign of M (see [15] and our Table 2). Experimental studies of the linear dependence show that the difference between the Zeeman component intensities is very small ($\sim 0.01-0.001$). If we assume that a small difference in the populations of the Zeeman sublevels is produced by reorientation processes which have somewhat different intensities for levels with different sign of M , then in the case of the formaldehyde maser the transitions between $M = 0$ and $M = \pm 1$ sublevels of the $J = 1$ level will determine both the generation power and the slope of the magnetic characteristics. In this case, the form of the dependence of the generation power and the slope of the characteristics on the reorienting voltage (periodicity, position of extremum) should be the same. We note that, in the case of ammonia, the effects corresponding to different values of M ($M = 0, 1, 2, 3$) are superimposed and there is no simple relation between the excitation parameter and the slope of the characteristics.

In the course of our experiments with the formaldehyde maser, we recorded the generation power and slope of the magnetic tuning characteristics as functions of the reorienting voltage U_r . The position of the minimum on this curve has enabled us to determine the slope α of the characteristics.

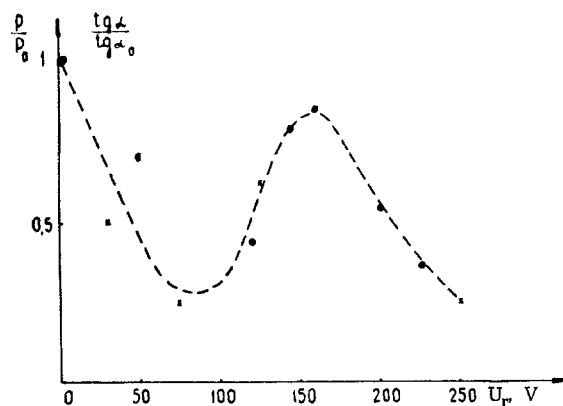


Fig. 6. Normalized curves showing the generated power (dots) and the slope of the magnetic tuning characteristics (crosses) as functions of the reorienting field U_r .

Some slope is present even for $U_r = 0$. The relative variation in this slope with U_r is shown in Fig. 6 together with the normalized dependence of the generated power as a function of the voltage. The fact that the two curves coincide confirms the reality of the proposed mechanism for producing unequal intensities of the Zeeman components by the reorientation process.

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