BRIEF COMMUNICATIONS AND LETTERS TO THE EDITORS

INCREASING THE BEAM LENGTH IN MOLECULAR OSCILLATORS WITH SPACED CAVITIES

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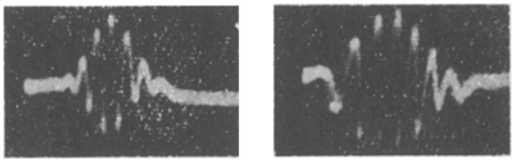
One of the trends in maser development is the narrowing of their initial spectral line by increasing the beam length. As a rule, one uses the Ramsey setup with two spaced cavities, which has been the subject of a number of investigations, both theoretical and experimental [1-5]. Success in this direction will depend on the ability to increase substantially the length of the beam of active molecules (by, say, an order of magnitude in comparison with the usual cavity length of 8-10 cm) while retaining sufficient intensity to excite self-oscillations. A typical figure for the spacing between cavities achieved to date is 15 cm (see [3-5]).



a) b)

Fig. 1. Ramsey-type radiation line in a two-cavity molecular oscillator. The frequency scale of the two photographs is different: a) distance between cavities 0.5 m, width of each maximum 700 cps; b) distance between cavities 1 m, width of each maxima 350 cps.

The present paper invesitages a number of practical methods of substantially increasing the beam length (i.e., means of increasing the Q of the line).

1. Various system versions for generating a long beam of active molecules were investigated. A natural criterion for assessing their efficiency is the maximum distance between the state selector and the cavity, compatible with achieving self-excitation. The molecular oscillator used in the experiments operated on the (J = 3, K = 3)-transition in $N^{14}H_3$. The beam source was a channel 0.15 mm in diameter and of length equal to the diameter. Facilities were provided for displacing the beam source with respect to all three axes without having to switch off the oscillator. Ammonia was purified by recrystallization in a vacuum. The best state selector was found to be one of the ring type of 100-mm length, 6-mm diameter, and 3-mm distance between adjacent rings. Between state selector and cavity there was a cold diaphragm whose aperture had the same diameter as the state-selector ring. The cavity, resonating in the E_{010}-mode, was 100 mm in length and has a Q of about 9000. With such a setup self-oscillation was obtained for a distance between state selector and cavity of up to 70 cm. The corresponding optimum distance between beam source and state selector was equal to 19 mm, and a decrease in this distance caused a more drastic reduction in the excitation parameter than did an increase. A 0.5-mm deviation of the beam source from the state-selector axis approximately halved the excitation parameter. This is evidence of the inadvisability of increasing the beam diameter, since molecules leaving the periphery of a broad source will not reach the cavity but will only increase collisions in the beam.

The results obtained confirm the conclusions reached in [6] as to the value of using point sources for the beam, as well as ring-type state selectors having an azimuth-independent field to facilitate the absence of "azimuthal aberrations" in the active molecular beam generated. Quadrupole systems gave the worst results and were not investigated in any great detail. The excitation parameter was found to depend little on the state-selector dimensions, and the advisability of reducing the system diameter and length, as recommended in [6], was not confirmed. For example, with a ring-type state selector of 3.5-mm diameter and 40-mm length we obtained self-oscillation for a distance of 50 cm between state selector and cavity with a signal-to-noise ratio of about 50, and at a distance of 42 cm with a ring-type state selector of 2-mm diameter and 17-mm length. The distance between rings was equal to the ring radius in these systems.

We also observed the Ramsey-shape molecular ratiation line. To do this, a cavity of 1-cm length (designed for the E_{010}-mode) was placed immediately beyond the state selector and was coupled by a waveguide to a second cavity. The radiation line in these cavities was observed by the usual method. Figures 1a and b show photographs of the spectral line for a spacing between cavities of 50 and 100 cm, with a width of the individual maxima of the order of 700 cps and 350 cps, respectively. By comparing the theoretical shape of the line for a Maxwellian velocity distribution in [7] with Figs. 1a and b, it can be seen that we have observed a considerably larger number of interference maxima. This may be attributed both to focusing, in the distant cavity, of molecules in a narrow velocity range, and to the superposition of the interference patterns of two components of the 3-3 line.

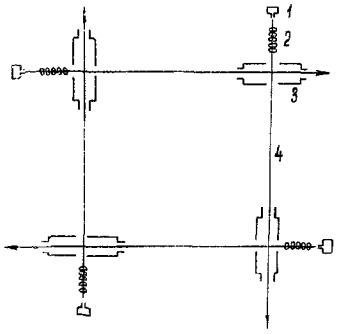


Fig. 2. Four-beam maser configuration: 1) beam source; 2) state selector; 3) cavity; 4) molecular beam.

The first hypothesis is not confirmed by data of [14], where the shape of the single spectral line was found to be close to the theoretical one for approximately the same parameters of the experimental setup. On the other hand, the second hypothesis agrees with results of this paper where the cavities had to be spaced by one meter in order to resolve the satellites of the J = 3 K = 2 ammonia line that are found at 3-kc frequency separation and have nearly the same intensity; the corresponding width of an individual Ramsey's maximum was equal to 350 cps. In our case, from data of [8], the J = 3, K = 3 ammonia line in the state-selected beam consisted practically of two components of approximately equal intensity separated in frequency by little more than half the frequency separation of the satellites of the J = 3, K = 2 line, namely, 1600 ± 400 cps. Using the experimental shape of the line obtained in [14], we can plot the expected profile of the J = 3, K = 3 line for 1-m spacing between the cavities. Such a profile is in good agreement with the experimental line of Fig. 1. To resolve the components of the line completely, the spacing of the cavities should be increased to approximately 2 m.

It seems premature to conclude, as in [1], that a partial resolution of the structure can be obtained with a cavity spacing of approximately 30 cm. The asymmetry of the oscillator's amplitude-frequency characteristics, on which such a conclusion was based, could have been caused by technological factors.

By using 50-cm spacing of the cavities, self-oscillations were obtained with approximately the same ease in either only the first or only the second cavity (first and second with respect to the beam), by suitably tuning them. The Q's of the cavities approximately the same, and the length of the first cavity was one-tenth of that of the second. Therefore, the excitation of the first cavity required 10 times more active molecules, from which we can infer the value $\chi = 0.1$ for the beam attenuation between cavities.

2. To increase the resolving power of a Ramsey-type beam maser, use can be made of the phase-transfer principle of RF oscillations from one molecular beam to another [10]. Proceeding from these considerations an experiment was undertaken where the first cavity of a Ramsey setup was an ordinary long cavity designed for the E_{010}-mode, mounted "across the beam." The beam was admitted via coupling apertures of the cavity; thus, we could be certain of retaining the initial oscillation mode. We suceeded in inducing transitions by the field of such a cavity; with 42-cm spacing between the cavities a Ramsey-shaped line was observed with approximately the same inducing-signal power as with the above-described short cavity tuned to the E_{010}-mode. In [9] an experiment is described in which the first cavity operated in the E_{010}-mode and the second in the H_{011}-mode, the first-cavity oscillations inducing no "ringing" in the second. Our result shows that this is not a consequence of the orthogonality of the E fields in the cavities. Note, however, that approximately the same interaction of the beam with the crossed fields of the cavities occurs merely because of the large set of M-numbers in ammonia. A quite different interaction may be expected in the case of formaldyhyde [11].

The possibility of such a double utilization of the cavities suggests a convenient four-beam maser configuration (Fig. 2). Data of the present investigation indicate that such a system could operate with an effective beam length of the order of 2-3 m, corresponding to a linewidth of about 150 cps.

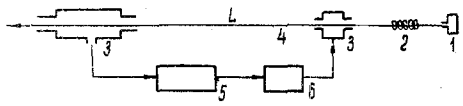


Fig. 3. Oscillator circuit using a narrow "molecular-ringing" line as a feedback element: 1) beam source; 2) state selector; 3) cavity; 4) beam; 5) amplifier; 6) phase shifter.

3. The maximum beam length in Ramsey-type molecular oscillators is limited by the distance at which the self-excitation condition can be satisfied. This limitation can be removed by including an amplifier in a beam maser (as shown in Fig. 3) and utilizing the "molecular-ringing" effect for transmitting the feedback signal from output to input of the amplifier. Such a setup is similar to that suggested in [12], except for the fact that in [12] it is proposed to use it to produce population inversion in a laser, whereas in our case the beam, already state-selected and coupling the two cavities, plays the part of a selective feedback element. A source of instability in such a circuit will be phase fluctuations in the amplifier channel. For a phase drift of the amplified signal by $\Delta\varphi$ the oscillation-frequency change $\Delta\nu$ will be of the order of $\Delta\nu \simeq \Delta F \Delta\varphi/\pi$, where $\Delta F \simeq 0.6/T$ is the spectral linewidth. The phase excursion in the amplifier (whose bandwidth is practically always much larger than the linewidth) may be stabilized, for example, be means of an auxiliary signal displaced in frequency beyond the limits of the spectral line. The auxiliary signal passing through the amplifier should beat with the reference signal transmitted along the wave guide, and the detected voltage—a function of the phase difference of the signals—could be used to control the phase excursion in the amplifier channel.

We investigated a similar system, where amplified "molecular-ringing" oscillations were obtained by means of automatic phase control of a klystron by "molecular ringing" (the apparatus described in [13] was used). The presence of considerable phase drift in the automatic phase-control system greatly restricts the long-term frequency stability of the oscillations in such a system. It was therefore employed solely to verify the feasibility of the system in principle, and to measure some of its characteristics. Reliable locking of the circuit was obtained, and sinusoidal beats with the signal of the auxiliary molecular oscillator were observed. The oscillation frequency was measured as a function of the retuning of the cavity where "molecular ringing" was obtained.* The rate of retuning by means of the stub tuner is shown in the table for various values of the spacing between cavities. The rate of retuning of an ordinary molecular oscillator with the same cavity was equal to 200 cps per 0.01 mm.

Spacing between cavities, L(cm)	1	10	50
Rate of retuning (cps per 0.01 mm)	50	14	5.5

Note added in proof. To date, a radiation line has been observed with 2-m spacing between cavities. It has been fully resolved into two components separated by 1586 ± 80 cps.

*In the presence of an amplifier, the first cavity need neither be long nor have a high Q, so that the effect of parameter variations on the oscillation frequency can be made very small.

REFERENCES

1. F. Holuj, H. Daams, and S. N. Kalra, J. Appl. Phys., **33**, 2370, 1962.

2. E. M. Belenov and A. N. Oraevskii, Radiotekhnika i elektronika, **8**, 158, 1963.

3. A. F. Mukhamedgalieva and G. M. Strakhovskii, Izv. VUZ. Radiofizika [Soviet Radiophysics], **8**, 824, 1965.

4. A. F. Mukhamedgalieva, A. N. Oraevskii, and G. M. Strakhovskii, Pis'ma v redaktsiyu ZhETF, **1**, 22, 1965.

5. V. S. Kazachov, Izv. VUZ. Radiofizika [Soviet Radiophysics], **9**, 620, 1966.

6. G. Becker, Zs. angew, Phys., **15**, 281, 1963.

7. N. Ramsey, Molecular Beams [Russian translation], IL, Moscow, 1960.

8. K. Shimoda, J. Phys. Soc. Japan, **12**, 1006, 1957; J. P. Gordon, Phys. Rev., **99**, 1253, 1955.

9. A. N. Oraevskii, Molecular Oscillators [in Russian], izd. Nauka, Moscow, 1964.

10. G. L. Suchkin, Author's Certificate no. 155 240, with priority from 1960.

11. A. F. Krupnov and V. A. Skvortsov, Radiotekhnika i elektronika, **10**, 378, 1965.

12. N. G. Basov and V. S. Letokhov, Pis'ma v redaktsiyu ZhETF, **2**, 6, 1965.

13. L. N. Bershtein, Yu. A. Dryagin, and V. L. Sibiryakov, Izv. VUZ. Radiofizika, **2**, 130, 1959.

14. S. G. Kukolich, Phys. Rev., **138**, A1322, 1965.

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