A RADIOSPECTROSCOPE WITH ACOUSTIC DISPLAY FOR THE MILLIMETER AND SUBMILLIMETER RANGES

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Thermal acoustic (or pneumatic) receivers proposed by Golay [1] are extensively used in the infrared and submillimeter ranges of the spectrum. Veingerov [2] proposed a version of such a receiver in which the radiation is absorbed directly in a gas having the corresponding absorption lines; this allows the presence of a specific gas to be detected. However, as far as we know, the principle of acoustic reception has not been used in radiospectroscopy (i.e., for the investigation of the microwave absorption spectrum of a gas filling the receiver cell by means of a monochromatic frequency-tunable signal). Such a radiospectroscope was constructed by us and tested in the $\lambda = 2.4$–0.5 mm range. In the present note we report the preliminary results of the investigation and consider certain advantages of a radiospectroscope having acoustic display.

The block diagram of our installation is displayed in Fig. 1. The radiation from the signal source 1 (a backward wave tube) [3] passes through a Teflon cell transparent to the radiation and $L = 10$ cm long which is filled with the investigated gas. The frequency of the backward wave tube can be tuned in the required range. For coincidence of the radiation frequency with the frequency of the spectral line the gas in the cell absorbs a power

$$P = P_0[1 - \exp(-\gamma L)] \simeq \gamma L P_0 \qquad (\gamma L \ll 1), \tag{1}$$

where P_0 is the incident power, γ is the absorption coefficient of the line.

The side wall of the cell is the membrane of the capacitor microphone 3. The absorbed power heats the gas which expands and bends the membrane, thus creating a signal that is amplified by the amplifier 4. As usual, the constant component of the pressure against the membrane is eliminated by connecting the cavity under the membrane to the main cell via a thin channel, while the source radiation is modulated. The spectral lines were observed either on the screen of an oscilloscope 6 for modulation of the backward wave tube by frequency wobbling at a frequency of 50 Hz, or they were recorded on the tape of an automatic recorder 8. In the latter case the frequency of the backward wave tube was keyed by means of a relay 5 having a frequency of 180 Hz and a deviation that was larger than the width of a line; it was also simultaneously tuned slowly by means of a motor. After synchronous detection by the detector 7, the signal was recorded on the tape of the automatic recorder. Figure 2 displays the recording of the 2_2-3_{-2} line of water H_2O^{16} ($\lambda = 1.6$ mm). The width of the line is approximately 600 MHz (pressure ~ 20 mm Hg), the backward wave tube power is of the order of tens of milliwatts, and the signal-to-noise ratio is about 1700 for an averaging time constant of approximately 1 sec. We also observe narrow lines of gas (width of the order of 1 MHz).

Note the features of such a radiospectroscope. The null character of the method is most essential; under these conditions the response of the system to the signal power is negligible outside the absorption line. Here the signal does not create additional noise outside the absorption line; moreover, the detection of the lines is not complicated by the presence on the screen of a large signal P_0 whose magnitude depends strongly on frequency due to the resonant properties of the microwave channel and the backward wave tube. This allows (as we were also convinced from the practical standpoint) easier detection of the absorption line than is possible with a conventional video radiospectroscope. Incidentally, it was clarified that the

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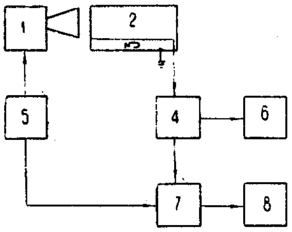

Fig. 1

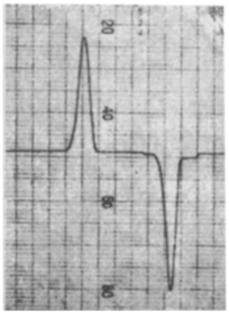

Fig. 2

steepest frequency dependences of the signal power are due to resonant properties of the channel, including the microwave detector; the power of the backward wave tube varies with frequency much more slowly. This fact, together with the null character of the method, made it possible to observe broad (in our experiments up to 600 MHz) spectral lines.

In the infrared range the frequency tunable signal is obtained by excising a sector of the continuum of the thermal radiation from a blackbody by means of the appropriate monochromator [2]. The low spectral density of the thermal radiation power limits the sensitivity of the spectroscope and makes it impossible to observe narrow spectral lines. Therefore, an acoustic receiver [2] is used basically as a convenient indicator of the resultant absorption in broad vibrational-rotational bands of various molecules (a "gas analyzer"). The position in the radio range, where sources of coherent radiation having a very high spectral power density exist which are frequency-tunable, is essential. The possibility of observing broad lines and the null character of the method facilitate the detection of low values of absorption by increasing the power of the signal that transilluminates the cell. As is well known, the power required to saturate a spectral line increases quadratically with the width of the line [4].

Let us perform estimates of the allowable (without saturation of the line) signal power for a cell cross-section area of 1 cm^2 and a dipole moment of the molecule of the order of 1 debye. If for a line width $\Delta\nu = 1$ MHz the power of the transilluminating signal is limited to a value of the order of 10 mW, it follows that for $\Delta\nu = 100$ MHz the allowable power has already increased to 100 W, while for $\Delta\nu = 3000$ MHz (of the order of the width of the lines in the atmosphere) the power has risen to 100 kW.* Under these conditions (at least in principle) the noise of the receiver must not change, while the magnitude of the signal (1) increases with a growth of the power P_0.

The limiting power sensitivity of an acoustic receiver must be determined by thermal fluctuations of the gas [1, 2]. We shall present the appropriate estimates. For fluctuations of the gas temperature we have [6]

$$\sqrt{\overline{\Delta T_f^2}} \simeq T/\sqrt{N}, \tag{2}$$

where $\sqrt{\overline{\Delta T_f^2}}$ is the mean-square value of the fluctuations; T is the temperature; N is the number of gas particles in the cell. The temperature elevation of the gas during its absorption of the power P in the quasistatic mode is conveniently written in the form

$$\Delta T_s \simeq P\tau_0/C. \tag{3}$$

Here $C \simeq Nk$ is the specific heat of the gas; $\tau_0 \sim C/G$ is the time constant of the thermal processes in the gas (the time constant of the cell); $G \sim l\varkappa$ is the thermal conductivity of the gas; l is the characteristic (least) cell dimension; $\varkappa$ is the coefficient of thermal conductivity; k is Boltzmann's constant. Setting (2) and (3) equal to one another, we have

$$P_{\min} \simeq \frac{kT}{\tau_0}\sqrt{N} \tag{4}$$

for the threshold power.

*Such values of power are now attainable in the millimeter–submillimeter range [5].

Equations (3), (4) are conveniently written in terms of the time constants τ_0 of the cell because the choice of the quantity τ_0 turns out to be fairly rigorously constrained from the practical standpoint: from the bottom it is constrained by reasonable dimensions of the cell and by the gas pressures, while from above it is constrained by the low-frequency noise of the equipment (of the flicker-noise type) which prevents the increase in sensitivity by increasing τ_0 (and consequently the modulation period). Most frequently τ_0 is chosen to be about 10^{-2} sec. Substituting $kT \simeq 4 \cdot 10^{-21}$ W, $N \simeq 10^{19}$, $\tau_0 \simeq 5 \cdot 10^{-3}$ sec, we have $P_{min} \simeq 3 \cdot 10^{-10}$ W. This is the order of magnitude of the sensitivity of well-designed Golay receivers [1].

From (1) we have the following relationship under these conditions for the minimum detectable absorption coefficient (for L = 10 cm and P_0 in watts):

$$\gamma_{min}\ (\mathrm{cm}^{-1}) \simeq 3 \cdot 10^{-11}/P_0. \tag{5}$$

In the best radiospectroscopes $\gamma_{min} \simeq 3 \cdot 10^{-9}\ \mathrm{cm}^{-1}$ has been achieved in the centimeter range [8]. The estimates presented show that this sensitivity may be exceeded in a null radiospectroscope having acoustic display for the appropriate choice of P_0. The noise may be nonresonant absorption (for example, in the walls of the cell if the oscillator power depends on frequency).

In our first prototype the practical sensitivity was considerably lower than the limiting value ($\sim 10^{-6}$ W), basically due to the nonoptimal construction of the microphone that had a low sensitivity and was subject to vibrations. Correspondingly, for a single pass of the power from the backward wave tube available to us through the cell the minimal detectable absorption coefficient varied from $5 \cdot 10^{-6}\ \mathrm{cm}^{-1}$ in the 150 to 280 GHz range to $10^{-4}\ \mathrm{cm}^{-1}$ in the 360 to 570 GHz range.* Thus, considerable reserves are available here.

Note, however, that the sensitivity obtained exceeds by at least one order the sensitivity of existing radiospectroscopes in this range [7]. Thus, for spectroscopy of water vapors we observe, besides lines of ordinary water H_2O^{16}, lines of its isotopic variety H_2O^{18} and HDO in natural concentration ($2 \cdot 10^{-3}$ for H_2O^{18} and $2 \cdot 10^{-4}$ for HDO). On the $1_{10}-1_{01}$ transition of H_2O^{16}, however, ($\lambda \simeq 0.54$ mm) a signal-to-noise ratio of approximately $9 \cdot 10^3$ was obtained; this makes it possible to use such a radiospectroscope for frequency stabilization. Note also that the small dimensions of the cell (in our case a volume $\sim 20\ \mathrm{cm}^3$) facilitates an investigation of unstable molecules; the variation of the gas temperature, for example, likewise does so.

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Note During Editing. An analogous situation – a large signal power and a very small absorption coefficient – holds, for example, in the observation of narrow saturation resonances in CO_2 which is irradiated by a CO_2 laser [9, 10]. Here the null acoustic display method may evidently likewise be advantageous.

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*An increase in the signal may be achieved by multiple passage of radiation through the cell (for example, by placing it into the cavity resonator).