remarks apply to the three-level, solid-state maser.

Although further development of these resonators is required, such developments appear feasible in contrast to the present difficulties in applying conventional resonators to mm and sub-mm wavelengths. Such difficulties are very severe and most probably conventional resonators are impractical. There appears to be no reason why the ideas presented here should not be intensively pursued, as the rewards and knowledge to be gained from this virtually unexplored region of the electromagnetic spectrum are very great.

Note added in proof: The biconical spherical resonator has now been operated very satisfactorily by Dr. R. W. Zimmerer at wavelengths around 8 mm. The diameter of the sphere used was 4 inches, and the cone angle Ψ was 45°. Coupling holes after the manner described were used only in areas illuminated by the focused radiation. Both quarter-wavelength and half-wavelength resonances were observed and were the dominant ones. The Q value approaches the theoretical one, and higher mode effects are small.

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The author would like to acknowledge the assistance and encouragement derived from discussions with his colleagues, and in particular, with Dr. R. C. Mockler.

A Recording Microwave Spectrograph*

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Summary—**The principle of operation and the fundamentals of realization of a recording microwave spectrograph designed for use in the study of the absorption and the index of refraction of gases under medium pressures (1 mm Hg to 1 atm) are presented. The apparatus results from a similar spectrograph with synchroscope, in which the responses of the cavity resonators are interpreted by means of a pulse method. The high performances of the apparatus render its use advantageous, not only as a spectrograph, but also as an accurate recording refractometer, as well as a direct-reading *Q*-meter.**

I. INTRODUCTION

THE IDEA of the application of the pulse technique to microwave spectrographs with cavity resonators [12] was originally suggested in 1953 by Professor A. Gozzini of the University of Pisa (Italy) and his coworkers [2d]. Spectrographs of this type, although subject to continuous improvements, have been constructed in Pisa (Istituto di Fisica), in Paris (Laboratoire de Physique de l'Atmosphère) and in Amsterdam (Natuurkundig Laboratorium Universiteit). The new experimental setup has already been used successfully in various investigations [3]–[7].

The electronic indicator of this apparatus is an oscillograph used as a synchroscope. The result of the measurement is given by the relative positions of the pulses which appear on the screen of the synchroscope. In the following, we will refer to this apparatus as the "spectrograph with synchroscope."

The work described here makes use of this spectrograph to function as a recording instrument. As an output indicator, the synchroscope is replaced by an automatic recorder. The absorption coefficient or the index of refraction is recorded as a function of the pressure of the gas. The apparatus works, as does the previously mentioned spectrograph with synchroscope, in the centimetric (as well as in the millimetric) region of radio waves and is used in the study of gases under medium pressures (from about 1 mm Hg to 1 atm).

This function has been obtained through suitable modifications of the electronic parts of the instrument, especially those of the pulsers. The resulting recording spectrograph extends the possibilities of research in the field of microwave spectroscopy since it can also be used as a refractometer and as a *Q*-meter.

II. THE PRINCIPLE OF THE SPECTROGRAPH WITH SYNCHROSCOPE

The original spectrograph with synchroscope has been the subject of previous papers [2a], [5]. Briefly its principle is as follows.

The block diagram is shown in Fig. 1. The energy of the microwave source (a klystron) is frequency modulated by means of an isosceles triangular signal. The modulated energy is guided both to the channel of meas-

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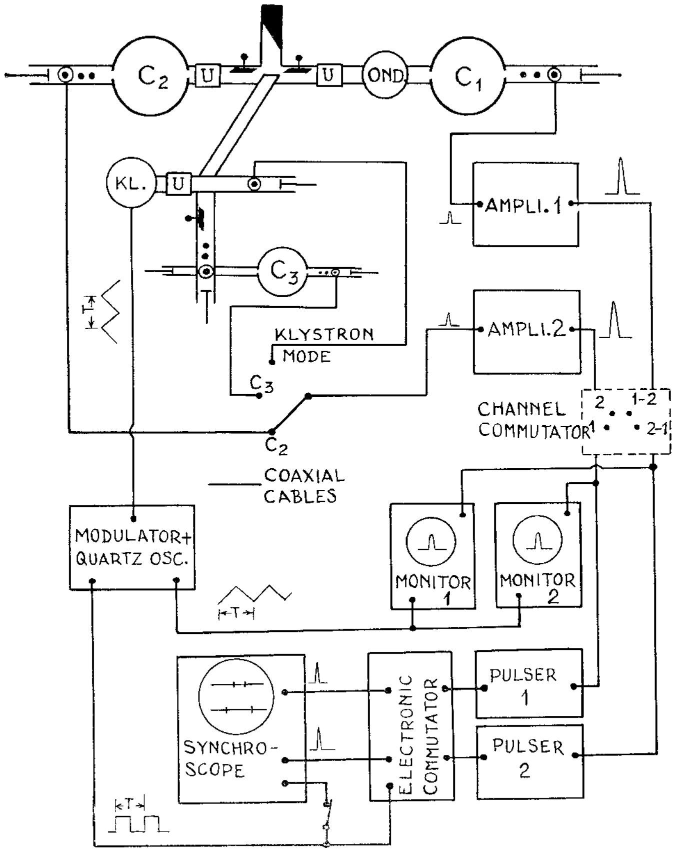

Fig. 1—Block diagram of the spectrograph with synchroscope.

urement and to the channel of reference of the apparatus. The resonance signals (responses) given by the cavity resonators are coupled to the inputs of the pulsers, after detection and amplification.

The pulse technique is used in order to mark, with the best possible accuracy and sensitivity, the relative position and the form of the response of the channel of measurement with respect to that of the channel of reference. This is achieved by the production of very narrow pulses in predetermined points of the response curves. This method is much more advantageous than any of the older methods of direct comparison.

The theory of the apparatus proves that the distances of the pulses appearing on the synchroscope are related, by simple relations, to the index of refraction and the absorption coefficient of the gas placed into the cavity of measurement. In fact, it is known that the introduction of a gas to a cavity resonator causes a displacement of the resonance frequency (effect of the index of refraction) and, at the same time, the resonance signal is broadened and weakened (absorption effect) (Fig. 4).

Although the recording spectrograph is based on the same theoretical considerations, its principle presents some quite essential differences, as will be shown. (See also a brief report in [1].)

III. The Principle of the Recording Spectrograph

Suppose the klystron is doubly modulated in frequency: 1) by the signal of a triangular modulator, and 2) by means of another sinusoidal modulator operating at a frequency of 1 Mc. The response signals received on the crystal detectors now show two secondary maxima due to the sidebands $\nu_0 \pm 1$ (Mc), apart from the central curve of the principal resonance ν_0 of the cavity (Fig. 2). The shape of the principal resonance is practically not disturbed by the presence of its lateral images, because the degree of modulation is adjusted so as to be weak enough, and because the frequency of 1 Mc is quite high with respect to the width of the principal resonance of the cavity.

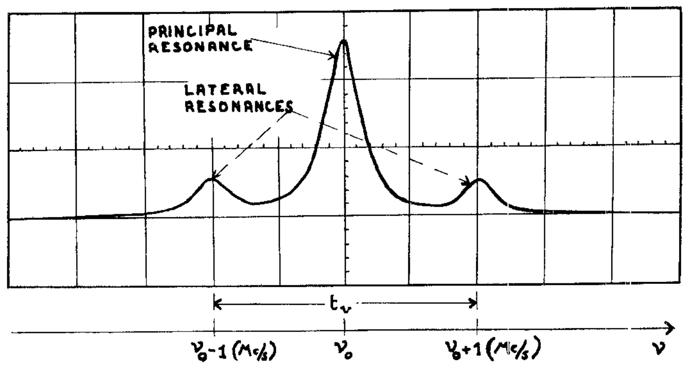

Fig. 2—Response of one cavity when swept by the doubly modulated klystron.

Also, suppose that the power falling on the crystal detector is weak enough so that the detection is quadratic ($P_{\max}$<about 10μW). Furthermore, given that the quality coefficient Q of the cavity is high enough (the special construction of the over-dimensioned cavities provides a quality of the order of 30,000 within the X-band) [2a], [5], we will have for the detected voltage [9], [10]:

$$V = \frac{V_{\max}}{1 + 4Q^2\left(\frac{\nu - \nu_0}{\nu_0}\right)^2}, \qquad (1)$$

where $V_{\max}$ is the voltage corresponding to the resonance frequency ν_0. The second derivative of this expression with respect to the frequency ν becomes zero at two points around the resonance frequency. The frequency distance of these points is finally given by the relation (Fig. 3):

$$\nu_a = \frac{\nu_0}{Q\sqrt{3}} \cdot \qquad (2)$$

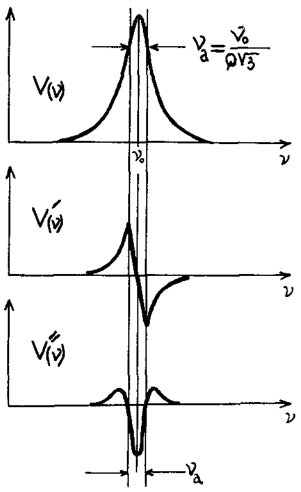

Fig. 3—Cavity principal response and its first and second derivatives.

However, owing to the triangular modulation of the klystron, its frequency is changed according to the equations:

$$\left.\begin{array}{ll}\nu = \bar{\nu} + vt & \text{during one half-period} \\ \nu = \bar{\nu} + v(T - t) & \text{during the next half-period}\end{array}\right\}, \quad (3)$$

where T is the sweep period of the klystron (1/50 sec, in our case) and v the velocity of modulation. Taking into account these equations, the above-mentioned frequency distance ν_a corresponds to a time distance t_a:

$$t_a = \frac{\nu_0}{vQ\sqrt{3}}, \quad \left(\text{from which } Q = \frac{\nu_0}{\sqrt{3}\, vt_a}\right). \quad (4)$$

Now let the two cavities of the apparatus be empty and in resonance (both at the same frequency ν_0) at the beginning of an experiment. Suppose we introduce to the cavity of measurement a gas under a certain pressure p, while keeping the reference cavity empty. Then (Fig. 4) the resonance frequency of the cavity of measurement is displaced to a new value, $\nu = \nu_0/n$, where n is the index of refraction of the gas under the pressure p and the temperature of the experiment, while, at the same time, in the case of an absorbing gas, the response curve is broadened.

The frequency displacement of the resonance $\nu_0 - \nu = \nu_0 - (\nu_0/n)$ corresponds to a time difference Δt_n [see (3)]:

$$\Delta t_n = \frac{\nu_0}{v}\left(1 - \frac{1}{n}\right), \quad (5)$$

from which

$$n - 1 = (v/\nu_0) \cdot \Delta t_n, \quad (6)$$

the index of refraction being near enough to unity.

On the other hand, the broadening of the response curves indicates a relative lowering of the quality co-

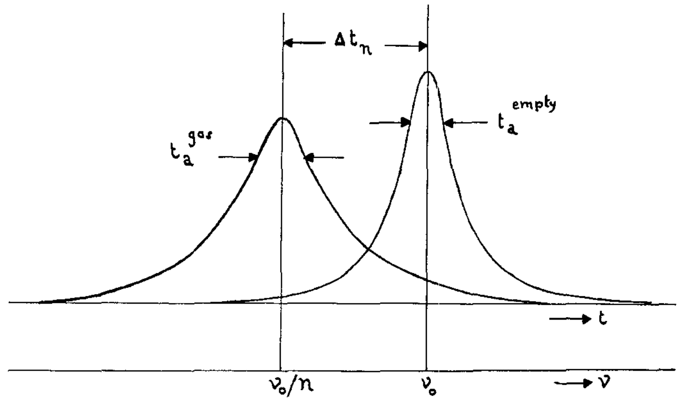

Fig. 4—Effect of the gas refractive index and of the absorption on the response of measurement cavity.

efficient of the measurement cavity. Thus, we have (4):

$$\Delta t_a = \frac{\nu_0}{v\sqrt{3}}\left(\frac{1}{Q} - \frac{1}{Q_0}\right). \quad (7)$$

Furthermore, since, as it is known,

$$(1/Q) - (1/Q_0) = \epsilon_r'' = \alpha c / 2\pi\nu,$$

where $\epsilon_r = \epsilon_r' - i\epsilon_r''$ is the complex dielectric constant of the gas, α its absorption coefficient (small as compared to unity), and $c \approx 3 \cdot 10^8$ msec (the magnetic permeability of the gas is taken as $\mu_r = 1$), it follows that:

$$\alpha = \frac{2\pi\sqrt{3}\, v}{c} \cdot \Delta t_a, \text{ (neper/m)}. \quad (8)$$

Finally, the relations (6), (8) and (4) take the following practical form if the sweep velocity v is replaced in them by the expression $v = 2(\text{Mc/s})/t_v$, where t_v is the time distance between the two side maxima of the response signal (Fig. 2):

$$N = (n - 1) \cdot 10^6 = \frac{2 \cdot 10^6}{\nu_0} \cdot \frac{\Delta t_n}{t_v} = C_n \frac{\Delta t_n}{t_v}, \quad (9)$$

$$\alpha = \frac{4\pi \cdot 10^6 \sqrt{3}}{c} \cdot \frac{\Delta t_a}{t_v} = C_a \frac{\Delta t_a}{t_v}, \quad (10)$$

$$Q = \frac{\nu_0}{2\sqrt{3}} \cdot \frac{t_v}{t_a} = C_Q \frac{t_v}{t_a}. \quad (11)$$

where ν_0 is measured in megacycles, α in neper/m, the time t in microseconds, $c = 3 \cdot 10^8$ m/sec, and C_n, C_a and C_Q are constants.

The measurement of the index of refraction of the gas, its absorption and the quality coefficient of the cavity of measurement, is thus reduced to the measurement of the times t_n, t_a and t_v. This is achieved by so designing the time circuits of the apparatus that a direct current is produced at their output, which is proportional to the intervals being measured; the proportionality factor is constant for every sort of measurement. This direct current is used to drive an autographic voltmeter destined to record continuously, on a paper tape, the curves of variation of the measured quantities as a function of the gas pressure.

IV. Operation of the Apparatus

The block diagram of the recording spectrograph is shown in Fig. 5. The different stages of the electronic part can be distinguished, from the operation point of view, into two discrete sets:

1) The block "amplifier—derivation and clipping—electronic windows—pulsers" (one block for each channel of the apparatus) provides at every half-period of the sweep one pair of suitable pulses separated by the time interval t_a, t_n or t_v.

2) The other block which includes the "scale of two," the integrator and the output recorder, and which is connected to the preceding block by means of a relay, receives the above mentioned pairs of pulses and produces a direct current proportional to their distance.

A. Measurement of the Interval t_a

During the measurement of the time t_a (measurement of the absorption, position II of the commutator), a first derivative of the response of the measurement cavity is realized by a resistance-capacity circuit at the output of the preamplifier (oscillogram 1*a* of Fig. 5). After amplification, a second derivation, followed by a clipping deep and symmetrical with respect to the zero level, makes the interval t_a appear in the form of a rectangular signal (central part of oscillogram 2*a*). However, this useful signal appears among other parasitic signals with which it is confused. The discrimination is obtained by means of electronic windows 3*a* and 4*a*) properly synchronized, which allow the pulser to work only when the desired signal is initiated or interrupted. The leading edges of the pulses given by the pulsers thus constitute very accurate marks which repeat the distance t_a.

The next stage, a bistable multivibrator (scale of two), driven by these pulses, restores the original rectangular signal, but this time free of parasites (oscillogram 6*a*). Finally, an integrator produces a direct current:

$$i_a = 2 \cdot 50 \cdot I_{\max} \cdot t_a$$

($T = 1/50$ sec the period of the principal modulation of the klystron) by means of which the recorder is driven. The integrator is a constant current pentode ($I_{\max}$) which conducts only during the intervals t_a and the current of which passes through a rectifying filter.

B. Measurement of the Interval t_n

A similar process is applied for the measurement of the time t_n (measurement of the refractive index, position *I* of the commutator). The difference is that the two pulses (5*n* and 5′*r*) which determine the interval t_n, now originate from the channel of measurement and from the channel of reference, respectively, and they correspond to the maxima of the principal resonances of the response curves of the cavities.

To produce these pulses, the signals of response are applied, after amplification, directly to the circuits of derivation and clipping. Their first derivatives undergo a strong clipping and they appear in the oscillograms 2*n* and 2*r*. The leading edges corresponding to the maxima of the principal resonances of the cavities excite the pulsers, while the effect of any other pulse is eliminated by means of electronic windows.

C. Measurement of the Interval t_v

The pair of pulses used for this measurement corresponds to the maxima of the two side resonances of the cavity of reference (oscillogram 5*r* in Fig. 5).

To pass to this sort of measurement, the triggering of the previously mentioned relay is required. The resistance R, which is then connected at the output of the integrator, protects the microammeter from an excessive direct current. The same resistance, if it has been designed to be variable and calibrated, serves also the measurement of the ratio t_a/t_v when the apparatus is used as a Q-meter.

D. Pressure Marker

The records are obtained during the slow evacuation of the cavity of measurement. A special barometric setup (Fig. 5) allows the calibration of the time axis of the record in pressure units.

The barometric setup consists of a glass tube (internal diameter of the order of 10 mm) provided with metallic contacts 10 mm apart from one another (this distance is suitably corrected so that the effect of the vessel containing the mercury can be taken into account). The metallic contacts consist of tungsten wires sealed along the side of the glass tube so that they penetrate it.

Every contact is connected outside of the barometric tube to a small capacity (100 pF). The free ends of these condensers are short-circuited and brought together, through a resistance of a few tenths of ohms, to a positive potential (90 volts) with respect to the mass of the mercury.

The slow rising of the mercury during the evacuation of the cavity of measurement establishes one contact at every 10 mmHg of pressure. The pulses produced at every new contact because of the charging of the corresponding condenser, after amplification, trigger the monovibrator which acts on the relay. The relay remains triggered for a certain time adjustable from 1 to 20 seconds. During this period, the block "scale-of-two

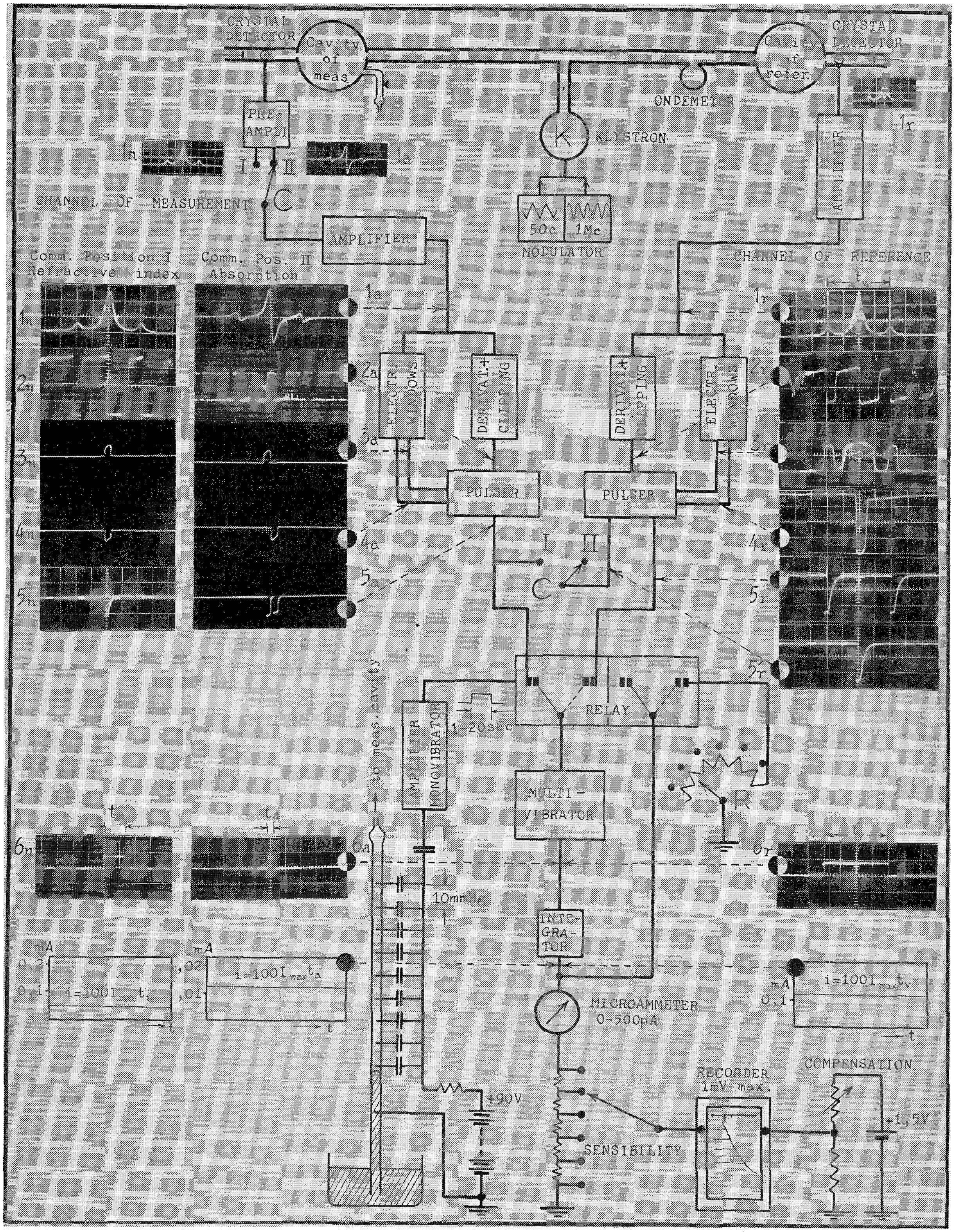

Fig. 5—Block diagram and oscillograms (400 μsec/cm horizontal sweep) illustrating the operation of the recording spectrograph.

recorder" is connected to the circuits which correspond to the measurement of the interval t_v. The traces of the resulting displacements of the recording pen constitute the marks of the pressure for every 10 mm Hg. In order to prepare the apparatus for the next measurement, the capacities of 100 pF are shunted by high resistances (20 MΩ) which provide a rapid discharge during the next filling of the cavity.

If the sweep velocity of the klystron (which is proportional to t_v) is stable enough, the ends of the pressure traces should lie on a straight line corresponding to one and the same value measured by the recorder. This value can be used as zero-reference provided that the resistance R is adjusted so that the recorder will show the same value when the cavity of measurement is empty. It is evident that any change of the sweep velocity disturbs the straightness of the line formed by the ends of the pressure traces. This permits one to control and, if necessary, to correct the stability of the sweep velocity and thus to ensure a sort of permanent calibration of the spectrograph.

V. Design

We give here in brief some information on the design of the recording spectrograph and in particular on those parts which are essentially different or absent in the previous spectrograph with synchroscope. Since the microwave block remains as in Fig. 1, we will not deal with it (see [2a], [5]). The electronic block can be divided into the following parts (Fig. 5):

A. Double Modulator of the Klystron

This includes a generator of an isosceles triangular signal synchronized to the power line (frequency of 50 cps, variable amplitude for the adjustment of the sensitivity of the apparatus), as well as a sinusoidal crystal generator (frequency of 1 Mc). The design of the triangular modulator should provide high linearity and symmetry.

B. Low-Frequency Amplifiers

These amplify the response signals of the cavities and have been designed to present low noise level, sufficient frequency pass band and high gain (of the order of 60 db). The peak value of the amplified signal is of the order of 100 or 200 volts.

The two amplifiers, corresponding to the two channels of the apparatus, are identical except in the following respect: The first tube (preamplifier) of the channel of measurement is connected to the rest of the amplifier by means of a double coupling circuit RC. One of these circuits is identical with the corresponding circuit of the amplifier of reference. The other one has a time constant of far less (of the order of 0.5 microsecond) and provides the first preliminary derivation of the response of the channel of measurement in the case of the absorption measurement.

C. Derivation and Clipping, Electronic Windows, Pulsers (Channel of Measurement) (Fig. 6)

Suppose that one is dealing with the measurement of the absorption. The input signal immediately undergoes a second derivation by means of the circuit $R=5000$ ohms, $C=100$ pF. If the signal of the second derivative were directly applied to the dc amplifier (12AT7), a displacement of the zero-level as a function of the amplitude of the signal might result. To avoid this, one connects, at the input of the 12AT7 and in parallel with the resistance R, a set of two crystal diodes with opposing polarities. This set provides a preliminary clipping and keeps the amplitude of the input signal at low levels. Furthermore, since the two diodes have been selected to be identical, the zero level can no longer be displaced for any amplitude of the input signal.

The dc amplifier is thus used mainly for the amplification of a signal which has already undergone a preliminary clipping; this is facilitated by the presence of a weak positive feedback.

The pulsers (two thyratrons 2D21) are fed by the amplified signal through a decoupling stage ($\frac{1}{2}$12AU7). However, since the clipping is deep and the amplification high, the system could be activated not only by the useful signal but also by any disturbance in the input voltage (noise, secondary resonances). This possibility is eliminated by means of electronic windows (one for each thyratron). The windows are synchronized on the input signal (the first derivative of the response of the measurement cavity for the absorption measurement). This signal is doubled by means of a phase inverter ($\frac{1}{2}$12AU7) and it feeds two detection circuits. The current flows only near the maximum and minimum of the input signal. The corresponding pulses are amplified and they constitute the suitably synchronized electronic windows.

In the case of measurement of the refractive index, one obtains in the same way two electronic windows, but this time the windows appear both in the same position, that corresponding to the principal resonance of the cavity of measurement. However, the two thyratrons do not work together at the same time, since one of them works during the rising part of the clipped signal and the other one during the falling part. Therefore, one will receive at the output only one pulse.

D. Respective Circuits of the Channel of Reference (Fig. 7)

The input signal consists here of the response signal itself of the cavity of reference (amplified to about 200 volts, peak value). The output is double: The two pulses received from the output S_1 correspond to the two side maxima of the input signal (measurement of the sweep velocity of the klystron). Only one pulse, placed at the maximum of the principal resonance of the reference cavity, comes out of the output S_2 (measurement of the refractive index).

The derivation and the clipping are produced by exactly the same procedure as in the channel of measurement. The fronts of the triple rectangular signal thus produced, as well as the fronts of the parasite signals (Fig. 5, oscillogram $2r$), feed the mutually short-circuited grids of the two thyratrons (V_{16} and V_{19}). On the other hand, these grids receive the signal of a triple electronic window, the apertures of which are synchronized to the three maxima of the reference response. Thus, the potential level of the three "useful" wave fronts is raised relatively to any other wave front. This, however, does not result in the triggering of the two thyratrons at the positions of the three useful fronts. The polarizations of the thyratrons are, in fact, adjusted so that the conditions of ignition are then satisfied only for the output S_1, and not for the output S_2.

Under such a situation, one should receive three pulses at the output S_1. However, the screen of the corresponding thyratron (V_{16}) receives a negative signal which is also produced by the circuits of the electronic windows and which is synchronized with the maximum of the principal resonance of the input signal (Fig. 5, oscillogram $4r$). Thus, at the output S_1, two pulses only are obtained, by means of which the two side maxima are pointed out.

The same pulse of selection (oscillogram $4r$) is also applied to the cathode of the other thyratron (V_{19}). Its action consists of rendering this thyratron, which otherwise is kept off, able to select the sole pulse corresponding to the maximum of the principal resonance of the input signal.

The single (negative) electronic window is produced by the method of detection, as in the case of the channel of measurement. To obtain the triple window, the response signal of the cavity of reference is forced to pass through a crystal diode (OA5) polarized by a cell of 1.5 volts. The clipping performed by the diode reduces the three maxima of the response curve to the same height. The remainder of the process is quite evident.

E. Scale of Two, Integrator and Recorder (Fig. 8)

The pairs of pulses, obtained as outlined above, correspond to the time intervals t_a, t_n or t_v. They are re-

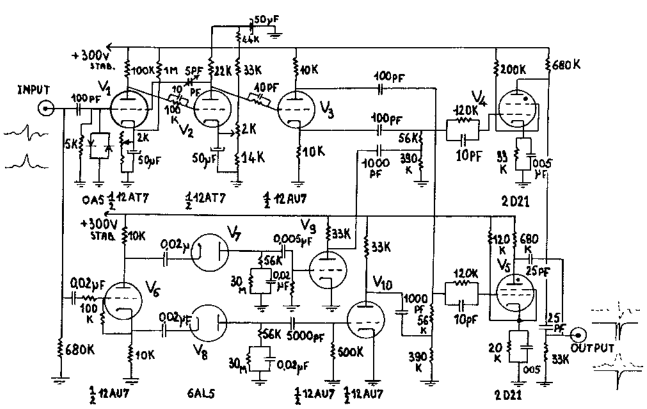

Fig. 6—Pulse circuits (channel of measurement).

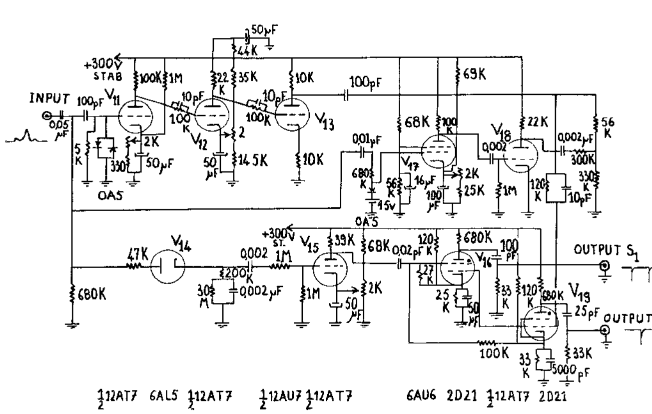

Fig. 7—Pulse circuits (channel of reference).

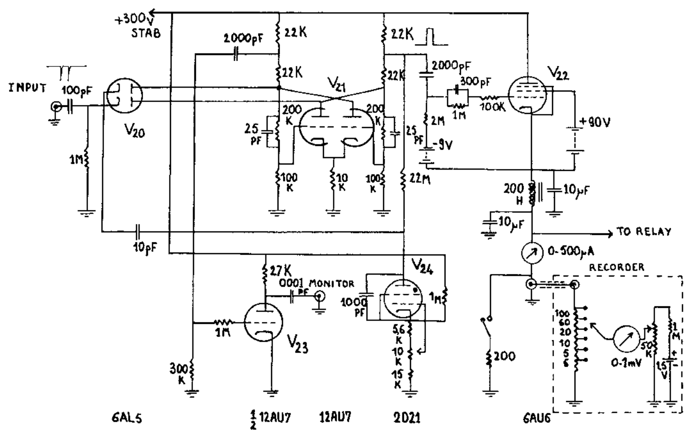

Fig. 8—Scale of two, integrator and recorder.

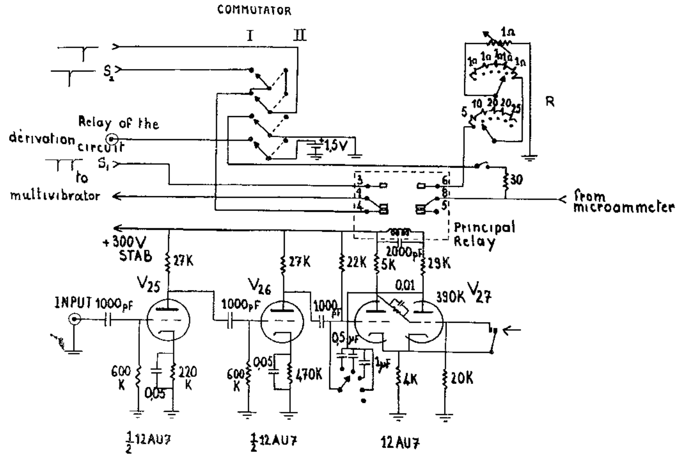

Fig. 9—Pressure circuits.

peated at the rate of 100 per second and couple, through a double diode (V_{20}), to the two plates of a bistable multivibrator (V_{21}). The width of the rectangular signal provided with this "scale of two" represents the time distance separating the two pulses of the respective pair.

The rectangular signal received by one of the plates of the multivibrator is used, after decoupling (V_{23}), for the control of the operation of the scale by means of the monitor.

The rectangular signal from the other plate is applied to the grid of an integrating pentode (V_{22}). This tube becomes conductive and supplies a constant current, only during the time periods defined by the rectangular signal of the scale. The action of the rectifying filter (LC), placed at the cathode load of the tube, permits one to obtain at the output a direct current proportional to the width of the rectangular signal. The proportionality factor (of the order of 1 μa/μsec) is very stable.

Finally, since it might be possible for the polarity of the rectangular signal of the scale to be inverted because of some disturbance, whatever it may be, which would put in danger the operation of the apparatus, a set for automatic re-establishment of the polarity has been foreseen (V_{24}).

F. Pressure Circuits (Fig. 9)

The pulses for the identification of the gas pressure (see Section IV-D) are amplified and they feed a monostable multivibrator. The plate current of its one part controls the main relay of the apparatus: the appearance of a pulse at the input causes the activation of the relay which passes, for an adjustable time, from the position "measurement" over to the position "pressure marker." The same result, and for any time, can also be obtained by means of a press-button (use of the instrument as a Q meter).

G. Monitors

The operation of the apparatus is controlled by means of two monitors (one for each channel of the instrument). The response signals obtained at the outputs of the low-frequency amplifiers appear on the screens of the respective cathode ray tubes.

VI. Results and Conclusions

The photograph in Fig. 10 shows a general view of the recording spectrograph. Its performance is comparable with that of the spectrograph with synchroscope [2a], [5]. The sensitivity remains at the order of 10^{-6} neper/m for the absorption and of 10^{-8} for the index of refraction. The precision evidently depends on the type of measurement (the error can be of the order of 1 per cent for the absorption, even less for the refractive index). The stability of measurements seems to favor the use of a recorder instead of a synchroscope, where the calibration is subjected to a permanent control. The reproducibility of the measurements is also highly satisfactory.

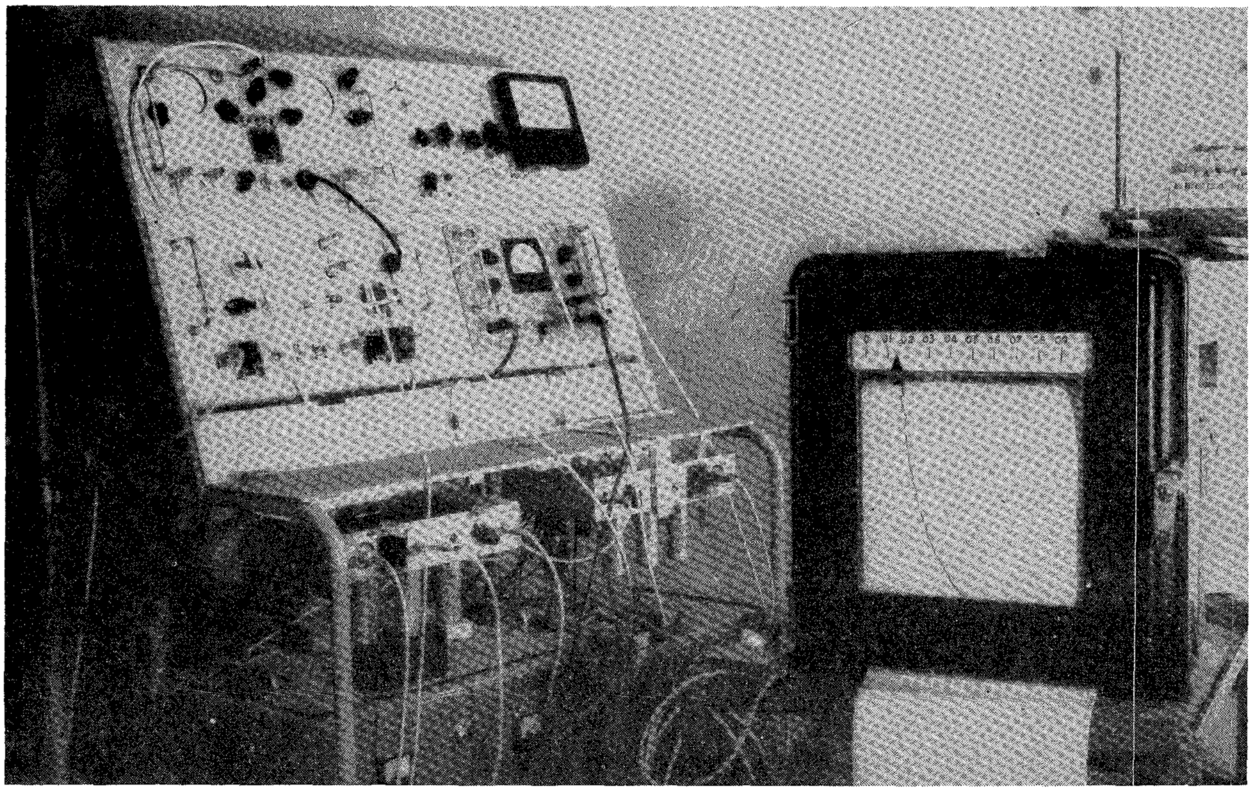

Fig. 10—Photograph of the apparatus (electronic part). (For the microwave part, please see [2] and [5].)

Figs. 11 and 12 illustrate an example of measurement of the absorption by ammonia. The apparatus is now ready and is being used in carrying out some original research work.

In conclusion, we remind the reader of the principal features of this recording spectrograph:

1) Convenient measurements through the use of an automatic recorder.
2) Possibility of use, after modifications to reduce size and weight, as a light, accurate airborne refractometer (like the existing Crain's refractometer [8]).
3) Possibility of use as a direct-reading Q meter.
4) High general performance, due to the application of the pulse method to the interpretation of the cavity responses.

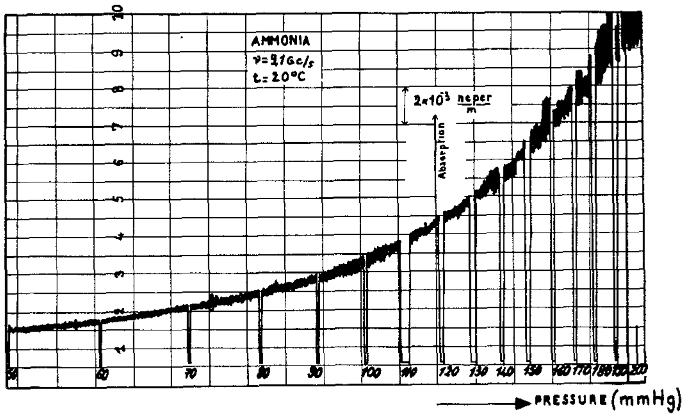

Fig. 11—Microwave absorption (ν=9100 Mc) by ammonia at 20°C.

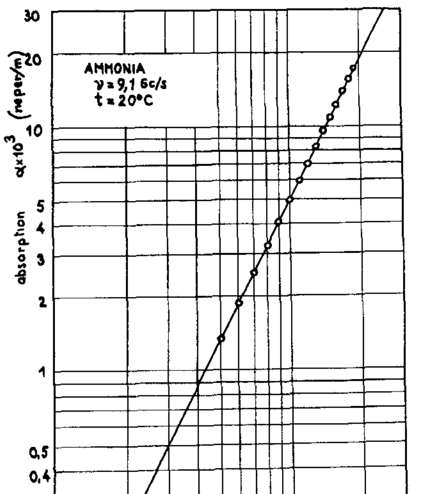

Fig. 12—The recorded curve (Fig. 11) transferred in log-log scales (straight line with a slope equal to 1.97: $\alpha=(\text{Cte})p^{1.97}$).

Acknowledgment

The authors wish to express their thanks to Prof. A. Gozzini of the University of Pisa, pioneer of the application of the pulse method to microwave spectrographs, for his permanent interest in carrying out the present work.

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