A K-Band Oscillator Locked to the First Water Resonance

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***Abstract*—Locking a microwave oscillator to a rotational spectral line has the unique advantage that the frequency of oscillation is defined by the spectral line of the polar molecule involved and is thus immune to any drift caused by extraneous effects. In instruments and communication systems involving microwave sources, varying degrees of frequency stabilization are required. Frequency stabilization using the absorption line of a polar gas as the frequency reference standard obviates the need for external frequency reference sources. It thus provides a low cost alternative to phase locking the oscillator to a stable source. A Gunn diode oscillator has been locked to the rotational absorption line of water at 22 235.170 MHz. The water in vapor form was obtained from atmospheric air. The air was held in a vacuum chamber which was inserted in a Fabry–Perot open semiconfocal resonator. A sinusoidal electric field, the Stark field, was impressed upon the gas in the cavity which is coupled to the Gunn oscillator, thus modulating the water vapor absorption of microwave energy. The second harmonic of the Stark field was used to lock the Gunn oscillator. Working with the water spectral line (16_{16}–5_{23}) at 22 235 GHz, frequency stability of the order of ±50 KHz was achieved.**

I. Introduction and Brief Review of Literature

The PRINCIPLE of locking a microwave oscillator to a rotational line is well-known, developed by Cram and Paris [1]. A long absorption cell was used with a Stark electrode to modulate the line of methyl fluoride at 102.2 GHz. The Stark modulation principle is covered in Townes and Schawlow [2] and in Varma and Hrubesh [3].

Later workers such as Wineland *et al.* [4], locked a stripline oscillator to the ammonia 23.870 GHz ($J = 3$, $K = 3$) line, by frequency modulating a 500 MHz oscillator at a rate of 10 kHz. Then this frequency was multiplied to the line frequency and passed through an absorption cell containing ammonia at reduced pressure. The harmonics generated as the frequency of the frequency modulated source crossed the absorption profile of the ammonia line were employed to lock the source oscillator. The fractional frequency stability achieved was of the order of 2×10^{-10}. Similar principles have been employed in the design of the atomic clocks discussed by Audoin and Vanier [5].

In the work reported here, a novel locking system is employed. An earlier version of this method is described in detail in previous publications by the author [6] and by Thirup *et al.* [7].

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II. System Description and Theory

A brief description of the system is given below for continuity. The gas, in this case atmospheric air, is contained in a Fabry–Perot semiconfocal resonator coupled to a K-band Gunn diode oscillator as it is shown in Fig. 1. An off the shelf Gunn diode package is used (Plessey GDO 33), to provide the microwave energy required. The radiation is then attenuated to 3 mW by a home made vane attenuator. When the energy reaches the hybrid "T" some of it travels towards the Fabry–Perot resonator and some of it travels towards the diode detector (HP 3333 OC).

Inside the Fabry–Perot resonator a polytetrafluoroethylene (PTFE) cup is placed and it is evacuated to 1.3×10^{-4} mbar via ports in the spherical mirror of the cavity against which it makes a seal. On the outside of the end wall of the PTFE cup is a serpentine wire grid of 4 mm spacing, which runs to and fro across the wall. The grid is oriented perpendicular to the microwave electric field which exists in the cavity between the spherical mirror and PTFE cup so that the interaction between the field and the wire is minimized. Onto the grid a sinusoidal Stark field is impressed of peak to peak intensity in the order of 12 kV at a frequency of 8.33 kHz. This signal is generated by an audio oscillator, then it is amplified by a power amplifier, the Stark amplifier, which feeds the primary coil of an extremely high voltage, (EHT) transformer. When the frequency of the Gunn diode matches the resonant frequency of the Fabry–Perot resonator which is made to coincide to the absorption frequency of the water molecule, the interaction of the sinusoidal Stark field with the molecular energy levels of the water molecule, generates amplitude modulation of the microwave signal at even harmonics of the Stark frequency [7], [8]. The microwave signal which is reflected from the Fabry–Perot cavity travels towards the diode detector through the hybrid "T." Some energy from this signal is detected by the detector, but the rest travels through the hybrid "T" and the vane attenuator towards the Gunn diode oscillator. Since the frequency of the Gunn diode oscillator is closely coupled to the Fabry–Perot cavity, any change in the distance between the two mirrors will change it. Horizontal movement is achieved by moving the flat wall of the cavity

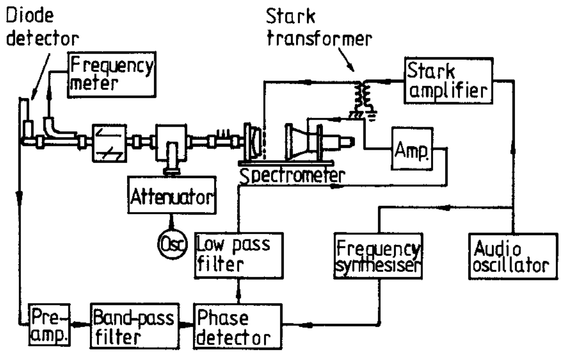

Fig. 1. System block diagram.

along the x-axis. This mirror is attached to a loudspeaker cone.

The second harmonic of the Stark field frequency is extracted by a high quality factor band pass filter from the diode detector output signal which has been preamplified. A phase sensitive detector is used to detect the variation of the second harmonic of the Stark field modulation of the energy absorbed by the water line at 22.235 GHz. The reference signal of the phase sensitive detector is supplied by doubling the signal frequency of the audio oscillator using a phase locked loop frequency synthesizer. The output of the phase sensitive detector is low passed, amplified, and it is used to drive the loudspeaker thus closing the control loop. The frequency control system described in this paper is based on the fact that the oscillator being closely coupled to the cavity is locked to the spectral or absorption line of the gas inside the cavity. Thus all three frequencies, namely the Gunn diode frequency, the resonant frequency of the Fabry–Perot resonator, and the absorption frequency of the water molecule are locked together in the same control loop.

The theory of the locking procedure developed below is partly based on the work of Hershberger [8], who carried out an analysis of Stark modulation and identified the generation of harmonics by the spectral line. He noted that the second harmonic of the Stark field frequency reduced to zero very close to the line frequency of the gas.

Using this method, a stable oscillator has been developed which can be locked to the frequency of the absorbing spectral line of any polar gas exhibiting absorption strengths in the order of 7×10^{-6} cm^{-1} and above.

The fractional change in the voltage amplitude ΔV of the reflected wave V from the cavity at resonance with the absorbing gas in the cavity is given by [2]:

$$(\Delta V/V) = Lx\gamma \tag{1}$$

where

$L = (Q\lambda/2\pi)$ = the equivalent path-length of the Fabry–Perot cavity with Q being its quality factor.

λ = the wavelength of the resonant frequency of the cavity.

x = the fractional abundance of absorbing gas in the cavity, in this case it was atmospheric air containing water vapor with water content of 10 000 ppm.

γ = the attenuation per unit length of a wave propagating in the gas, given by: $\gamma = [8\pi^2 Nf|\mu_{ij}|^2\nu^2\ \Delta\nu]/[3ckT((\nu-\nu_o)^2+\Delta\nu^2)]$ as it is given by [2].

N = the number of molecules per cc in the absorption cell.

f = the fraction of those molecules in the lower of the two energy states i and j involved in the transition.

$|\mu_{ij}|^2$ = the square of the dipole moment matrix for the transition summed over the three perpendicular directions in space.

ν = the frequency at which γ is defined.

$\Delta\nu$ = the half width of the line at one-half the maximum value of γ.

ν_o = the resonant frequency, or to a good approximation the centre frequency of the gas absorption line.

k = the Boltzmann's constant.

T = the absolute temperature.

c = the speed of light.

So from [6] and [7] it follows that

$$\begin{aligned}(\Delta V/V) = \{&L \times ANf\Delta\nu^2\}/\{(\nu-\nu_o)^2 - p(\nu-\nu_o)\\ &+ (3/8)p^2 + p\cos 2\omega t(\nu-\nu_o-0.5p)\\ &+ (p^2/8)\cos 4\omega t + \Delta\nu^2\}\end{aligned} \tag{2}$$

where

$$A = \frac{8\pi^2|\mu_{ij}|^2\nu^2}{3KTc\ \Delta\nu}$$

and

ω = the Stark field frequency.

The output signal, of the phase detector which is locked on the second harmonic of the Stark field, extracts it and after it is low passed and amplified, it is used to drive the loudspeaker. The instrument has two major components, the Gunn diode oscillator and the Fabry–Perot semiconfocal cavity resonator. The Plessey Gunn diode used was coupled to the cavity via a vane attenuator and a hybrid "T," via a slit iris running perpendicular to the electric field in the waveguide. The iris is sealed with a mica sheet set in paraffin wax. The dimensions of the iris are critical for optimum coupling, and in this case they were 5 × 1 mm.

The cavity itself comprises a spherical mirror of diameter 93 mm, radius of curvature 186 mm into which two vacuum ports were machined at a radius of 35 mm ninety degrees apart. The vacuum seal with the PTFE cup was achieved with an "O" ring 106 mm in diameter recessed into the circumference of the curved mirror. The flat plate mirror of the resonator was a 120 mm diameter copper clad epoxy glass printed circuit board mounted onto an audio loudspeaker cone, 110 mm in diameter, via a perspex annulus. This arrangement is a simple and low cost means of displacing horizontally the flat mirror of the resonant cavity. Mechanical vibration due to the vacuum pump was found to introduce a loudspeaker movement of 28 Hz. A piezocrystal could be used instead of the loudspeaker. The frequency meter used during the course of these experiments was an EIP548 device, and the diode detector was a Plessey GDO 33 Schottky barrier device.

The Phase locked loop synthesizer, diode preamplifier, loudspeaker, amplifier, second harmonic bandpass filter, phase sensitive detector low pass filter, power amplifier and Stark field voltage transformer were all home made devices.

III. Results and Observations

The second harmonic of the Stark field frequency was detected at the 22.235 GHz water absorption frequency by introducing atmospheric laboratory air of relative humidity 58% to the cavity. The EHT was set to oscillate at 8.3 kHz with an intensity of about 10 kV.

Originally, the diode detector used was a HP 3333OC device with a specified sensitivity of more than 0.08 mV/μW and the microwave power was supplied by a Wiltron SNA 6669 programmable sweeper which was set to sweep at a rate of 20 kHz/sec in the water line frequency region. The microwave power level was kept to 3 dBm. The signal from the diode detector was preamplified by 85 dB and the output signal of the phase sensitive detector was displayed on a Gould series 6000 X-Y plotter. The x-axis movement of the plotter was in synchronization with the horizontal sweep of the Wiltron programmable sweeper. The vacuum kit consisted of a Leybold Heraeus rotary/turbo-molecular pump combination and originally the cavity was pumped down to a pressure of 5×10^{-5} mbar. A constant leak of air from the atmosphere to the cavity through the mica window at the iris, assured a constant supply of water vapor. The Fabry–Perot cavity was set to resonate at exactly 22.235 GHz. In order to demonstrate the generation and shape of the second harmonic of the Stark field the programmable microwave oscillator was set to sweep from 22.234 GHz to 22.236 GHz in 10 s.

A frequency meter was employed to monitor the frequency since the frequency indicating facility of the sweeper is accurate to ± 10 MHz. After a little deliberation the second harmonic was detected and it is shown in Fig. 2, where it is seen to exhibit a zero crossing at 22.23517 GHz. The frequency difference between the maximum and minimum was measured to be 450 ± 40 kHz. The minimum and maximum points of the absorption line are closely related to the half-peak-intensity points of the absorption line according to P. L. Cook [9].

The pressure broadening coefficient for water is given

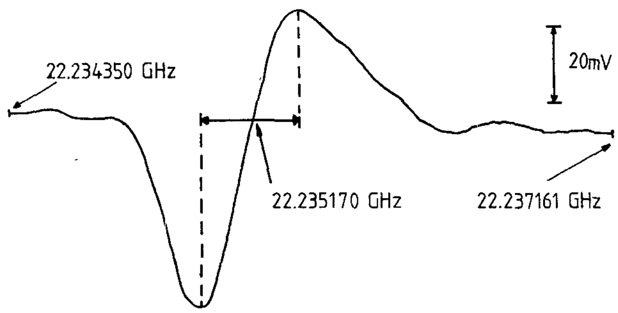

Fig. 2. Second harmonic trace at a cavity pressure of 6×10^{-3} mbar and Stark field voltage of 6 Kv. The bandwidth of the line between the minimum and maximum is 450 kHz.

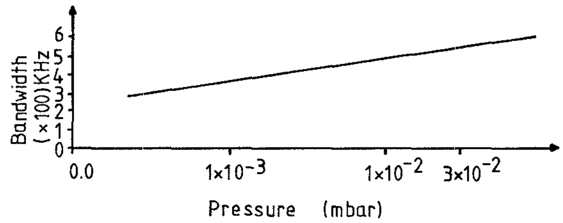

Fig. 3. Second harmonic bandwidth variation with pressure. Stark field at 6 kV.

to be 18 MHz/Torr, at a pressure of 0.1 Torr, by Liebe [10]. The variation of the line bandwidth with cavity pressure was investigated and the results are plotted in Fig. 3.

The slope of the line in Fig. 3, was found to be 11 MHz/mbar or 14.6 MHz/Torr. Experimental error has to be included before this value is compared to Liebe's. According to Liebe and also to Benedict *et al.* [11], Stark or Zeeman saturation effects destroy the equilibrium conditions and hence the true shape and width of a line.

The variation of the peak to peak voltage intensity of the signal with changes in the intensity of the Stark field was investigated next and the results obtained are plotted in Fig. 4. Next the solid state Gunn diode oscillator package was introduced as the microwave source of energy. The home made vane attenuator was fitted in series with the Gunn diode assembly in order to decrease the microwave energy entering the spectrometer to around 1.7 mW so the gas did not get saturated. A power meter, (HP 432B), was used to measure the power output of the oscillator-attenuator package.

Since the frequency pulling or scanning effect of the cavity was only realizable by the variation of the horizontal dimension of the Fabry–Perot resonator, the frequency scan over the water line region was achieved by feeding a ramp signal at a rate of 540 mV/s to the loudspeaker, which carried the flat mirror of the resonant cavity thus pulling the frequency of the closely coupled Gunn diode oscillator.

The output of the phase sensitive detector is plotted and the second harmonic results obtained are shown in Fig. 5, where it can be seen that the second harmonic signal lies on a sloping floor which is probably due to the combined effect of the wide resonance response of the Fabry–

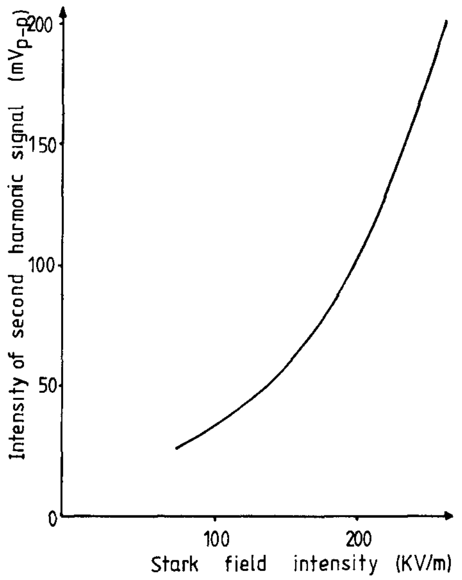

Fig. 4. Second harmonic amplitude variation at different Stark field strengths. Pressure is 3×10^{-3} mbar, water content is 10 000 ppm.

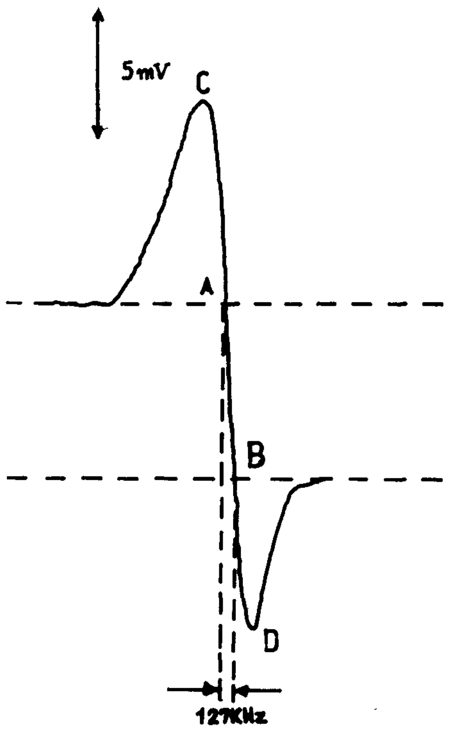

Fig. 5. Noise second harmonic trace at a cavity pressure of 5×10^{-3} mbar and Stark field voltage of 12 kV.

Perot cavity, and the much narrower bandwidth of the water absorption line.

From Fig. 5, it is also seen that points A and B do not lie on the same horizontal level as it is the case with the trace shown in Fig. 2.

This observation of the uncertainty of the zero crossing of the signal represents in frequency terms, a measured 127 kHz of frequency instability, at a pressure of 5×10^{-3} mbar, which is going to be added to the inherent instability of the oscillator when it is locked on to the water molecular line.

Also the line between points C and D represents the signal that is sent to the loudspeaker in order to follow and correct any changes in radio frequency of the solid state microwave source.

If the pressure is further decreased then the linewidth of the line will decrease thus making the line between points C and D steeper with the consequence of an increased demand on the time constants of the system.

In turn, if the pressure was increased the reverse would apply. When the feedback loop was closed, the frequency variation was monitored and the frequency stability results obtained are represented by trace (a) in Fig. 6. where it can be seen that the Gunn oscillator is locked to the water line at 22.2357 GHz. There is a frequency variation in the order of as ± 50 kHz as expected because the zero crossing uncertainty which is due to the non-clear definition of the zero crossing point of the second harmonic. When the feedback loop was opened the frequency varied in an unpredictable fashion as shown by trace (b) in Fig. 6. The design of the feedback loop was not optimized due to severe time constraints so any sudden mechanical vibration would cause the oscillator to jump out of lock because the paper membrane of the loudspeaker was set in motion so the system could not compensate for the sudden change of the horizontal distance of the cavity.

The mathematical model describing the system follows the general lines of [1] and its block diagram is shown in Fig. 7. To establish the dependence of the oscillator frequency f_1 to the frequency of the second harmonic crossing f_2, the following analysis is given:

Let the initial oscillator frequency be f_{00}. If the flat mirror of the Fabry–Perot resonator is moved by a small distance x, then the new oscillating frequency becomes f_1 and is given by

$$f_1 = f_{00} + xK_5 \tag{3}$$

where

$$K_5 = \text{constant in (MHz/mm)}.$$

Then, the error voltage E from the PSD is given by

$$E = K_4(f_2 - f_1) \tag{4}$$

where

$$K_4 = \text{constant in (V/MHz)}.$$

The horizontal displacement of the loudspeaker, x, is given by

$$x = K_6 \frac{E}{R} \tag{5}$$

where K_6 = constant in (mm/A), and R = resistance of speaker coil $\cong 4\ \Omega$. Substituting (4) and (5) in (3):

$$f_1 = \frac{f_{00}}{1 + \frac{K_4K_5K_6}{R}} + \frac{f_2K_5K_6\left(\frac{K_4}{R}\right)}{\frac{K_4K_5K_6}{1 + \frac{K_4K_5K_6}{R}}} \tag{6}$$

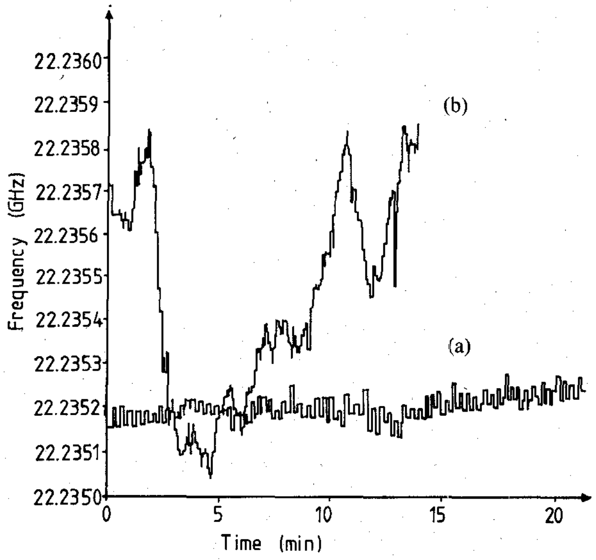

Fig. 6. (a) Locked oscillator frequency variation with time. (b) Unlocked oscillator frequency variation with time.

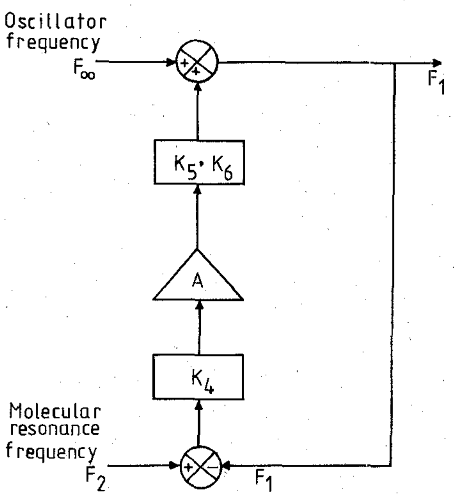

Fig. 7. Control block diagram of the system.

where the loop gain is $A = (K_4K_5K_6)/R$. If the loop gain is 99, then f_1 depends only 1% on f_{00}, but it depends 99% on f_2.

The constants K_4, K_5 and K_6 were evaluated by experimentation. K_4 was found by calculating the slope of the second harmonic signal shown in Fig. 2, and it was found to be 1.74 V/MHz. K_5 was found to be 29 MHz/mm using data characterizing the frequency pull ability of the resonator to the solid state source [6]. Finally K_6 is in the order of 5 mm/A. The overall loop gain achieved was 252.

IV. Conclusion

A Gunn diode oscillator was locked to the first rotational resonance frequency of the water molecule. A high quality factor, Fabry–Perot semiconfocal open resonator was coupled to the solid state microwave source. The frequency stability achieved was of the order of ±50 kHz.

The stability of the control loop would be enhanced if the physical distance between the Gunn oscillator and cavity load is kept to a minimum. Ideally the Gunn diode should be placed at the iris plane.

This arrangement involving an off the shelf cheap Gunn diode, a high quality factor cavity and a detector can achieve a considerable frequency stability adequate for microwave spectrometry. Also, a relatively expensive atomic clock stable reference oscillator is not required as is the case when a microwave oscillator is phase locked to a stable reference oscillator. The frequency stability obtained here is achieved at 22.235 GHz so there is no need for up conversion as would be required if an atomic frequency standard such as the HP 5061B with option 004 was used.

There is plenty of development work to be carried out in order to enhance the frequency stability of the system. Following this principle several polar gases could be held in the same cavity exhibiting distinct resonant lines so a multi-frequency secondary standard stable oscillator could be realised. Taking this a bit further, individual miniaturized units could be manufactured in the form of vacuum diodes exhibiting several stable frequencies.

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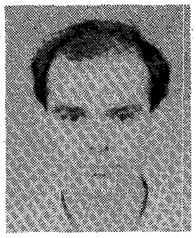

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