

TECHNICAL INSTRUCTION
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THE RUBIDIUM FREQUENCY STANDARD

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Introduction

The Rubidium Frequency Standard generates outputs of 5 MHz, 1 MHz and 100 kHz with a stability better than 5 parts in 10^{11} . These can be used to produce very accurate transmitter-carrier or colour-subcarrier frequencies. The Standard operates by stabilising the frequency of a crystal oscillator against a natural atomic resonance of the isotope Rubidium 87.

The BBC has purchased a number of Hewlett Packard 5065A Rubidium Frequency Standards and the explanation which follows is based on this unit. Other Rubidium Standards are available but the principles by which they operate are virtually identical.

A pair of Rubidium Frequency Standards are on loan to the BBC from the National Physical Laboratory. These are installed at Droitwich Transmitting Station and are used to derive an accurate 200-kHz carrier for the Radio-2 transmitters. These transmitters are sufficiently powerful for their output to be received in most parts of the United Kingdom without the need for a sophisticated receiver. The carrier can thus be extracted and used as an accurate frequency standard.

If light of a particular wavelength falls on Rubidium 87 in its vapour form some of the light energy is absorbed by the vapour. Provided the wavelength of the light is correct some of the atoms in the lower ground state are excited into a third energy level which is significantly higher than the two ground states. This process is known as *optical pumping*. (See Fig. 1). The absorption of light energy can be observed as an apparent increase in the opacity of the Rubidium 87 vapour.

Atoms in the optically-excited state, after a time, fall back to one of the two ground states; there is no preference and approximately equal numbers of atoms fall back into each state. However, an excess of atoms in the upper ground state results because those which fall back into the lower ground state are rapidly pumped back to the optically-excited state. In this way the process of optical pumping transfers atoms originally in the lower ground state to the upper ground state via the optically-excited state.

If the vapour is now irradiated with microwave energy at a particular frequency (known as the hyperfine frequency) atoms in the upper ground state give up energy and return to the lower ground state where

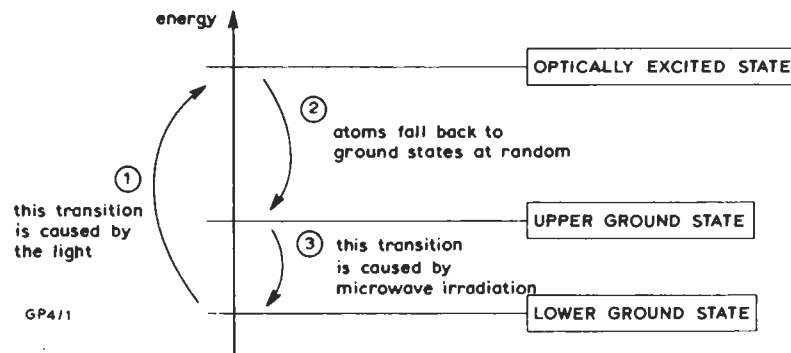


Fig. 1. Energy Levels in the Rubidium 87 Atom

Initial Considerations

Before the operation of the Standard can be understood it is necessary to appreciate a simplified explanation of some of the properties of the Rubidium atom.

A naturally-occurring atom of Rubidium 87 usually has one of two energy levels. These two energy levels, which are known as the upper and lower ground states, exist because there are two possible ways in which an electron can spin in a given orbit. Normally in a sample of Rubidium 87 a condition of equilibrium exists with about half the atoms in the upper ground state and half in the lower ground state.

they are available again for optical pumping.

Thus by simultaneous irradiation of Rubidium 87 vapour with light of the correct wavelength and microwave energy of the correct frequency the atoms can be cycled continuously between the three energy levels. This is the process which occurs in the Rubidium Frequency Standard and the fact that the microwave frequency must be of a precise value gives the Standard its accuracy.

In practice some atoms in the upper ground state are made unstable by collisions with each other and with the walls of the cell containing the vapour. The unstable atoms fall back to the lower ground state and this has the undesirable effect of equalising the

numbers of atoms in the two ground states. This is avoided by including a so-called buffer gas in the cell at a significantly higher pressure than the rubidium vapour. The buffer gas reduces the number of rubidium-to-rubidium and rubidium-to-cell collisions and so prevents large numbers of atoms falling back from the upper to the lower ground state independently of the presence of microwave irradiation.

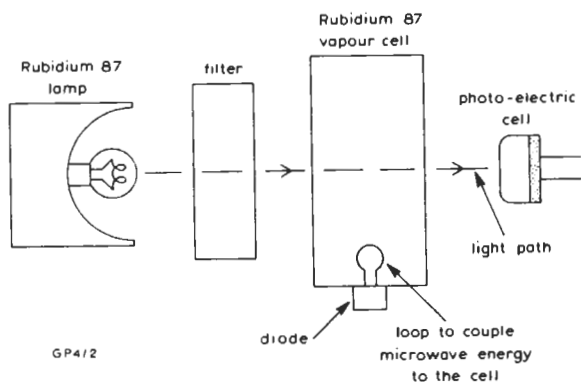


Fig. 2. The Optical System

Operation of the Rubidium Frequency Standard

Light of the wavelength required to stimulate transitions from the lower ground state to the optically excited state is derived from a rubidium 87 discharge lamp as shown in Fig. 2. Unfortunately the lamp also provides a wavelength which would excite atoms in the upper ground state. This wavelength is not required and so it is filtered out by a rubidium 85 filter. (The atomic structure of rubidium 85 is such that it provides a strong absorption in the region of this wavelength.) Light of the remaining required wavelength passes into a cell containing rubidium 87 vapour where it excites atoms from the lower ground state to the optically excited state.

A diode coupled to the vapour cell is fed with two signals; one at 60 MHz and the other at approximately 5.314 MHz, both derived from a 5-MHz crystal oscillator. The inherent non-linearity of the diode yields a whole gamut of frequencies including one of approximately 6834.686 MHz which is the frequency required to produce the transition from the upper to lower ground state.

Only when the microwave signal (and hence the 5-MHz signal from which it is ultimately derived) is at exactly the correct frequency is the opacity of the vapour a maximum. The change in opacity is detected by allowing the light which has passed through the vapour cell to fall onto a photo-electric cell. The output from the p.e.c. is amplified and used to control the frequency of the 5-MHz oscillator to maintain the microwave signal at the correct frequency for maximum opacity of the vapour. Because only a very small change in the microwave frequency causes an easily detectable change in vapour opacity, the frequency of the 5-MHz oscillator is maintained within very fine limits.

The variation of light passing through the vapour cell (and hence of the p.e.c. output) as the frequency of the irradiating microwave signal is varied as shown in Fig. 3.

Production of the 6834.686-MHz Signal

The 6834.686-MHz signal is formed by the interaction of 60-MHz and 5.314-MHz signals in the diode.

The 5-MHz signal is used to synthesise a signal of 5.314-MHz. The 60-MHz signal is derived by straightforward multiplication of the original 5-MHz signal. (See Fig. 4.)

One of the signals formed in the diode is the 114th harmonic of 60 MHz (i.e. 6840 MHz). This mixes with the 5.314-MHz signal to produce 6834.686 MHz.

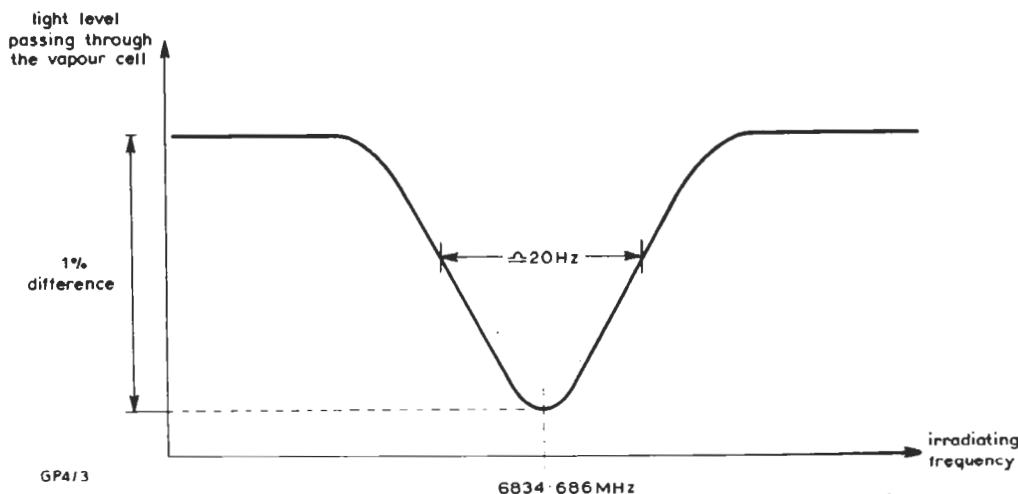
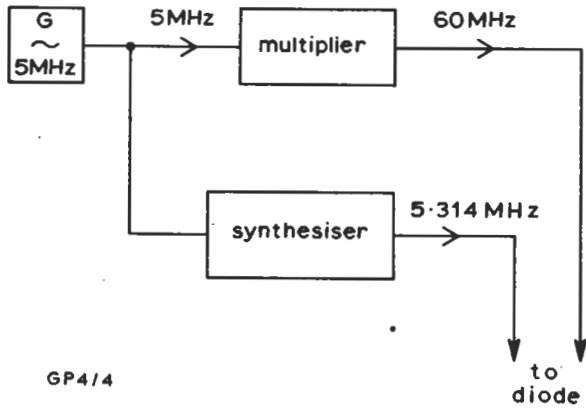


Fig. 3. Change in Opacity with frequency of the Vapour Cell



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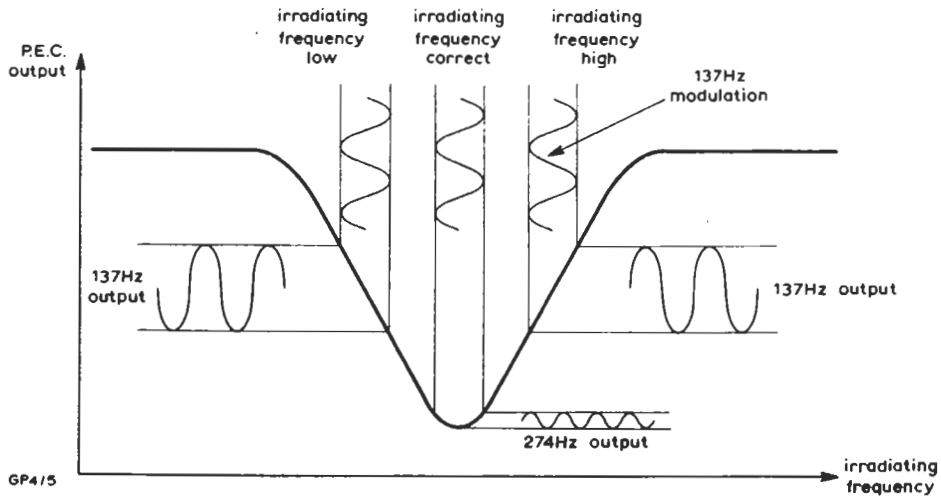
Fig. 4. Hewlett Packard 5065A: Production of 5.314-MHz and 60-MHz signals

Control of the 5-MHz Oscillator

Before multiplication to 60 MHz the 5-MHz signal is phase modulated at 137 Hz. This results in a 137-Hz variation in the light passing through the vapour cell as the modulation sweeps the irradiating signal frequency back and forth across the dip in the light output/irradiating frequency characteristic.

The p.e.c. senses the variation in light level and generates an a.c. signal which is at 274 Hz if the irradiating signal is at the correct frequency, but at 137 Hz if it is high or low. If the irradiating frequency shifts from one side of the dip to the other, the phase of the p.e.c. 137-Hz output changes by 180°. This enables discrimination between 'frequency high' and 'frequency low' conditions to be made, as shown in Fig. 5.

The p.e.c. output is amplified and then applied to a phase detector which senses the phase of any 137-Hz component in the p.e.c. output. The resulting d.c. signal is integrated and applied to the 5-MHz oscillator as a control signal.



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Fig. 5 Variation in output signals from the photo-electric cell with change in microwave frequency

Text continued overleaf

A block diagram showing the arrangement of the complete frequency standard is shown in Fig. 6.

Frequency Stability of the Rubidium Standard

The presence of the buffer gas in the cell has the effect of slightly modifying the frequency of the microwave signal required to produce the transition from upper to lower ground state (the hyperfine frequency). The buffer gas also makes the hyperfine frequency temperature-dependent but this effect can be minimised by careful choice of buffer gas. Other factors which affect the hyperfine frequency are the temperature of the vapour cell and the static magnetic field within it.

3000 years or, 1° of subcarrier phase in 1 minute. Short-term stability is typically better than 7 parts in 10^{13} over 100 seconds.

Output Frequency Adjustments

The output frequency of the Standard can be adjusted by two independent methods:

1. A coarse frequency control can be effected by changing the division ratio in the 5.314-MHz synthesiser. This changes the microwave frequency applied to the vapour cell and consequently changes the 5-MHz oscillator via the control loop.
2. Fine frequency control can be effected by

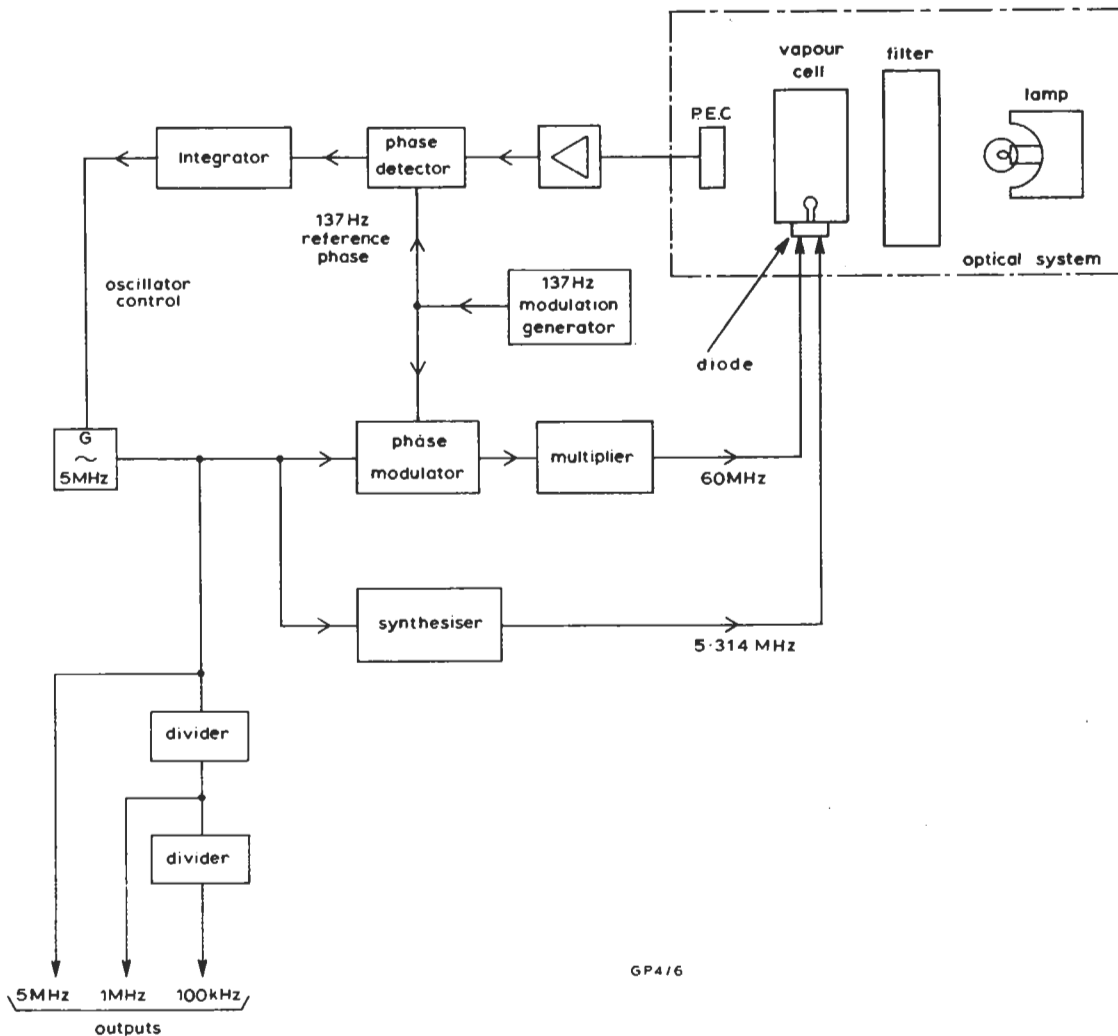


Fig. 6. A simplified block diagram of the Hewlett Packard 5065A Rubidium Frequency Standard

Because the above factors affect the hyperfine frequency (and hence the output frequency) the Rubidium Frequency Standard is a secondary Standard and must be adjusted (e.g. by reference to a Caesium Standard or Hydrogen Maser) after manufacture.

Once set, the long-term stability of the Standard is typically better than 1 part in 10^{11} per month. This is approximately equivalent to 1 second in

adjusting the static magnetic field within the vapour cell. A coil carrying d.c. is placed around the cell and permits variation of the magnetic field.

Coarse corrections typically cover a range of 100 parts in 10^9 with fine adjustments over a range of 2 parts in 10^9 . The final resolution is about 2 parts in 10^{12} .