The Passive Optically Pumped Rb Frequency Standard: the Laser Approach

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***Abstract*—This paper provides an overview of the efforts accomplished during the last few decades in the attempt of implementing a Rb-cell frequency standard using optical-microwave double resonance and laser optical pumping. The results of a new analysis based on a three-level model are summarized. Pumping rates, line widths, light shifts, cell radiation transmission and resonance signal size relative to background are calculated making use of the coherence property of the pumping laser. The expected frequency stability is calculated. The results obtained by several research groups are reviewed, compared to the analysis, and evaluated in the context of the implementation of a practical frequency standard. It is concluded that compromises must be made between the goal of obtaining a frequency stability close to the shot noise limit and that of minimizing complexity. Two directions that address such compromises are outlined.** [1]

I. Introduction

Early in the development of passive Rb frequency standards using a closed cell and double resonance, microwave-optical radiation, lasers have been suggested as sources of radiation for optical pumping. The evident advantage is the narrowness of the radiation spectrum, which can provide efficient optical pumping without the need of hyperfine filtering as in the classical approach. Such a characteristic reduces the stray background radiation and minimizes shot noise at the detector. However, sources at the proper wavelength were not readily available until the advent of the solid state diode laser, except for the case of the cumbersome dye laser. In the 1970's, solid state diode lasers became available at wavelengths corresponding to the resonant D_1 and D_2 spectral lines of some alkali atoms, and soon optical pumping experiments were attempted with those devices [1, 2]. With a power of several mW, lasers having the appropriate wavelength with a spectral width less than 100 MHz provided sources of radiation that appeared suitable to replace the spectral lamps. Following these pioneer experiments, the field has been the subject of numerous studies. In general, experimental results have fulfilled expectations relative to signal characteristics, but in general the predicted frequency stability was not reached unless special arrangements were implemented in order to compensate for the extra noise introduced by the laser itself. At the time of writing, sealed cell frequency standards using laser optical pumping and the double resonance technique have been the subject of a large number of laboratory implementations but are not available yet commercially.

[1] The present document is a short version of an Invited Article that will appear in Applied Physics B, 2007.

II. Experimental Setup

A typical experimental arrangement is shown in Fig. 1. The system includes two servo loops, one for locking the laser wavelength to the optical absorption line selected, and one for locking the frequency of the microwave generator to the hyperfine resonance line. In some setups the laser frequency is locked to a narrow absorption line obtained by means of saturated absorption in an external cell and in some cases is stabilized on an external cavity. When switch SW is closed, the arrangement acts as a frequency standard, while when it is opened the arrangement may be used as a spectrometer for studying the response of the resonance cell to either double resonance (optical-microwave), or laser excitation alone.

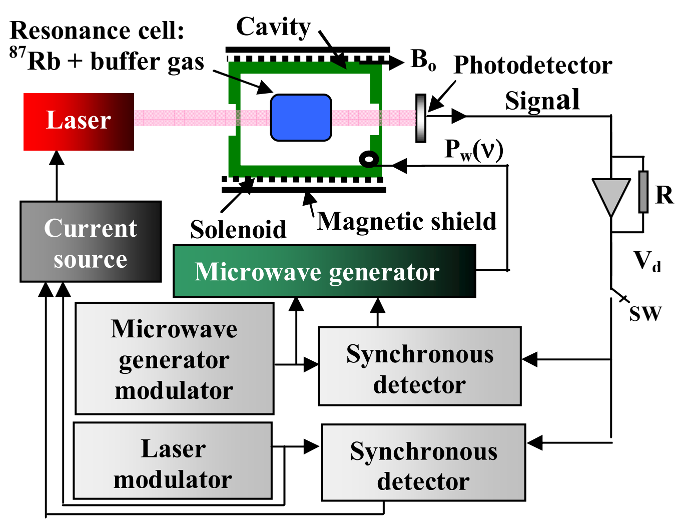

Figure 1. Typical experimental setup used in the study of laser optical pumping for the implementation of a frequency standard with a sealed cell. The system can be used as a spectrometer (switch SW opened), or a frequency standard (switch SW closed).

The frequency stability of the system in the time domain is given by [3, 4]:

$$\sigma(\tau)=\frac{KN}{\nu_0 I_{bg} q}\tau^{-1/2} \tag{1}$$

where N is the noise spectral density observed at the photo detector originating from all sources, I_{bg} is the current developed in the photodetector by the background radiation and τ is the averaging time. K is a factor that depends on the modulation waveform and is of the order of 0.2. The parameter "q" is the so-called quality factor defined as the ratio of the contrast C to the line width (several hundreds of Hz). C is the ratio of the resonance signal intensity to background intensity (several percent). In general, shot noise is a natural limit to the achievable frequency stability and its power spectral density is given by:

$$N^2 = 2eI_{bg} \tag{2}$$

where e is the charge of the electron.

The above equations show that in the case of shot noise, frequency stability is controlled by three parameters: line width, contrast and background current. Consequently, a reduction in background radiation should result in better frequency stability in the shot noise limit. This consideration and possible simplification in design and construction created an interest in the use of solid state diode lasers instead of spectral lamps for implementing that type of clock. This is due to the fact that the laser spectrum being very narrow, <100MHz, more efficient optical pumping results, leading to less background radiation, less shot noise and higher contrast of the hyperfine resonance line. In practice, as will be shown below, a contrast larger than 10% is calculated and observed with laser optical pumping, due essentially to a reduction of the background current by about two orders of magnitude.

III. BASIC ANALYSIS

An analysis based on a simple three-level model, as shown in Fig. 2, provides the necessary background for evaluating contrast line width and the important inherent light shift that appears when the atomic system is submitted to optical pumping at a single wavelength.

The system "radiation fields-atomic ensemble" is analyzed in the density matrix formalism [4, 5]. The dynamical behavior of the matrix elements representing the population of the energy levels, ρ_{ii}, and the coherence, ρ_{ij}, existing in the system, is obtained from Liouville's equation:

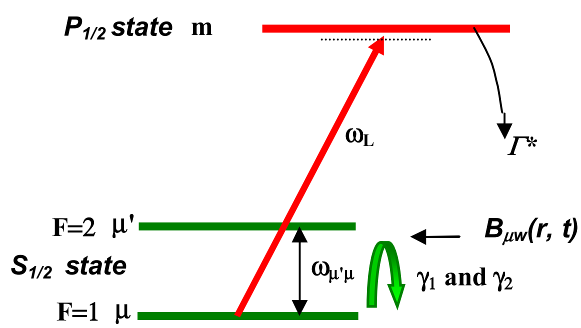

Figure 2. Three-level model used in the present analysis for double resonance in [87]Rb. In practice the laser is tuned close to either of the two transitions from μ or μ' to m.

$$\frac{d}{dt}\rho_{jk}=(i\hbar)^{-1}\sum_i\left(H_{ji}\rho_{ik}-\rho_{ji}H_{ik}\right) \tag{3}$$

where H is the interaction Hamiltonian of the various fields applied, in occurrence the laser and the microwave radiation fields. All relaxation mechanisms are added in a phenomenological way. The intensity of the radiation traversing the cell is calculated from the following differential equation, obtained from Maxwell's equations:

$$\frac{\partial\Omega_{L\mu m}}{\partial z}=\alpha\, Im\,\delta_{\mu m} \tag{4}$$

where $\Omega_{L\mu m}$ is the Rabi frequency associated with the atom-optical radiation interaction and $\delta_{\mu m}$ is the complex amplitude of the optical coherence $\rho_{\mu m}$. The parameter α is the absorption coefficient given by:

$$\alpha=\left(\frac{\omega_{\mu m}}{c\varepsilon_0\hbar}d_{\mu m}^2\right)n \qquad [\mathrm{m^{-1}s^{-1}}] \tag{5}$$

with c being the speed of light, ε_o the permeability of free space and n the atomic density. The problem consists in solving Eq. 4, with the laser coherence, $\delta_{\mu m}$, a solution of Eq. 3 for a typical experimental situation. The Rabi frequency, $\Omega_{L\mu m}$, being proportional to light intensity, gives the intensity of the radiation at any point, z, within the resonance cell, and consequently contains all information on background intensity, signal size, line width and frequency shifts. The results of the analysis are best represented as graph as shown in Fig. 3 to 5 calculated at the exit of a 2 cm long cell These results are presented as a function of the pumping rate proportional to the light intensity.

As is readily observed, for a typical situation with a pumping rate of the order of the relaxation rates of the atomic ensemble, ~1000-2000 s^{-1}, the contrast may be as high as 10 %, while the line width is of the order of 550 Hz.

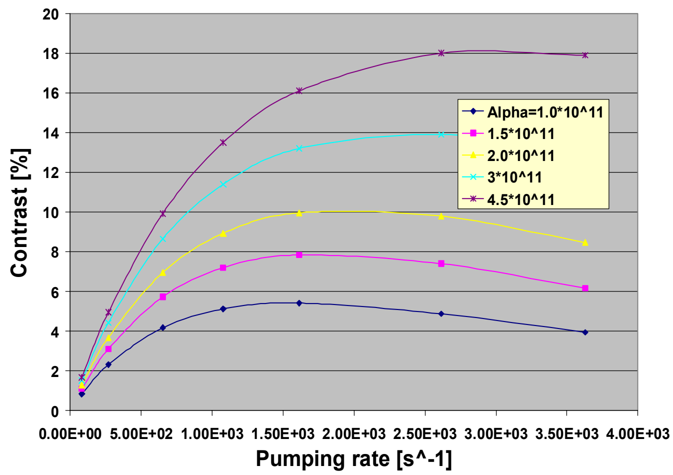

Figure 3. (Theory) Contrast calculated as a function of pumping rate for various values of the absorption coefficient. The microwave Rabi frequency is assumed to be $1.41 \times 10^3\ s^{-1}$. The points in the graphs originate from the software used in the calculation and help in identifying the various curves.

This high contrast is essentially due to the narrow width of the laser spectrum, which is more than an order of magnitude less than that of a spectral lamp, thus, reducing background radiation. Using Eq. 1, assuming an absorption coefficient $\alpha = 2 \times 10^{11}\ m^{-1}s^{-1}$, corresponding to a cell temperature of about 65 ^{o}C, and a background current of the order of 1 µA, as is observed in a typical experimental setup, the shot noise limited frequency stability expected is approximately:

$$\sigma(\tau) \cong 10^{-13}\ \tau^{-1/2}$$

as calculated from Eqs. 1 and 2.

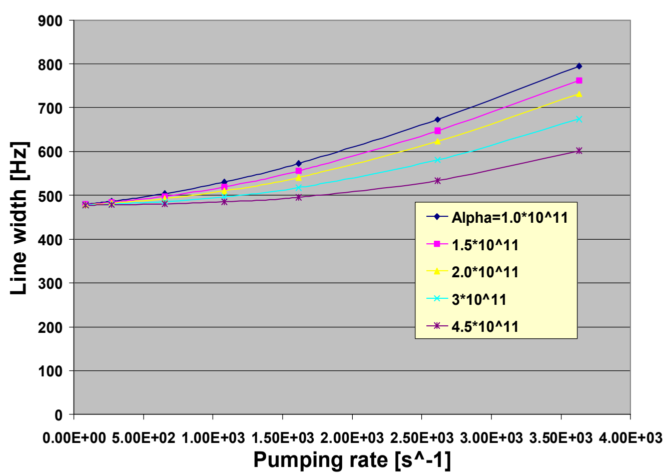

Figure 4. (Theory) Line width calculated as a function of pumping rate for various values of the absorption coefficient. The microwave Rabi frequency is assumed to be $1.41 \times 10^3\ s^{-1}$.

On the other hand, Fig. 5 shows that the light shift is rather important, being as large as a few hundred Hz depending on pumping rate and laser detuning from exact optical resonance. This behavior imposes severe constraints on the stability of the laser frequency and intensity, constraints that can be taken care of experimentally by appropriate stabilization schemes.

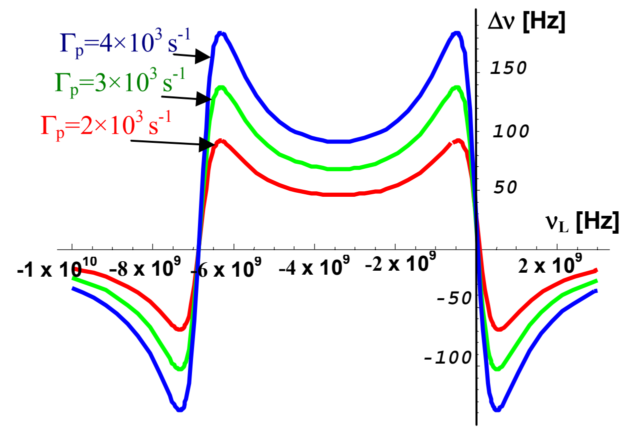

Figure 5. (Theory) Light shift expected in ^{87}Rb within the three level model for three values of the pumping rate corresponding to rates that produce visible broadening (see Figures 4 and 5). The parameter ν_L used as abscissa is the laser frequency and has its origin at the frequency of the transition $S_{1/2}$, F=2 to P.

IV. EXPERIMENTAL OBSERVATIONS

The implementation of a setup for observing the double resonance signal in ^{87}Rb with a laser is straignforward. Observed signal contrast and line width are of the size calculated above in the three-level model [6]. Consequently, the theoretical short term frequency stability calculated above in the shot noise limit holds.

On the other hand the light shift has been investigated by many authors [7-18]. In general it is found to be of the order of magnitude of the size shown in Fig. 5. A typical result as reported by Lewis and Feldman for optical pumping in ^{87}Rb from ground state level F=1 to the $P_{3/2}$ state is shown in Fig 6 [8].

It is readily observed that the size of this light shift requires a laser frequency stability of the order of a few kHz if a clock frequency stability of the order of 10^{-13} is desired in the long term. This sets rigid requirements on the frequency stabilization of the laser itself. Furthermore the servo system used to stabilize the laser frequency may not be locked exactly to zero light shift. This may happen even in the case when the laser frequency is locked to the absorption line in the resonance cell. Due to distortions created by overlaping absorption lines of various intensities, the maximum of the absorption may not coincide with zero light shift. In that case, the clock fequency may depend on the intensity of the laser. This light shift, in certain cases, may be as large as several parts in 10^{11} for 1% change in light intensity.

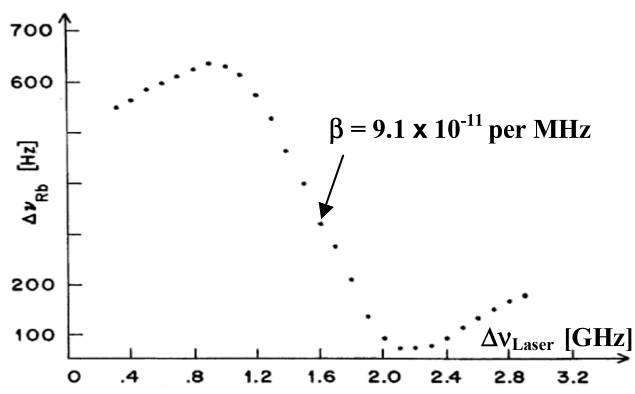

Figure 6. Light shift as measured by Feldman and Lewis in ^{87}Rb using and edge emitting diode at ~250µW per cm^2 and tuned to the D_2 transition (reproduced from [8] © IEEE 1981). The origin of thevertical axis is arbitrary.

In the short term, the frequency stability observed with arrangements using off the shelf edge emitting laser diodes is of the order of 10^{-11} at 1 second averaging time. Considerable efforts have been made to understand the origin of the discrepancy between observed frequency stability and that expected from shot noise alone. In this context, the characteristics of the laser have been extensively studied in connection to noise originating from intensity and frequency fluctuations. The situation can be summarized as follows:

1) <u>Intensity noise:</u> Intensity noise is generally represented as a fractional quantity, the Relative Intensity Noise (RIN). For an edged emitting laser diode : RIN ~ 5 x 10^{-13} [Hz^{-1}] [19]. Its contribution to frequency instabilities can be calculated by means of Eq. 1 where N is now the intensity noise spectral density. Two paths are identified:

- direct effect at the photodetector: $\sigma(\tau) \sim 10^{-13}$
- through the light shift. For a typical light shift of 5 x 10^{-11} per 1% change in light intensity, as observed in a typical experimental setup, one obtains: $\sigma(\tau) \sim 3 \times 10^{-16}$

2) <u>Frequency noise</u>: Frequency noise is generally represented by the spectral density $S_\nu(f)_{laser}$ of the laser power output. It is found that:

-this type of noise is not visible directly at the photodetector

- it may contribute to frequency instabilities through the light shift. With an edge emitting diode locked to linear absorption in a resonance cell, $S_\nu(f)_{laser}$ may be of the order of 1.6 x 10^5 [Hz^2/Hz] [20], and $\sigma(\tau) \sim 3 \times 10^{-13}$.

It is thus concluded that these contributions cannot account totally for the frequency instability observed. The cause of the frequency instability appears to reside in the conversion of FM noise to AM noise through non linear absorption effects within the resonance cell [21]. Solutions to this problem have been proposed and were found to be relatively successful. In the first case a narrow spectrum laser such as a DBR type was used. It was stabilized in frequency by means of saturated absorption on an external cell [22]. The results obtained are shown in Fig. 7. In that case special care was also taken to avoid aliasing noise at the second harmonic in the detection signal [23, 24].

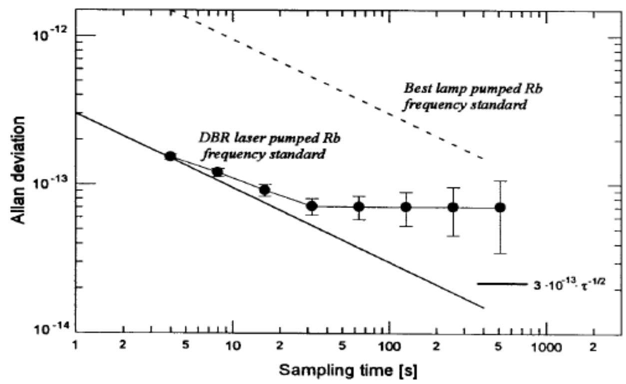

Figure 7. Frequency stability reported for a passive Rb frequency standard using a DBR laser as pumping source, locked to saturated absorption in an external cell (reproduced from [22] © IEEE1998). In that case special care was taken to minimize intermodulation effects from the local oscillator. This appears to be the best results obtained for a laser pumped double-resonance Rb system reported to date.

Another approach consisted in broadening the optical absorption line by filling the cell at a high buffer gas pressure, such as 100 Torr [25]. The optical line being broad, the FM to AM conversion is less efficient. The results are shown in Fig. 8.

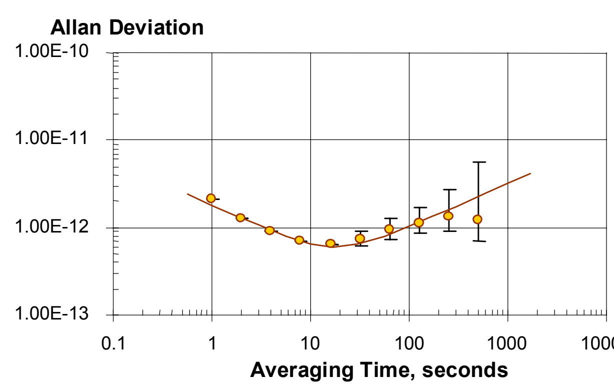

Figure 8. Frequency stability of a Rb frequency standard using a JTS (Junction Transverse Stripe) laser as optical pumping source and a cell with a buffer gas at a pressure of 100 Torr (J. Camparo, private communication 2007, and [25] © IEEE 2004).

In that setup used , the laser frequency was locked to the resonance cell optical absorption line. It appears that the approach provides a good compromise between complexity and frequency stability.

Other techniques have been proposed to reduce the effect of noise at the photodetector, such as canceling the noise generated by FM to AM conversion in the resonance cell, by means of a clone cell generating a correlated noise [18]. However, such a technique is rather complex and appears to miss to a large extent the original goal of simplifying the system.

SUMMARY AND PROSPECTS

The classical approach used in implementing a double-resonance passive frequency standard with a spectral lamp as pumping source shows limitations relative to frequency stability mainly due to the resulting large background current that produces shot noise and reduces signal contrast. The frequency stability in typical small units is of the order of $10^{-11}\ \tau^{-1/2}$ for averaging times shorter than 100 seconds and is generally limited by shot noise. Furthermore, the use of a spectral lamp limits the possibility of a reduction of power consumption as well as size.

The use of a laser diode for optical pumping shows great promises either relative to short term frequency stability, size reduction and at the same time power consumption. The advantages of using a laser diode resides particularly in its narrow spectral width (≤50MHz) relative to a spectral lamp (~ 1GHz). This provides more efficient optical pumping, increases contrast, reduces the background radiation by orders of magnitude, and consequently reduces shot noise. A calculation shows that a shot noise limited frequency stability better than $10^{-13}\ \tau^{-1/2}$ should be observed in the short term with commonly available edge emitting diodes. However, it is found in practice that using this type of diode a frequency stability less than $10^{-11}\ \tau^{-1/2}$ is observed. It has been shown that several phenomena may be responsible for this characteristics. In particular, the conversion of laser frequency noise to intensity noise (FM-AM conversion) by the cell has been claimed to be a main contributor to the measured limited frequency stability. The laser intensity noise (RIN) appears to play a role only at a level of frequency stability in the range of 10^{-13}.

In some special laboratory configurations, laser pumped frequency standards have been implemented with frequency stability reaching the 10^{-13} level at an averaging time of 1 s, close to the shot noise limit. However, these were constructed with elaborate techniques such as extended cavity laser stabilized by saturated absorption in an external cell, passive noise cancellation by means of an extra clone cell, or still using rather costly DBR or DFB lasers.

In the long term, that is for periods over hours or days, the light shift may be an important factor in the determination of frequency stability if the laser is not well stabilized and tightly locked to the optical resonance line used to create the optical pumping. Even in that case, the locking frequency may not be corresponding to zero light shift and a residual intensity dependent light shift may be present.

It appears at present that if the conditions, small size, low power consumption, and low cost are the primary goals, a compromise in choice of components and construction is required. In this respect a common type laser with a spectral width in the tens of MHz used in conjunction with a ^{87}Rb cell containing a mixture of buffer gases at a pressure of 100 Torr or higher can lead to frequency stability in the low $10^{-12}\ \tau^{-1/2}$. In all cases, as in the optical pumping with a spectral lamp approach, care needs to be taken in using an interrogation oscillator, that is quartz oscillator and synthesizer, having noise spectrum characteristics at the second harmonic of the modulating frequency that are compatible with the frequency stability desired. The reliability of laser diodes, although rather satisfactory when such lasers are used in a laboratory environment, may also be a factor affecting decision when field applications are considered [26].

ACKNOWLEGMENT

The authors wish to thank J. Camparo for invaluable advices on the original text to appear in Applied Physics B.

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For a more complete bibliography, the reader is invited to consult the long version of the paper in Appl. Phys. B, 2007.