Characterisation of rubidium vapour lamps for atomic clocks

Ulas Gokay, Nitika Gupta, Rabia Ince, Hugh Klein, Guilong Huang, Mohsin Haji
Time and Frequency Department, National Physical Laboratory, Teddington, Hampton Road, TW11 0LW, UK
ulas.gokay@npl.co.uk

***Abstract*— Since the 1960s, alkali-based RF discharge lamps have been used as frequency-stable light sources due to their reliable performance [1]. However, it is often reported that rubidium (Rb) lamp-based standards suffer from lamp-related frequency ageing phenomena such as light-shift effects [2, 3]. To understand this behaviour, we are characterising a commercial Rb-based RF discharge lamp over extended periods and will present an analysis of data collected so far. Electrical and optical measurements on a Rb lamp are presented here after about 40 days of monitoring. The output of the lamp was coupled into an optical fibre to observe its emitted light characteristics with an optical spectrum analyser. Optical spectra results indicated that the lamp had substantial buffer gas content. The lamp spectra exhibited various buffer gas excitation lines as well as strong Rb excitation lines of 780.0 nm (D2 line) and 794.8 nm (D1 line). Subsequently, the lamp was monitored for output optical power, temperature, and electric current dynamics in a laboratory environment. During monitoring, sudden changes in light output were observed along with longer term trends. From previous studies, we can expect that temporal changes in the light intensity of the lamps may lead to observable frequency fluctuations in an atomic clock [4].**

Keywords—Rb lamps, atomic clocks, ac-Stark shift

I. Introduction

Rb lamp-based frequency standards exhibit lamp-related ageing effects, which directly affect the frequency stability of an atomic clock [2]. Among these ageing effects are sudden 'jumps' in intensity, which lead to an ac-Stark shift of the clock transition frequency [3, 4]. In this study, we investigate the operational characteristics of a Rb vapour lamp through optical power, temperature, and electric current measurements performed over an extended period of time. We observed several jumps in the lamp intensity along with a correlation of light output with the lamp temperature and current drawn.

II. Measurement setup

Fig. 1 shows a schematic of the measurement setup for lamp lifetime testing. A Rb lamp was housed in an enclosure which contained the electronics needed for the temperature and RF power controls. An electrical power supply unit controls the RF power and the operational temperature of the lamp enclosure and sends the electrical data to the computer (PC). Light from the lamp was collected and collimated with a plano-convex lens, while a bandpass filter was used to isolate the lamp spectrum between 750.0 nm and 800.0 nm. A photodetector (PD) was used to measure the optical power and send the data to the PC. An independent thermistor and a digital multimeter were used to measure the resistance values of the temperature sensor positioned inside the lamp housing. Thermistor resistance values were converted to temperature readings in degrees using the Steinhart-Hart equation. The sampling rate for the data collection was set to 4 samples/min for all devices to prevent thermistor self-heating effects from biasing the measurement results.

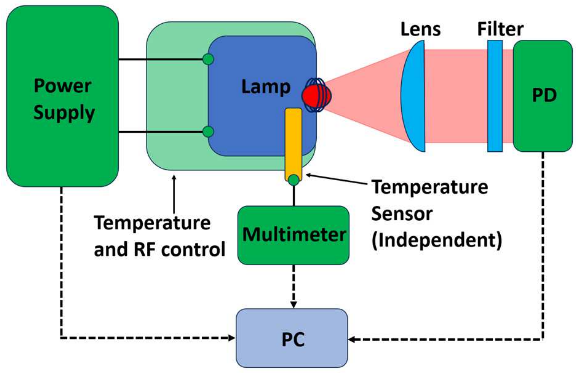

Fig. 1. Schematic for the measurement setup.

III. Results and analysis

In this section, optical spectra of the 'Lamp A', along with long term monitoring results for the normalized optical power, lamp temperature and current drawn are given.

A. Optical Spectra

Fig. 2 shows the optical spectra results for 'Lamp A'. The lamp exhibits strong ^{87}Rb excitation lines of 780.0 nm (D2 line) and 794.8 nm (D1 line), where several other lines show that 'Lamp A' contains a bulb with Xe buffer gas along with the ^{87}Rb. The observed spectral lines were identified by using the known inert gas lines in the NIST Atomic Spectra Database [5].

B. Electrical and Optical Performance

Fig. 3 shows the normalised optical power, temperature, and current drawn for 'Lamp A' against time since activation.

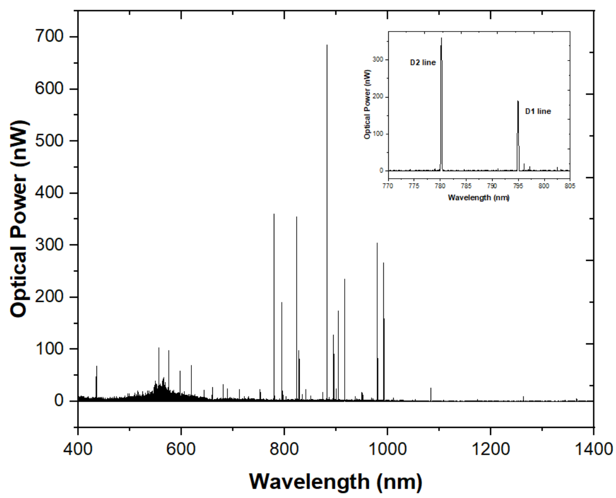

Fig. 2. Spectral lines of the gas contents of 'Lamp A'.

The authors acknowledge funding support from Innovate UK.

Yellow-coloured stars show the detected jumps in the normalised optical power data. These jumps were identified using a custom detection algorithm (explained below).

When analysed, there are various normalised optical power fluctuations and trends associated with changes in the current drawn or the lamp's temperature. Especially around the day 15, an optical power spike was observed which wasn't flagged as a 'jump' by the detection algorithm. The spike was correlated with a sudden increase in the lamp temperature and a drop in the current drawn. This spike is currently under investigation and the cause is thought to be related to external factors. Additionally, there are a few occasions when an intensity 'jump' occurs without a corresponding 'jump' in current drawn or temperature. The origin of these jumps is unknown, and further study is required. Nevertheless, both types of intensity 'jumps' will result in an unwanted ac-Stark shift, which affects an atomic clock's frequency stability [4].

An extrapolation-based detection algorithm was prepared to detect the optical power jumps [6]. A linearly extrapolated optical power value is calculated for each term n, by using the previous four values of the normalised optical power dataset. Then a difference between each normalised optical power value $P(n)$, with the extrapolated optical power value $P_{ext}(n)$ was calculated. The resulting difference, $\Delta P(n) = |P_{ext}(n) - P(n)|$ is compared with $k\sigma_{opt}$, where σ_{opt} is the standard deviation of the normalised optical power dataset and $k = 1$ is a threshold parameter selected to minimize false detections [7]. While running the detection algorithm, if $\Delta P(n) > k\sigma_{opt}$, then a jump is flagged with its occurrence time and the associated normalised optical power value. The algorithm was beneficial for eliminating false jumps, i.e., longer-term optical power changes due to temperature or current drawn.

Fig. 4 shows the jump magnitude difference (given as a percentage) from the mean normalised optical power against time since activation. By using the detection algorithm, a total of 18 jumps were flagged in the normalised optical power data of 'Lamp A'. In this context, jump magnitude difference in percentage was calculated for each jump by subtracting the mean normalized optical power ($P_{mean} = 1$) from the flagged jump magnitude and multiplying the difference by 100%.

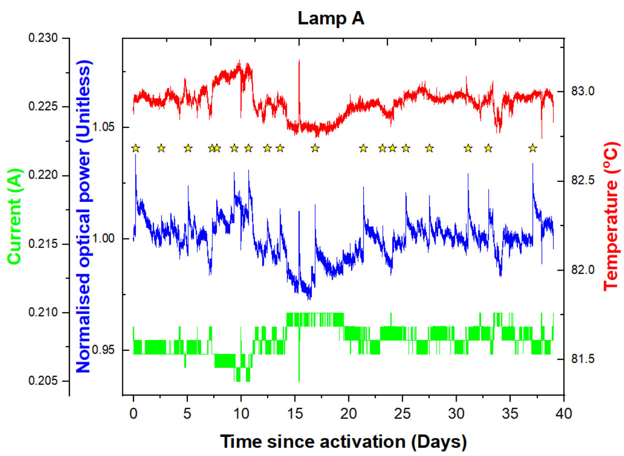

Fig. 4. Measurement results for 'Lamp A'.

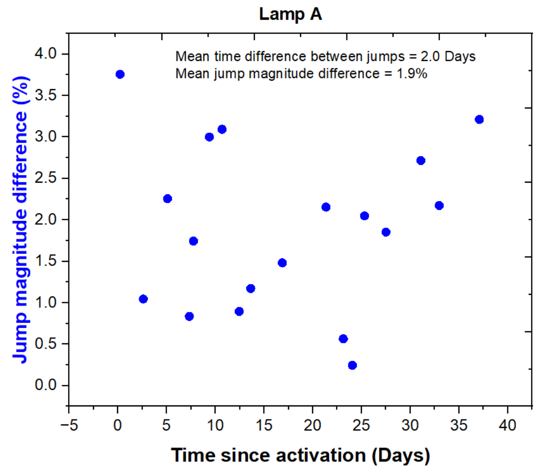

Fig. 3. Jump magnitude in percentage calculated with respect to the mean optical power of 'Lamp A'.

The mean jump magnitude difference for 'Lamp A' was found to be 1.9%. The mean time difference between jumps was found to be 2.0 days.

IV. Conclusions

Further investigations are underway for understanding the relationship between the buffer gas contents of the lamps and the observed intensity jumps along with the causes of the observed current variations and temperature spikes. A statistical analysis of the intensity shifts, and a failure mode analysis for the Rb lamps are also planned.

References

[1] W. J. Riley, "A history of the rubidium frequency standard", IEEE UFFC-S History, vol. 2, 2019.

[2] C. H. Volk and R. P. Frueholz. "The role of long-term lamp fluctuations in the random walk of frequency behavior of the rubidium frequency standard: A case study", Journal of applied physics vol. 57.3, p. 980-983, 1985.

[3] J. Camparo, "The rubidium atomic clock and basic research", Physics today, vol. 60.11, p. 33-39, 2007.

[4] J. Camparo, "Does the light shift drive frequency aging in the rubidium atomic clock?", IEEE transactions on ultrasonics, ferroelectrics, and frequency control, vol. 52.7, p. 1075-1078, 2005.

[5] A. Kramida, et al., NIST Atomic Spectra Database

(ver. 5.11), [Online], (accessed on 13 June 2024), https://physics.nist.gov/PhysRefData/ASD/lines_form.html

[6] L. Galleani and P. Tavella, "An algorithm for the detection of frequency jumps in space clocks", Proceedings of the 42nd Annual Precise Time and Time Interval Systems and Applications Meeting., 2010.

[7] L. Galleani and P. Tavella, "Detection of atomic clock frequency jumps with the Kalman filter", IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 59(3), 504-509, 2012.