Noise Investigation on Optical Detection in a Cesium Beam Clock with Magnetic State Selection

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***Abstract*—Noise sources in optical detection of a magnetic-state-selection cesium beam clock are analyzed in this paper. Atomic shot noise, photon shot noise, laser frequency noise and stray light noise are considered. Experimental measurements and estimations of the noise magnitude are made.**

Keywords—frequency standard; cesium clock; laser; noise;

I. INTRODUCTION

We reported the use of optical detection in a cesium beam tube where state selection is accomplished by magnets [1]. Short-term frequency stability of $1.0\times10^{-11}\cdot\tau^{-1/2}$ is achieved. Theoretical and experimental results on short-term stability in frequency standards of different types are reported, such as in [2-5]. The short-term stability of an atomic frequency standard is dependent on the line width and the signal-to-noise ratio. The atomic-shot-noise limit is believed to be reached in a well-tuned magnetic-state-selection beam tube. When optical methods are applied to improve the performance, additional noise arises. Noise sources in an optically pumped cesium beam tube are analyzed [6]. In this paper, we give a description the main noise sources in the optical detection in our cesium beam clock. The noise power spectrum density measurement under different conditions helps with estimation of noise magnitude.

II. EXPERIMENTAL SET-UP

As shown in Fig. 1, cesium atoms are deflected by the inhomogeneous magnetic field caused by magnet A. Double beam scheme is used, i.e. two atomic beams are emitted and deflected symmetrically, which is not shown in the figure. The microwave cavity has two interaction lengths of 1 cm each and a microwave-free distance of 17 cm. An external cavity diode laser with line width of 100 kHz, which is frequency-locked to $(F=4\leftrightarrow F'=5)$ transition of cesium D2 line with help of saturated absorption spectroscopy, serves as the light source. The laser-induced fluorescence of the atomic beam is collected by a pair of spherical mirrors and detected by a photodiode, which is different from the storage bulb in [1]. The photo current is converted to voltage signal with an equivalent resistance of 10^7 ohm. The fluorescence signal is processed by a digital servo system similar to that in [7]. Power spectrum density of the fluorescence signal is measured with a digital data acquisition card from National Instruments, whose sample rate is set as 20 kHz. Square wave frequency modulation on the microwave input is adopted where the modulation frequency is 78 Hz. Allan deviations of the frequency output are measured against an H-maser, whose short-term stability is believed to be several-fold better than this clock.

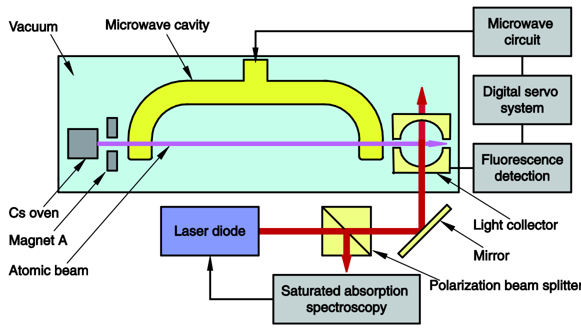

Fig. 1. Schematic diagram of our cesium beam clock.

III. NOISE IN THE DETECTION

A. Signal-to-noise ratio

The general equation for estimating short-term frequency stability in a frequency standard is

$$\sigma(1s)\propto\frac{1}{S/N}\frac{\Delta\nu}{\nu_0}. \tag{1}$$

$\Delta\nu$ and ν_0 are respectively the line width and central frequency. S/N is the total signal-to-noise ratio which is defined as

$$S/N=\frac{U_S}{\sqrt{S_N}}. \tag{2}$$

U_S is the amplitude of Ramsey spectral line. S_N is the noise power spectrum density when there is only white noise, which is usually the case when we consider short-term frequency stability. The noise powers from different sources are considered to be statistically independent. Hence their power spectrum density could be added to obtain the total noise power. The total signal-to-noise ratio can be written as

$$S/N = \frac{1}{\sqrt{\sum_i \frac{1}{(S/N_i)^2}}} \qquad (3)$$

where S/N_i is the partial signal-to-noise ratio when only one noise source is taken into account.

B. *Atomic shot noise*

In a thermal atomic beam device, the atoms arrive at the detection region with a particular rate, depending on oven temperature. The number of atoms arrived during certain period is modeled by Poisson process. The variance of atom number arriving during time τ is

$$\mathrm{Var}(N_{\mathrm{a}}) = I_{\mathrm{a}}\tau \,. \qquad (4)$$

I_{a} is the rate of atom arrival, i.e. average number of atom arriving in one second. All $F=4$ atoms at the detection region are detected, including both the effective atoms that undergoing microwave interrogation, and the residual $F=4$ atoms due to the imperfection of state selection, the rate of which are defined as I_{e} and I_{r} respectively. By the way, I_{e} is proportional to the difference between the number of $(F=3, m_F=0)$ and $(F=4, m_F=0)$ atoms after magnet A, because they both interact with microwave and the actual Ramsey spectrum is a subtraction of them.

The partial signal to noise ratio of atomic shot noise is

$$(S/N)_{\mathrm{a}} = \frac{I_{\mathrm{e}}}{\sqrt{I_{\mathrm{e}} + I_{\mathrm{r}}}} \,. \qquad (5)$$

Theoretically derivation of the ratio between I_{e} and I_{r} is impractical because the lack of knowledge of exact atom trajectory near magnet A. The spectrum of atomic beam when sweeping the detection laser's frequency is shown in Fig. 2. The spectrum is taken at laser power of 1.5 mW and oven temperature of 100°C. It is seen that the ratio is approximately $I_r / I_{\mathrm{e}} = 4.5$. This ratio varies little with the oven temperature which is experimentally verified, while I_{e} and I_r can both be enhanced with high oven temperature.

C. *Photon shot noise*

The fluorescence photons emitted by atoms are detected by some probability because the finite efficiency of the light collector and the photodiode. This can be equivalently treated as Poisson process as well, where the rate of the arrival of photons is

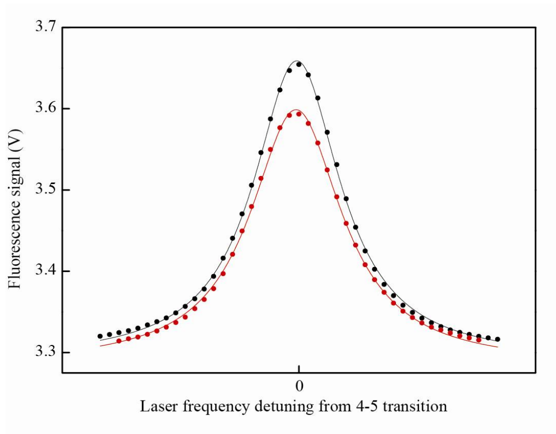

Fig. 2. The atomic beam spectrum versus the laser frequency near $(F=4 \leftrightarrow F'=5)$ transition. Black and red points are experimental results with microwave on and off respectively. The lines are fitted lorentz lineshapes.

$$\alpha + \beta = \chi. \quad I_{\mathrm{p}} = \beta\eta I_{\mathrm{a}} \,. \quad (1) \qquad (6)$$

β is the average number of photons emitted by an atom. η is the detection efficiency of each photon. The partial signal-to noise-ratio is

$$(S/N)_{\mathrm{p}} = \sqrt{\beta\eta}\,\frac{I_{\mathrm{e}}}{\sqrt{I_{\mathrm{e}} + I_{\mathrm{r}}}} = \sqrt{\beta\eta}\,(S/N)_{\mathrm{a}} \,. \qquad (7)$$

This noise is negligible compared with the atomic shot noise when $\beta\eta$ is much greater than unity, which is easily satisfied when $(F=4 \leftrightarrow F'=5)$ transition, the cyclic transition, is used for detection.

D. *Laser frequency noise*

$\alpha + \beta = \chi.$ (1) (1)

For the atomic beam's laser spectrum is not flat around $(F=4 \leftrightarrow F'=5)$ transition, fluctuations of the laser frequency will result in fluctuations of the fluorescence signal. This is an effect that correlates all $F=4$ atoms in the detection region, making the noise power proportional to $(I_{\mathrm{e}} + I_{\mathrm{r}})^2$, which leads to a signal-to-noise ratio

$$(S/N)_{\mathrm{f}} \propto \frac{I_{\mathrm{e}}}{I_{\mathrm{e}} + I_{\mathrm{r}}} \qquad (8)$$

independent of oven temperature [6, 8]. This indicates that a limit of short-term stability usually emerges when the oven temperature is high, because the laser frequency noise increased faster than atomic shot noise when the atomic beam flux intensity is large.

E. *Stray light noise*

Fluctuations in laser intensity have two influences. One is on the average photon number emitted by an atom and the other is on the stray light which is directly detected. The former is relatively small because the fluorescence is much weaker than scattered light, which is seen by the comparison of the peak and background in Fig. 2. Its property of independence of atoms makes the measurement of the stray light noise possible.

IV. Measurement and Estimation of the Noise

A. Stray light noise measurement

In this experiment, the laser frequency is locked to the crossover line between $(F = 4 \leftrightarrow F' = 4)$ and $(F = 4 \leftrightarrow F' = 5)$ in a saturated absorption spectrum. Because the atomic beam spectrum is Doppler-free, laser locked to the crossover line hardly excites any atoms. The noise here is mainly the stray light noise. Fig. 3 shows the noise power spectrum density around the modulation frequency with respect to the background voltage, which is proportional to the power of the incident light. By the way, the noise power of the detection system is about one order of magnitude less than the measured value and has been subtracted from all the data in this paper.

It is experimentally verified that U_S increases linearly with laser power when the power is small and saturates when laser power is large. Hence this partial signal-to-noise will show a peak when the laser power is tuned. However, for its relatively small power density compared with the atomic shot noise and laser frequency noise, this noise is almost negligible with a large range of laser power when the oven temperature is not too low.

B. Laser frequency noise measurement

Measurement of the noise power spectrum density at varies oven temperature is made when the laser is locked to $(F = 4 \leftrightarrow F' = 5)$ transition. The measured stray light noise power has been removed from the data. The power densities are plotted with respect to U_S, the amplitude of Ramsey spectral line in Fig. 4. In this case, the laser frequency noise and the atomic shot noise are coupled. However, they are proportional to different orders of atomic flux intensity as mentioned earlier. Fitted quadratic line of Fig. 4 indicates that the laser frequency noise is dominating within the temperature range in this experiment, from 95°C to 135°C. By direct measuring the frequency stability, we see that the short-term stability varies little within this temperature range, which is in accordance with the theory.

V. Conclusion

Noise sources in optical detection are analyzed in a cesium beam clock with magnetic state selection. The power spectrum densities of fluorescence signal are measured for estimation of the noise. This method is easy to realize and is possible for cases when the local oscillator cannot be locked. It is theoretically shown that the large ratio of I_r / I_e affect both atomic shot noise and laser frequency noise. The second-order relationship makes its influence on the laser frequency noise more serious, which leads to the limit of short-term stability at oven temperature above 95°C. Improvement on selection method that reduces this ratio will help to effectively enhance signal-to-noise ratio at high oven temperature.

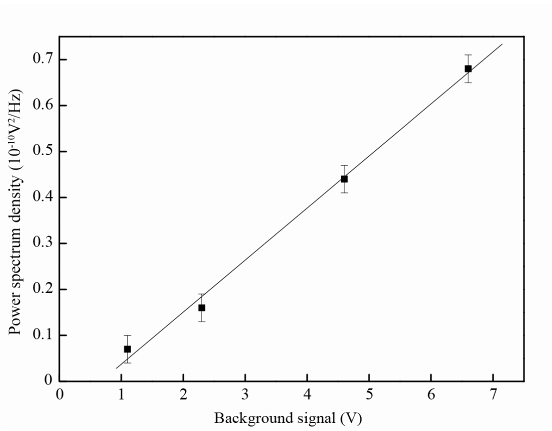

Fig. 3. The experimental data and fitted linear line of power spectrum density depending on the background signal with laser locked to the crossover line.

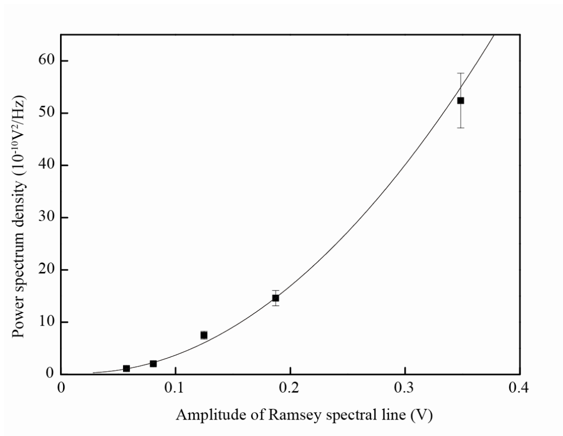

Fig. 4. The experimental data and fitted quadratic line of power spectrum density depending on the Ramsey line amplitude, U_s, with laser locked on the cyclic transition.

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