Atomic Clocks and Lasers

EP3338 - Photonics & Laser

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Abstract

In this report I cover an important uses of lasers in modern-day atomic clocks - laser cooling. Specifically used in the working of a caesium-fountain clock, which is employed to define the 'second'.

1 Introduction - Lasers

A laser - light amplification by stimulated emission of radiation - is a form of electromagnetic radiation which finds use in systems which require narrow width, high spatial-temporal coherence, and tuning capability. Atomic clocks specifically use lasers for cooling, probing, and excitation of atoms. They do so with the use of diode lasers.

Laser diodes are semiconductor devices where the a p-n junction diode acts as the gain medium in the laser. As electrons cross the p-n junction and recombine with holes, they release photons. To amplify the coherent photons released, mirrors are used on either side of the semiconductor to trigger the electrons to recombine prematurely. The photons may then escape through the partially-reflective end of the laser diode.

2 Application (Laser Cooling)

2.1 Defining The Second

The present definition of the second relies on the concept of frequency of oscillations of a certain object. The simplest form of such an experiment to measure the duration of a second, is a simple pendulum. Assume a standard second pendulum (one which can be constructed regardless of how we calculate the second). Having a time period of two seconds, one swing of the pendulum takes a second, exactly, theoretically. Hence, if one were to measure the time duration of a swing, that would be equal to a second.

Modern watches use quartz clocks where the quarts crystal replaces a simple pendulum (shown in 1a). Similarly, the definition of a second is defined as follows -

> ... It is defined by taking the fixed numerical value of the caesium frequency Δv_{Cs}, the unperturbed ground-state hyper-fine transition frequency of the caesium 133 atom, to be 9 192 631 770 ...

By using an even higher number of cycles we achieve higher accuracy.

$$\sigma \propto \frac{\Delta v}{v_0\sqrt{N}}\sqrt{\frac{1}{\tau}}$$

Where, Δv is the frequency line-width, N is the atoms sampled, and τ is the interaction time which can be tweaked using other methods. We see that the instability of a clock (σ) decreases with a lower clock frequency (v_0), and hence the hyper-fine transition of the Cs atom is used, and there are talks of using optical clocks in the visible light spectra for even more accurate clocks.

2.2 Principle of Working: Caesium-Fountain Clocks

The principle of working is essentially how a simple pendulum works, but using ultra-cold Caesium atoms instead, and using lasers, as shown in 1b. The group of atoms that needs to be probed is confined to vacuum-space in the chamber, using six lasers in all orthogonal directions. To make measurements accurately, the atoms need to be ultra-cold, and as close to absolute zero as possible. This is achieved using **Laser Cooling**, (primarily Doppler Cooling coupled with more advanced techniques). The temperature of the atoms is related to the r.m.s velocity as such:

$$v \propto \sqrt{T}$$

Further on, the atoms are sent through a cavity and radiated with MASERS and later a laser is used to probe them to find the resonant frequency.

2.3 Laser Cooling - Doppler Cooling

As mentioned before, the atomic gas of Caesium is brought down to near-absolute zero through the laser cooling. The primary method used is a concept called Doppler Cooling, which is based on the Doppler shift of frequencies experienced by the atoms in their frame.

$$f_{atoms} = f_{laser}\sqrt{\frac{1-\beta}{1+\beta}}$$

$$\beta = \frac{v_{atoms}}{c}$$

Consider an atom moving with a significant velocity. For a laser to affect the movement of the atom, it will have be absorbed. Thus, a photon with an appropriate frequency can be absorbed by the atom and its momentum is transferred thus. Now, this excited atom will (depending on its excitation period) re-emit a photon and be scattered isotropically. Since this re-emission can be in any direction, there is no net momentum change due to it.

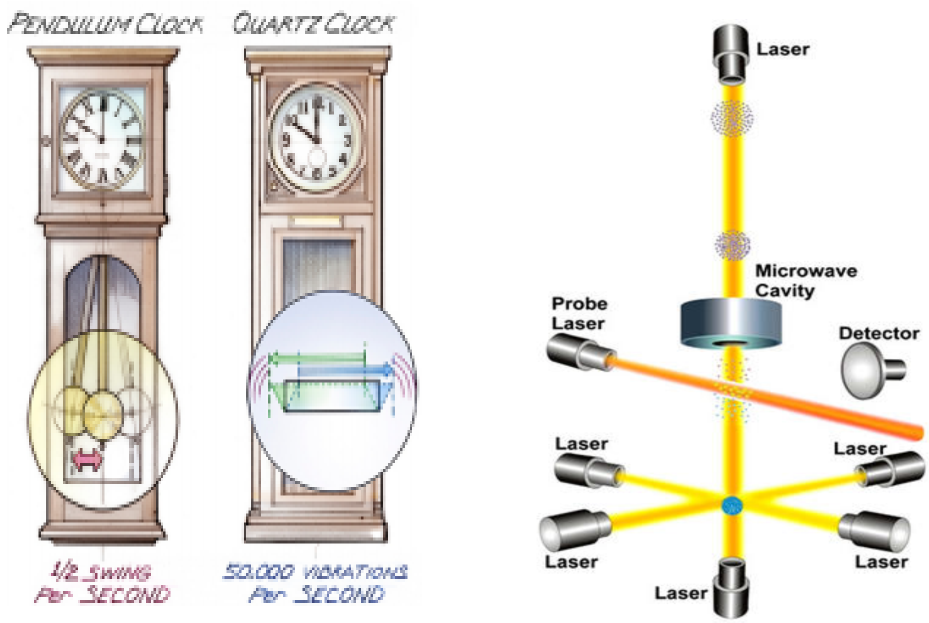
Now, if the atom starts moving the other way, a tuned laser will end up pushing it further through absorption. This problem is solved through laser de-tuning, which employs the Doppler effect. In the example case, when an atom is travelling against a laser, the laser's frequency will be up-shifted and hence absorbed, thus damping the atom's motion. When the atom starts moving in the opposite direction, the opposing de-tuned laser will now act as the damper, while the other laser will have no effect as it has been red-shifted and the frequency is even further de-tuned. Thus, the lasers can be continuously tuned in order to attain a certain maximum velocity and minimum temperature.

This system of cooling and launching makes use of an 'optical molasses', shown in 2a. An *optical molasses* is a set-up consisting of two counter-propagating lasers that use Doppler cooling to trap and lower the temperature of atomic gas. Here we use three such pairs of lasers to trap the atoms and cool them.

Once the atoms are cooled down, they need to pushed up. For this, the vertical lasers are de-tuned such that the bottom laser is slightly below the resonant frequency and the top laser is slightly above, while also maintaining the temperature of the 'optical molasses'. For a stationary optical molasses the two lasers are slightly below the resonant frequency, but here since the frequency above is greater, it gives a resultant velocity, hence a 'moving molasses', shown in 2b.

Further, the cooled atoms may also diffuse through random-walks, and this prevented by using a Magento-Optical Trap, which employs the Zeeman effect to push the atoms back into the molasses.

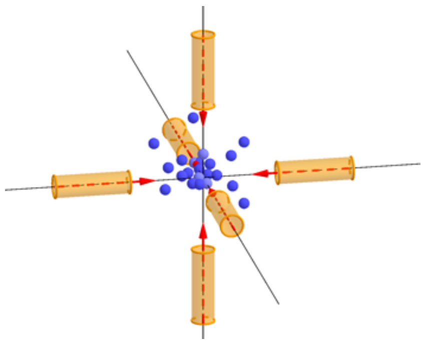
3 Figures



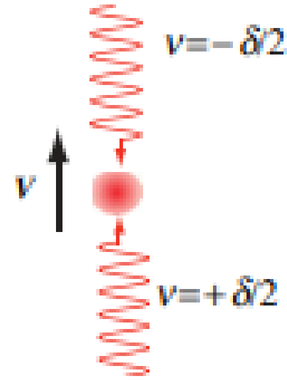
(a) Measuring Second Using Frequency Standard (Pendulum vs Quartz)

(b) Caesium Fountain Clock)

Figure 1



(a) Optical Molasses in 3 Orthogonal Directions



(b) Launching Cold Atoms using De-tuned Lasers

Figure 2

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