

Optical system design of a portable coherent population trapping (CPT) atom clock

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We present the mechanism of coherent population trapping (CPT) atom clock. The optical system is designed for a portable CPT atom clock. In this system, single transverse mode vertical-cavity surface-emitting laser is used as a miniature pump laser. The driven circuit is designed based on a field-programmable gate array full digital control system and special-purpose chip MAX1968. The experimental results show that the optical system can provide circularly polarized light, and has small volume and low power consumption. These indicate that the optical system is a promising candidate for a portable CPT atom clock engineering prototype.

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In recent years, the coherent population trapping (CPT) phenomenon^[1,2] has drawn more and more attention in the time and frequency community. The possibility of using the CPT phenomenon for the implementation of atomic clocks was proposed in the last decade, and experiments are currently being carried out on several laboratories^[3-11]. Portable atom clock with small volume has been in demand for portable equipment such as GPS and BEIDOU receivers, in-field telecommunication devices, and various kinds of measuring instruments. Since CPT atom clock is the smallest atom clock in theory, it has been appointed as the candidate for satellite space-positioning system.

A CPT atom clock consists of optical system, physical package, and electrical control system. To realize a portable CPT atom clock, the most important problem is designing minimum and low power consumption subsystems. However, the optical system of a CPT clock usually has a large pump laser and high power consumption, which are not suitable to a commercial portable product.

In this letter, we present the principle of CPT phenomenon, and describe a typical CPT atom clock system. Furthermore, the optical system of CPT atom clock is designed. The experimental results show that the optical system meets the requirement of a portable CPT atom clock engineering prototype.

Figure 1 shows the three level Λ system in alkali-metal atoms with two long-lived ground states $|1\rangle$ and $|2\rangle$ and one excited state $|3\rangle$. The transition frequencies from ground states $|1\rangle$ and $|2\rangle$ to $|3\rangle$ are ω_1 and ω_2 . The ground-state hyperfine-splitting frequency is ω_0 . The CPT resonance can be excited by circularly polarized bichrome light fields, and the light frequencies are ω_1 and ω_2 . At exact resonance, no atoms are excited to the $|3\rangle$ state. Fluorescence disappears and the cell becomes transparent because no energy is absorbed from the light field. Using the fluorescence or transmission spectrum, a CPT atom clock can be achieved.

Figure 2 shows a schematic view of a CPT atom clock, comprising optical system, physical package, and electrical control system. In optical system, the bichrome light fields are made by a pump laser, and the frequencies of light fields are modulated to ω_1 and ω_2 transition. The polarized state of the light is circularly polarized. The light passes through a vapor cell containing atom gas and buffer gas. This vapor cell is surrounded by a magnetic shield and placed inside a solenoid which applies a longitudinal magnetic field of the order of $10 \mu\text{T}$ to lift the Zeeman energy levels' degeneracy and to separate the "clock" resonance, which has no first-order magnetic field dependence, from the field-dependent resonances. The electrical control system comprises two control loops. The first loop locks the laser wavelength to the minimum of the absorption spectrum and the second loop locks the modulation frequency and output standard frequency.

For a commercial portable CPT clock, the main problem is the miniaturization of key systems, especially of optical system. Usually, the optical system of CPT clock has a large pump laser and high power consumption, which are not suitable to a commercial product. A proper optical system should have three characters:

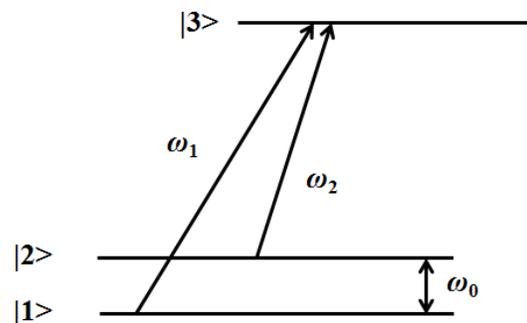


Fig. 1. Three level Λ system in alkali-metal atoms.

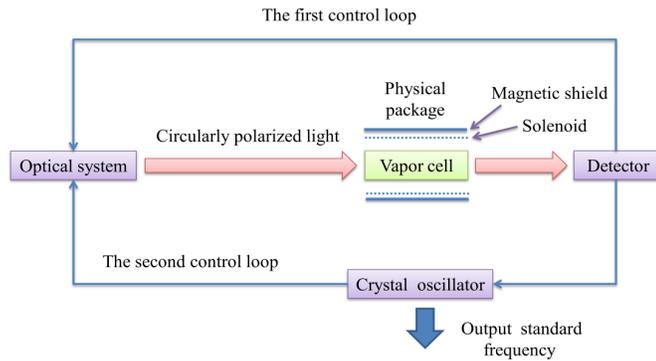


Fig. 2. Schematic view of a CPT atom clock.

1) the pump laser should have a small volume, 2) the power consumption is low, and 3) the optical system can provide circularly polarized light. Based on the above discussion, we design an optical system and test the parameters.

Figure 3 shows the detailed setup of optical system, comprising pump laser, driven circuit, and optical elements to adjust the light field. Pump laser is the light source of optical system in CPT atom clock. In order to reduce both the size and power consumption of pump laser, near-infrared vertical-cavity surface-emitting laser (VCSEL) is the most promising pump laser source owing to their most remarkable features such as small volume (\sim mL) and low power consumption (\sim mW)^[12-14]. Here, a single transverse mode 795 nm VCSEL modulated by an RF source in TO-5 is used as the pump laser. However, VCSEL is quite sensitive to the temperature, so a temperature controlling system should be designed in the optical system. Therefore, the VCSEL is the integrated thermal electric cooler (TEC) and thermistor that allow for temperature and wavelength stabilization.

The driven circuit consists of a current source, which can be tuned from 0 to 5 mA, and a temperature controlling circuit including thermistor test circuit and a field-programmable gate array (FPGA) controlling circuit. In order to realize temperature controlling circuit, fuzzy PID control algorithm and temperature acquisition circuit is designed based on the FPGA full digital control system and special-purpose chip MAX1968.

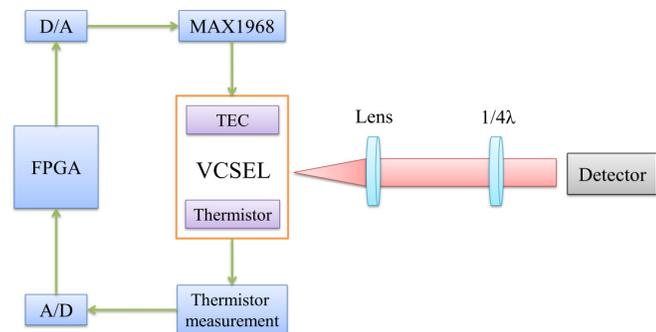


Fig. 3. Detailed setup of optical system.

The temperature controlling circuit can achieve temperature controlling range up to 20–85 °C, precision of 0.02 °C, and power consumption of 0.1 W. This electric driven circuit can achieve control algorithm in digital domain, and more flexible control method is supplied using fuzzy PID algorithm. These advantages are quite benefit of further research of whole portable CPT atom clock.

The light-current out power ($L-I$) curve at ambient 25 °C is shown in Fig. 4. The threshold current is about 0.5 mA. The voltage-current ($V-I$) characteristic is shown in Fig. 5. As the current increases from 0 mA, the voltage of the VCSEL increases rapidly at low current and then slowly increases. The experimental data indicate that the corresponding power consumption of VCSEL is only several milliwatts. The linearly polarized optical output from the VCSEL was sent through a lens and a quarter-wave plate to create circular polarization. The polarization degree p was measured by

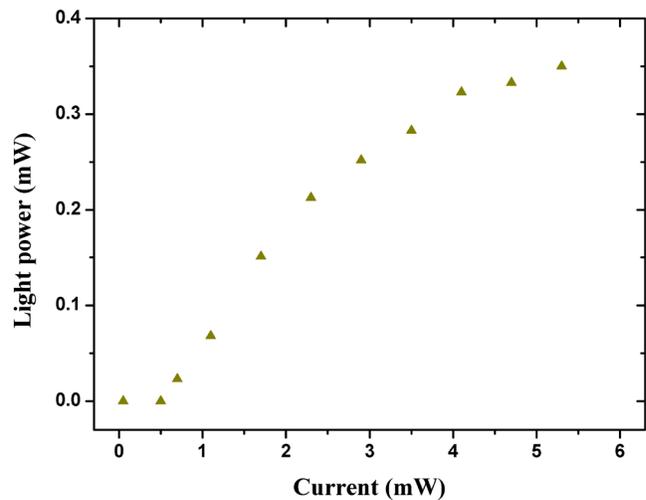


Fig. 4. $L-I$ curve at ambient 25 °C.

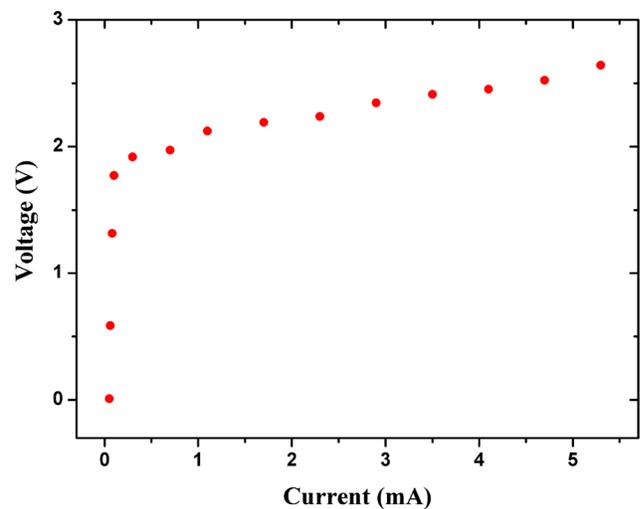


Fig. 5. $V-I$ curve at ambient 25 °C.

a Glan–Taylor prism and the result was $p = 0.003$. To distinguish between circular polarized and natural light, the light beam created by the optical system was passed through another quarter-wave plate, and the polarized measurement showed $p = 0.997$. These proved that the light beam created by the optical system was circular polarized.

The optical system in this work is designed for the future portable engineering prototype. Compared with traditional principle prototype, it has the following advantages: 1) its volume of the optical system in this work is only several milliliters, while it is usually several liters in a principle prototype; 2) the power consumption is only several milliwatts, which is much smaller than the power consumption of the traditional principle prototype; 3) this small and low power consumption optical system can provide circularly polarized light, which meets the requirement of CPT phenomenon. Based on this system, the portable CPT clock engineering prototype is being designed now, and the work will be completed in this year.

In conclusion, based on the discussion of the mechanism of CPT atom clock, the optical system is designed for a portable CPT clock. In this system, a single transverse mode VCSEL is used as the miniature pump laser. Moreover, the servo electric circuit is designed to drive the VCSEL and control the operating temperature. The experimental results indicate that the optical system has small volume, low power consumption, and can provide circularly polarized

light. These results indicate that the optical system is a promising candidate for a portable CPT atom clock engineering prototype.

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