脉冲激光抽运铷原子钟理论与实验研究

杜志静†

(中国科学院国家授时中心 西安 710600)

原子钟作为导航系统的星上时间基准，是卫星导航系统的导航定位系统的定位精度和寿命。目前星载原子钟主要为传统铷原子钟，从可靠自主运行及技术多样化角度出发，开展新型原子钟研究具有重要意义。

基于传统铷原子钟体积小、重量轻、结构简单等优点，本文对新型高精度原子钟—脉冲激光抽运(POP)铷原子钟进行了深入的理论和实验研究。采用在时间上分离的脉冲激光抽运，Ramsey微波脉冲与原子相互作用方式，原子为二能级系统，消除了光场与微波场的耦合，从而可以获得更好的长周期稳定度。获得微波和光学Ramsey信号，采用微波探测方式，实现了原子钟的闭环锁定，短期稳定度达国际先进水平，同时开展了微波频段引起EIT (electromagnetically induced transparency)信号Autler-Townes分裂的实验研究。推进了POP铷原子钟的研究。主要研究内容如下：

(1) 采用密克矩阵方法，对POP铷原子钟进行了理论研究。研究表明：(a) 微波脉冲面积为π/2时，POP Maser铷原子钟的中心Ramsey条纹线宽为1/(4T)，其中T为Ramsey频率，是传统Ramsey方式的1/2，提高了子线的品质因子；(b) 剩余光频移和腔牵频移大大减小，比传统铷原子钟小3个量级，可以获得更好的中长期稳定度。

(2) 从原子钟稳定度的需求出发，对光学和物理部分的实验器件进行了理论和实验研究，完成了激光系统、微波腔、锁腔、C场和时序的研制，对POP铷原子钟的关键器件—锁腔和微波腔进行了重点研究。理论研究Ar和N2比例对温度系数和信噪比的影响，获得了适合的缓冲气体比例；对微波腔的模式、Q值、温度特性、充冷分子以及耦合因子等进行了理论和实验研究。

(3) 设计了POP Maser铷原子钟实验装置，实现了闭环锁定，获得了较好的短期稳定度，并对其进行了实验研究。为了消除光频移和腔牵频移，测量了POP Maser铷原子钟的中心频率以及两个微波脉冲后原子自感应微波辐射信号强度与微波脉冲Rabi频率的关系，结果表明满足要求的合适微波脉冲面积大于π/2；获得了POP Maser原子钟的微波Ramsey条纹和光学Ramsey条纹，线宽分别为65 Hz和150 Hz，实现了POP Maser铷原子钟谱面的闭环锁定，短期稳定度为4.5×10^{-13}τ^{-1/2} (1≤τ≤100 s)，短期稳定度与国际水平相当。

(4) 在POP铷原子钟实验装置上，对^{87}Rb热原子室中微波场扰动EIT三能级耦合跃迁和探测跃迁两种情况进行理论和实验研究。研究表明EIT信号的Autler-Townes分裂频率与微波Rabi频率和失谐相关，对POP原子钟的非0-0跃迁频率以及微波腔内原子感应有效微波场强度，进行了实验验证，推进了POP铷原子钟的研究。

†2011-07-08获得博士学位，导师：中国科学院国家授时中心张百刚研究员；duzj@ntsc.ac.cn
Theoretical and Experimental Study of Pulsed Optically Pumped Rubidium Frequency Standard

DU Zhi-jing
(National Time Service Center, Chinese Academy of Sciences, Xi’an 710600)

Atomic clocks have been recognized as the critical equipments for the global navigation satellite systems, and their performances determine the positioning accuracies and lifetimes of the satellite navigation systems. In order to ensure the reliability and technological diversity, it is of great importance to study new type atomic clocks with high precision.

The advantages such as simple operation, compactness, and small size, make the Rb frequency standard preferred for satellite navigation systems. In order to reduce the light shift and cavity pulling shift, the Pulsed Optically Pumped (POP) Rb frequency standard has been theoretically and experimentally studied in this thesis, in which the pumping, interrogation, and detection phases are separated in time to avoid coupling between the microwave and optical field coherences. A laboratory POP $^{87}$Rb frequency standard prototype has been realized. Meanwhile, the Autler-Townes splitting in electromagnetic induced transparency (EIT), which is induced by microwave, has been studied theoretically and experimentally. The main works and results are as follows:

(1) In the formalism of the ensemble-averaged density matrix and in the rotating-wave approximation, a set of equations describing the POP clock dynamics with a three-level model has been obtained, and the optimum physical parameters are derived. When atoms are submitted to $\pi/2$ Ramsey pulses, it is indicated that: (a) With microwave detection, the full width at half maximum (FWHM) is $1/(4T)$ ($T$ represents the Ramsey time), and the quality factor of the atomic line is increased by a factor of 2 with respect to the traditional approaches. (b) The light shift effect may be canceled, and cavity pulling effect may be strongly reduced. A better medium-, and long-term frequency stability is obtained.

(2) The required characteristics of optics and physics packages have been analyzed. The instruments such as the laser system, microwave cavity, Rb vapor cell, quantization field, and time sequence have been developed. The influences of buffer gas ratio between Ar and N$_2$ on the temperature coefficient and signal to noise ratio have been studied. The parameters of microwave cavity have been theoretically and experimentally studied, such as mode, quality factor, filling factor, coupling factor, etc.

(3) A prototype $^{87}$Rb atomic clock has been designed and realized. In order to reduce light shift and cavity pulling shift, an optimum microwave pulse area bigger than $\pi/2$ has been found experimentally. The Ramsey fringes in microwave and optical domain have been measured with FWHM of 65 Hz and 150 Hz, respectively. The achieved frequency stability is $4.5\times10^{-13}\tau^{-1/2}$ ($1 \leq \tau \leq 100$ s), which ranks among the best short-term stability achieved by vapor cell standard in the world.

(4) The Autler-Townes doublet splitting in EIT induced by an additional microwave field has been studied, in which a fourth level has been coupled to coupling or probe transition level of A-type EIT system. The frequency difference of Autler-Townes doublets depends on microwave field intensity and detuning, providing a way to measure the adjacent transition frequency and effective microwave Rabi frequency in POP atomic clock.