用于铯原子里德伯态激发的 509 nm 波长脉冲激光系统*

刘瑶[1)] 何军[1)2)†] 苏楠[1)] 蔡婷[1)] 刘智慧[1)] 刁文婷[3)‡] 王军民[1)2)††]

1) (山西大学光电研究所, 量子光学与光量子器件国家重点实验室, 太原 030006)

2) (山西大学, 省部共建极端光学协同创新中心, 太原 030006)

3) (中国空间技术研究院西安分院, 空间微波技术国家级重点实验室, 西安 710000)

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介绍了一种用于里德伯原子激发的纳秒脉冲激光系统. 实验利用两个 kHz 线宽的 1018 nm 连续激光器作为种子源, 通过两个 20 GHz 带宽的光纤调制器产生时间分离的脉冲激光; 脉冲激光经掺镱光纤放大器后输出峰值功率约 4600 W, 单次穿过 PPLN(周期极化铌酸锂) 晶体倍频获得 509 nm 脉冲激光, 典型脉冲激光峰值功率约 173 W. 该激光系统单路输出脉冲重复频率在 300 kHz—100 MHz 范围连续可调, 脉宽在 1—100 ns 范围连续可调. 该 509 nm 激光在聚焦条件下可以实现 GHz 带宽的铯原子里德伯态激发.

关键词: 里德伯原子, 脉冲激光器, 非线性频率转换, 单光子源

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1 引 言

单光子源是具有最大反聚束效应的非经典光场[1], 其在基本物理问题研究[2,3]、量子精密测量、量子通信[4]以及量子计算[5–7]等领域具有广泛的应用. 目前, 实现单光子源的主要方案包括: 单量子系统方案[8,9]、参量下转换后选择探测方案[10,11]、系综原子集体激发方案等, 这些系统各有优缺点. 基于室温系综原子集体相互作用实现的单光子源[12], 具有线宽窄、产率高、系统简单等优点, 近年来引起广泛关注.

具有强相互作用的系综里德伯原子, 通过激发阻塞效应可以实现单光子源[13]. 基于室温里德伯原子的单光子源, 要求微米尺度的原子气室实现空间局域, 由于原子多普勒效应以及原子气室相互作用导致的退相干, 这要求大功率光源以实现 GHz 带宽的原子态调控. 2012 年, Kölle 等[14]利用脉冲激光系统在室温原子气室中实现了 ns 尺度的原子态调控; 在这个时间尺度上, 热原子的运动距离小于光波长, 外部自由度可以近似为准稳态. 该研究组于 2014 年利用可调谐的染料激光器产生大功率脉冲激光[15], 实现了 GHz 尺度的原子态调控, 并实现了室温原子范德瓦耳斯相互作用实验测量. 2016 年, Ripka 等[16]基于短脉冲激光实现了原子态测量, 实验证实由于室温原子气室的空间不均匀性、多普勒效应等因素影响, 里德伯态原子的相干时间约为 1.2 ns, 这要求激光脉冲强度的等效拉比频率大于 GHz.

图 1 为基于铯原子四波混频方案的单光子源

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† 通信作者. E-mail: hejun@sxu.edu.cn

‡ 通信作者. E-mail: dwt1124@163.com

†† 通信作者. E-mail: wwjjmm@sxu.edu.cn

原理示意图, 该方案选择铯原子$|6S_{1/2}\rangle$, $|6P_{3/2}\rangle$, $|85S_{1/2}\rangle$为四波混频能级, 利用 852 和 509 nm 脉冲光制备原子到里德伯态, 通过微米气室里德伯原子的长程相互作用实现单个里德伯原子激发, 进而实现单光子源. 微米尺度的长程相互作用要求利用微米气室对原子系综进行空间局域, 这会导致原子的退相干时间在微秒或甚至纳秒量级, 这要求大功率脉冲激光以实现在 ns 尺度制备里德伯原子. 对于 852 nm 激光系统, 可以通过电光强度调制器 (EOIM) 实现 ns 尺度的脉冲光[17,18]; 对于 509 nm 激光系统, 由于材料和工艺的限制, 目前并没有 ns 尺度的 EOIM 器件. de Vries 等[19] 基于掺镱光纤激光器及放大器实现了 1010 nm 的脉冲激光系统, 其可产生重复频率 5 Hz—1 MHz 连续可调的 ns 脉冲激光, 脉冲峰值功率大于 100 W. Poem 等[20] 基于掺磷拉曼光纤放大器实现了 1260 nm 的脉冲激光系统, 其可产生 0.25 ns 的脉冲激光, 输出峰值功率为 1.4 kW. 上述方案可获得大功率的微米波长脉冲激光, 在此基础上, 通过非线性波长转换技术, 可以获得短波长的脉冲激光.

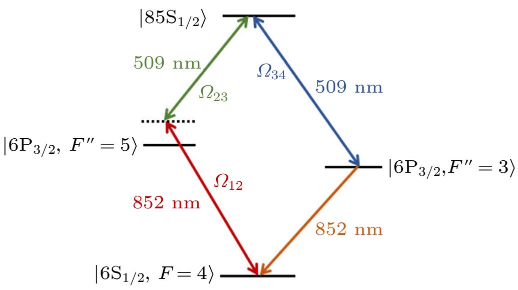

图 1 基于铯原子四波混频的单光子源能级结构示意图. 两个频差 GHz 的 509 nm 脉冲激光用于实现四波混频过程的里德伯态激发

Fig. 1. Schematic diagram of single-photon source energy level structure based on four-wave mixing of cesium atoms. Two 509 nm pulsed lasers with a frequency difference of GHz are used to achieve Rydberg state excitation in a four-wave mixing process.

本文介绍了一种用于里德伯原子 GHz 带宽激发的 ns 脉冲激光系统. 考虑四波混频要求, 利用两个 kHz 线宽的 1017.5 和 1017.8 nm 连续激光器作为种子源, 通过两个 20 GHz 带宽的光纤调制器产生交替双脉冲激光, 双脉冲激光经掺镱光纤放大器级联放大, 输出脉冲激光峰值功率大于 4600 W, 单次穿过 PPLN (周期极化铌酸锂) 晶体倍频获得 509 nm 脉冲激光, 典型脉冲激光峰值功率 173 W. 该激光系统单路输出脉冲重复频率 300 kHz—100 MHz 连续可调, 脉宽 1—100 ns 范围连续可调.

2 实验系统

我们的脉冲激光器工作原理如图 2 所示. 激光系统由种子源、电光强度调制器、光纤放大器 (PA) 和倍频器 (SHG) 组成. 种子源输出激光分别通过光纤连接到各自的电光强度调制器 (EOIM) 用于产生纳秒脉冲激光, EOIM 输出脉冲激光光纤连接进入掺镱保偏光纤放大器进行功率放大, 输出脉冲激光经过倍频器产生 509 nm 脉冲激光.

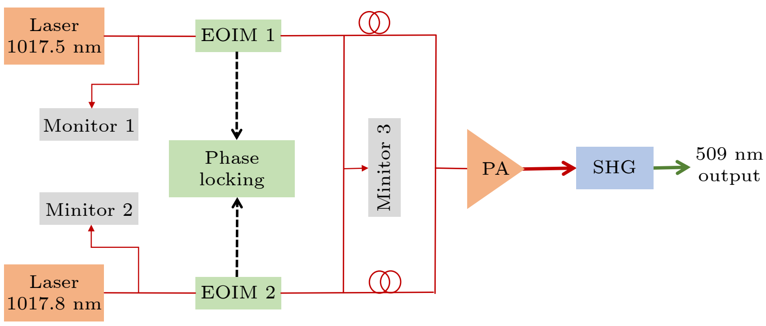

图 2 脉冲激光器示意图. 种子源激光为连续输出的光纤激光器, 输出激光经电光强度调制器 EOIM 1 或 EOIM 2 产生纳秒脉冲激光, 脉冲激光输入光纤放大器 PA 进行功率放大, 放大后激光输入 PPLN 晶体进行倍频 (SHG), 获得 509 nm 脉冲激光. Laser 1017.5 nm, Laser 1017.8 nm 分别为种子源 1 和种子源 2; EOIM 1 和 EOIM 2 分别为 Mach-Zehnder 型电光强度调制器; PA 为掺镱保偏光纤放大器; SHG 为倍频器; Monitor 1, Monitor 2 分别为两个种子源的监测端口; Monitor 3 为 EOIM 输出的激光参数监测端口

Fig. 2. Schematic diagram of pulsed laser. The seed source laser is a fiber laser with continuous output. The output laser generates nanosecond pulse laser through the electro-optical intensity modulator EOIM 1 or EOIM 2. The pulse laser is input into the fiber amplifier PA for power amplification. Laser 1017.5 nm and Laser 1017.8 nm are seed sources 1 and 2, respectively. EOIM 1 and EOIM 2 are Mach-Zehnder electro-optical intensity modulators, respectively. PA, ytterbium-doped polarization-maintaining fiber amplifier; SHG, frequency multiplier. Monitor 1 and Monitor 2 are monitoring ports for the two seed sources respectively. Monitor 3 is the port that monitors laser parameters output by EOIM.

3 实验结果和分析

种子源激光器的中心波长分别为 1017.5 nm 和 1017.8 nm, 典型输出功率大于 10 mW, 线宽约 8 kHz; 输出激光通过光纤连接进入 EOIM; 由任意波形发生器来驱动 EOIM, 其典型光脉冲信号见图 3, 图 3(a) 为光脉冲信号波形, 图 3(b) 为电脉冲信号波形, 插图为典型脉冲的放大显示. EOIM 产生的光脉冲具有很好的重复性与稳定性, 其脉宽在 0.5—100 ns 范围连续可调, 重复频率在 0.3—100 MHz 连续可调, 脉冲峰值功率起伏约 1.3%.

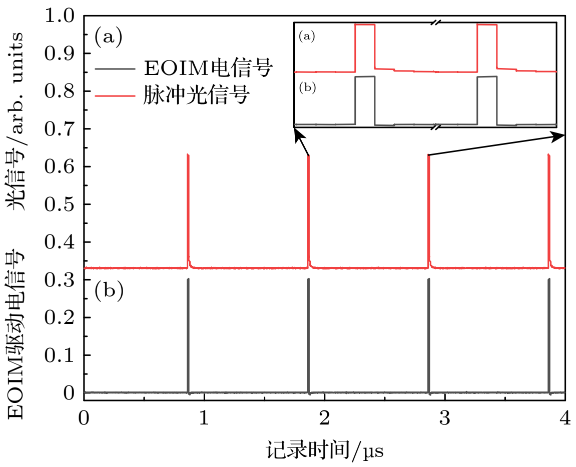

图 3 电脉冲和光脉冲实验测量信号 (a) 光脉冲信号; (b) 电脉冲信号, 重复频率 1 MHz、脉宽 10 ns. 光脉冲重复频率与脉冲宽度是与电脉冲信号一致, 其中, 脉冲峰值功率起伏约 1.3%

Fig. 3. Experimental measurement signal of electrical pulse and optical pulse: (a) Optical pulse signal; (b) electrical pulse signal, the pulse repetition frequency is 1 MHz, the pulse width is 10 ns. The optical pulse repetition frequency and pulse width are consistent with the electrical pulse signal, in which the peak pulse power fluctuates about 1.3%.

EOIM 产生的 1018 nm 脉冲激光经脉冲光纤放大器级联放大后, 输入 PPLN 晶体倍频得到 509 nm 的脉冲激光. 倍频过程通过温度调谐实现准相位匹配. 在重复频率 1 MHz、脉宽为 5 ns 参数条件下, 注入 1017.5 nm 基频光功率 2.78 W, 得到 509 nm 脉冲激光的最大输出平均功率为 523 mW, 脉冲峰值功率大于 105 W, 对应的最佳匹配温度 69.82 ℃, 如图 4 所示.

图 5 为倍频功率、倍频效率的实验测量结果. 随着基频光功率的增加, 509 nm 激光的功率显著

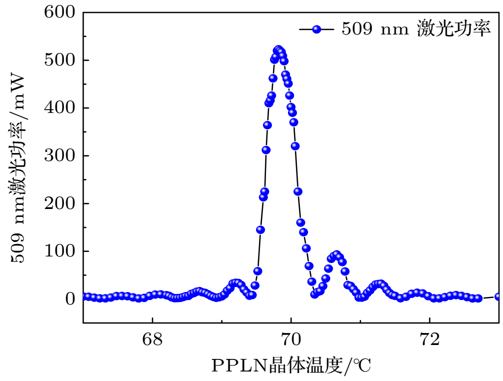

图 4 509 nm 脉冲激光的倍频温度匹配曲线, 在重复频率 1 MHz、脉宽为 5 ns 参数条件下, 最佳匹配温度为 69.82 ℃, 倍频转换效率为 16%

Fig. 4. Matching curve of frequency doubling temperature of 509 nm pulsed laser. Under the conditions of pulse repetition frequency of 1 MHz and pulse width of 5 ns, the optimal matching temperature is 69.82 ℃, and the conversion efficiency of frequency doubling is 16%.

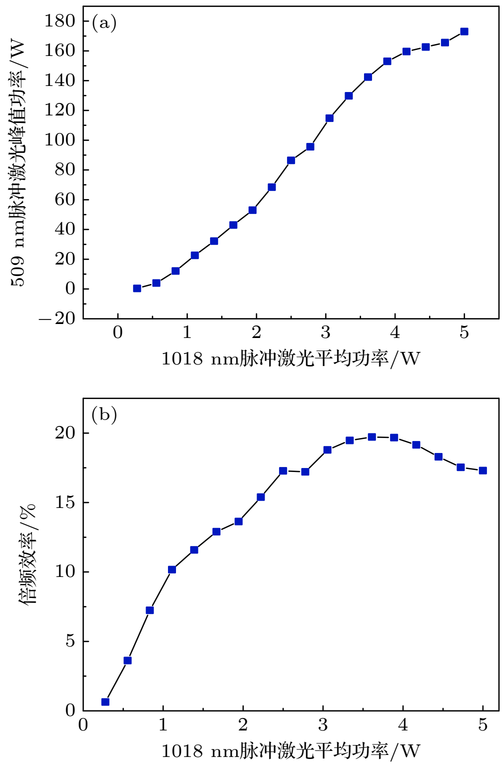

图 5 (a) 倍频光输出峰值功率随基频光平均功率的变化; (b) 基频光平均功率和倍频效率之间的关系

Fig. 5. (a) Curve of peak power of the 509 nm pulsed laser with the average power of 1018 nm pulsed laser; (b) the efficiency vs. the average power of 1018 nm pulsed laser.

增大, 由于热透镜效应, 1017.5 nm 基频光超过 4 W 后, 509 nm 激光增加缓慢, 倍频效率趋于饱和, 如图 5(b) 所示. 图 6 为 509 nm 脉冲光时域信号, 其典型脉冲宽度为 10 ns, 重复频率为 1 MHz, 脉冲

形状与电信号一致, 脉冲峰值功率起伏约 1.3%, ON/OFF 比优于 100000. 种子源 2 产生的脉冲光信号参数与种子源 1 相同, 其与种子源 1 时分复用放大器获得功率放大. 种子源 1 和 2 产生的激光通过拍频实现频率相对锁定. 实验所用方案可产生双脉冲激光 509 nm 激光, 脉宽 0.5—100 ns、重复频率 300 kHz—100 MHz 连续可调.

激光峰值功率依赖于脉宽和频率, $P_{\rm peak} = P_{\rm avg}/(\tau/\Delta t)$, 其中, $P_{\rm peak}$ 为峰值功率, $P_{\rm avg}$ 为平均功率, τ 为脉冲宽度, Δt 为脉冲周期. 由于放大器输出功率限制, 峰值功率与脉宽成反比, 短脉冲条件下输出功率较大. 如图 7 所示, 509 nm 脉冲激光功率随脉宽增加而减小. 脉冲功率同样依赖重复频率. 如图 8 所示, 低频条件下, 脉冲功率随频率增加而增加; 在当重复频率大于 20 MHz 后, 基本不随重复频率增加而变化.

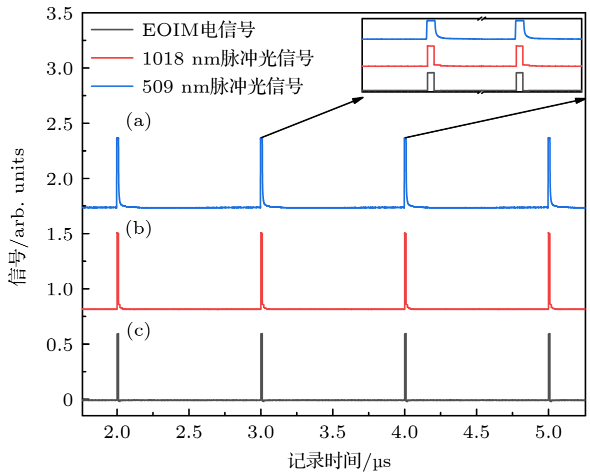

图 6 509 nm 脉冲序列图 (a) 509 nm 光脉冲信号; (b) 1018 nm 光脉冲信号; (c) EOIM 电脉冲信号; 插图为典型脉冲的放大显示, 典型重复频率 1 MHz、脉宽 10 ns. 光脉冲重复频率与脉冲宽度是与电脉冲信号一致

Fig. 6. The 509 nm pulse sequence: (a) 509 nm optical pulse signal; (b) 1018 nm optical pulse signal; (c) EOIM electrical pulse signal; the inset is typical pulse amplification display. Typical pulse repetition frequency is 1 MHz, pulse width is 10 ns. The optical pulse repetition frequency and pulse width are consistent with the electrical pulse signal.

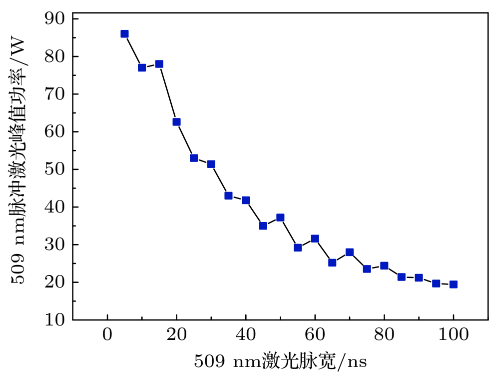

图 7 509 nm 脉冲激光的峰值功率随脉宽的变化

Fig. 7. Peak power of 509 nm pulsed laser varies with the pulse width.

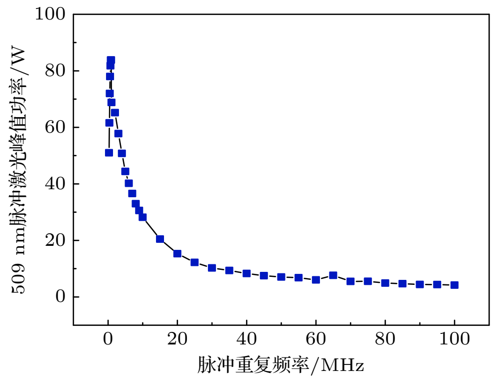

图 8 509 nm 脉冲激光的峰值功率随重复频率的变化

Fig. 8. Peak power of 509 nm pulsed laser varies with the pulse repetition frequency.

4 总结和展望

该激光系统实现了脉冲输出峰值功率大于 4600 W; 输出 1018 nm 激光单次穿过 PPLN 晶体倍频, 获得 509 nm 激光典型脉冲峰值功率 173 W. 单路输出重复频率范围 300 kHz—100 MHz, 脉宽在 1—100 ns 范围连续可调.

系综里德伯原子可以通过激发阻塞效应实现单光子源, 室温原子由于空间局域导致的原子态退相干在μs 甚至 ns 量级, 这就要求高质量的激发光源以实现 GHz 带宽的原子态调控, 如图 9 所示. 本文所述脉冲激光器系统, 可以输出最大峰值功率

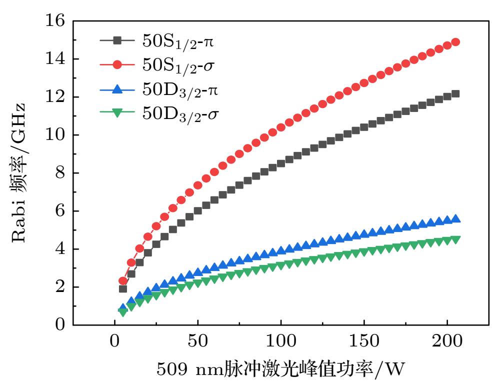

图 9 铯原子 $6P_{3/2} \rightarrow 50S_{1/2}, 6P_{3/2} \rightarrow 50D_{3/2}$ 跃迁 Rabi 频率随 509 nm 脉冲激光峰值功率的变化

Fig. 9. The $6P_{3/2} \rightarrow 50S_{1/2}$, $6P_{3/2} \rightarrow 50D_{3/2}$ transition Rabi frequency vs. peak power of 509 nm pulsed laser.

170 W 的 509 nm 激光, 脉宽在 0.5—100 ns 范围连续可调、重复频率在 300 kHz—100 MHz 范围连续可调. 该激光系统基于双种子源, 可以输出波长差几十 GHz 的交替脉冲, 可应用于铷、铯等原子系统通过四波混频实现单光子源.

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A 509 nm pulsed laser system for Rydberg excitation of cesium atoms*

Liu Yao [1)] He Jun [1)2)†] Su Nan [1)] Cai Ting [1)] Liu Zhi-Hui [1)]
Diao Wen-Ting [3)‡] Wang Jun-Min [1)2)††]

1) (*State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan* 030006, *China*)

2) (*Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan* 030006, *China*)

3) (*National Key Laboratory of Science and Technology on Space Microwave, China Academy of Space Technology* (*Xi'an*), *Xi'an* 710000, *China*)

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Abstract

Single photon source is a non-classical light field with anti-bunching effect, which has a potential applications in the research of fundamental physics problems, quantum precision measurement, quantum communication, quantum computing, etc. The strong interaction between highly excited Rydberg atoms presents an excitation blockade effect. In a dense Rydberg atomic ensemble, the excitation of more than one

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† Corresponding author. E-mail: hejun@sxu.edu.cn

‡ Corresponding author. E-mail: dwt1124@163.com

†† Corresponding author. E-mail: wwjjmm@sxu.edu.cn

Rydberg atom within a blockade volume is suppressed, where the interactions of Rydberg atoms shift the atomic states out of resonance with an excitation laser.

We consider here the generation of single photon source by using a four-wave mixing scheme in a room-temperature atomic vapor cell. In a homemade micrometer-sized atomic vapor cell, one-dimensional size is smaller than the radius of Rydberg blockade and the other two-dimensional size is limited by the size of focused laser beam. The blockade radius is on the order of a few micrometers, depending on the Rydberg atom states. An excitation blockade effect can be used to realize single photon source in thermal cesium vapor microcells. The micron cesium-cell is used to spatially localize atomic groups, which results in the atomic decoherence time on the order of microseconds or even nanoseconds. This requires a high-power pulsed laser to prepare the Rydberg atomic state at a nanosecond scale.

Four-photon excitation schemes with narrow linewidth lasers are also used experimentally. The cesium-Rydberg state can usually be excited by the lasers with optical wavelengths 852 and 509 nm, respectively. The laser system is well-stabilized so that the detuning is small compared with the spontaneous linewidth of Rydberg state, while the laser power and temporal mode need to be specified for ns-time coherence in thermal cesium vapor microcells. The 852 nm laser can be achieved by modulating the continuous laser beam with the help of an electro-optic intensity modulator (EOIM). While this remains a technical challenge for 509 nm laser with ns-laser pulse. There is no EOIM to generate the ns-laser pulse with high power.

We demonstrate a novel generation method of 509 nm laser system. In our experiments, a 1018 nm fiber laser is used to produce a continuous laser with a typical linewidth of ~8 kHz and power of 10 mW. The nanosecond pulse is generated with the help of an electro-optic intensity modulator (EOIM) by modifying the continuous laser beam. The peak power of modulated optical pulse is amplified to 4600 W by using a homemade fiber amplifier. The output beam of 1018 nm is then injected into a periodically poled lithium-niobate (PPLN) to generate the second harmonics laser of 509 nm. The typical peak power of 509 nm reaches 173 W by optimizing PPLN phase matching parameters. The pulse repetition frequency of the 509 nm laser can be continuously tuned in a range of 300 kHz–100 MHz, and the pulse width can be continuously tuned in a range of 1–100 ns. Peak power fluctuation of the pulses is about 1.3%. The power 509 nm laser with optimized pulse parameters can be used to excite the cesium atom with GHz bandwidth. Meanwhile the two seed source lasers is well established experimentally, which allows alternating pulses with a different wavelength. This is an essential capability for realizing a single photon source through four-wave mixing.

Keywords: Rydberg atom, pulse laser, nonlinear frequency conversion, single photon source

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