Metastable Magnesium fluorescence spectroscopy using a frequency-stabilized 517 nm laser

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Abstract: We present a laser operating at 517 nm for our Magnesium laser-cooling and atomic clock project. A two-stage Yb-doped fiber amplifier (YDFA) system generates more than 1.5 W of 1034 nm light when seeded with a 15 mW diode laser. Using a periodically poled lithium niobate (PPLN) waveguide, we obtained more than 40 mW of 517 nm output power by single pass frequency doubling. In addition, fluorescence spectroscopy of metastable magnesium atoms could be used to stabilize the 517 nm laser to an absolute frequency within 1 MHz.

OCIS codes: (190.2620) Frequency conversion; (140.3510) Lasers, fiber; (020.7010) Trapping

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1. Introduction

The developments in laser cooling and trapping of atoms have opened the doors for a variety of research fields in precision measurements and its applications. Access to atoms in an ultra-cold regime has resulted in tremendous improvements in precision spectroscopy and the development of a new class of atomic clocks. Alkali atoms have been the first choice for laser cooling and trapping, due to the single unpaired electron structure and transitions easily accessible with diode lasers. Laser cooled cesium atoms are currently used to define the SI second [1, 2]. The Cs fountain clocks of today are approaching an accuracy and stability level of a few parts in 10^{16}, equivalent a clock losing only one second in 300 million years.

Alkaline-Earth and Alkaline-Earth-like atoms are excellent candidates for future optical frequency standards, as the internal level structure allows for laser cooling and narrow clock transitions. The main effort has concentrated on the cooling of Magnesium, Calcium, Strontium and Ytterbium atoms. So far, accurate optical atomic clocks have been realized using Ca [3-5], Sr [6-9] and Yb [10, 11].

In this letter, we report a 517 nm laser source suitable for our Magnesium laser cooling and atomic clock project. The laser system is intended for optically pumping atoms between the (3s3p) $^3P_{0,1,2}$ states by addressing the (3s3p) $^3P_j \rightarrow$ (3s4s) $^3S_1$ transitions. The 517 nm second harmonic generation (SHG) system is constructed using a two-stage Yb-doped fiber amplifier (YDFA) system and a periodically poled lithium niobate (PPLN) waveguide [12]. In this setup, we can get an output power of more than 40 mW at 517 nm. In addition, fluorescence spectroscopy of metastable magnesium atoms is used to stabilize the 517 nm SHG system to within 1 MHz on an absolute scale.

2. Experiment and results

A schematic diagram of the experiment is shown in Fig. 1. The seed laser is an external-cavity diode laser in Littrow configuration operating at 1034 nm. After a 40 dB optical isolator, the laser power is measured to be 15 mW. A telescope is used to optimize the fiber-coupling efficiency of the 1034 nm laser. The Yb-doped fiber amplifier used in our laboratory is a polarization maintaining (PM) fiber, providing amplification of light with wavelengths ranging from 1030 nm to 1120 nm. The YDFA has an Yb-doped single-mode core with a 10 µm diameter, and a large multimode pump guiding cladding with a 125 µm diameter. The pump laser wavelength is 976 nm for the maximum absorption efficiency of YDFA. The fiber lengths of both the YDFA are about 2.5 meters with a cladding pump laser absorption of 6 dB/m. Dichroic Mirrors (DM) are employed to overlap and couple both 976 nm and 1034 nm lasers into the YDFA. An interference filter (IF) transmitting 1034 nm light is placed after the two-stage the YDFA, to remove the 976 nm pump light from the output.

In Fig. 2, the blue points show the gain of the one-stage YDFA at 1034 nm, which is measured as a function of pump power at a coupled seed laser power of 8 mW. It is observed that the gain saturates at a pump power of about 4.5 W. We get a maximum 1034 nm output of around 400 mW from the one-stage YDFA, limited by spontaneous emission of the Yb-

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Doped fiber centered at 1035 nm [13]. The typical output of the two-stage YDFA is shown with the red circles in Fig.2, where a maximum output of 1.5 W at 1034 nm is reached. The coupling efficiency between Yb-doped cores of the 1st stage and 2nd stage YDFA is around 50 %.

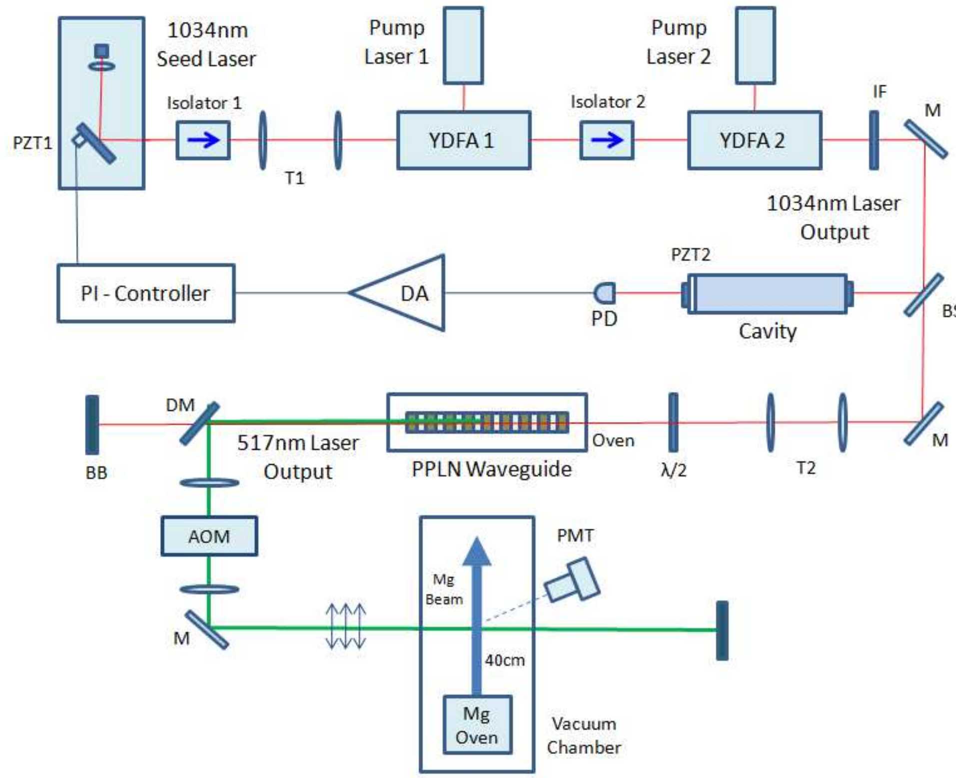

Fig. 1. Schematic diagram of 517 nm laser system: T, telescope; DM, dichromatic mirror; IF, interference filter; M, mirror; λ/2, half waveplates; BS, beam splitter; AOM, acousto-optic modulator; PMT, photomultiplier tube; PD, photodiode; BB, beam block; DA, differential amplifier; PZT, piezoelectric actuator. A two stage YDFA system is used for 1034 nm amplification, and a PPLN waveguide produces second harmonic generation (SHG) at 517 nm. The PPLN temperature is about 35 °C, and 40 mW of 517 nm SHG output is obtained with 1.4 W of incident 1034 nm laser. An external cavity is used to stabilize the two-stage YDFA system, and spectroscopy is performed on a metastable magnesium beam.

The 1034 nm output from the two-stage YDFA is collimated and then focused into the PPLN waveguide, with a beam waist of 30 µm. The domain period of the PPLN waveguide is 6.37 µm with a quasi-phase matching temperature around 35 °C and temperature coefficient of 0.09 nm/K. An oven is used to stabilize the PPLN's temperature within 0.01 °C. A half waveplate controls the polarization direction of the 1034 nm laser to optimize the SHG output of the PPLN waveguide.

A TEM_{00} Gaussian laser beam at 517 nm is obtained from the PPLN waveguide. In Fig. 3, we show the generated 517 nm power (blue points) with simply single pass, where a maximum of 40 mW is obtained with 1.4 W of incident power at 1034 nm. In this plot, the wavelength of the input laser is 1034.860 nm, and the quasi-phase temperature is 34.2 °C. The red circles in Fig. 3 show the frequency doubling efficiency as a function of incident 1034 nm power. We observe a decreasing doubling efficiency, from 2.5 % $W^{-1}cm^{-1}$ to about 2 % $W^{-1}cm^{-1}$ at high power output. This is due to increased amplified spontaneous emission (ASE) of YDFA [14,15]. A dichroic mirror is used to reflect the 517 nm output and transmit the infrared 1034 nm laser. We have chosen to use a single pass SHG compared to frequency doubling in an external cavity, as it provides the possibility of pumping several ^{25}Mg hyperfine transitions simultaneously by rapidly scanning the laser frequency. Frequency doubling in an external cavity can provide significantly higher output powers, however, for the repumping purposes intended, the 40 mW demonstrated here by single pass frequency doubling is more than sufficient.

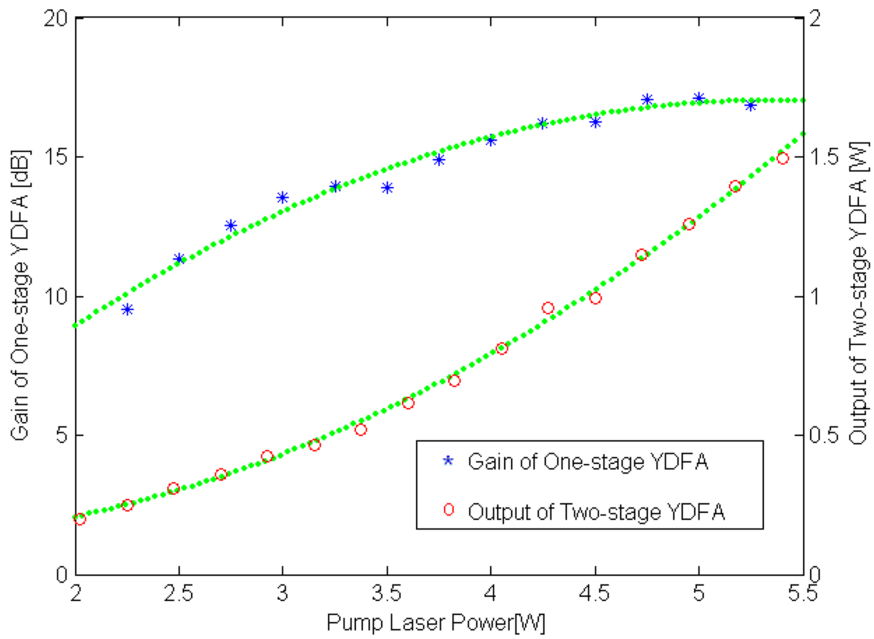

Fig. 2. The blue points show 1034 nm gain of one-stage YDFA as a function of pump laser power. The red circles show 1034 nm output of two-stage YDFA, where 1.5 W output obtained. The green lines are added as a guide for the eye .

An external enhancement cavity is used to stabilize the two stage YDFA system by fringe locking. The cavity is constructed by two high reflective concave mirrors coated for 1034 nm. 60 μW of the IR laser beam is coupled into this cavity, the transmitted signal is collected by a photodiode. After a differential amplifier and a PI-controller circuit, the output signal is sent to the piezoelectric actuator (PZT) of the seed laser, to stabilize the 517 nm SHG system. The FWHM linewidth of the 517 nm laser is measured to be 1.2 MHz.

An oven containing magnesium is operated at T = 793 K and produces an effusive magnesium beam which after the discharge region has a non-maxwellian velocity distribution with a mean velocity of 1000 m/s and total output of 10^{13} atoms/s. Metastable magnesium atoms are produced by electron impact in a self sustained discharge which runs at a stable current of one ampere. The metastable Mg beam setup is similar to the one described in [16] and has a generation efficiency of metastable magnesium atoms of 40 %.

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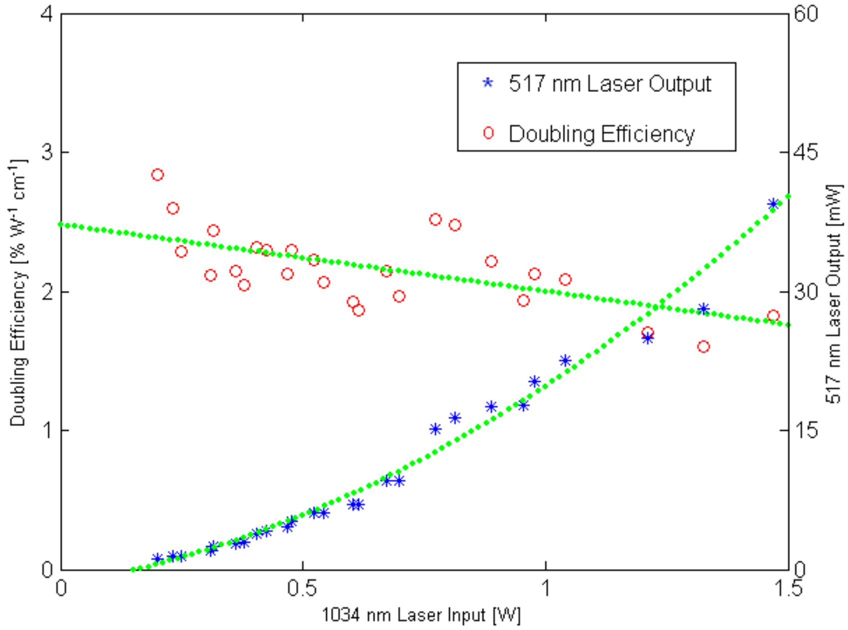

Fig. 3. The blue points show 517nm SHG laser generation, where 40 mW of 517 nm laser obtained. The red circles show frequency doubling efficiency of the PPLN waveguide. The green lines are added as a guide for the eye.

Absorption spectroscopy is performed at a distance of 40 cm from the oven orifice, with a diameter of 2 mm, using linearly polarized 517 nm light. A lens of 50 mm focal length focuses the fluorescence on to the photomultiplier tube (PMT). A typical absorption spectrum is shown in Fig. 4. The curve shows the absorption spectroscopy of the metastable Mg (3s3p) $^3P_1$ - (3s4s) $^3S_1$ transitions at 517.4 nm. From the spectrum, the isotope shift of ^{24}Mg and ^{26}Mg, and the hyperfine $(^3P_1)_F$ – $(^3S_1)_F$ transitions of ^{25}Mg can be observed. We use 0th and 1st order of a 275 – 400 MHz AOM for absolute frequency calibration and linearity test of the frequency scale. The two laser beams are superimposed to be better than 0.4 mrad, and the PMT records the fluorescence of both 0th and 1st order laser beams. The double spectrum is then used to determine the linearity of the scan. The ^{24}Mg - ^{26}Mg isotope shift of $^3P_1$ – $^3S_1$ transition is found to be 390.1 ± 1.4 MHz, which is consistent with previous measurements giving 393 ± 10 MHz [17] and 391 ± 4.5 MHz [18]. For the ^{24}Mg peak, we obtain a FWHM width of 71 MHz in agreement with our probing geometry, which gives a Doppler broadening of 50 MHz due to the transverse velocity distribution.

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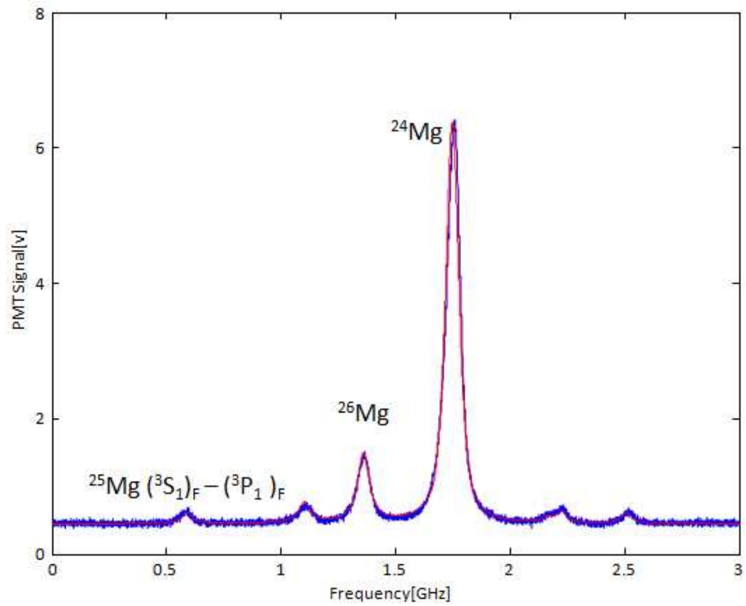

Fig. 4. Absorption spectroscopy of the metastable Mg $(3s4s)^3S_1$-$(3s3p)^3P_1$ transitions at 517.4 nm. The blue line is the fluorescence signal taken by photo multiplier tube, and the red line is the fitting curve. The isotope shift of ^{24}Mg and ^{26}Mg, and the hyperfine of ^{25}Mg can be observed. The value of ^{24}Mg – ^{26}Mg isotope shift of $^3S_1$ – $^3P_1$ transition can be estimated as 390.1 ± 1.4 MHz.

In Fig. 4, the S/N ratio of the ^{24}Mg peak exceeds 80. The 517 nm laser system is frequency stabilized by fringe locking to the ^{24}Mg peak. An error signal is generated by offsetting the fluorescence signal by a differential amplifier. The error signal is then sent to a PI-controller circuit, which controls the PZT of the seed laser. Assuming white noise limitation [19], the resolution of the frequency-stabilized 517 nm laser system at one second time scale is estimated to about 0.5 MHz.

3. Conclusion and discussion

In conclusion, we report the construction of a 517 nm SHG system for our magnesium laser cooling and atomic clock experiment. Using a two-stage YDFA system, we get 1.5 W of 1034 nm laser, which is single pass frequency doubled in a PPLN waveguide resulting in 40 mW of power at 517 nm. An external cavity was used for frequency stabilizing the 517 nm SHG laser system. Fluorescence spectroscopy performed on a metastable magnesium beam could be used to stabilize the 517 nm laser within 1 MHz. In addition, we obtained the value of ^{24}Mg – ^{26}Mg isotope shift of $^3S_1$ – $^3P_1$ transition as 390.1 ± 1.4 MHz.

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