Achieving strong doubling power by optical phase-locked Ti:sapphire laser and MOPA system

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Received June 12, 2011; accepted September 29, 2011; posted online November 25, 2011

We show two external cavity-enhanced second-harmonic generations of 922 nm with periodically poled potassium titanyl phosphate crystal, whose doubling cavities are locked separately with Hansch–Couillaud and intra-modulation methods. The outputs of second-harmonic generation reach 310 mW, 54.8% of the conversion efficiency from the Ti:sapphire laser with the crystal length of 10 mm, and 208 mW, 59% of the conversion efficiency from the MOPA system with the crystal length of 30 mm. It consists of heterodyning the Ti:sapphire laser and the MOPA system, and compares the phase of the beat frequency signal with the phase of a reference RF local oscillator. The resulting phase error is used as a feedback signal and fed back to the reference cavity of the Ti:sapphire laser to lock the two lasers in phase. A stable blue power of 520 mW is obtained, which supplies enough power for the cooling and trapping step of the strontium (Sr) optical lattice clock. Four stable isotopes of Sr, ^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr, are detected by probing the laser during a strong 460.7-nm cycling transition ($5s^{2}\,{}^{1}S_0{-}5s5p\,{}^{1}P_1$).

OCIS codes: 140.3515, 140.3580, 140.2020, 140.3320, 300.6280.

doi: 10.3788/COL201210.031403.

Blue light with high power is a key issue in many areas such as spectroscopy and cooling of atomic species[1]. The usual method is to convert a solid state or a semiconductor using a second-harmonic generator[2]. For laser cooling of the ${}^{1}S_0{-}{}^{1}P_1$ strontium line at 461 nm, in our experiment, periodically poled potassium titanyl phosphate (PPKTP) is applied because of its high effective nonlinearities (d_{eff} 7–9 pm/V). In Ref. [3], Targat *et al.* obtained 234-mW blue light by PPKTP with the net conversion efficiency of 75%. Doubling light with 130 mW was generated by Saenz *et al.* from a continuous wave (CW) master oscillator power amplifier (MOPA) laser with an efficiency of 32% in the enhancement cavity[4]. In our experiment, we heterodyne one Ti:sapphire laser[5] and one MOPA system, and compare the phase of the beat frequency signal with the phase of a reference radio frequency (RF) local oscillator. The resulting phase error is used as a feedback signal and fed back to the piezoelectric transition (PZT) of the reference cavity of the Ti:sapphire laser to lock the two lasers in phase. The difference frequency between the two lasers must be controlled to a few megahertzs for long time periods. A digital phase locked loop (DPLL)[6−8] is successfully created using the piezoelectric movement of a Fabry-Perot cavity mirror. The reference cavity is a confocal interferometer produced from a single piece of invar rod thermally isolated from the enclosure. The back mirror of the interferometer is mounted on a piezo-stack to allow scanning of the reference cavity, which has a free spectral range of 750 MHz and finesse between 25 and 50. The concave mirror cannot be modulated at rates more than 100 kHz, which is enough for a carrier tracking loop. The beat signal between the two laser beams is observed on a photo detector. In a phase detector, the phase difference between this signal and a local oscillator is formed. The loop is closed by feeding back the signal to the reference cavity of the Ti:sapphire laser to keep the phase constant. Four stable isotopes of strontium (Sr), ^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr, are also detected by probing the laser during a strong 460.7-nm cycling transition ($5s^{2}\,{}^{1}S_0{-}5s5p\,{}^{1}P_1$).

Ti:sapphire laser (Coherence's MBR110) is used for a bowtie ring lasing configuration, and provides a single-longitudinal-mode power of 570 mW at a wavelength of 922 nm. By locking the laser to one of the fringes of the high-finesse reference cavity, the laser linewidth can be reduced to less than 75 kHz. The reference cavity length can be scanned using a long extension piezoceramic. Consequently, the laser can be scanned by maintaining the laser lock to the scanning reference cavity. Small-current modulation of the reference cavity has been used to scan the cavity, and these modulation signals have been successfully tracked by the DPLL. Triangle modulation has also been used. Given the limited locking range, the modulation has at present been limited to frequency deviations of 10–20 MHz.

The commercial MOPA laser is a master diode laser in Littrow configuration with a tapered amplifier injected. After a Faraday isolator, the system supplies a single-mode power with 310 mW at a wavelength of 922 nm and a linewidth around 1 MHz.

The experimental setup (Fig. 1) consists of one MOPA system and one Ti:sapphire laser operating at a wavelength of 922 nm and DPLL. Frequency noise of the Ti:sapphire laser is reduced by employing optical feedback from the external high finesse resonator. The output beams are superimposed and shone on a Si:PIN photodiode. By applying proper voltages to the corresponding PZT, the feedback levels are adjusted while the frequency of the lasers is swept by applying a slow current ramp. The locking range, i.e., the current range where

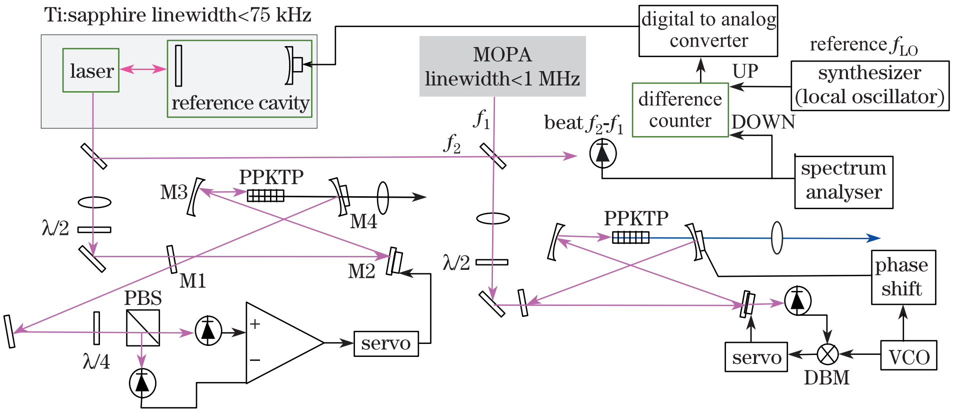

Fig. 1. Diagram of the experimental demonstration system.

the frequency of the systems is kept within the cavity resonance width owing to optical feedback, $f_2=f_1+f_{LO}$, in which f_{LO}=30 MHz. Typical beat note spectra between both optically stabilized lasers show 200 kHz full-width at half-maximum (FWHM) wide lines of almost Lorentzian shape (Fig. 2). By permitting a larger root mean square (RMS) phase error than analog detectors, it can be operated at substantially lower locking bandwidth and allows very stable phase locking. The basic element of this phase detector is a counter where the local oscillator counts up and the beat signal counts down. The counter has a range from 0 to 64 and is initialized at 32. Therefore, the phase detector can track a $+/-32\,\pi$ phase difference between the two sources (Fig. 3).

Figure 1 shows the setup of the two frequency doubling systems. The single-mode Ti:sapphire laser generates output power with 570 mW in 922 nm and linewidth around 75 kHz. Hansch–Coulliaud discriminated signal[9,10] can be adjusted by a half-wave plate. This discriminated signal can be applied to lock the laser frequency to the cavity resonance with modulating mirror M2 using a piezo transducer through a servo circuit. A bowtie ring cavity configuration is chosen as enhancement cavity to provide unidirectional output. It includes two curved mirrors with a radius of curvature of 45 mm. The distance between the two curved mirrors is 54 mm. The total cavity length is around 236 mm, which corresponds to the free spectral range of the 1.3-GHz cavity. Additionally, the reflectivity of the output coupler is less than 3.0% for the frequency-doubled light to extract

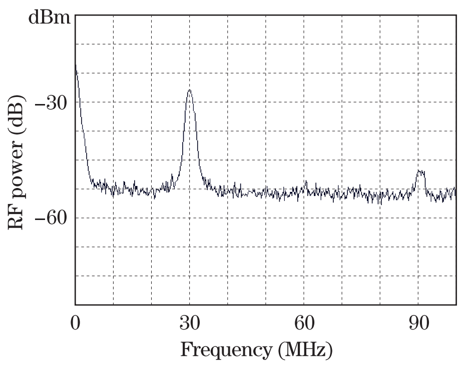

Fig. 2. RF spectrum of the photocurrent beat note under phase-locked condition. Filter bandwidth: 1 MHz; video bandwidth: 1 MHz; sweep time: 4 ms.

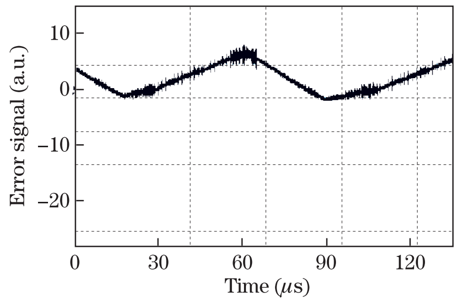

Fig. 3. Reference set at 30 MHz. When the offset frequency is only slightly higher than the reference, the signal will look like this.

Table 1. Parameter of Two Doubling Systems

Crystal Length (mm)	Waist (μm)	Doubling Power (mW)	Input Angle (deg.)	Net Conversion Efficiency (%)	Cavity Length (mm)
30	50	208	3.4	73.3	561
10	34	310	5.7	71.3	236

output power from the cavity successfully (Table 1). The reflectivity of a chosen input coupler is 91%, and the other mirror has a high reflectivity of 99.99%. The facets of the nonlinear crystal are coated with high transmission for both wavelengths. To combine good beam quality and high conversion efficiency, the length of this crystal is set as 10 mm. The output power of doubling power and power conversion efficiency are shown in Fig. 4. The maximum output power is 310 mW at 461 nm, with 570 mW of the fundamental input power. M4 is dichroically coated at 461 nm, 922 nm with $R_{922\,\mathrm{nm}}>99.9\%$ and $T_{461\,\mathrm{nm}}=98\%$. The dimension of the PPKTP crystal is 2×1×10 (mm). The temperature of PPKTP is controlled better than ±100 mK using a temperature controller.

The commercial MOPA (Toptica) provides single-longitudinal-mode power to mode-matches of the input fundamental frequency beam to the larger resonator waist located between the 2 plane mirrors M1 and M2. The curved mirrors M3 and M4 have a 106-mm radius of curvature. The PPKTP crystal has a dimension of 2×1×3 (mm). The total length of this cavity is around 561 mm, which corresponds to the free spectral range of

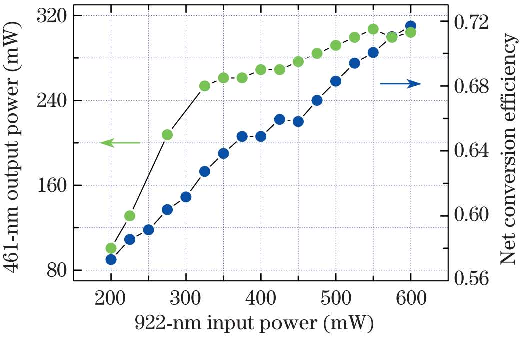

Fig. 4. Frequency-doubled output power and corresponding net conversion efficiency as function of the fundamental input power in the case of short crystal (10 mm).

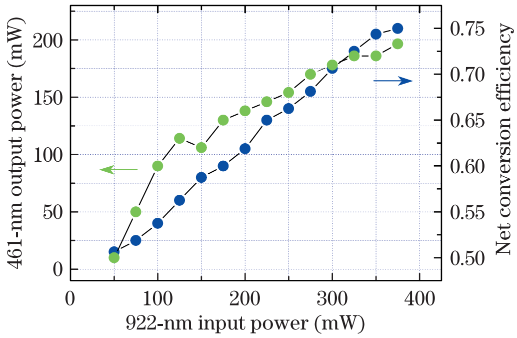

Fig. 5. Frequency-doubled output power and corresponding net conversion efficiency as function of the fundamental input power in the case of long crystal (30 mm).

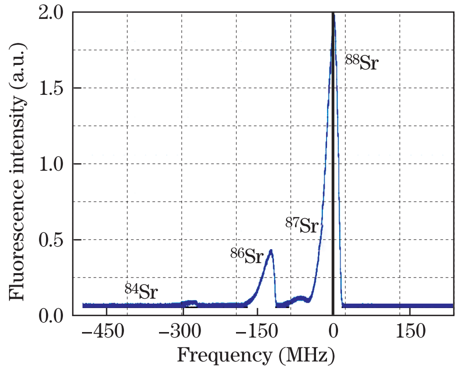

Fig. 6. Laser-induced fluorescence as a function of the laser frequency in the atomic beam.

the 5-GHz cavity. The distance between the two curved mirrors is 132 mm.

M1 with a reflectivity of 91% was also chosen. The PZT mounted on M4 was added with the modulation of 62.5 kHz, which can be used for locking a laser frequency to a cavity resonance by modulating the piezo transducer mounted on M2 through a servo circuit.

We have generated more than 208 mW of blue power at 461 nm starting from 340 mW of a MOPA system, with a net power efficiency of 73.3% (Fig. 5). On the other hand, we have generated more than 310 mW of blue power at 461 nm starting from 570 mW of mode-matched fundamental power from a Ti:sapphire laser, with a net power efficiency of 71.3% (Fig. 4). The key to achieving such high doubling power is the use of a shot crystal length which prevents blue absorption saturation, although with smaller focusing parameter than the former. Thus, the net conversion efficiency of the two doubling cavities is at the same level, although the former one takes two times longer than the other.

The Sr contains four stable isotopes, ^{88}Sr, ^{87}Sr, ^{86}Sr, and ^{84}Sr, with abundances of 82.56%, 7.02%, 9.89%, and 0.56%, respectively. The strong 460.7-nm cycling transition ($5s^{21}S_0-5s5p^1P_1$) is used to slow down and trap the Sr atoms. The relative isotope shifts from ^{88}Sr are −270.6, −124.5, and −49.2 MHz for ^{84}Sr, ^{86}Sr, and ^{87}Sr, respectively. As a general rule, due to spin pairing of the nucleons, isotopes with an even atomic number Z and an even atomic mass number A have a nuclear spin $I=0$. This is the case for the even isotopes of Sr, which have $Z=38$. The odd isotope ^{87}Sr has $I=9/2$. Figure 6 shows the fluorescence spectrum from the atomic beam. The x axis shows the relative frequency from the fluorescence peak of ^{88}Sr. The marks show the positions of the fluorescence peaks for each isotope.

In conclusion, two second-harmonic generations of 922 nm with PPKTP are constructed whose doubling cavities are locked separately using the Hansch–Couillaud and intra-modulation methods. The outputs of second-harmonic generation reach 310 mW, 54.8% of the conversion efficiency from the Ti:sapphire laser with the crystal length of 10 mm, and 208 mW, 59% of the conversion efficiency from the MOPA system with the crystal length of 30 mm. It consists of heterodyning the Ti:sapphire laser and the MOPA system, and comparing the phase of the beat frequency signal with the phase of a reference RF local oscillator. The resulting phase error is used as a feedback signal and fed back to the reference cavity of the Ti:sapphire laser with PZT to lock the two lasers in phase. A stable blue power of 520 mw is also obtained. Four stable isotopes of Sr, namely, ^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr, are detected by probing the laser during a strong 460.7-nm cycling transition ($5s^{21}S_0-5s5p^1P_1$).

This work was supported by the National Major Research Program China (No. 2010CB922902), the National Key Technology R&D Program in the 11th Five-year Plan of China (No. 2006BAK03A20), and the National "973" Program of China (No. 2005CB724501).

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