Tunable continuous ultraviolet light source based on diode laser

Yu Peng (彭 瑜)[1,2*], **Zhanjun Fang (方占军)**[1], **and Erjun Zang (臧二军)**[1]

[1] *Division of Electricity and Quantum Metrology, National Institute of Metrology, Beijing 100013, China*

[2] *Department of Precision Instruments and Mechanology, Tsinghua University, Beijing 100084, China*

**Corresponding author: y-peng07@mails.tsinghua.edu.cn*

Received July 30, 2011; accepted November 16, 2011; posted online May 9, 2012

We report on extra cavity frequency doubling lasers for 266 nm with a compact, tunable extended cavity diode laser (ECDL) at 1 064 nm. The ECDL injected into a tapered amplifier yields a power of 290 mW. In a first frequency-doubling stage, about 47-mW green light at 532 nm is generated. Subsequent second-harmonic generation (SHG) employing a BBO crystal leads to about 30 μW of ultraviolet (UV) light at 266 nm. The tunable characteristic of this UV light source is discussed. The tuning span of quasi-phase matching of doubling cavity for 532 nm with PPKTP crystal is achieved with –3.5 nm by changing the temperature of PPKTP and is achieved with –1.186 nm by adjusting angle of PPKTP.

OCIS codes: 140.2020, 140.3515, 140.3610.

doi: 10.3788/COL201210.S11405.

Hg is, so far, the heaviest nonradioactive atom that has been laser-cooled and trapped. Systematically evaluation of various sources of uncertainty for the Hg-based optical lattice clock is obtained and an accuracy better than 10^{-18} is attainable, which is an order of magnitude of improvement over Sr or Yb based clocks because of reduced susceptibility to the blackbody radiation field, which sets a major limitation on the accuracy of atomic clocks[1]. The $^1\mathrm{S}_0 -^3\mathrm{P}_0$ transition at 265.6 nm is exploited as a clock transition. The diode laser system described represents clock laser towards realization of optical frequency standard on the basis of mercury atoms[1].

Presently, diode lasers cover the spectrum from red to infrared (IR) almost continuously and additionally provide radiation at selected wavelengths in the green and far IR. With the advent of tapered amplifiers (TA)-currently available from 730 to 1 080 nm, the drawback of the usually moderate output power of a single-mode diode laser can be overcome by using a diode laser and a TA in series[2−7]. A wide range of applications is thus afforded, increasing the versatility of this type of laser. In particular, the higher output power allows the benefits of diode lasers to be transferred to the green, and even ultraviolet (UV) parts of the spectrum by means of the second harmonic generation (SHG). Here, frequency doubling has been efficiently accomplished in recent years by using periodically poled crystals. Another drawback of diode lasers with high intrinsic frequency instability, has been partiall overcome in the past by using an extended-cavity design where the width of the broad diode laser output spectrum is reduced to typical below 1 MHz by the optical feedback from a grating[2−7]. In this letter, we describe a power-amplified diode-laser system at 1 064 nm with frequency doubling to 532 nm and there after to 266 nm that combines the benefits mentioned above, as shown in Fig. 1.

The master laser is a standard extended-cavity diode laser (ECDL) in Littrow configuration. A single mode diode at 1 064 nm with an output power of 17 mW and antireflection (AR)-coated front facet is frequency-controlled by the feedback of the first diffraction order of a grating. Due to the high-quality AR coating, the tuning range of the ECDL is rather large, from 950 to 1 100 nm. Single-pass traveling wave amplifier diodes with a tapered gain geometry (tapered amplifiers) allow efficient amplification of laser radiation up to continuous wave (CW) output powers of 300 mW. Tapered amplifiers thus allow the advantages of diode lasers, such as reliability, tunability and ease of maintenance, to combine with high single-mode output power. We use a TA with the central wavelength of 1 095 nm that can be efficiently used from 985 to 1 135 nm. The IR light from the ECDL is first passed through a 40-dB optical isolator and then coupled via an aspherical lens into the TA. Under the condition of 1 800-mA current driver of TA, the output power of TA dependent on the injection power from master laser is shown in Fig. 2(a).

For the subsequent SHG the output-mode structure of the TA plays an important role. It can be understood by considering the internal geometry of the amplifier that the narrow waveguide behind the input facet itself works as a mode-selective element. However, a strong dependence of the output-mode structure on both the input

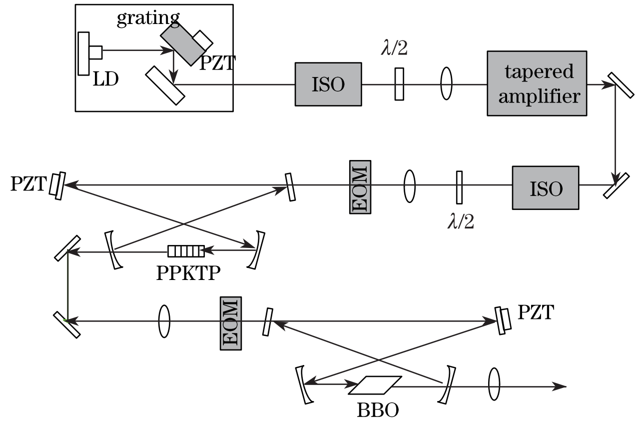

Fig. 1. Scheme of the setup. LD: laser diode; PZT: piezo-actuator; ISO: optical isolator; PD: photodiode; EOM: eletrical-optical modulator.

1671-7694/2012/S11405(3)

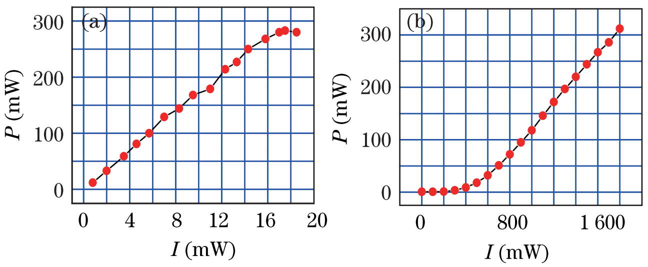

Fig. 2. (a) Output of TA versus injection power from master laser; (b) output power of TA versus the current of TA.

beam alignment and the amplifier current was observed. Under the condition of 19-mW LD injection, the output power of TA dependent on the current of its driver is shown in Fig. 2(b). Only a small fraction of the TA light can be mode-matched to the enhancement resonator. Here, about 30 percent of the power can be coupled into the external enhance enhancement resonator used for the first frequency doubling.

SHG for a broad range of frequencies in the visible spectrum has been achieved in recent years by using periodically poled ferroelectric crystals. In comparison with traditional birefringent phase matching, larger effective non-linear coefficients are accessible through quasi-phase matching, which can additionally be achieved in a non-critical interaction configuration for any wavelength combination within the transparency range of the non-linear medium[8]. For frequency doubling of the TA light at 1064 nm, we use a 5-mm-long PPKTP crystal[8] AR-coated on both sides for IR and green radiation. Scattering and absorption losses of the crystal are at a level of 1–2%. To increase the output power at 532 nm, the crystal is placed inside a bow-tie enhancement resonator with a coupling mirror with 5% transmission. The total resonator optical path length is 525 mm. The crystal is placed between two concave mirrors (radius of curvature r=50 mm, optical distance of 55 mm) leading to a beam waist inside the crystal of 28.1 μm along both symmetry axes, close to the optimum value. The crystal temperature can be tuned between 25 and 100 °C with a stability of below 100 mK. One of the four resonator mirrors is mounted on a piezoelectric transition (PZT) and actuated to keep the cavity resonant with the incoming laser light by means of the Pound-Drever-Hall locking technique.

With TA output power of 290 mW, we achieve a maximum of 47 mW of CW green light, corresponding to an overall optical-to-optical efficiency of 17%. The green output power of the frequency-doubling stage as a function of the crystal temperature is shown in Fig. 3(a), Optimum quasi-phase matching was achieved at a crystal temperature of 58 °C. A temperature acceptance bandwidth of 11 °C (full-width at half maximum (FWHM)) is observed at the central resonance. On this case, we can get 47-mW green power. Under the condition of inputting 290 mW of 1 064 nm, the coupling efficiency is around 30%, the conversion efficiency of the crystal about 50%, respectively. By changing the polarization direction of 1 064-nm beam, we get the doubling power relationship with direction of polarization, as shown in Fig. 3(b).

The tunable characteristic of this UV light source includes 3 parts. The first is tunability of ECDL, which can be achieved by adjusting ECDL gratings. The second is doubling cavity for 266 nm with BBO crystal, which can be achieved by adjusting the angle of BBO 's stage. The third is doubling cavity for 532 nm with PPKTP crystal, which can be achieved by changing the temperature of PPKTP or the angle of PPKTP. In this experiment, the third factor is the most crucial and is taken as main focus of tunability for whole system. Figure 4(a) shows that the relationship between optimum temperature and wavelength in PPKTP crystal. The fundamental beam is almost perpendicular to the PPKTP surface. If the fundamental frequency change, correspondingly, for phase matching with the fundamental frequency again, the optimum temperature of PPKTP will change, shown in Fig. 4(a). The mechanism is that when changing the wavelength of master laser, we need to increase or lower the temperature of PPKTP, so that the space of gratings agrees the wavelength again. From Fig. 4(a), we can get $\mathrm{d}T/\mathrm{d}\lambda = 16.87$ °C/nm, where we infer that it's necessary to cool down the crystal to below 0 °C if setting the wavelength at 1 062.2 nm. From Fig. 4(b), we can see that the temperature can be changed from 40 °C to 100 °C, thereby wavelength changed from 1 065 nm to 1 068.5, so the tuning of the wavelength is $\Delta\lambda_{\mathrm{T}} = -3.5$ nm.

In order to obtain the relationship between angle and optimum temperature of PPKTP crystal, we tilt the angle of PPKTP from –22° to 22°, correspondingly optimum temperature is changed. The mechanism is that when tilting the angle of PPKTP, the space of gratings on the beam direction inside the crystal increased, therefore under the condition of the same fundamental wavelength, we need to cool down the crystal, so that

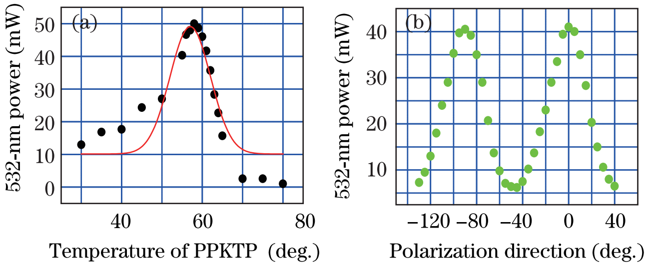

Fig. 3. Green output power of the frequency-doubling stage as a function of the crystal temperature, which shows the optimum temperature of 58 °C; (b) green power by adjusting polarization direction of 1 064 nm.

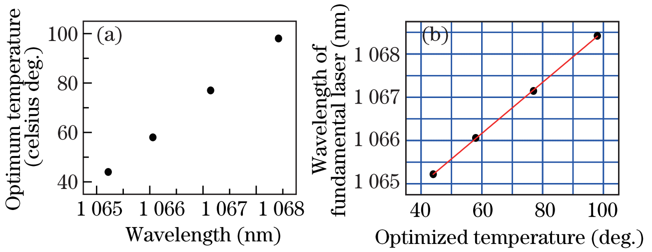

Fig. 4. (a) Relationship between optimum temperature and wavelength in PPKTP crystal; (b) span of quasi-phase matching by temperature of PPKTP. The temperature can be changed by controller from 40 to 100 °C, thereby wavelength changed from 1 065 to 1 068.5 nm, and the tuning of the wavelength is $\Delta\lambda_{\mathrm{T}} = -3.5$ nm.

the space of gratings agree the wavelength again. In Fig. 5(a), the x axis is the angle between input beam and crystal, while the y axis denotes optimum temperature. The tuning of the wavelength is $\Delta\lambda_{\text{angle}} = -1.186$ nm. Therefore totally span of quasi-phase matching of the PPKTP is $\Delta\lambda = -4.686$ nm.

In a second enhancement resonator (total optical path length 585 mm), birefringent type-I phase-matched SHG from 532 to 266 nm is performed by means of a 10-mm-long BBO crystal[9,10]. The BBO crystal is placed between two concave mirrors (r=75 mm, optical distance is 90 mm), the beam waist inside the crystal closes to the optimum value of 29.6 μm. For stabilizing the enhancement resonator onto the green light, the Pound-Drever-Hall locking technique is applied a second time. To protect the hygroscopic BBO crystal from condensing water, it is kept in a box. At optimum phase matching, with a green input power of 47 mW, 30 μW of UV light at 266 nm is achieved. Figure 6 shows UV power dependent on the polarization of green power, in which inset is the photograph of UV laser.

In conclusion, we present a compact and versatile laser source for tunable green and UV radiation. Seeding the master laser light into a TA, an IR power of 290 mW with an almost Gaussian beam profile is obtained. Efficient quasi-phase-matched frequency doubling by means of a periodically poled KTP crystal results in more than 47 mW of green light at 532 nm. 30 μW of UV light at 266 nm is generated by birefringent phase-matched frequency doubling using a BBO crystal. The tuning span of quasi-phase matching of doubling cavity for 532 nm with PPKTP crystal is achieved with –3.5 nm by changing the temperature of PPKTP, and achieved with −1.186 nm by adjusting angle of PPKTP.

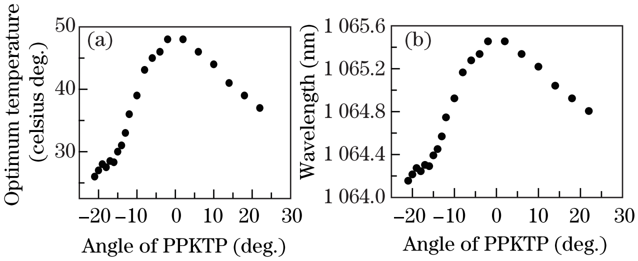

Fig. 5. (a) Relationship between optimum temperature and angle of PPKTP crystal; (b) span of quasi-phase matching by angle of PPKTP. The angle of PPKTP can be changed from –22° to 22°, thereby wavelength changed from 1 064.2 to 1 065.4 nm. The tuning of the wavelength is $\Delta\lambda_{\text{angle}} = -1.186$ nm.

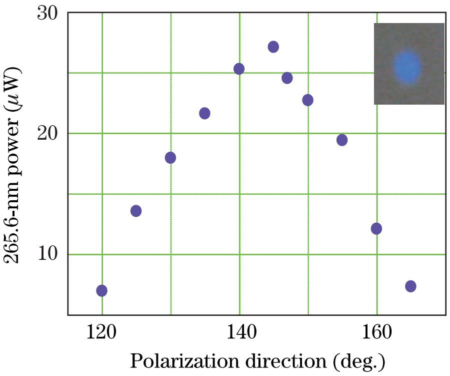

Fig. 6. UV power by changing polarization direction of 532 nm. The inset is UV profile taken by camera.

References

1. H. Hachisu, Phys. Rev. Lett. **100,** 053001 (2008)
2. L. Goldberg and D. A. V. Kliner, Opt. Lett. **20,** 1145 (1995)
3. D. A. V. Klinter, J. P. Koplow, and L. Goldberg, Opt. Lett. **22,** 1418 (1997)
4. C. Zimmerman, V. Vuletic, A. Hemmerich, and T. W. Hansch, Appl. Phys. Lett. **66,** 2318 (1995)
5. J. Alnis, A. Matveev, N. Kolachevsky, T. Wilken1, R. Holzwarth, and T. W. Hansch, Eur. Phys. J. **163,** 89 (2008).
6. E. Mimoun, L. De Sarlo, J. J. Zondy, J. Dalibard, and F. Gerbier, Appl. Phys. B **99,** 31 (2010)
7. Ch. Schwedes, E. Peik, J. von Zanthier, A. Y. Nevsky, and H. Walther, Appl. Phys. B **76,** 143 (2003).
8. R. Le Targat, J. J. Zondy, and P. Lemonde, Opt. Commun. **247,** 471 (2005).
9. D. N. Nikogosyan, Appl. Phys. A **52,** 359 (1991)
10. K. Kato, IEEE J. Quantum Electron. **QE-22,** 7 (1986)