Second harmonic 423-nm laser generated by BIBO crystal for calcium optical frequency standard

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Calcium is one prospective element for the modern optical frequency standard. The 423-nm transition line of calcium atoms has been widely used in laser slowing and laser cooling, the precise spectrum measurement, and the magnetic optical trapping (MOT). However, there is no any available commercial diode laser working at this wavelength. We built a 423-nm laser based on extra bow-tie cavity and by using a Brewster-cut uncoated BIBO (BiB_3O_6) crystal, which worked at room temperature, with conversion efficiency of 3.75%, and a potential up to 20%.

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The $^1P_1 - {}^1S_0$ transition line is an important transition line of calcium atom. In the study of modern frequency standard technology, calcium plays a more and more vital role for its prospective potential application in optical frequency standard[1,2]. Calcium has an isotope ^{40}Ca which has a ground state without hyperfine structure, thus all ^{40}Ca atoms in ground state can contribute to the clock transition signal. Considering the technical factors, there is a mature commercial diode laser working at the clock transition wavelength of 657 nm. But as a matter of fact, the stabilized laser locking to Ca transition has been recommended for the realization of the SI unit of length, the meter[3]. And the 423-nm transition line of Calcium is widely used in laser slowing and cooling, the precise spectrum measurement and the magnetic optical trapping (MOT). However, to the best of our knowledge, there is no any available commercial diode laser that can act as light source at this wavelength right now. So we developed a 423-nm laser through second harmonic generation technology (SHG) based on extra bow-tie cavity, and then this laser will be used in Zeeman slowing and MOT.

In 1961, Franken reported the SHG experiment by leading a 694.2-nm laser light pass through a quartz crystal. Then nonlinear optical frequency conversion became a research hot topic of modern optics. Since 1990s, there was a great progress of SHG technics. The high power intra-cavity SHG green laser (1064 nm/532 nm) came ture[4,5] and SHG blue light was also reported[6,7]. In China, Shanxi University realized high efficiency SHG green light by extra-cavity and quasi-phase-matched KTP crystal, with a conversion efficiency of 50.6%[8]. Beijing University of Technology also reported a 31.4% conversion efficiency of Q-switching Nd:YAG laser by bow-tie cavity technology[9]. In 2002, Manoel reported a SHG 423-nm laser by $KNbO_3$ crystal with a high power diode master laser[10]. $KNbO_3$ has also been widely used as the SHG crystal by NIST (National Institute of Standards and Technology) and PTB (Physikalisch-Technische Bundesanstalt) in the research of calcium frequency standard for a long time[11,12]. But for sake of phase matching, the $KNbO_3$ crystal has to be cooled to a temperature near −10 °C and thus it needs an additional temperature control system which causes other problems such as coagulation of hydrosphere on the crystal surfaces. In the same year, 2002, Grünert realized a SHG 423-nm laser by using LBO ($Li_2B_2O_4$) crystal[13] for Ca optical frequency standard. But the hygroscopic nature of LBO would cause the instabilities of the whole system. Recently, the company of Sacker is trying to build the commercial SHG blue light laser. Here, we report a SHG 423-nm laser using Brewster-cut uncoated BIBO crystal, which can work at room temperature without the hygroscopic problem.

To obtain the 423-nm light by frequency doubling, one needs a stable single-mode 846-nm laser as the fundamental light source. We choose an extra cavity diode laser (ECDL) in Littrow configuration as the 846-nm light source. The ECDL output power is about 40 mW with a linewidth about 1 MHz. The light will pass through two isolators in order to avoid the influence induced by the reflective light to the diode laser. Then the light is injected into a commercial tape amplifier (Sacker TEC400). When using 2000-mA operating current with 16-mW injecting light power, the output power of amplifier can reach 400 mW. After a 60-dB isolation, the power fluctuation is less than 2 mW over 3 h. Then the amplified fundamental light is coupled into the bow-tie cavity.

The bow-tie cavity or called butterfly cavity consists of four mirrors as shown in Fig. 1: two of them are plane mirrors and the others are curve mirrors. The first mirror (M_1) is a coated coupling mirror with an optimized reflectivity of 95% to the 846-nm infrared light. The other mirrors M_2, M_3, and M_4 are all coated with a reflectivity of 99.5% to fundamental light. For the sake of effective coupling the SHG blue light out of the cavity, M_4 is anti-reflection (AR)-coated with a transmission

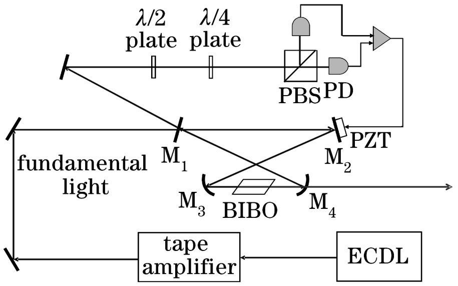


Fig. 1. Experimental setup scheme.

coefficient of 90% for the 423-nm light. The curve radii of M_3 and M_4 are both 55.7 mm. The distance between the two curve mirrors is 60 mm. To compensate the astigmatism between the tangential and sagittal plane of optical path, the folding angle of cavity is 11.4°. The tangential cavity mode waist between the two plane mirrors is 305 μm and the sagittal waist is 337 μm, while the tangential waist between the two curve mirrors is 33.7 μm and the sagittal waist is 38.8 μm.

The nonlinear optical crystal used here is uncoated Brewster-cut BIBO (BiB_3O_6) crystal. BIBO crystal is a biaxial crystal and belongs to the monoclinic crystal system. Its point group is 2 and space group is C2. BIBO crystal has a wide transparent spectrum (270 − 2600 nm), as well as high effective nonlinear optical coefficient d_{eff} compared with KTP crystal. Moreover, it has other advantages such as high damage threshold (600 MW/cm^2 for 1064-nm light), good chemical stability, and low deliquescence[14]. In this experiment, the BIBO crystal size is 3 × 3 × 5 (mm) and Brewster-cut with both faces polished without any coating. For 423-nm SHG, the working temperature of BIBO crystal is 21 °C, which can be easily achieved with a simple temperature control system. To find the suitable phase-matching angle, we calculate the refractive index properties of BIBO according to the Wang's paper[14]. The principal axis refractive index equations are shown as follows:

$$n_x^2 = 3.0740 + 0.0323/(\lambda^2 - 0.0316) - 0.01337\lambda^2,$$

$$n_y^2 = 3.1685 + 0.0373/(\lambda^2 - 0.0346) - 0.01750\lambda^2,$$

$$n_z^2 = 3.6545 + 0.0511/(\lambda^2 - 0.0371) - 0.02260\lambda^2,$$

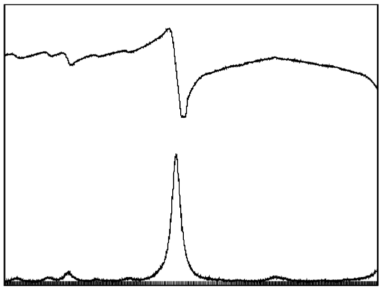
where λ is the selected wavelength. The calculation result is shown in Table 1. Consequently, the phase-matching angles are found as $\theta = 154.1°$ and $\varphi = 90°$, respectively and the refractive index of the polarization for SHG is 1.814. Correspondingly, the Brewster angle of the crystal is 61.4°. In our setup, we place the crystal in the cavity setting: its x axial vertical to horizon plane, and the fundamental light's polarization is tuned to parallel to the horizon to fulfill the phase-matching condition.

Table 1. Refractive Index of 846-nm Light and 423-nm Light

	n_x	n_y	n_z
846 nm	1.76399	1.79185	1.92708
423 nm	1.81407	1.85035	2.00269

Considering the power fluctuation of the tape amplifier, we adopt Hänsch's locking technique[15]. As shown in Fig. 1, the reflective light from M_1 will first pass a $\lambda/2$ plate and a $\lambda/4$ plate. Then it is splitted by a polarizing beam splitter (PBS) and detected by two photodiodes. The differential signal of two photon detectors (PD) is input to an amplifier to get the error signal. Finally, the error signal feedback to piczoelectric ceramic (PZT) for mode locking. This method acquires the error signal by tracing the phase shift of a round-trip in the cavity, so that it will not lost locking when the tape amplifier's power changes. The experimental result about the error signal and cavity mode signal for the locking system are shown in Fig. 2.

The allowed maximum injecting light power of tape amplifier is 20 mW and the recommended injecting power is 15 mW. Thus the amplifier output power is greatly depended on the working current of amplifier. The changing of injecting power will not cause much influence on output power, when the amplifier is working at high current. Considering the safety and long-term stability of amplifier, we set the injecting light power to 16 mW. When injecting 16-mW 846-nm laser light into the tape amplifier, the output power before the isolation is shown in Fig. 3. During the whole period of our experiment, the tape amplifier worked normally. With a working current of 2000 mA, the output fundamental 846-nm lights power is 400 mW after a 60-dB isolation before entering the bow-tie cavity. When turning on the locking system, the cavity can be locked to the peak of longitudinal mode for 15 min. When the cavity is locked, we measure the SHG output power. The experiment result is shown in Fig. 4. The SHG power curve shows a nonlinear feature which is according to the nonlinear optics theory, but the curve has a small distortion at high power region due to the high conversion efficiency. The



upper: error signal; lower: cavity mode signal

Fig. 2. Error signal and cavity mode signal for the locking system.

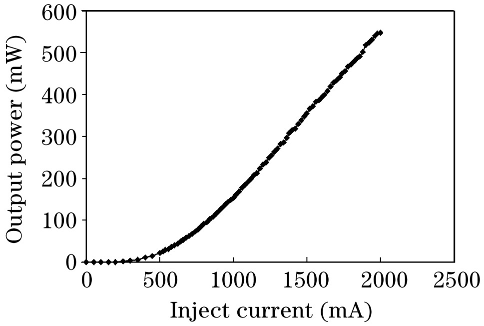


Fig. 3. Tape amplifier output power versus the inject current.

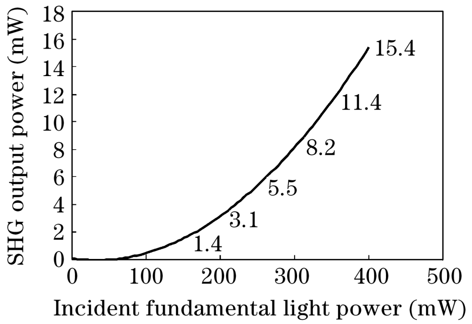


Fig. 4. SHG output power versus the fundamental light power.

curve also shows a threshold current, but actually it is caused by loss locking of cavity. So this phenomenon actually does not indicate a threshold feature of the system. Providing 2000-mA working current of the amplifier, the measured continuous SHG 423-nm light is about 15 mW with a linewidth less than 700 kHz, so that the conversion efficiency is 3.75%. The stability of the locking system is also tested. It is found that the system is more sensitive to low frequency vibration than high frequency vibration and is easy to loss locking when the fundamental light power is lower than 200 mW. But when working at high injecting power, the system shows a good locking stability and even can re-locked after a relative strong outer perturbation such as loudly speaking and slight patting on the experiment optical table.

Considering the facet loss of 28% due to Brewster cut and the reflective loss of the M_4, the actual crystal conversion efficiency should be 5.8%. Assuming a higher Q-parameter cavity by using higher reflectivity mirrors, a better out-coupling mirror and a nonlinear optical AR-coated crystal instead of a Brewster cut crystal, this system setup would have a great potential to achieve a conversion efficiency over 20%, which shows a good potential for cold atom experiment of calcium.

In conclusion, based on extra bow-tie cavity and Hänsch' locking technic, we built a laser working at the special wavelength of 423 nm for Ca optical frequency standard system by using the nonlinear optical crystal BIBO. This system do not need a complex crystal cooling system and can work at the room temperature without the hygroscopic problem. This laser has a wide application in laser Zeeman slowing, the precise spectrum measurement and MOT. As a vital part of the calcium optical frequency standard system, it will play an important role in Zeeman slowing and magnetic optical trapping. Considering the potential high conversion efficient, convenient set-up, and low cost of this laser system, it will also have a prospective application in cold atom physics, hyperfine spectroscopy, laser physics, modern frequency standard research and so on.

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