Proc. SPIE, Vol.8772 (2013) 87721B-1 ~ 87721B-7 [7 pages]

Frequency doubling of cw 1560nm laser with single-pass, double-pass and cascaded MgO:PPLN crystals and frequency locking to Rb D_2 line

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ABSTRACT

We implemented and compared three different quasi-phase-matching (QPM) frequency-doubling configurations for 1560nm laser of single pass, double pass and cascade by using of MgO:PPLN bulk crystals. Also a fiber-pigtailed MgO:PPLN waveguide is utilized in single-pass frequency doubling configuration in the case of low-power 1560nm fundamental wave (FW) laser. Employing the second-harmonic wave (SHW) output at 780nm and a rubidium (Rb) vapor cell, we also performed the modulation transfer spectroscopy (MTS). MTS is insensitive to the fluctuation of laser intensity and the temperature drift of atomic vapor cell, so it is a good choice for laser frequency stabilization against atomic hyperfine transition line. The laser frequency stability is significantly improved after being locked via MTS scheme compared with the free-running case.

Keywords: MgO:PPLN bulk crystal, MgO:PPLN waveguide, single-pass frequency doubling, double-pass frequency doubling, cascade frequency doubling, modulation transfer spectroscopy (MTS)

1. INTRODUCTION

The rapid progress in atomic physics over the past few decades has largely hinged on the development of high power, high beam quality, narrow linewidth laser sources for manipulating and probing atoms. High performance laser source also makes it a favorite species for precise laser spectra measurement, laser frequency calibration and atom cooling experiment (especially the rubidium (Rb) atom cooling experiment)[1]. Additionally, atom interferometry is also one of the most promising candidates for ultra-accurate measurements of gravito-inertial force, narrow linewidth, high power laser are a pre-requistite to achieving higher sensitivities[2].However, the traditional commercial 780nm (the resonance frequency of the Rb D_2 line) diode lasers are restricted by the limited maximum power output (sometime needs the tapered amplifier), the laser linewidth, frequency stability and so on, it doesn't perform as well as desired. In recent years, the nonlinear frequency doubling process has been shown a novel method to obtain the desirable laser radiation[3]. Benefited from the mature nonlinear optics technology, especially the quasi-phase-matching (QPM) nonlinear process by using of periodically-poled materials, the 780nm laser has played more and more important roles in the Rb cooling and trapping experiment.

There are various ways to realize the laser frequency conversation, such as the nonlinear grating, phase-matched crystal, be with the convenient setup and higher conversation efficiency , the QPM frequency doubling technology is used widely, the usual commonly used QPM materials are periodically-poled lithium niobate (PPLN)[4~8] , periodically-poled $KTiOPO_4$ (PPKTP) [9,10], periodically-poled lithium tantalite (PPLT)[11] and other periodically-poled ferro-electric crystals. Among all existing QPM materials, PPLN has been most widely established for nonlinear frequency conversion applications, due to the mature fabrication technology, the large effective nonlinearity (d_{eff}~16 pm/V) and widespread availability in interaction lengths.

In this paper, we present a rigorous study of continuous-wave (cw) laser second-harmonic generation (SHG) from FW at 1560 nm to SHW at 780 nm utilizing MgO:PPLN crystal (fabricated by HC Photonics) with three different configurations quantitatively. The optimum parameters are considered, including mode matching, focus waist and phase-matching temperature. Taking the diode laser as the seed laser, the laser power is amplified by a Er-doped fiber amplifier (EDFA). We demonstrated the frequency doubling of the cascade configuration, and the maximum SHG efficiency is almost ~ 2 times for that of the single-pass configuration with only one crystal. We have characterized the performance of these laser systems and demonstrated that SHG can be used to lock the FW laser frequency to Rb atomic hyperfine transition lines.

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Nonlinear Optics and Applications VII, edited by Mario Bertolotti, Joseph Haus, Alexei M. Zheltikov,
Proc. of SPIE Vol. 8772, 87721B · © 2013 SPIE · CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2016839

2. EXPERIMENTAL SCHEMES

2.1 Experimental setup

SHG of cw laser near 1.5 micrometer with periodically-poled QPM materials has recently shown to be an attractive approach for the generation of high-power laser radiation. A z-cut MgO:PPLN sample with dimensions of 1mm × 3.4mm × 25 mm is fabricated by HC Photonics. The MgO:PPLN crystal contains a single grating with a period of 19.48 μm, which is phase matched at about 80 ^{o}C for frequency doubling from 1560 nm to 780 nm. It is AR-coated at both facets for 1560 nm and 780 nm. Based on our experiment measuring results, we deduce that d_{eff} of the sample is ~9.8 pm/V. In our experiment, a commercial EDFA (Keopsys) is seeded by an extended-cavity diode laser (ECDL, Newport TLB-6328, linewidth ~ 300 kHz), producing up to 5 W of cw power at 1560 nm. We have also used a butterfly-packaged 1560 nm distributed-feed-back (DFB) diode laser as a seed laser, and obtained similar results. The cascaded two bulk crystals configuration utilizes two identical 25-mm-long MgO:PPLN crystals with a single poling period (Λ=19.48 μm), housed in two separate ovens stabilized by temperature controllers with temperature stability of 0.01 ^{o}C. All the MgO:PPLN crystals faces are antireflection coated (R<0.5%) at 1560 nm and 780 nm. Half-wave plate is used to adjust the polarization direction of the fundamental to achieve the higher SHG efficiency.

The schematic of the experimental setup is shown in Fig. 1, a) is the scheme of the single-pass configuration with one bulk crystal; b) is the scheme of the single-pass f configuration with cascaded two bulk crystals (in order to describe clearly, we named the two crystals as A and B). The two mirrors after the first crystal are mounted on a rail, allowing the relative phase between the fundamental and the second harmonic to be varied by adjusting the path length between the two crystals; c) is the double-pass configuration with one bulk crystal. the face of the focus lens are all anti-reflection (AR) coated for 1560 nm and 780 nm, the 0^{o} high reflective mirror is used to reflect both FW and SHW go back along the same routine, and taking a dichroic filter separated FW and SHW finally. Compared with the pure PPLN crystal, doping MgO into PPLN not only reduces the photo-refractive effect, but also increases the laser damage threshold.

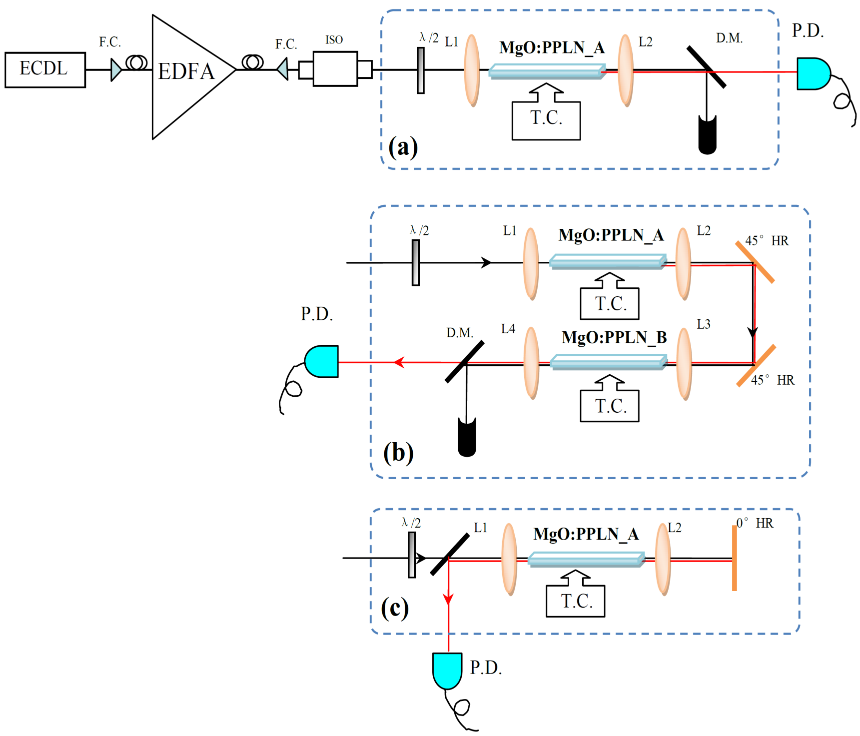

Fig. 1 The three different configurations for frequency doubling: **a)** for single-pass frequency doubling, **b)** for the cascaded crystals frequency doubling, and **c)** for double-pass frequency doubling. Keys to figure: FC: fiber coupler; EDFA: Er-doped fiber amplifer; IOS: optical isolator; TC: temperature controller; PD: photodiode; DM: dichroic mirror; Red solid lines for 780-nm laser beam; Black solid line for 1560-nm laser beam.

2.2 Single-pass SHG with one MgO:PPLN bulk crystal / one waveguide and cascaded two bulk crystals

In this frequency doubling configuration, we not only take one MgO:PPLN bulk crystal (Fig. 1(a)), but also one MgO:PPLN waveguide (HC Photonics, length: 30mm). Compared to the bulk crystal, the waveguide provides tight confinement of FW over the entire length of the crystal, and therefore it will yield a higher SHG efficiency at the same FW power level. The schematic diagram is shown in Fig.2. So the MgO:PPLN waveguide is good choice for SHG with low-power FW laser.

(a) (b)

Fig. 2 (a) Periodically-poled bulk crystal: the Gaussian laser beam is focused into the crystal with a focus waist. **(b)** Periodically-poled waveguide: the laser beam is coupled into the waveguide and confined in it. The accepted laser power is usually less than 250 mW to avoid damaging the waveguide structure.

In order to improve the SHW output power further, we employ the cascaded two bulk crystals configuration (Fig. 1(b)), where we equivalently increased the crystal length to 50 mm from the single 25-mm-long bulk crystal. The system consists two stages: in the first stage, FW power beam is focused at the centre of the first one bulk crystal to a beam radius $\omega_{opt} \sim 35$ μm, close to the theoretical optimum focus beam size [12]; in the second stage, both FW and SHW laser beams are collimated using lens L2 (f = 50 mm), then they are refocused at the center of the second one bulk crystal using the lens L3 with the optimum beam size ~ 35 μm, we are also able to maintain desirable mode matching of FW and SHW at the center of MOg:PPLN_B crystals. After being collimated with the lens L4, FW and SHW are separated by a dichroic filter. The dichroic filter is coated for high reflectivity (R > 99%) at 1560 nm and high transmissivity (T > 99.8%) at 780 nm

2.3 Double-pass SHG with single MgO:PPLN bulk crystal

To simply the experiment setup further, and maintain relatively higher SHG efficiency, we employ the double-pass configuration with single MgO:PPLN bulk crystal (Fig. 1(c)). In this case, only one bulk crystal, therefore only one set of crystal oven and the temperature controller, are utilized.

SHG process consists of two stages: the first stage is FW single-pass frequency doubling after the bulk crystal being appropriate focusing condition; in the second stage, both FW and SHW laser beams are collimated by the L2, and then are reflected by the 0^{o} high-reflection mirror, refocusing to the central of the bulk crystal again by the L2. Then FW and SHW beams are separated by a dichroic mirror. In our experiment, in order to reduce the insert loss of optical elements, all the lens' surfaces are AR coated for 1560 nm and 780 nm, and the transmissivity is larger than 99%. The reflectivity of 0^{o} high-reflection mirror is larger than 99.5%.

3. EXPERIMENT RESULT

3.1 The optimum phase matching temperature

There is no need to consider the "walk-off" effect between FW and SHW for the QPM technology, but only control the crystal working at appropriate temperature. It is clear that the optimum temperature of the crystal is the key to obtain the higher SHG efficiency. In order to get the optimum phase matching temperature, we vary the temperature of crystal housed in the oven at the fixed input fundamental power, and gain the optimum phase matching temperature. The results are shown in Fig. 3. Compared with the undoped PPLN crystal,[9,10] optimum phase matching temperature for the MgO:PPLN crystal is much lower, the phase matching temperature is 43.0 °C for the MgO:PPLN waveguide and 81.3 °C for the MgO:PPLN bulk crystals.

The variation of SHW output with temperature at a fixed FW laser power determines the temperature acceptance bandwidth of the nonlinear crystal, compared with the MgO:PPLT[11], MgO:PPLN crystal owns broader temperature accepted bandwidth. The experimental measurement results are well coincided with the calculated values of ~ 4 °C. The equation of the temperature acceptance bandwidth can be found in ref. [13].

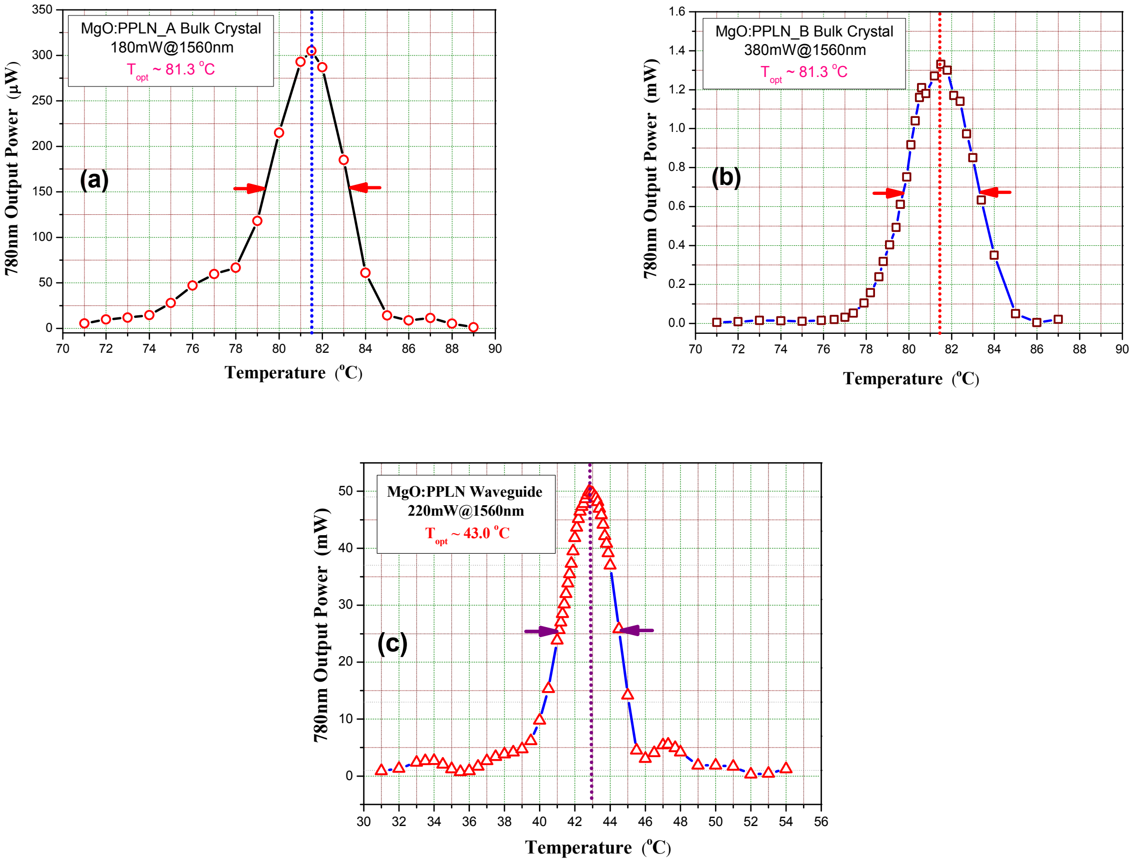

Fig. 3 The temperature tuning curves for the bulk crystal MgO:PPLN_A **(a)**, MgO:PPLN_B **(b)**, and the MgO:PPLN waveguide **(c)**. The solid lines are just connections of data for guiding eyes.

3.2 Single-pass SHG with one MgO:PPLN bulk crystal / MgO:PPLN waveguide and two cascaded crystals

The 1560nm laser power was measured before L1, and the 780nm laser power is measured after the dichroic mirror. In the case of cascaded two MgO:PPLN bulk crystals (Fig. 1(b)), we obtained maximum SHG efficiency of 14% for the 1560nm laser power of 4500 mW, and the 780nm output of 630 mW. According to the experiment results we can find the 780nm laser output is almost the sum of that for the two single-pass configuration with singe bulk crystal (Fig. 1(a)). As shown in Fig. 4(a). The inset in Fig. 4 shows the spatial intensity profile of 780 nm laser detected by using a CCD camera, where after being collimated from the dichroic mirror. We measured the output laser beam's spatial profile, and found out M^2 ~1.07.

Replacing the single bulk crystal in Fig. 1(a) with the 30-mm-long MgO:PPLN waveguide, and also replacing the 1560 nm ECDL with the 1560 nm DFB laser diode, controlling the maximum 1560 nm output power from EDFA below 250mW, we obtained 50 mW@780 nm when 220 mW of FW laser power is coupled into the waveguide via the input single-mode polarization-maintained fiber. The corresponding maximum SHG efficiency is 22.7%, as shown in the Fig. 4(b).

3.3 Double-pass SHG with single MgO:PPLN bulk crystal

To simply the experiment setup further, and achieve relatively high SHG efficiency, we employ the double-pass configuration with single MgO:PPLN bulk crystal (Fig. 1(c)). When 1560 nm FW laser power increases to 4224mW, we obtain 442 mW@780 nm. The corresponding SHG efficiency is ~ 10.4%, which is ~ 1.7 times compared with the single-pass configuration with single bulk crystal (~ 6.1%). This value looks a little bit lower than that for the cascaded two bulk crystals configuration, maybe due to the higher depletion of FW laser power in the last stage and a non-ideal overlap of FW and SHW laser beams in the second stage.

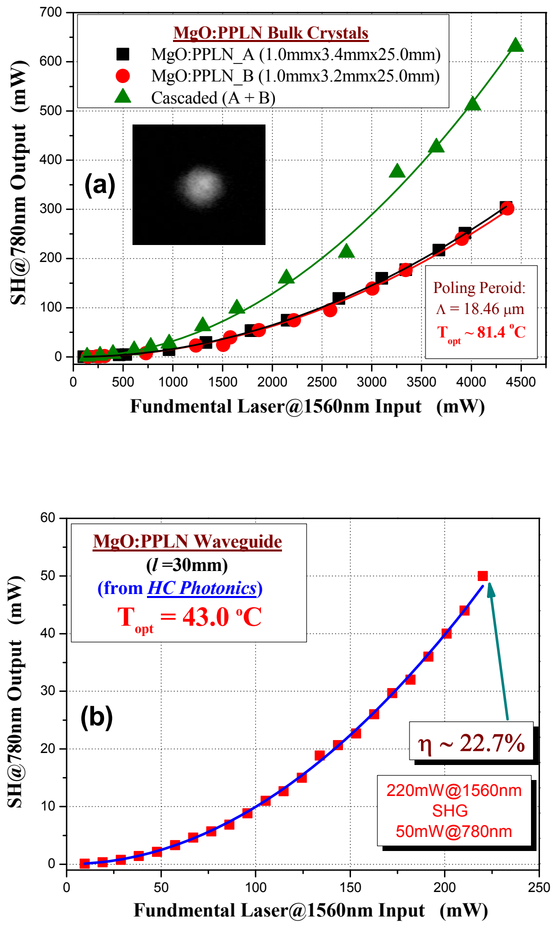

Fig. 4 SHW@780nm laser output power versus FW@1560nm laser power. **(a)** Single-pass frequency doubling with one MgO:PPLN crystal, and cascaded two MgO:PPLN crystals; **(b)** Single-pass frequency doubling with the fiber-pigtailed MgO:PPLN waveguide.

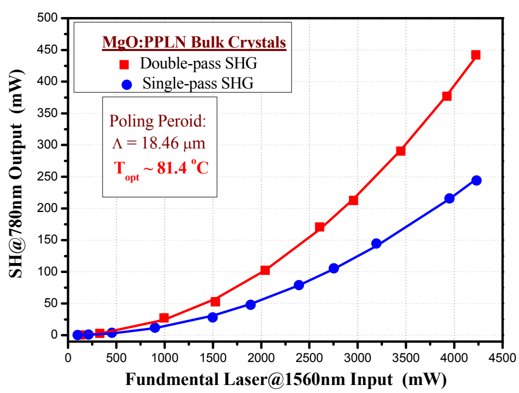

Fig. 5 SHW@780nm laser output power versus FW@1560nm laser power for the single-pass and double-pass frequency doubling cases.

3.4 Locking laser frequency to Rb D_2 line by using MTS scheme

Scanning the 1560 nm laser diode's injection current, we can obtain the modulation transfer spectra (MTS) of ^{87}Rb D_2 line. The MTS device is not shown in Fig. 1. Modulation at 4.1 MHz is applied on a phase-type electric-optical modulator (EOM) on the strong pumping laser beam for conventional saturation absorption spectroscopic (SAS) device, while the un-modulated weak laser beam is used as the probe beam, which counter-propagates with the modulated strong pumping beam inside a Rb atomic vapor cell. When and only when the hyperfine transitions is resonated with laser frequency, the modulation is transferred from the pumping beam to the probe beam due to the nonlinear four wave mixing process in the Rb atomic vapor. Detecting the probe beam by a fast photodiode and de-modulating at 4.1 MHz by using a double-balanced mixer (Mini-Curcuits), the dispersion-like MTS signal can be observed, as shown in Fig. 6(a). Compared with the conventional SAS signal and the polarization spectroscopic signal, the MTS has better signal-to-noise ratio and completely no background, and it is also not sensitive to the laser intensity's fluctuation and the temperature drift of atomic vapor cell. So that MTS is a good choice for laser frequency stabilization against atomic hyperfine transition line.

Taking T3 peak (^{87}Rb $5S_{1/2}$ (Fg=2) - $5P_{3/2}$ (Fe=3) cycling transition) of MTS signal as the reference frequency, we can stabilize 1560 nm diode laser's frequency. The typical laser frequency fluctuation for the free-running case is ~12 MHz within 60 seconds of the typical record time, the residual frequency fluctuation after being locked is +/- 0.23 MHz (see Fig. 6(b)). The laser frequency stability is significantly improved after being locked compared with the free-running case.

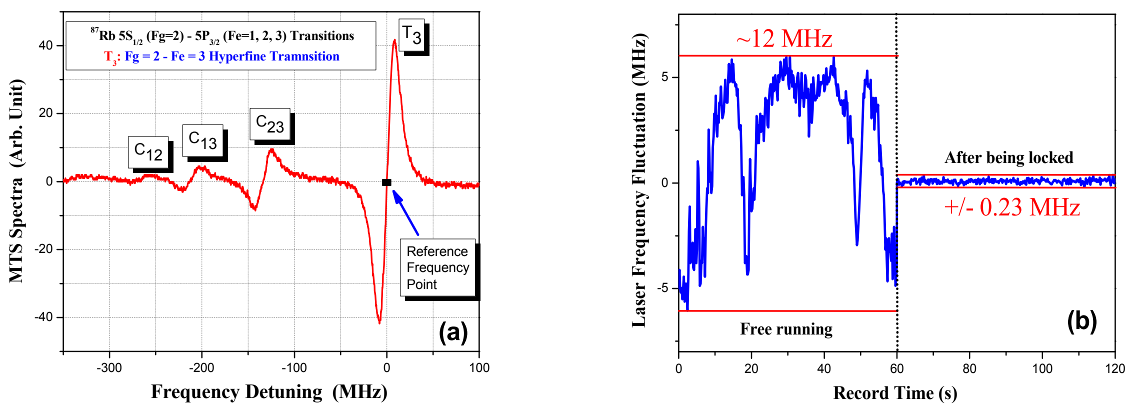

Fig. 6 (a) The MTS signals of ^{87}Rb $5S_{1/2}$ (Fg=2) - $5P_{3/2}$ (Fe=1, 2, 3) transitions. The ^{87}Rb Fg=2 – Fe=3 cycling transition is employed as the reference frequency point for laser stabilization. **(b)** Typical 1560nm laser frequency fluctuation for the cases of free running and after being locked. Obviously the laser frequency stability is significantly improved after being locked.

4. CONCLUSION

In conclusion, when the 1560 nm FW laser power is ~ 4500 mW, we have demonstrated the generation of ~ 300 mW of tunable cw single-frequency laser at 780nm by SHG in the single-pass configuration with single 25-mm-long MgO:PPLN bulk crystal, ~ 440 mW@780 nm by SHG in the double-pass configuration with single 25-mm-long MgO:PPLN bulk crystal, and~ 630 mW@780 nm by SHG in the cascaded two 25-mm-long MgO:PPLN bulk crystals configuration. Also we have demonstrated the generation of ~ 50 mW of tunable cw single-frequency laser at 780nm by single-pass SHG with the 30-mm-long input-fiber-pigtailed MgO:PPLN waveguide with 220 mW of 1560 nm laser input. The cascaded crystals configuration presents the highest SHG power output in these three configurations, but the double-pass configuration is much simpler.

Thanks to the MTS stabilization scheme, we have significantly improved the laser frequency stability after the frequency doubled laser is locked to ^{87}Rb $5S_{1/2}$ (Fg = 2) - $5P_{3/2}$ (Fe = 3) cycling hyperfine transition via MTS, compared with the free-running case. Several hundreds mW of 780 nm tunable cw single-frequency laser with good frequency stability, can find a important applications in the laser cooling and trapping of ^{85}Rb or ^{87}Rb atoms and related fields.

Actually, if we only use low-power 1560 nm DFB laser diode (~ 50 mW) and the fiber-pigtailed MgO:PPLN waveguide, > 2.5 mW@780 nm can be achieved. Married with the MTS scheme, we can expect that the compact and robust stabilized 1560 nm laser system can be used for calibrating the fiber telecom channels for dense-wavelength-division-multiplexing (DWDM) protocol via the help of laser wavelength meter.

ACKNOWLEDGEMENT

This work is partially supported by the National Natural Science Foundation of China (Grant Nos. 61078051, 11274213, 61205215, and 612279002), the Shanxi Scholarship Council of China (Grant No. 2012-015), the Research Program of Sci & Tech Star from Taiyuan, Shanxi Province, China (Grant No. 12024707), the Project for Excellent Research Team of the National Natural Science Foundation of China (Grant No. 61121064), and the National Major Scientific Research Program of China (Grant No. 2012CB921601).

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