Efficient green-light generation by frequency doubling of a picosecond all-fiber ytterbium-doped fiber amplifier in PPKTP waveguide inscribed by femtosecond laser direct writing

Chenghou Tu,[1] Zhangchao Huang,[1] Kai Lou,[1] Hongjun Liu,[2] Yishan Wang,[2] Yongnan Li,[1] Fuyun Lu,[1] and Hui-Tian Wang[1,3,4,5]

[1]*School of Physics, Nankai University, Tianjin 300071, China*
[2]*State Key Laboratory of Transient Optics and Photonics Technology, Xi'an Institute of Optics and PrecisionMechanics, Chinese Academy of Sciences, Xi'an, 710119, China*
[3]*National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093,China*
[4]*htwang@nankai.edu.cn*
[5]*htwang@nju.edu.cn*

Abstract: We have demonstrated an ultrashort, compact green light radiation by frequency doubling of an all-fiber ytterbium-doped fiber laser source in a PPKTP waveguide fabricated by femtosecond laser pulses. Using the fabricated PPKTP waveguide crystal containing a 10 mm single grating with a period of 9.0 μm, we generate 310 mW of picosecond radiation at 532 nm for a fundamental power of 1.6W, corresponding to a conversion efficiency of 19.3%. The temperature tuning range of 8°C is achieved for a fixed fundamental wavelength of 1064 nm, the FWHM of the wavelength tuning curve is 4.2 nm at room temperature. The generated ultrashort pulses at 532 nm are of great importance and have comprehensive applications in photobiology research and high-resolution spectroscopy.

OCIS codes: (190.7110) Ultrafast nonlinear optics; (190.2620) Harmonic generation and mixing; (220.4000) Microstructure fabrication; (320.7090) Ultrafast lasers; (060.2320) Fiber optics amplifiers and oscillators

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1. Introduction

The recent progress in photobiology research, such as microscopy, optical micromanipulation and bio-medical imaging continues to justify the need for compact, low-cost visible and near-infrared lasers that demonstrate true portability and practicality. Laser sources at the shorter green and blue wavelengths provide clear advantages over infrared lasers in allowing for stronger beam focusing and enhanced resolution in multi-dimensional imaging techniques [1]. By using ultrashort-pulse lasers in preference to continuous-wave sources, it is possible to investigate ultrafast biological processes [2], increase the resolution of spectroscopy, microscopy [3,4], etc.

Highly efficient green and blue light generation by quasi-phase-matched (QPM) frequency doubling of diode laser [5] and picosecond (ps) pulses from mode-locked solid state lasers have been reported [6,7]. Nonetheless, the choice of the traditional solid-state or diode laser sources limit the range of accessible wavelength and the device compactness. Fiber lasers has the advantages of high efficiency, excellent beam quality, efficient diode-pumped operation, very good heat dissipation, broad gain bandwidth, compactness and the potential of all-fiber integrity [8–10]. Therefore, fiber laser sources are becoming ideal pump sources of frequency doubling towards the new range, environmentally stable, and fiber-integrated radiation.

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In PPKTP crystals the second harmonic generation (SHG) based on fiber-format laser sources has been demonstrated [11–13]. However, periodically poled ferroelectric waveguides have attracted a lot of attention as higher conversion efficiencies are possible as a result of prolonged wave interaction at higher intensity [14–16]. PPKTP waveguide is normally fabricated by ion-diffusion [17] which is only suitable for fabricating channel waveguides close to the surface, and in which high visible degradation has to be involved. Recently, femtosecond laser inscription has been applied successfully to create waveguides in a variety of optical materials including glasses [18–20], overcoming the limitations of waveguide fabricated by ion diffusion, and improving the optical quality of the inscribed waveguides. Frequency doubling with a conversion efficiency (CE) of 0.22% W^{-1} has been achieved in femtosecond laser inscribed PPKTP waveguides from a continuous-wave (CW) Ti:sapphire laser [21]. Using a Q-switched Nd:YAG laser as the pump source, we have demonstrated efficient 532 nm green light generation in a double line type II PPKTP waveguide with a CE of 39.6% [22].

In this paper, we report efficient frequency doubling of a tunable all-fiber ytterbium-doped fiber amplifier in a single pass configuration that incorporates periodically poled KTP waveguide fabricated by femtosecond laser direct writing. The SHG conversion efficiency of 19.3% is achieved, yielding 310 mW fiber-format, compact green light radiation.

2. Waveguide preparation and experimental setup

2.1 PPKTP Waveguide fabrication and characterization

A z-cut PPKTP sample with dimensions of 10 × 10 × 1 mm^3 was fabricated by electrical poling technique. Periodic aluminum electrodes were patterned on the + *z* face of the KTP crystal wafer by a lithographic lift-off process. The + *z* electrodes were separated by electrically insulating photoresist, and KCl liquid electrodes were used to provide contact with the external poling circuit. The samples were poled by applying electric pulses of 2.0 kV/mm. The PPKTP crystal contains a single grating with a period of about 9.0 μm, which is phase matched at the center wavelength of 1064nm at room temperature. It is not AR-coated at both facets. The PPKTP sample was characterized using a CW laser with respect to the nonlinear coefficient (d_{eff}) [12] and the nonlinear interaction length (L_{eff}) [23]. Based on the measurement results, we deduce that d_{eff} is ~8.28 pm/V (~77% of the theoretical value of 10.75 pm/V) for the 10 mm long PPKTP sample, and L_{eff} is 8.81 mm. The discrepancy between the physical length and the measured effective length is attributed to imperfections in the grating structure. Furthermore, the non-zero linewidth of the CW laser can also broaden the crystal temperature tuning curves, which consequently reduces the value of L_{eff} [12].

To inscribe waveguides in the prepared PPKTP sample, we used an amplified Ti:sapphire laser system (HP-Spitfire, Spectra-Physics Inc.) operating at a central wavelength of 800 nm. The laser emitted linearly polarized femtosecond pulse trains with an FWHM duration of 50 fs and a maximum energy of 2 mJ at a repetition of 1 kHz. The laser beam was focused into the sample (along the *z* axis) with a 25 × microscope objective (NA = 0.4) at a depth of 300 μm beneath the sample surface. A CCD (KA-320) detector was used to monitor the focusing condition. In order to produce a thermally stable double line written type waveguide, we consecutively wrote a pair of straight lines separated by 14 μm in the *x* direction of the sample [24]. Figure 1(a) shows the optical micrograph of the end face of the fabricated waveguide, obviously two lines are successfully written in the PPKTP crystal.

To investigate the guiding properties of the fabricated PPKTP waveguide, a CW 1064 nm laser source was coupled onto one end of the waveguide using a microscope (NA = 0.25), and the output facet was then imaged onto a camera. The guiding experiments showed that the waveguide exhibits strong modal polarization dependence. For the polarization of the injected beam parallel to the *z* axis of the crystal, hereafter referred to as TM mode, the guiding is very strong. However, for the TE mode, the guiding is very weak. Figure 1(b) illustrated the near-filed intensity distribution of a single mode field (TM mode) emitted from the produced waveguide. It is clear that the mode profile is circular and has a good symmetry. From the

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corresponding near-field image of the guided 1064 nm mode, together with the simulated mode distribution, we assessed the maximum refractive index change (Δn) of the waveguide to be about 3×10^{-3}. Correspondingly, the NA of the fabricated waveguide can be estimated about 0.105 from $\mathrm{NA} = (2n\Delta n)^{0.5}$. The propagation loss at 1064 nm was measured to be ~1.2 dB/cm using the simpler and more reliable Fabry-Pérot method [25].

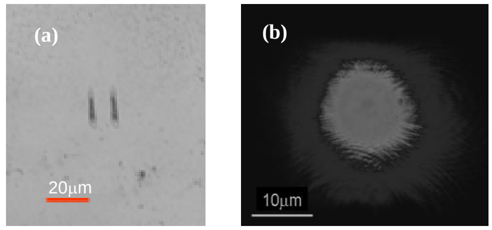

Fig. 1. (a) Optical micrograph of the end face of the double line type II waveguide written by femtosecond pulses, and (b) the near-filed guided mode profile at 1064 nm.

2.2 Experimental setup for second harmonic generation

Figure 2 shows the experimental setup for generating ultrashort green radiation. A compact tunable high power picosecond source based on Yb-doped fiber amplification of gain switch laser diode is used as the fundamental radiation source. A multi-stage single mode Yb-doped fiber preamplifier was combined with a single mode double-clad Yb-doped fiber main amplifier to construct the amplification system. In the preamplifers, two pieces of Yb-doped single mode fibers (INO Inc, Canada, core/clad = 5/125 µm, NA = 0.13) were used, and the fiber lengths were 8 and 5 m, respectively. A semiconductor diode laser emitted at 976 nm with a pump power up to 300 mW was used as the pump source for the two preamplifiers. For realizing wavelength-tunable output, a self-made tunable filter, composed of a reflective diffraction grating, a movable slit and a fiber-coupling system, was used to filter the broadband spectrum from the first stage preamplifier. The incident beam from the first stage preamplifier is angularly separated to its different frequency components by the reflective grating, and then a movable slit was used to select the interested frequency components, which is directly coupled into a fiber-format coupling system and output to the next amplifier. After pre-amplification, the pulses were amplified by a two-stage power amplifier, which was pumped by two high-power multimode semiconductor lasers operating at 976 nm. Two pieces of 3 and 4 m double cladding Yb-doped fibers (core/clad = 25/130 µm, NA = 0.08/0.46) were used as the gain fiber, and the pump and the signal were combined through a 6 + 1 beam combiner (ITF Inc). Using this method, 90 ps pulses with an average power of 3.5 W at 1 MHz repetition rate were generated with high stability and good beam quality ($M^2 \leq 1.1$) [inset in Fig. 3(b)] under a total pump power of ~13W. Figure 3 showed the spectra of the tunable laser source at different wavelengths and the pulses intensity autocorrelation. The central wavelength was tunable from 1053 to 1073 nm with a spectral width (FWHM) of ~1.8 nm. The output beam has a Gaussian profile with a sech^2 temporal shape.

The PPKTP waveguide was placed inside a temperature controlled oven (HC photonics), in which the operation temperature can be controlled from room temperature up to 200°C with an accuracy of 0.1°C, allowing for precise thermo-optic tuning.

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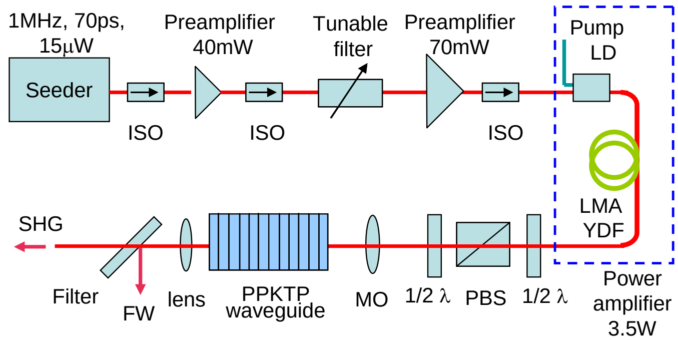

Fig. 2. The experimental set-up used for SHG. ISO: optical isolator, LMA: large mode area, YDF: ytterbium-doped fiber, 1/2λ: half wave plate, PBS: polarization beam splitter, MO: microscope objective, FW: fundamental wave.

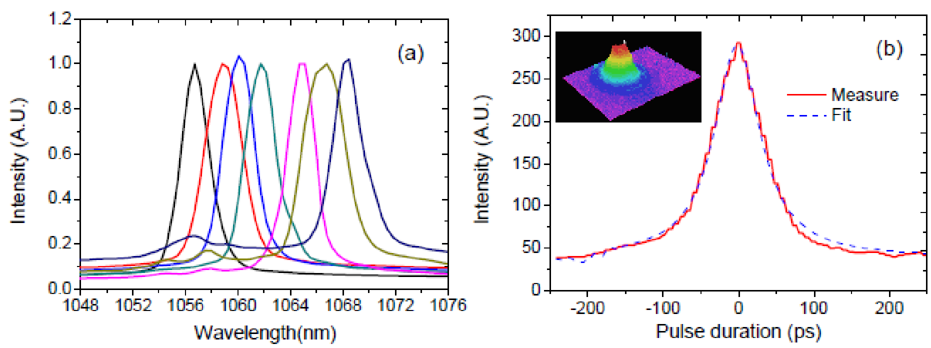

Fig. 3. (a) The tunable spectra and (b) the intensity autocorrelation of the fundamental pulses. In (b) the dotted line represents the theoretical autocorrelation of a pedestal-free $sech^2$ pulse with $\tau_{FWHM} = 90$ ps, inset is the Gaussian shape beam profile.

The performance of PPKTP allows high power radiation in simple single pass configuration at room temperature. To maintain the stable output, we operated the pump source at the maximum power and used an attenuator comprising a λ/2 wave plate and a polarization beam splitter (PBS) to vary the input fundamental power. The monitoring of the pulse duration and its shape as well as the average pump power shows that the fundamental pump after PBS is very stable due to the good stability of the all fiber amplifier system. The maximum available pump power after PBS was ~2.0 W. Another λ/2 wave plate was used to achieve the desired pump polarization for phase matching. The fundamental beam was collected and focused to the PPKTP waveguide by a 10 × microscope objective (NA = 0.25). A dichroic filter, coated for high reflectivity $R > 99\%$ at 1064 nm and high transmission $T > 99\%$ at 532 nm, was used to extract the generated green output from the fundamental pump pulses.

3. Results and discussions

The first-order reciprocal of the PPKTP crystal is used to achieve the quasi-phase-matched SHG, in which the d_{33} nonlinear coefficient was utilized. To characterize the SHG properties in PPKTP waveguide, we first investigated the effect of crystal temperature on the SHG power. To avoid the influence of the thermal effect, we performed the measurements at a low fundamental power of 600 mW at 1064 nm, resulting in a maximum green output power of 78 mW at the matching temperature of 24°C, which is shown in Fig. 3. The FWHM of the temperature tuning curve is $\Delta T = 8$°C, which is much larger than the value of 2.2°C by using the CW fundamental pump source [12]. At the optimal phase matching temperature of 24°C, we investigated the fundamental wavelength tuning curve, as shown in Fig. 4. The FWHM of

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the tuning spectrum for the pump is 4.2 nm and the peak output is located at 1064 nm. The far-field profile shown in the inset of Fig. 5 indicates that the generated second-harmonic light has a good beam quality.

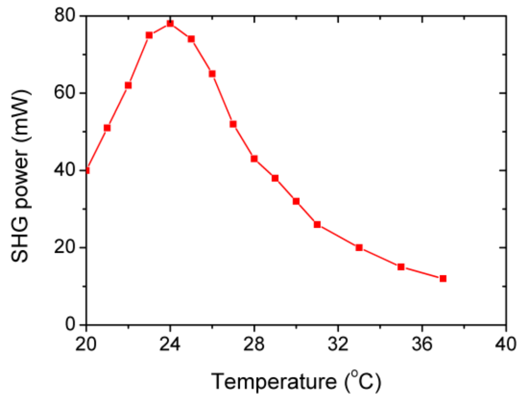

Fig. 4. Measured temperature tuning curve for SHG at the matching temperature of 24°C.

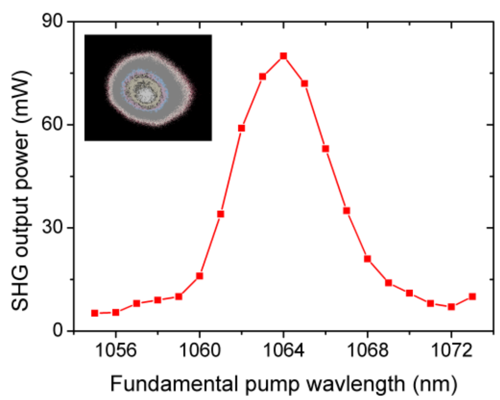

Fig. 5. Measured wavelength tuning curve for SHG. Inset is the far-field profile of generated green beam.

At the QPM wavelength of 1064 nm and the phase-matching temperature of 24°C, we performed measurements of the SHG efficiency and power up to the maximum fundamental pump power of 1.6 W, with the results shown in Fig. 6. The fundamental power was measured at the input to the waveguide, while the SHG power was measured after the dichroic filter. As shown in Fig. 6, the SHG power exhibits a quadratic growth as the input power increases up to 1.6 W. The SHG efficiency rapidly increases under the power lower than 600 mW, while above this value it slowly grows with the fundamental power. Such a saturation effect may be attributed to depletion of the fundamental pump and the temperature detuning in the PPKTP crystal [12,13,23,26]. At an pump power of 1600 mW, the SHG power of 310 mW is obtained, corresponding to a single-pass conversion efficiency of 19.3%, which is higher than 15.6% obtained in the bulk crystal. Supposing 80% of the pump light coupled into the waveguide (coupling loss ~1 dB), and taking the Fresnel reflection (8.6% at 1064 nm, corresponding to a Fresnel reflection loss ~0.39 dB/face) into account, we get a total insertion loss of 2.6 dB for the fundamental pump. If the Fresnel reflection for green light (9.5%) and the total insertion loss for fundamental light are considered, then the maximum conversion efficiency obtained in the produced waveguide is ~39%, which is much larger than the recent

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published results [27]. We expect that with the use of antireflection-coated front and end facets, it is possible to further enhance the second-harmonic output power and also to increase the efficiency.

For comparison, the output power of the second harmonic pulses in the bulk PPKTP crystal was also measured. We used the same PPKTP crystal and switched from the waveguide area to the bulk crystal for this experiment. The SHG power at different pump power is shown in Fig. 6, the SHG power in the PPKTP crystal is always lower than that in the PPKTP waveguide. This result implies that the waveguide can supply a good confinement for the propagating pulses, which is helpful for better mode overlapping and consequently higher conversion efficiency.

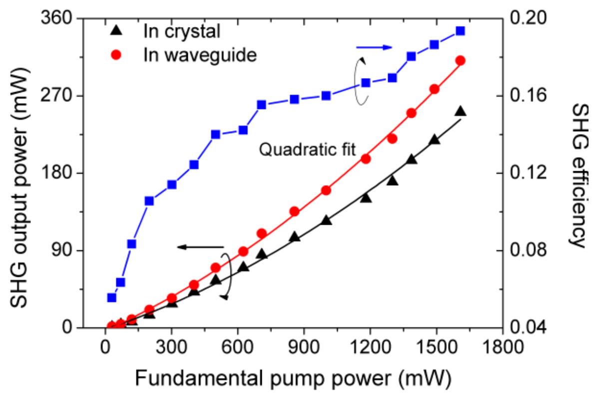

Fig. 6. Dependence of the measured SHG power (in waveguide and in crystal) and the corresponding conversion efficiency (in waveguide) on the incident fundamental power.

Due to the high power density in the waveguide area, the waveguide may be heated because of the linear and nonlinear absorption of the injected high power pump [12,13,23]. If the heating is significant, the temperature detuning of the SHG process would happen in PPKTP waveguide. To further investigate this phenomenon, we measured and compared the SHG spectra obtained at different pump levels (at 1064 nm), as shown in Fig. 7. It is clear that the central wavelength of the SHG spectra exhibits a red shift as the pump power increases. The central wavelength of SHG spectra shifts from 532.06 to 532.21 nm when the pump power changes from 0.8 to 1.6 W, which means that the phase-matching wavelength is changed. To get a higher conversion efficiency, the crystal should be cooled to be phase matched at 1064 nm. Otherwise, the conversion efficiency will be reduced by this temperature detuning. It is difficult for us to exactly measure the temperature change per watt caused by the power increase. To avoid this thermal effect, we try to arrange the experiment in a low power level. We also find from Fig. 7 that the SHG spectra become broader as the pump power increases. For example, the spectrum width varies from 0.35 to 0.48 nm when the pump power changes from 0.8 to 1.6 W. For 1MHz 90ps pulses, an average power of 1.6 W means a peak power of ~18 kW. We think the broadening of the SHG spectra is related to the self-phase modulation. However, because of the short waveguide length and the limited pump power, the spectra broadening due to self-phase modulation is not significant.

We measured the SHG spectra when the fundamental wavelengths are changed from 1056 to 1072 nm with a step of 2 nm under an output power of 1.6 W at room temperature. As shown in Fig. 8, the central wavelength of the SHG spectra is 532.1 ± 0.1nm, which is almost the same for all the fundamental wavelengths, and the FWHM of all the SHG spectra is about 0.45nm. The experimental results show that the SHG spectra are mainly determined by the grating period, as the PPKTP waveguide is designed for a central wavelength of 1064nm at room temperature. However, as shown in Fig. 5, the SHG output power for the wavelengths

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far beyond 1064nm is much smaller, which is just due to the big phase mismatch during the SHG process. For this reason, herein a pump power of 1.6 W was used.

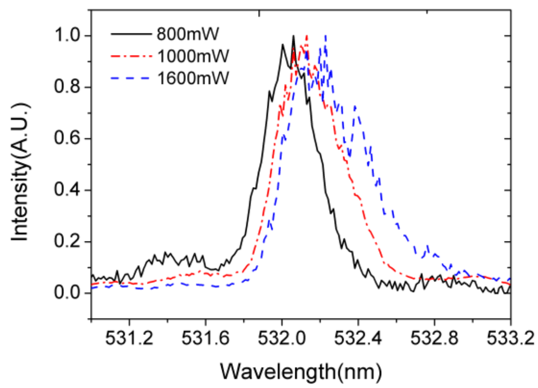

Fig. 7. The SHG spectra obtained at different pump levels.

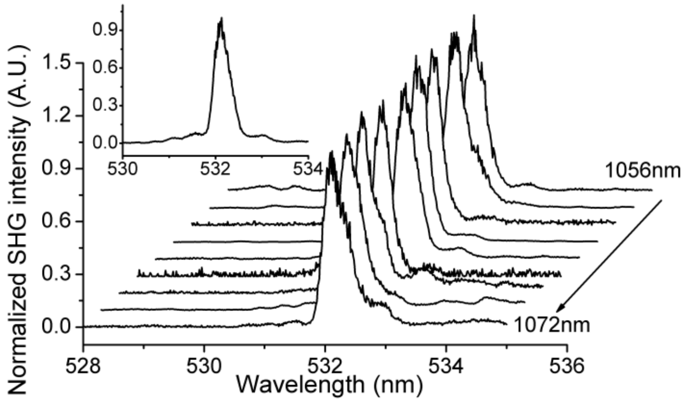

Fig. 8. The normalized spectra of the SHG pulses with different fundamental pump wavelengths. Inset is the SHG spectrum at a pump wavelength of 1064nm.

The efficiency of any parametric process is subject to limitations imposed by group velocity mismatch (GVM). The GVM effect is described by the well-defined temporal walk-off length, L_{nst}, defined by $L_{nst} = \tau/\alpha$, and the GVM parameter $\alpha = 1/v_2 - 1/v_1$, where τ is the time duration of the fundamental pulses, and v_2 and v_1 are the group velocities of the second harmonic (SH) and fundamental wave respectively. L_{nst} is a distance within which two initially overlapped pulses at different wavelengths become separated by a time equal to τ [28]. The temporal walk-off limits the conversion efficiency and, if this effect within the crystal length is significant, it can also lead to modified pulse shapes.

It should be noted that the green conversion efficiency was almost not limited by the temporal walk-off, as L_{nst} is estimated to be 50 cm for 90 ps pulses, which is much longer than the sample length in our experiment. At the same time, the broadening of SH pulse due to the group velocity dispersion (GVD) is almost negligible due to the very large dispersion length ($L_D = T_0^2/|\beta_2|$, L_D is ~10^5m for 90ps pulses) [29]. Taking into account the GVM, GVD and the cubic nonlinear effects, we studied the SHG process of 90ps pulses based on the model described by Eq. (1) in [30]. The results show that the SH pulse has an FWHM duration of

95ps, implying that the SH pulse is only broadened by 5ps. Therefore we estimated the generated second-harmonic pulses to be a hundred of picoseconds in our experiment.

4. Conclusion

In this work, we have demonstrated a fiber-format ultrashort green light source based on a PPKTP waveguide fabricated by femtosecond laser direct writing. Using simple single-pass frequency doubling of a self-made picosecond all-fiber YDF fiber laser source in PPKTP waveguide near room temperature, we have generated 310mW, 1MHz ultrashort pulses at 532nm with a conversion efficiency of 19.3% in a highly compact and practical design. We investigated the temperature and wavelength tuning curve for the SHG process of picosecond pulses, the FWHM of the temperature and wavelength tuning curve achieved are 8°C and 4.2nm respectively. The temporal duration of the SHG pulses is estimated to be a hundred of picoseconds. This fiber-format frequency conversion scheme would be well-suited to applications where ultrashort pulses, high repetition rates and portability are needed, such as in biomedical imaging.

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