517 nm - 538 nm tunable second harmonic generation in a diode-pumped PPKTP waveguide crystal

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ABSTRACT

Tunable continuous wave (CW) green light generation between 517 nm and 538 nm at room-temperature has been demonstrated from a frequency-doubled broadly tunable quantum well (QW) external-cavity fiber-coupled diode laser by use of an uncoated periodically poled potassium titanyl phosphate (PPKTP) crystal waveguide crystal. Green light at 530 nm with maximum conversion efficiency of 14.8% and output power of 12.88 mW has been generated using a PPKTP crystal waveguide with the cross-sectional area of 3x5μm^2. The possibility of tunable second harmonic generation in the PPKTP crystal waveguides with the cross-sectional areas of 4x4μm^2 and 2x6μm^2 was also investigated.

Keywords: Second harmonic generation, Quantum Dot Lasers, Nonlinear crystals, waveguides, PPKTP

1. INTRODUCTION

Compact continuous wave (CW) tunable laser sources in the visible spectral region are currently very demanding for a number of cutting-edge biomedical applications including photodynamic therapy[1], Laser-Doppler velocimetry[2] and Confocal Microscopy[3]. Typically, such applications require a number of lasers to provide the coverage of the whole visible spectrum. This makes the system bulky, expensive, and complex to operate. The most promising approach to develop a compact, efficient and broadly tunable visible laser source is second harmonic generation (SHG) in a periodically poled nonlinear crystal containing a waveguide, which not only allows highly efficient frequency conversion even at low pump power levels but also offers an order-of-magnitude increase of wavelength range for efficient SHG by utilizing the multimode-matching approach[4]. In this respect, semiconductor lasers with their small size, high efficiency, reliability, low cost and a wide spectral range coverage are very promising for realization of tunable visible laser sources.

Recently, a number of laser sources in the visible spectral region based on second harmonic generation in the periodically poled potassium titanyl phosphate (PPKTP) waveguide crystals were demonstrated[5-7], including broadly tunable second harmonic generation in PPKTP waveguide crystals[4,8-9].

In this work we show a compact all-room-temperature laser source generating tunable green light in the wavelength range between 517 nm and 538 nm by frequency doubling in a PPKTP crystal waveguide (with the cross-sectional area of 3x5 μm^2) using a broadly tunable quantum well external-cavity diode laser (QW-ECDL) coupled into a single mode fiber. Maximum output power of 12.88 mW and conversion efficiency of 14.8% was obtained at 530 nm using a not antireflective (AR) coated PPKTP waveguide with the cross-sectional area of 3x5 μm^2. Second harmonic tunability in the PPKTP crystal waveguides with the cross-sectional areas of 4x4 μm^2 and 2x6 μm^2 was also demonstrated and investigated.

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2. EXPERIMENTAL SETUP

Experimental setup used in this work is schematically illustrated in Fig.1 and consisted of a broadly tunable quantum well (QW) external-cavity fiber-coupled diode laser, a PPKTP crystal containing 3 waveguides with different cross-sectional areas (4x4 μm^2, 3x5 μm^2 and 2x6 μm^2), aspheric lenses, a diffraction grating, a half-wave plate (λ/2), and a filter at the fundamental wavelengths.

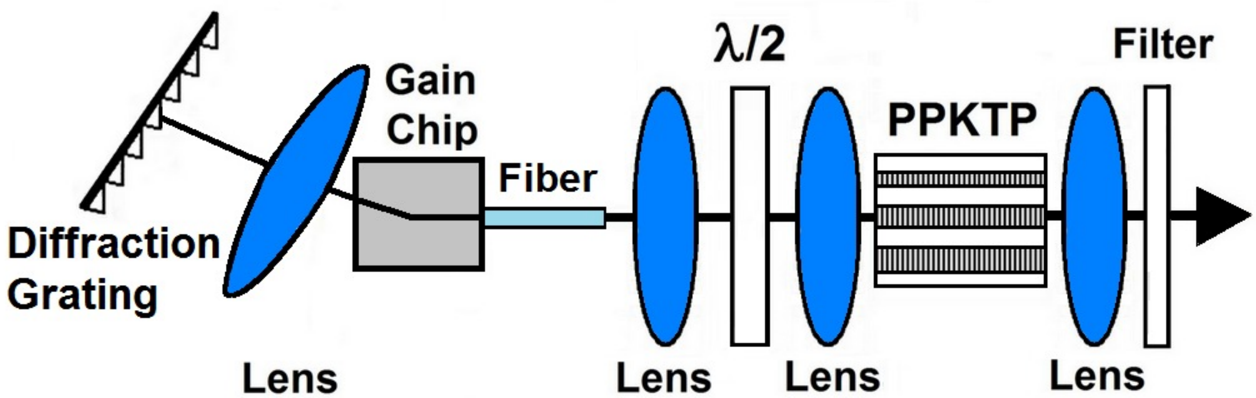

Figure 1. Simplified schematic of the experimental setup (including fiber-coupled quantum-well gain chip, aspheric lenses, diffraction grating, half-wave plate (λ/2), PPKTP waveguide crystal, and filter at fundamental wavelengths).

The QW gain chip had a length of 2.8 mm, and the ridge waveguide had a width of 5 μm and was angled at 7º relative to the normal of the antireflective (AR) coated back facet (both facets had conventional AR coatings, resulting in total estimated reflectivities of 10^{-2} for the front facet and less than 10^{-5} for the angled facet). The QW gain chip was embedded in a 14-pin open-butterfly package with the laser output from the front facet coupled into a single-mode polarization maintaining fiber PM-980. The external cavity was closed with a diffraction grating (1200 grooves/mm) in a quasi-Littrow configuration, whereby the radiation emitted from the back facet of the chip was coupled onto the diffraction grating which reflected the first order of the diffracted beam back to the gain chip[4]. Coarse wavelength tuning of the QW-ECDL between 980 nm and 1090 nm at 20°C was possible for pump current of 450 mA. The laser output was collimated with a 30x (NA ~ 0.50) AR-coated aspheric lens and then coupled into the PPKTP waveguide using a 40x (NA ~ 0.55) AR-coated aspheric lens. A half-wave plate was used to adjust the polarization of the pump beam for optimal SHG in the PPKTP crystal. The frequency-doubled output was collimated by a 30x (NA ~ 0.50) AR-coated aspheric lens onto a power meter after a suitable filter at the fundamental wavelength. Both the laser and the nonlinear crystal were operating at room temperature (20°C).

The PPKTP crystal had not-AR coated facets and was 15.5 mm in length. The crystal contained 3 waveguides with the cross-sectional areas of 4x4 μm^2, 3x5 μm^2 and 2x6 μm^2. These waveguides had a refractive index step below ~0.02 and were fabricated by the Rb ion-exchange technique[10,11]. The masked potassium titanyl phosphate (KTP) crystal was immersed in the ion-exchange bath consisting of molten nitrate salts of Rb ($RbNO_3$). Within this bath, the Rb ions diffused through a mask into the substrate, while the K ions diffused out of the KTP crystal. In the diffused regions, the Rb ions increased the refractive index relatively to the undiffused KTP and thus formed the optical waveguide. The periodic poling was performed after the waveguides were fabricated using an applied electric field to periodically invert the domains[8] for the efficient frequency-doubling at ~ 530 nm. However, due to the fact that the poling quality could be different in the waveguides with different widths, efficient SHG at ~529.2 nm, 530.2 nm and 531.2 nm was observed from the waveguides with the cross-sectional areas of 4x4 μm^2, 3x5 μm^2 and 2x6 μm^2, respectively.

3. EXPERIMENTAL RESULTS

The presented frequency-doubling source generated green light at 529.2 nm, 530.2 nm and 531.2 nm with an output power of 12 mW, 12.88 mW and 12.22 mW, and a maximum conversion efficiency of 14.63%, 14.8% and 14.04%, from the waveguides with the cross-sectional areas of 4x4 μm^2, 3x5 μm^2 and 2x6 μm^2, respectively (Fig. 2-4).

Utilizing the multimode-matching approach[4], we investigated the possibility of second harmonic generated wavelength tuning in these waveguides with different cross-sectional areas. With this technique, the phase-matching between a low-order fundamental and a high-order SHG modes allows the tunability of frequency-doubled light on the short wavelength side of the spectrum, and the interaction of a high-order fundamental with a low-order SHG modes corresponds to the tunability on the long wavelength side of the spectrum. The waveguides with the cross-sectional areas of 4x4 μm^2, 3x5 μm^2 and 2x6 μm^2 demonstrated the second-harmonic tunability in the wavelength ranges 516.8 nm – 538.2 nm, 517 nm – 538.6 nm and 518.2 nm – 537.4 nm, respectively (Fig.5). The waveguide with the cross-sectional area of 3x5 μm^2 demonstrated better results in terms of wavelength tunability and output power in comparison with the other waveguides (4x4 μm^2 and 2x6 μm^2).

In addition, wavelength tunability of the frequency-doubled light with the crystal temperature changing was also investigated. The continuous wavelength tuning between 529.2 nm and 532.5 nm with similar conversion efficiencies in the PPKTP waveguides with the cross-sectional areas of 4x4 μm^2, 3x5 μm^2 and 2x6 μm^2 was also demonstrated by changing the temperature of the PPKTP crystal waveguides from 20°C to 90°C while simultaneously tuning the QW laser (Fig. 6).

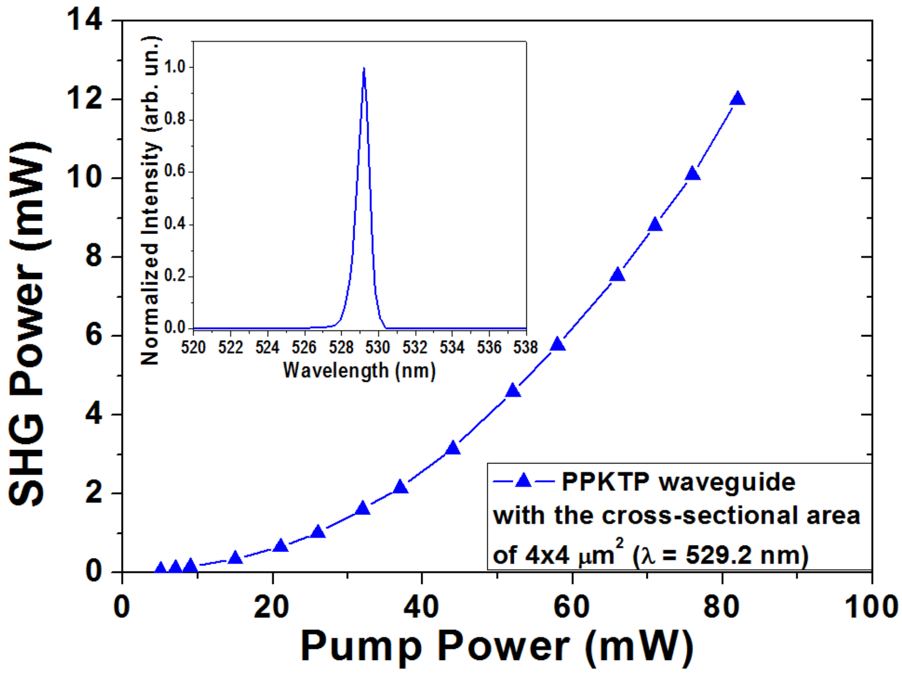

Figure 2. Frequency-doubled output power versus launched pump power at 529.2 nm in the waveguide with the cross-sectional area of 4x4 μm^2. Inset: Optical spectrum of the second harmonic generation at the wavelengths: 529.2 nm.

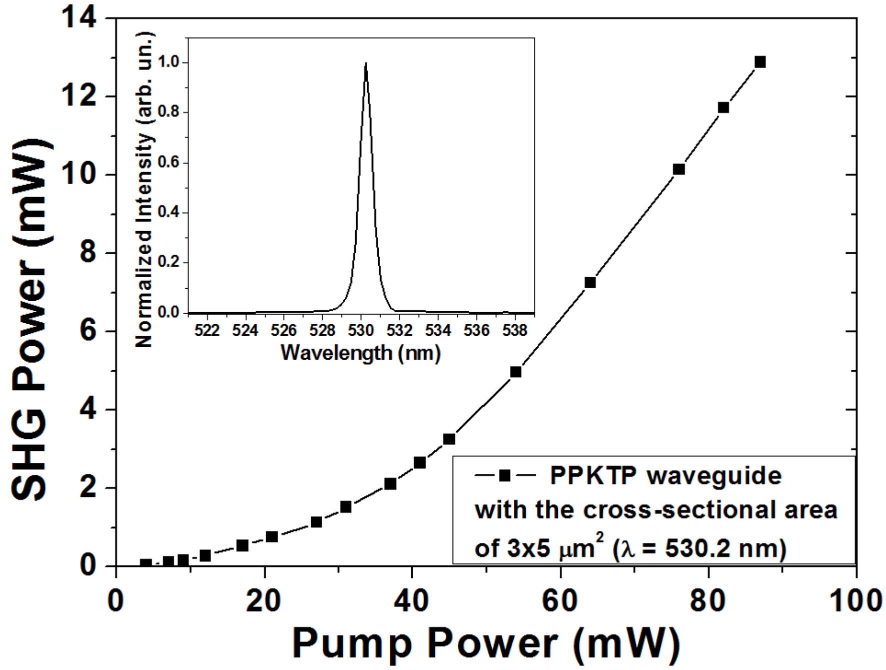

Figure 3. Frequency-doubled output power versus launched pump power at 530.2 nm in the waveguide with the cross-sectional area of 3x5 μm^2.. Inset: Optical spectrum of the second harmonic generation at the wavelengths: 530.2 nm.

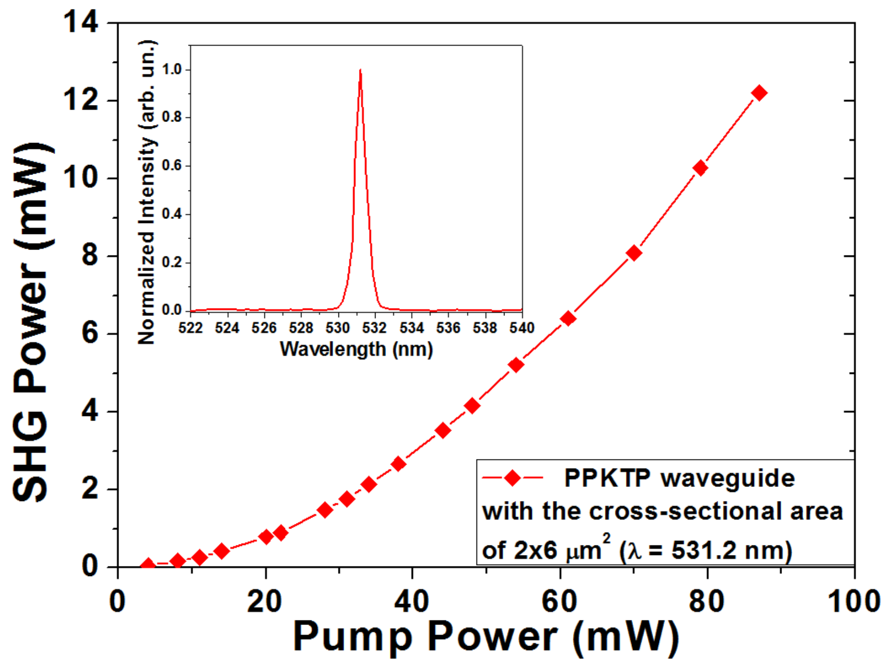

Figure 4. Frequency-doubled output power versus launched pump power at 531.2 nm in the waveguide with the cross-sectional area of 2x6 μm^2. Inset: Optical spectrum of the second harmonic generation at the wavelengths: 531.2 nm.

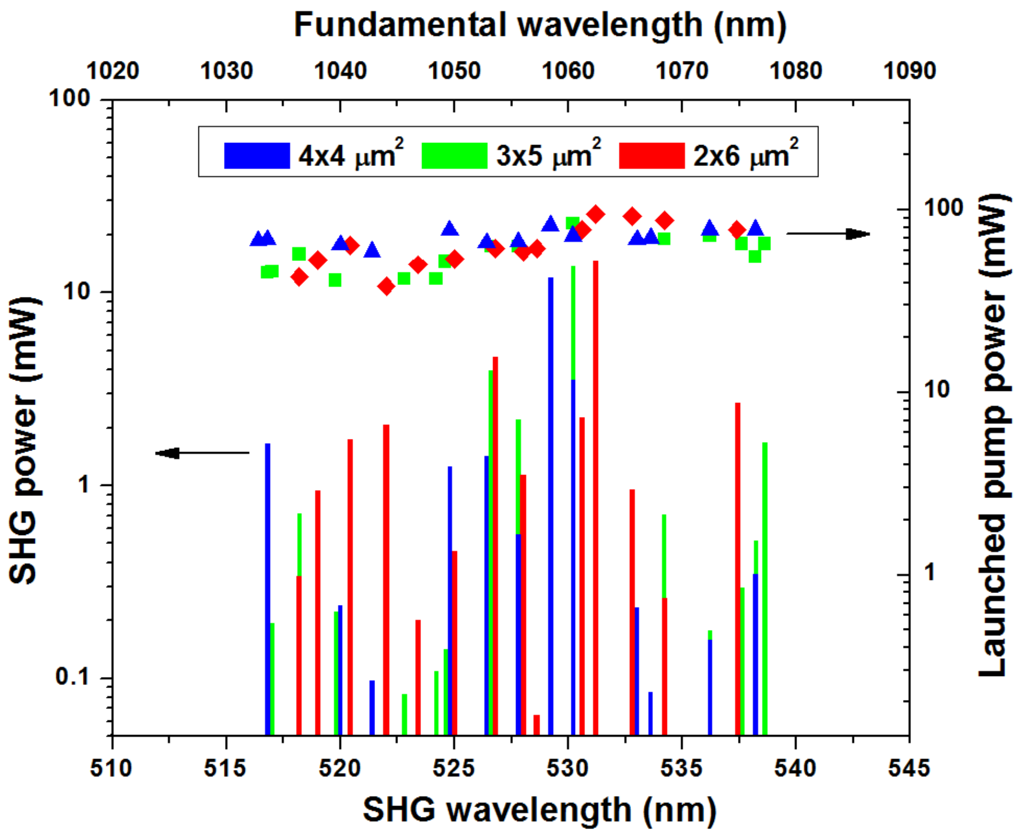

Figure 5. Frequency-doubled and launched pump power vs. wavelength for three waveguides with cross-sectional areas of 4x4 μm^2, 3x5 μm^2 and 2x6 μm^2.

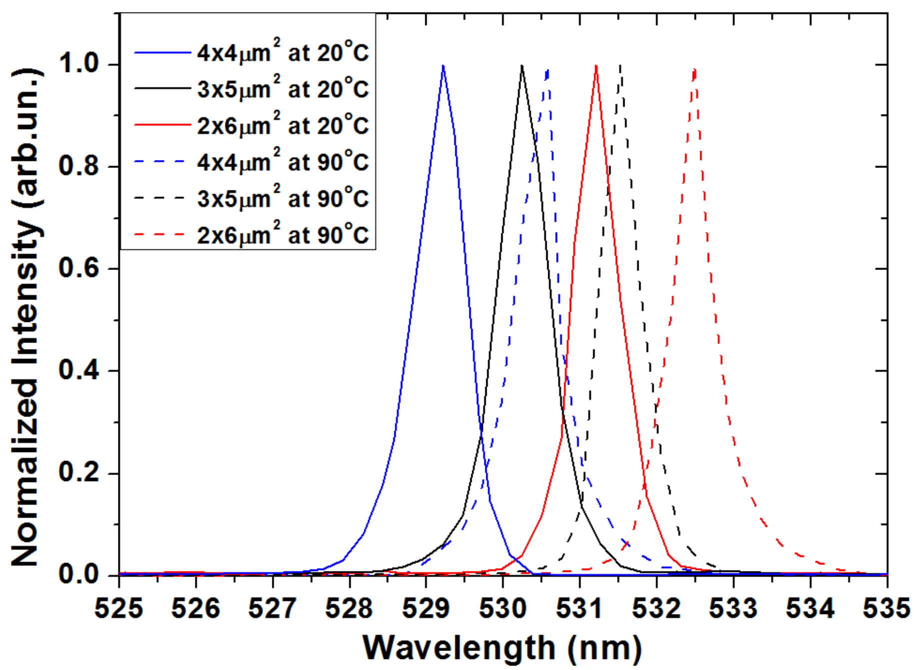

Figure 6. Optical spectra of the second harmonic generated output tuned across the 529.2 nm – 532.5 nm wavelength range achieved by increasing the temperature of the PPKTP crystal from 20°C to 90°C while simultaneously tuning the QW-ECDL.

4. CONCLUSION

We demonstrated a compact all-room-temperature broadly-tunable visible laser source in the 517 nm – 538 nm wavelength region by second harmonic generation in PPKTP waveguides with the different cross-sectional areas (4x4 μm^2, 3x5 μm^2 and 2x6 μm^2) using a broadly tunable fiber-coupled quantum well external-cavity diode laser. Maximum output power of 12.88 mW and conversion efficiency of 14.8% was obtained at 530.2 nm using a not-AR coated PPKTP waveguide with the cross-sectional area of 3x5 μm^2. Second harmonic tunability in all three PPKTP waveguides (with the cross-sectional areas of 4x4 μm^2, 3x5 μm^2 and 2x6 μm^2) was investigated. Tunable CW green light generation between 516.8 nm and 538.6 nm at room-temperature has been demonstrated.

The presented widely tunable laser source with the unique spectral coverage represents an important step towards a compact tunable green laser source operating at room temperature that can be extremely valuable in a wide range of cutting-edge biomedical applications and can replace available, inefficient and bulky visible lasers.

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