

# Tunable single- and dual-wavelength SHG from diode-pumped PPKTP waveguides

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**A compact, all-room-temperature, widely-tunable, continuous wave (CW) laser source in the green spectral region (502.1 nm – 544.2 nm) with a maximum output power of 14.7 mW is demonstrated. This was made possible by utilizing second-harmonic generation (SHG) in a periodically poled potassium titanyl phosphate (PPKTP) crystal waveguide pumped by a quantum-well external-cavity fiber-coupled diode laser and exploiting the multimode-matching approach in nonlinear crystal waveguides. The dual-wavelength SHG in the wavelength region between 505.4 nm and 537.7 nm (with a wavelength difference ranging from 1.8 nm to 32.3 nm) and sum-frequency generation in a PPKTP waveguide is also demonstrated. © 2016 Optical Society of America**

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The development of dual- and multiple-wavelength lasers, particularly in the visible spectral region, is a very attractive research direction that aims to address a number of important applications, including biomedicine [1-3], spectroscopy [4], advanced imaging techniques [5-7], television, and laser projection technology [8]. Currently, many of these applications rely on bulky, expensive and complex-to-operate lasers with a number of laser sources required to cover broad visible spectral regions. Therefore, a compact, easy-to-use, cost-effective laser system, which could be tunable across the entire visible spectrum with a possibility to simultaneously generate multiple wavelengths, is of great interest for such applications.

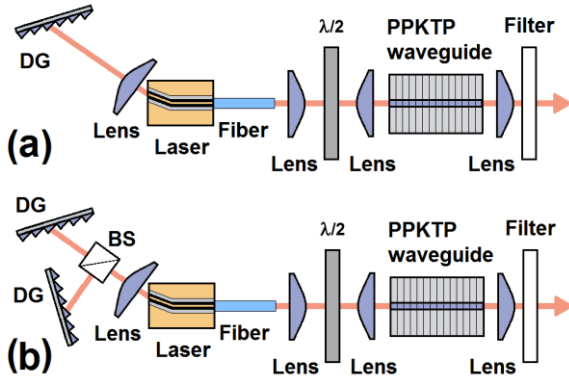
To address this demand, semiconductor lasers with their small size, high efficiency, reliability and low cost can be exploited to cover ultra-broad near-infrared spectral ranges, depending on the composition of their active medium [9-11]. By combining many of the advantages of semiconductor lasers with the most attractive features of nonlinear crystals, the frequency conversion into the visible spectral region can be further exploited. In this respect, periodically poled nonlinear crystal waveguides [12], which take an advantage of a strong optical wave confinement with high optical intensities being maintained over long propagation lengths, can offer an order-of-magnitude increase in the infrared-to-visible

conversion efficiency even at low pump powers, thus making the waveguided nonlinear optical conversion ideal for applications requiring CW or low-peak quasi-CW lasers [13]. Among several available periodically poled crystal waveguides, periodically poled lithium niobate [14-19] and periodically poled potassium titanyl phosphate (PPKTP) crystal waveguides [20-26] are usually used for highly efficient nonlinear wavelength conversion, particularly into the green spectral region. Moreover, the recently demonstrated multimode-matching approach [25] allows the realization of an all-room-temperature, compact, tunable visible laser source by second harmonic generation (SHG) in a periodically poled nonlinear crystal waveguide pumped by an infrared laser diode. By exploiting this technique, broad second-harmonic tunability up to 73 nm in the CW regime [27] and 27 nm in the pulsed regime [28] in the visible spectral region was achieved using a single PPKTP crystal waveguide and a single quantum-dot laser. This technique also allows multiple-wavelength SHG in a single crystal waveguide, thus making this approach a very attractive way to replace different lasers used in applications such as super resolution imaging techniques with a single compact versatile laser source.

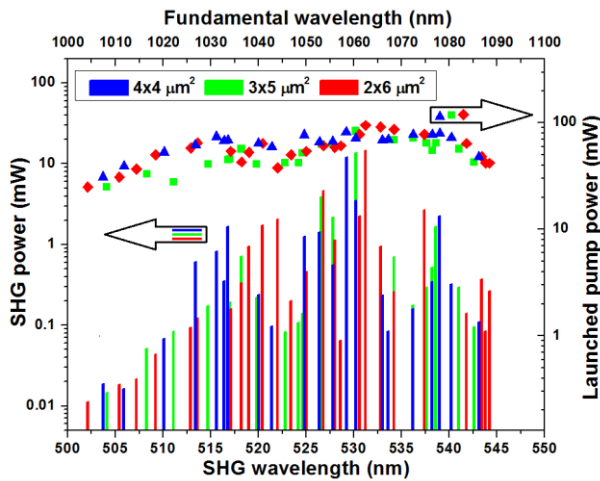
To date, several techniques have been shown to support the dual-wavelength operation of external-cavity diode lasers,

including the use of a dual-wavelength volume-Bragg grating [29], a Y-slit [30], a V-shaped double-stripe mirror [31], or a dual-period holographic element [32] in the laser cavity. However, these techniques have some drawbacks in terms of tunability of mode separation, although some of them can offer some tuning by moving the position of a slit or a mirror. In contrast to the mentioned approaches, the dual-grating external-cavity diode laser configuration [33] can offer dual-wavelength laser output with broadly tunable mode separation, limited only by the spectral bandwidth of its gain element. All these methods of dual-wavelength generation are of special interest for the terahertz generation [34] and the wavelength division multiplexing application, where the channels of information are encoded on light signals of different wavelengths, and also can be of great use for dual-color second harmonic generation into the visible spectral region.

In this work, we demonstrate the advantage of the use of the multimode-matching technique in nonlinear crystal waveguides for realization of compact broadly tunable single- and dual-wavelength laser sources in the green spectral region by second harmonic generation (SHG).



**Fig. 1.** Experimental setups of tunable (a) single- and (b) dual-wavelength SHG in a PPKTP waveguide pumped by a fiber-coupled QW-ECDL (DG – diffraction grating, BS – beam splitter).



**Fig. 2.** Frequency-doubled and launched pump power vs. wavelength for three PPKTP waveguides with cross-sectional areas of  $4 \times 4 \mu\text{m}^2$ ,  $3 \times 5 \mu\text{m}^2$  and  $2 \times 6 \mu\text{m}^2$  obtained in the single-grating quasi-Littrow configuration.

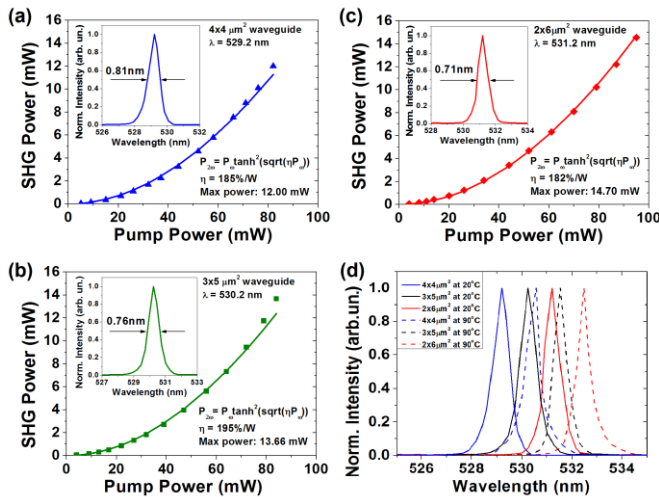
The experimental setup consisted of a fiber-coupled quantum-well external-cavity diode laser (QW-ECDL) and a 15.5-mm long PPKTP crystal containing three waveguides with the cross-sectional areas of  $4 \times 4 \mu\text{m}^2$ ,  $3 \times 5 \mu\text{m}^2$  and  $2 \times 6 \mu\text{m}^2$ , fabricated by the Rb ion-exchange technique [35,13] that provided refractive index step  $\Delta n \approx 0.01$ . The crystal was periodically poled for SHG at  $\sim 1060$  nm and did not have antireflective (AR) coated facets. The periodic poling was performed after the waveguides were fabricated using an applied electric field to periodically invert the domains for the efficient frequency-doubling at  $\sim 530$  nm. However, due to the fact that the poling quality could be different in waveguides with different widths, efficient SHG at  $\sim 529.2$  nm,  $530.2$  nm and  $531.2$  nm was observed from the waveguides with the cross-sectional areas of  $4 \times 4 \mu\text{m}^2$ ,  $3 \times 5 \mu\text{m}^2$ , and  $2 \times 6 \mu\text{m}^2$ , respectively. The QW laser chip had a length of 2.8 mm, and the ridge waveguide with a width of  $5 \mu\text{m}$  was angled at  $7^\circ$  relative to the normal of the AR-coated back facet. The QW laser 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. Second harmonic generation was investigated in two configurations using either a single diffraction grating with 1200 grooves/mm for single-wavelength tunable SHG (Fig.1(a)) or two similar diffraction gratings for dual-wavelength tunable frequency doubling (Fig.1(b)). In the case of the dual-grating quasi-Littrow configuration, the radiation emitted from the back facet of the laser chip was collected with a  $40\times$  AR-coated aspheric lens (numerical aperture of 0.55) and then split by a non-polarizing beam splitter into two beams with each one of them coupled onto a diffraction grating. The diffraction gratings reflected the first order of the diffracted beams back to the laser chip, thus allowing the simultaneous generation of two wavelengths from the QW-ECDL. The laser output in both configurations was collected with a  $30\times$  AR-coated aspheric lens (numerical aperture of 0.50) and then coupled into a PPKTP waveguide using a  $40\times$  AR-coated aspheric lens. A half-wave plate was used to adjust the polarization of the laser output for optimal SHG in the PPKTP waveguide crystal. The frequency-doubled output was collimated by a  $30\times$  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 ( $20^\circ\text{C}$ ).

By utilizing the multimode-matching technique [25], we investigated the possibility of SHG wavelength tuning in these waveguides with different cross-sectional areas. With this approach, 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  $4 \times 4 \mu\text{m}^2$ ,  $3 \times 5 \mu\text{m}^2$  and  $2 \times 6 \mu\text{m}^2$  demonstrated the second-harmonic tunability in the wavelength ranges  $503.7$  nm –  $543.1$  nm,  $504.1$  nm –  $542.6$  nm and  $502.1$  nm –  $544.2$  nm, respectively (Fig. 2). The presented single-grating frequency-doubling scheme (Fig.1(a)) generated green light at  $529.2$  nm,  $530.2$  nm and  $531.2$  nm with an output power of  $12$  mW,  $13.66$  mW and  $14.7$  mW, and a maximum conversion efficiency of  $14.6\%$ ,  $16.3\%$  and  $15.5\%$ , from the waveguides with the cross-sectional areas of  $4 \times 4 \mu\text{m}^2$ ,  $3 \times 5 \mu\text{m}^2$  and  $2 \times 6 \mu\text{m}^2$ , respectively (Fig. 3(a)-(c)). The experimental results were numerically  $\tanh^2$ -fitted according to the depleted pump approximation with normalized conversion

efficiencies of 185%/W, 195%/W and 182%/W for the  $4 \times 4 \mu\text{m}^2$ ,  $3 \times 5 \mu\text{m}^2$  and  $2 \times 6 \mu\text{m}^2$  waveguides, respectively. In addition, the SHG wavelength tunability with the crystal temperature changing was also investigated, and the obtained spectra are depicted in Fig. 3(d). The continuous wavelength tuning in the wavelength range between 529.2 nm and 532.5 nm with similar conversion efficiencies in the PPKTP waveguides with the cross-sectional areas of  $4 \times 4 \mu\text{m}^2$ ,  $3 \times 5 \mu\text{m}^2$  and  $2 \times 6 \mu\text{m}^2$  was demonstrated by changing the temperature of the PPKTP crystal waveguides from 20°C to 90°C while simultaneously adjusting the output wavelength of the single-grating QW-ECDL.

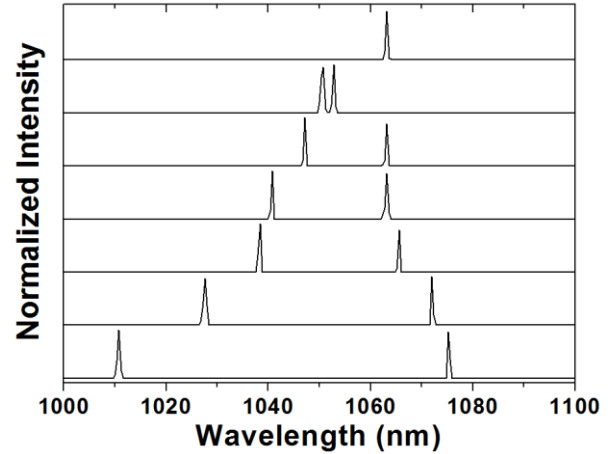
With the dual-grating quasi-Littrow configuration it was possible to achieve dual-wavelength laser operation in the wavelength region 1010 nm – 1075 nm with a mode separation ranging between 2 nm and 65 nm by adjusting the angles of the diffraction gratings (Fig. 4). The multimode-matching approach [25] also allowed us to demonstrate the generation of two frequency-doubled wavelengths in a single PPKTP crystal waveguide in the visible spectral region (505.4 nm – 537.7 nm) and the possibility to tune both of them simultaneously with a wavelength difference ranging from 1.8 nm to 32.3 nm (Fig. 5). The generation of the sum-frequency radiation was also observed (Fig. 5) indicating the concurrent generation of both infrared modes in the laser diode.

In the dual-grating frequency-doubling scheme, a maximum second harmonic output power of 8.4 mW at 531.2 nm with a conversion efficiency of 12% was obtained in the waveguide with cross-sectional area of  $2 \times 6 \mu\text{m}^2$  when both gratings were tuned to a position to reflect the first order of the diffracted beam at the same wavelength back to the laser chip. This configuration also led to the broadening of the optical spectrum of SHG resulting in a full-width at half-maximum (FWHM) of 0.95 nm in comparison to the single-grating laser configuration showing the FWHM of 0.71 nm.

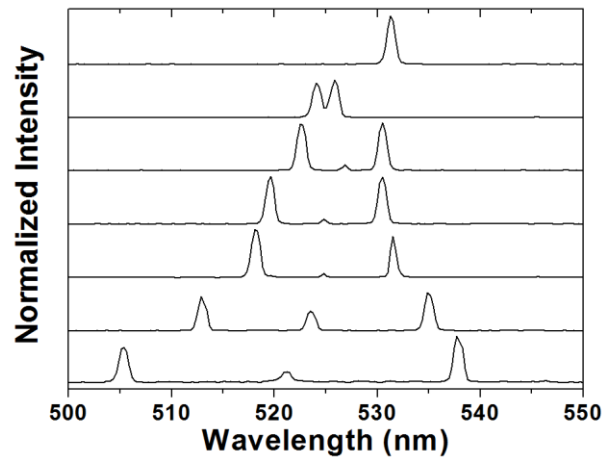


**Fig. 3.** (a), (b), (c) - Frequency-doubled output power versus launched pump power and optical spectra of the SHG at 529.2 nm, 530.2 nm, and 531.2 nm, correspondingly. (d) - Optical spectra of the SHG output tuned across the 529.2 nm – 532.5 nm wavelength range achieved by increasing the temperature of the PPKTP crystal from 20°C to 90°C while simultaneously tuning the QW-ECDL.

The demonstrated novel, compact, room-temperature laser source offering a broadband dual-wavelength tunability in the green spectral region is of great interest for a number of applications including Biomedicine and imaging techniques and offers the possibility for the future development of compact multicolor visible laser sources using a single laser diode and a single crystal waveguide.



**Fig. 4.** Normalized optical spectra of tunable dual-wavelength fiber-coupled QW-ECDL.



**Fig. 5.** Normalized optical spectra of tunable dual-wavelength second harmonic light in the waveguide with cross-sectional area of  $2 \times 6 \mu\text{m}^2$ .

In this work we investigated the use of the multimode-matching technique in PPKTP crystal waveguides to achieve a broadly tunable single- and dual-color SHG output in the green spectral region (502.1 nm – 544.2 nm) with a maximum output power of 14.7 mW and a maximum conversion efficiency of 16.3%. The demonstrated single- and dual-wavelength compact versatile laser sources with the unique spectral coverage and wide tunability in the visible spectral region can replace available inefficient lasers and thus offers endless possibilities for existing applications in Biophotonics and medicine, which can take advantage of both the broad tunability in the visible spectral region and the simultaneous generation of several wavelengths.

The further optimization of the crystal waveguides and gain medium of the pump lasers can lead to the realization of

significantly more power efficient laser devices and allow the extension of the generated wavelengths to cover the whole visible spectral region. The work on improvement of SHG conversion efficiency and further extension of operation to different spectral regions is currently underway.

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