Efficient generation of orange light by frequency-doubling of a quantum-dot laser radiation in a PPKTP waveguide

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ABSTRACT

Orange light with maximum conversion efficiency exceeding 10% and CW output power of 12.04 mW, 10.45 mW and 6.24 mW has been generated at 606, 608, and 611 nm, respectively, from a frequency-doubled InAs/GaAs quantum-dot external-cavity diode laser by use of a periodically-poled KTP waveguides with different cross-sectional areas. The wider waveguide with the cross-sectional area of 4x4 μm^2 demonstrated better results in comparison with the narrower waveguides (3x5 μm^2 and 2x6 μm^2) which corresponded to lower coupling efficiency. Additional tuning of second harmonic light (between 606 and 614 nm) with similar conversion efficiency was possible by changing the crystal temperature.

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

1. INTRODUCTION

Development of compact efficient visible laser sources in the orange spectral region is currently very attractive area of research with applications ranging from photomedicine [1] and biophotonics [2] to confocal fluorescence microscopy [3] and laser projection displays [4]. In this respect, semiconductor lasers with their small size, high efficiency, reliability and low cost are very promising for realization of such laser sources by frequency-doubling of the infrared light in a nonlinear crystal containing a waveguide [5]. Furthermore, the wide tunability offered by quantum-dot external-cavity diode lasers, due to the temperature insensibility and the broad gain bandwidth [6,7], is very promising for the development of tunable visible laser sources [8,9]. Recently, blue light generation at 488 nm in the continuous wave (CW) regime using a periodically poled potassium titanyl phosphate (PPKTP) waveguide crystal and high-brightness diode lasers with conversion efficiency of more than 260%/W was demonstrated [10]. Efficient frequency-doubling scheme generating 4.3 mW of orange light at 613 nm with conversion efficiency exceeding 10% from a PPKTP waveguide end-pumped by a CW quantum dot (QD) diode laser was also reported [5]. Blue light with maximum average power of 7.5 mW in picosecond pulses has also been generated at 486, 488, and 491 nm from a frequency-doubled, nonresonant injection seeded InGaAs GaAs diode laser by using a PPKTP waveguide with a Bragg grating section [11].

In this work we show a compact all-room-temperature laser source generating orange light at 606 nm, 608 nm and 611 nm with output power of 12.04 mW, 10.45 mW and 6.24 mW, respectively, and maximum conversion efficiency as high as 10.29%. This laser source is based on second harmonic generation (SHG) in periodically-poled KTP waveguides with different cross-sectional areas (4x4 μm^2, 3x5 μm^2 and 2x6 μm^2) using a InAs/GaAs quantum-dot external-cavity diode laser (QD-ECDL). The wider waveguide with the cross-sectional area of 4x4 μm^2 demonstrated better results in comparison with the narrower waveguides which corresponded to lower coupling efficiency. Additional tuning of second harmonic light (between 606 and 614 nm) with similar conversion efficiency was possible by changing the crystal temperature. The demonstrated laser source represents an important step towards a compact efficient orange light source.

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2. EXPERIMENTAL SETUP

Experimental setup used in this work was similar to that described in [8] and consisted of a QD gain chip and a PPKTP waveguide, as shown in Fig. 1. The QD gain chip had total length of 4 mm. The active region of the gain chip contained 10 non-identical InAs QD layers, incorporated into $Al_{0.35}Ga_{0.65}As$ cladding layers and grown on a GaAs substrate by molecular beam epitaxy. The gain chip ridge waveguide 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 QD gain chip was set-up in a quasi-Littrow configuration, whereby the radiation emitted from the back facet of the chip was coupled onto the diffraction grating (1200 grooves/mm) which reflected the first order of the diffracted beam back to the gain chip [7]. Coarse wavelength tuning of the QD-ECDL between 1140 nm and 1300 nm at 20°C was possible for pump current of 1.5 A. The laser output was coupled into the PPKTP waveguide using an AR-coated 40x aspheric lens (NA ~ 0.55).

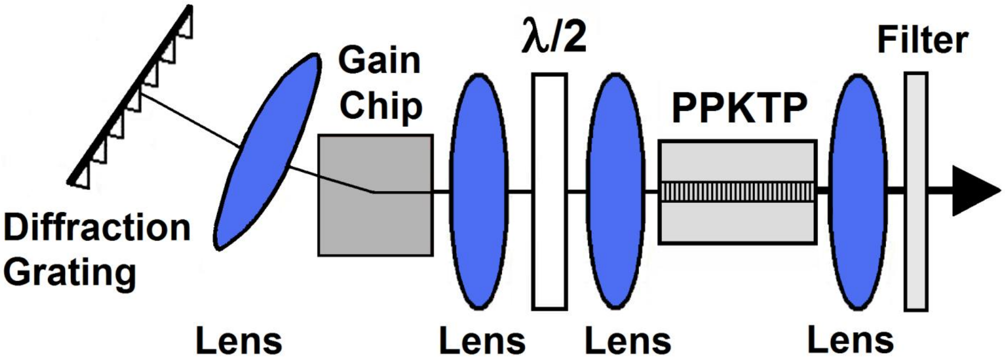

Figure 1. Simplified schematics of experimental setup consisting of diffraction grating, 40x AR-coated aspheric lenses, QD gain chip, half-wave plate (λ/2), PPKTP waveguide and filter.

The waveguide was fabricated by the ion-exchange technique [12] that provided refractive index step $\Delta n \approx 0.01$. With this technique, the masked KTP crystal was immersed in the ion-exchange bath consisting of a mixture of molten nitrate salts of Rb ($RbNO_3$) [13]. 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 [9].

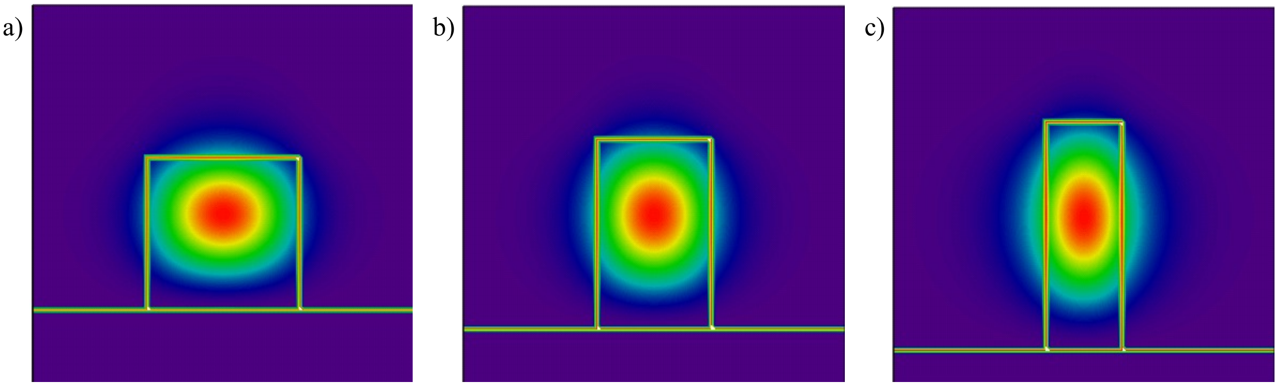

Figure 2. Calculated distribution of the fundamental TEM_{00} mode in the waveguides with cross-sectional areas of ~4x4 μm^2 (a), 3x5 μm^2 (c) and 2x6 μm^2 (c). Lines show the edge of the crystal and the median borders of the waveguides.

The PPKTP frequency-doubling crystal (not AR coated) used in our work was 18 mm in length and was periodically poled for SHG (with the poling period of ~ 11.574 μm). The crystal contained 3 different waveguides with cross-sectional areas of ~4x4 μm^2, 3x5 μm^2 and 2x6 μm^2. Both the pump laser and the PPKTP crystal were operating at room temperature. The frequency-doubled output light was then collected by a power meter after a suitable filter at the fundamental wavelength.

Figure 2 shows calculated distribution of the fundamental TEM_{00} mode intensity in the PPKTP waveguides (lines show the edge of the crystal and the median borders of these waveguides). Confinement of the modes is $\Gamma = 0.789$ for the waveguide with cross-sectional area of ~4x4 μm^2, $\Gamma = 0.753$ for 3x5 μm^2 waveguide and $\Gamma = 0.609$ for 2x6 μm^2 waveguide. Some deviations of the measured near-fields of the modes from the calculated distributions are due to unavoidable imperfections and gradients of the refractive index at the waveguide borders. However, the calculated confinement of the modes is in a good agreement with the experiment.

3. EXPERIMENTAL RESULTS

The demonstrated compact all-room-temperature laser source generated orange light at ~606 nm, 608 nm and 611 nm with output power of 12.04 mW, 10.45 mW and 6.24 mW, and maximum conversion efficiency of 10.29%, 10.15% and 6.93%, respectively. Figures 3-5 show the SHG output power versus the launched pump power for 3 different waveguides (4x4 μm^2, 3x5 μm^2 and 2x6 μm^2) and corresponding spectra of frequency-doubled light at 605.6 nm, 608.2 nm and 610.85 nm, respectively.

One could expect higher conversion efficiency with the narrower waveguides (3x5 μm^2 and 2x6 μm^2) comparing to the widest waveguide (4x4μm^2) due to higher power density in the waveguides with smaller cross-sectional area. Indeed, not only the waveguide cross-sectional area decreases for narrower waveguides, but also the cross-sectional area of the TEM_{00} mode intensity at the level of half-maximum is lowering from approximately 6.6 μm^2 for broader waveguide to about 6.4 μm^2 for the narrowest one. This seems to be in odds with the experiment that demonstrates decrease of the conversion efficiency with narrower waveguides. However, taking into account lower confinement of the fundamental TEM_{00} mode in the narrower waveguides one can see that the drop of conversion efficiency is in a good agreement with decrease of the square of the confinement factor Γ^2 in the narrow waveguides. Also, the drop of the conversion efficiency in the narrow waveguides can be partially attributed to the lower coupling efficiency to the astigmatic apertures.

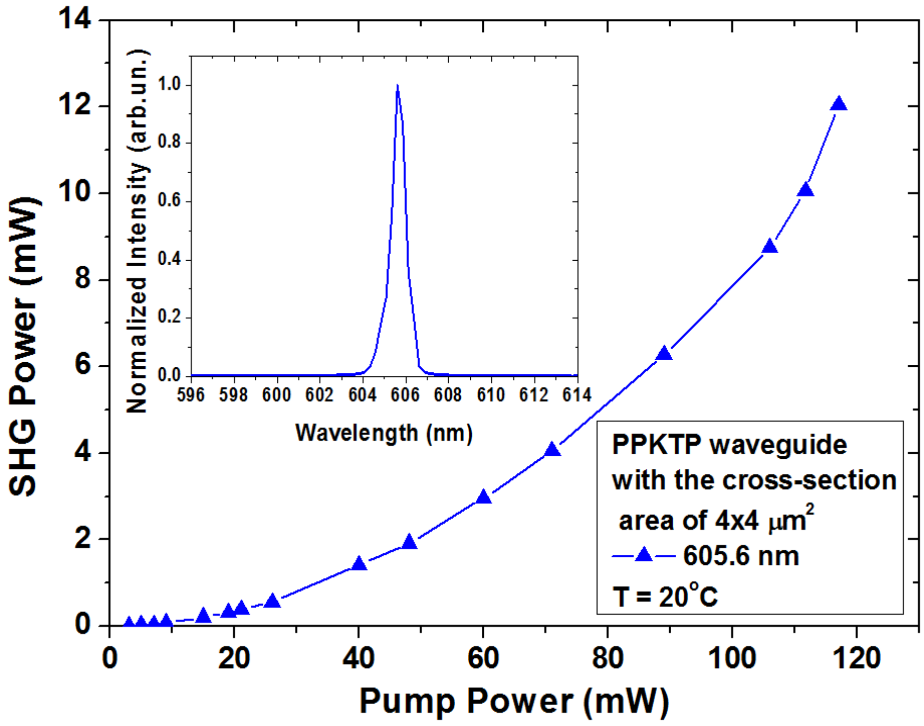

Figure 3. Frequency-doubled output power versus launched pump power at 605.6 nm. Inset: Optical spectrum of the second harmonic generation at the wavelengths: 605.6 nm.

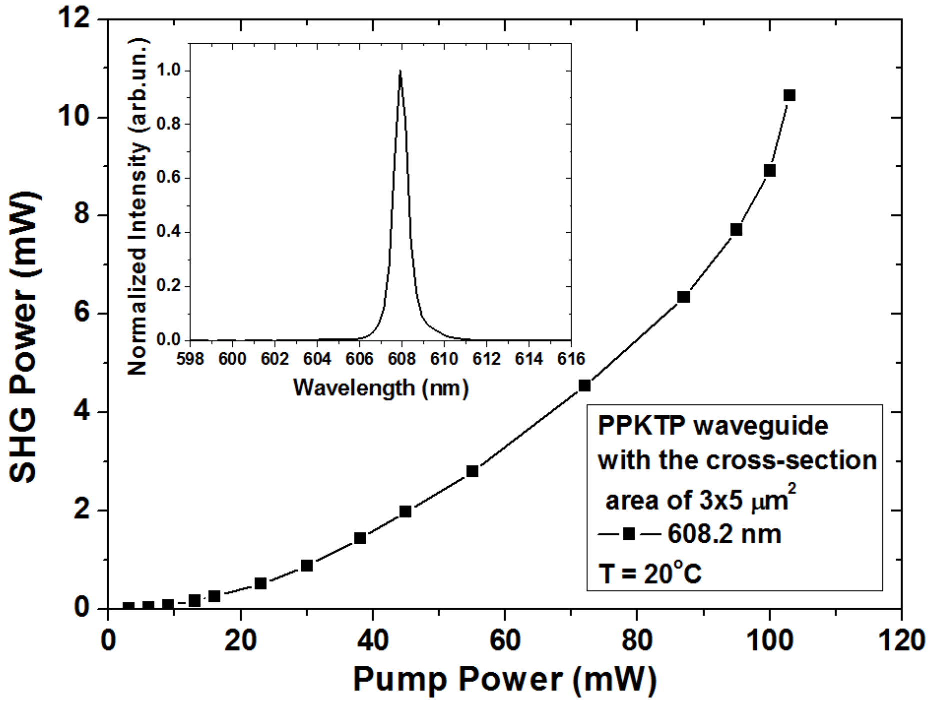

Figure 4. Frequency-doubled output power versus launched pump power at 608.2 nm. Inset: Optical spectrum of the second harmonic generation at the wavelengths: 608.2 nm.

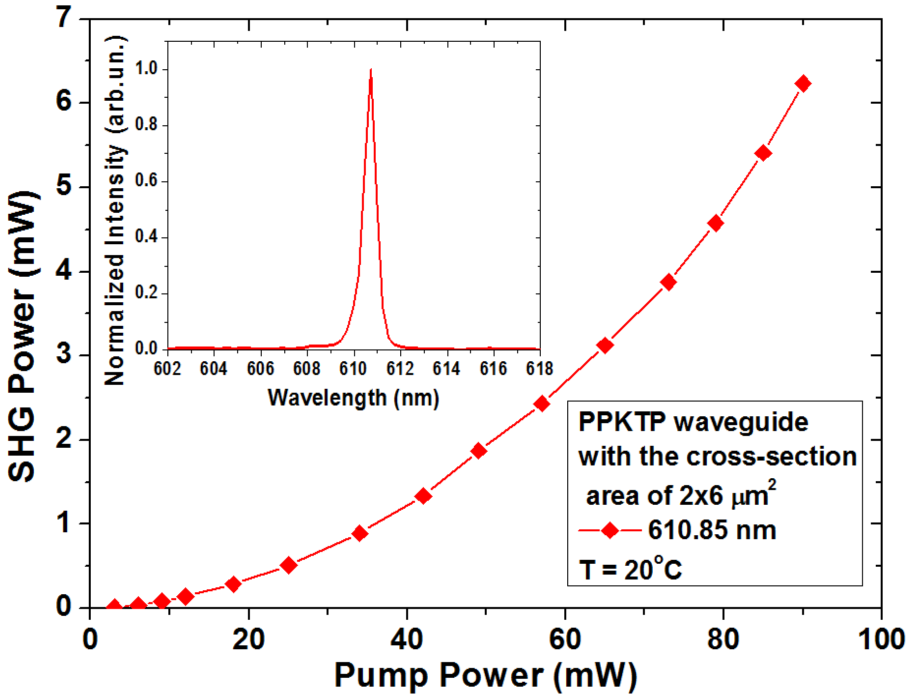

Figure 5. Frequency-doubled output power versus launched pump power at 610.85 nm. Inset: Optical spectrum of the second harmonic generation at the wavelengths: 610.85 nm.

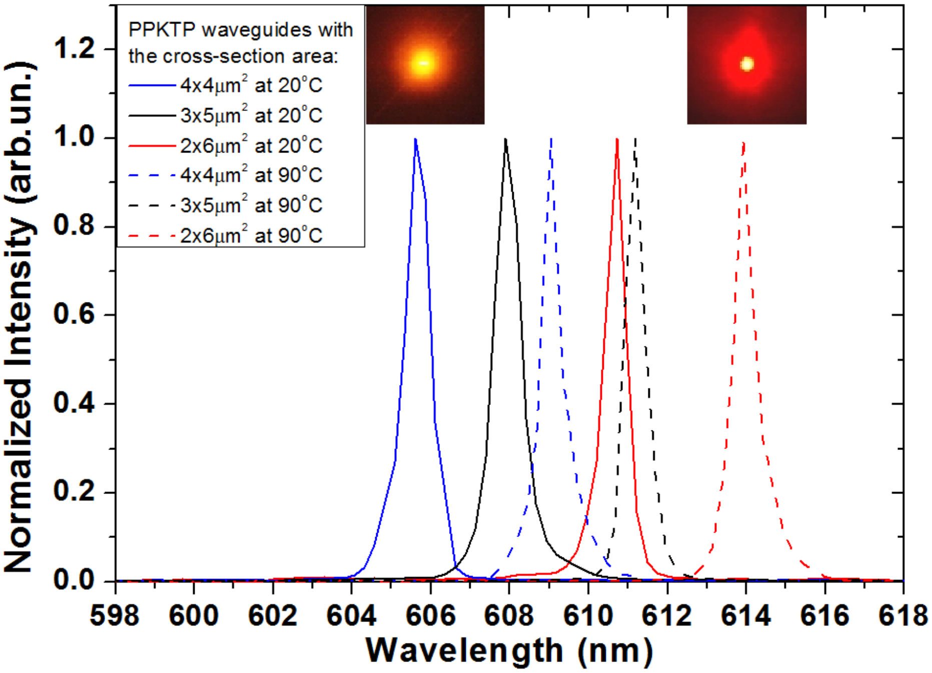

Figure 6. Spectra of second harmonic generated light tuned across the 605.6 nm – 613.9 nm wavelength range achieved by increasing the temperature of the PPKTP from 20°C to 90°C while simultaneously tuning the QD-ECDL.

The tunability of the SHG wavelength by increasing of the temperature of the PPKTP crystal waveguide from 20°C to 90°C while simultaneously tuning the QD laser was also investigated. By this method, we demonstrated tuning of the second harmonic light between 605.6 nm and 613.9 nm with similar conversion efficiency. Spectra of the second harmonic light for different waveguides measured at 20°C and 90°C are shown in Figure 6. The demonstrated laser source represents an important step towards a compact efficient orange light source.

4. CONCLUSION

We demonstrated a compact all-room-temperature laser source generating orange light at 606 nm, 608 nm and 611 nm with output power of 12.04 mW, 10.45 mW and 6.24 mW, and maximum conversion efficiency as high as 10.29%, 10.15% and 6.93%, respectively. This laser source is based on second harmonic generation in periodically-poled KTP waveguides with different cross-sectional areas (4x4 μm^2, 3x5 μm^2 and 2x6 μm^2) using a InAs/GaAs quantum-dot external-cavity diode laser. The wider waveguide with the cross-sectional area of 4x4 μm^2 demonstrated better results in comparison with the narrower waveguides (3x5 μm^2 and 2x6 μm^2) which corresponded to lower coupling efficiency. Additional tuning of second harmonic light (between 605.6 and 613.9 nm) with similar conversion efficiency was possible by changing the crystal temperature between 20°C and 90°C. The demonstrated laser source represents an important step towards a compact efficient orange light source which is of considerable interest for a range of applications. Further work on the improvement of SHG conversion efficiency is currently under way.

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