Powerful narrow-line source of blue light for laser cooling Yb/Er and Dysprosium atoms

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ABSTRACT

This report for the first time presents the results of parameter optimisation of ultra-narrow-linewidth frequency-doubled CW Ti:Sapphire lasers pumped with 12.5–18.5 W of 532-nm light. Proposed laser systems are designed for atom cooling and provide output radiation power of more than 1.5 W at 399/401 nm (Ytterbium/Erbium) and more than 1 W at 421 nm (Dysprosium) pumped at 18.5 W. The output power of single-frequency radiation at 421 nm achieved during the present work is the highest published to-date for a commercially available system achieving a 10 kHz linewidth.

Keywords: CW Ti:Sapphire laser, resonant frequency doubler, atom cooling

1 INTRODUCTION

For atomic cooling, there is a need for special powerful sources of radiation with narrow output lines and possibility of wavelength detuning. One of the most widely used means for this application is the CW single-frequency Ti:Sapphire laser with its relatively broad working spectral range (700–1100 nm) and comparatively high output power reaching 3–4 W when pumped with the most powerful commercially available green lasers. Their substantially high practical limit of the fundamental output power in the range of high gain for the Ti:Sapphire crystal (~720–1000 nm) allows these lasers to achieve equally impressive output levels in the second harmonic, correspondingly within the ~360–500-nm range, the maximum attainable output values being located within the narrower range of ~390–410 nm. The frequencies of the most important transitions of a series of atoms actively investigated at present (Yb, Er, Dy, Sr, &c) are located within the spectral range of second-harmonic generation of the Ti:Sapphire laser, therefore it is highly desirable to continue development of better systems based on second-harmonic generation of Ti:Sapphire lasers. This continued development means the improvement of the system's ability to deliver the highest possible power at the required wavelength, at the same time providing the narrowest possible linewidth and the longest uninterrupted operation time. The achievable progress in this domain is as much governed by the values of the maximum power available from the green pump lasers and by the efficiency of non-linear optical crystals, as it is by new technical solutions applied in Ti:Sapphire lasers and radiation frequency doublers.

It was reported earlier about the achievement of efficient second harmonic generation of a single-frequency Ti:Sapphire laser [1–8]. In the best implementations, the absolute values of the radiation power of the second harmonic ranged from several hundreds of mW [1–6] to watt-level [7, 8], whereas the measured linewidths of the second harmonic radiation varied between 3 MHz [3, 7] to 40 kHz rms [9], the narrowest line width of blue radiation [9] having been achieved at the second harmonic output power of 200 mW.

The present report announces, for the first time, the possibility to generate blue radiation with the linewidth of less than 10 kHz at the output power exceeding 1 W within the wavelength range 390–425 nm.

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2 EXPERIMENT

Powerful narrow-line source of blue light was built on the basis of a ring-cavity Ti:Sapphire laser and a resonant radiation frequency doubler. The general layout of the Ti:Sapphire laser is presented in Fig. 1.

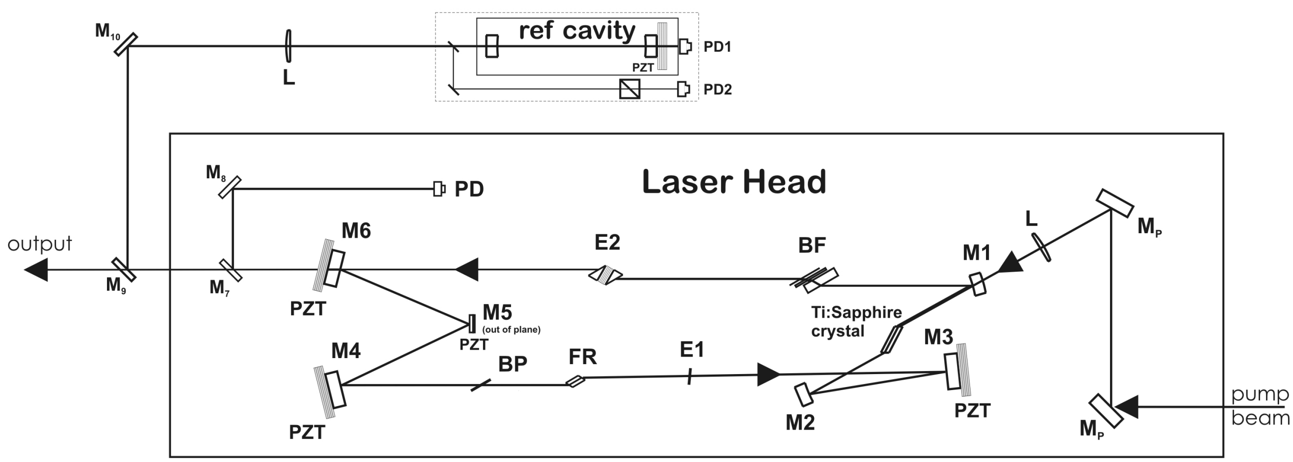

Fig 1 Optical layout of the CW single-frequency ring Ti:Sapphire laser: M_P - pump mirror, L - lens, M1 & M2 - spherical mirrors (R=100 mm, T < 0.1%), M3, M4, M5 - flat mirrors (T < 0.1%), M6 - flat output mirror (T=7-8%), AE - Ti:Sapphire crystal, BF - 3-plate birefringent filter, E1 - thin Fabry-Perot étalon, E2 - thick Fabry-Perot étalon, FR - Faraday rotator, BP- Brewster plate, EMD - electro-mechanical drive, PD - photodetector, M7 & M8 - auxiliary mirrors, PZT – piezoceramic.

Single-frequency operation of the laser was achieved by application of three selective elements: bi-refringent filter and two Fabry-Perot étalons. Other details of the optical layout and design of this laser are available in Refs [9, 10]. For continuous detuning of the laser generation frequency within a range of about 20 GHz, a Brewster plate was used with a galvanometer control. The generation frequency of this laser was stabilised with the help of a reference interferometer characterised by an approximately 2-MHz wide transmission peak. Small mirror M5 attached to a thin PZT element served as the fast actuator of the frequency stabilisation system. The first mechanical resonance of this element occurred at frequencies exceeding 100 kHz. For measurements of the absolute instantaneous radiation line width we used two identical Ti:Sapphire lasers, the radiation from which was combined and then the beat spectrum of which was taken. These two Ti:Sapphire lasers were pumped with identical green lasers and the output power of each of the Ti:Sa lasers amounted to 450 mW at the wavelength of 770 nm. Frequency beating between these lasers was detected with an avalanche photodiode and fed into an RF spectrum analyzer. Fig. 2 demonstrates typical beat spectra of these lasers recorded using 1-second scanning of the analyser in the range of 300–100 kHz around 1 MHz. The measured spectral width of the beats varied around 3–5.5 kHz, thereby indicating that the absolute short-time line width of each laser's radiation amounted to 2–4 kHz, its rms value being 1 kHz and even less.

In the course of the following experiments, powerful green lasers Verdi with the output ranging from 12.5 to 18.5 W were used in order to achieve higher output powers of the Ti:Sapphire laser's output radiation. A high-quality Ti:Sapphire crystal with FOM > 500 was used in the Ti:Sapphire laser, which provided linear growth of the output power versus pump intensity up to the level of ~13–13.5 W with the regular alignment of the cavity. Further increase of the output from the Ti:Sa laser pumped with ~13.5–18.5 W of green radiation required a special alignment of the resonator as well as more efficient cooling of the active element. Shown in Fig. 3 is the output power dependence of the Ti:Sapphire laser at 800 nm upon the pump power in the mode of special cavity alignment and at the Ti:Sa crystal temperature 10 ºC. One can readily see that this curve is steeper than the usual one: at 18.5 W of pump power the output level of the Ti:Sapphire laser amounts to 4.1 W, whereas at 10 W of pumping power the output power drops to just 1 W instead of the usual 2 W, and the generation threshold rises to 6 W instead of ~3 W. However, it is with this particular alignment of the Ti:Sapphire laser cavity that a quasi-linear growth of the output power as dependant of the pumping power was possible up to maximum available 18.5 W, while maintaining TEM_{00} output mode of the Ti:Sapphire laser within the full range of output powers.

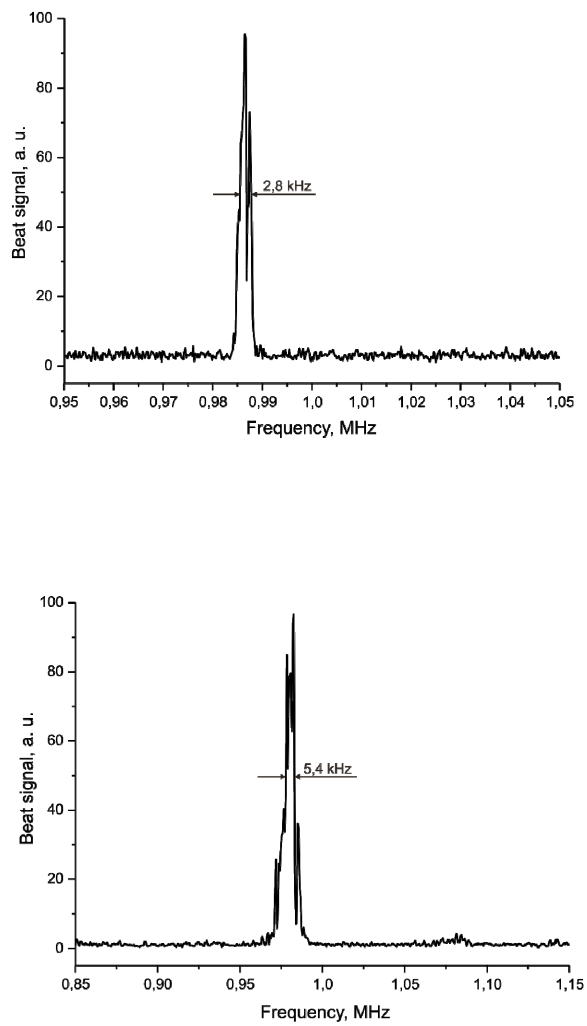

Fig 2 Beat spectra of two identical CW frequency-stabilized single-frequency ring Ti:Sapphire lasers.

Frequency doubling of the Ti:Sapphire laser was performed with resonant doubler whose technical parameters are given in Ref [11]. This unit used a 15-mm long LBO crystal with normal faces, anti-reflection coated for both the fundamental and the second harmonic radiation. Even though spurious reflections of the fundamental radiation from the non-linear crystal were quite low, good radiation mode matching between the cavity of the Ti:Sapphire laser and that of the frequency doubler lead to perceptible light feed-back from the doubler to the laser, which manifested itself by frequency hops of the Ti:Sapphire laser output. When optical isolator was used between the laser and the doubler, this parasitic effect completely disappeared. For uninterrupted operation of the frequency doubler, the Auto Relock system was used, which allowed automatic re-locking of the frequency doubler's resonator to the output wavelength of the Ti:Sapphire laser when it accidentally went out of lock.

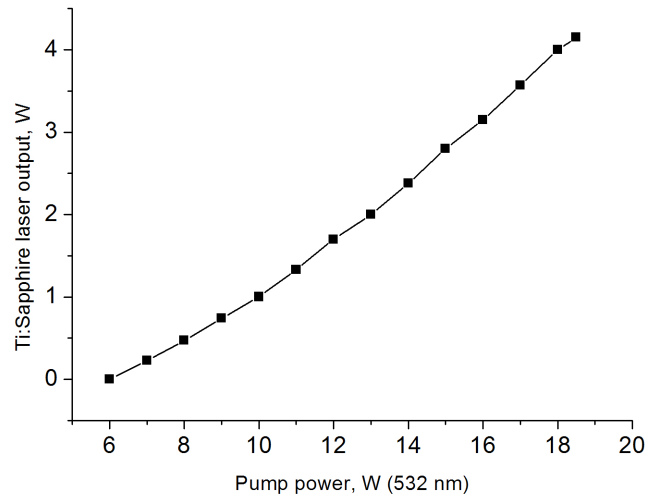

Fig 3 Ti:Sapphire laser output (800 nm) versus pump power.

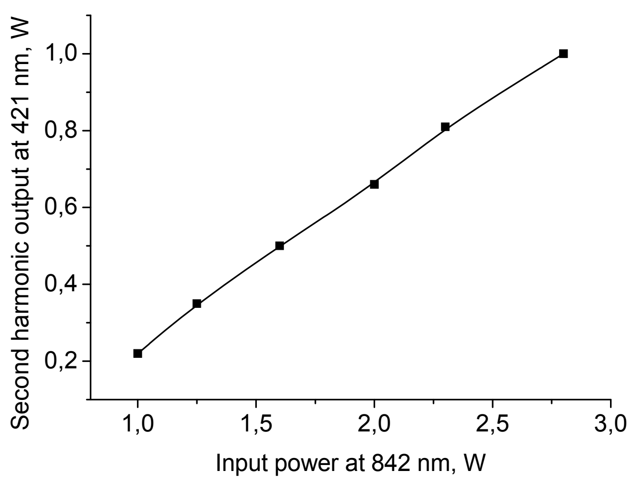

Fig 4 Second harmonic output at 421 nm versus input power at 842 nm

The maximum obtainable output power of the Ti:Sapphire laser at 842 nm reached 3.3 W when pumped with 18.5 W, however, because of optical losses along the path to the frequency doubler from an optical isolator, the maximum power at the entrance aperture of the doubler was only 2.8 W, the maximum output power in the second harmonic amounting to 1 W, and the conversion efficiency, to 35%. The magnitude of the second harmonic power fluctuations within several seconds did not exceed 6%. The measured linewidth of the second-harmonic radiation was less than 10 kHz. An external view of the laser system in shown in Fig. 5.

Fig. 5. Powerful narrow-line source of blue light based on CW frequency-stabilised ring Ti:Sapphire laser and resonant frequency doubler.

The output power of the Ti:Sapphire laser at wavelengths around 800 nm is higher than that at 842 nm, therefore the power of the second harmonic in the vicinity of 400 nm is also higher than that at 421 nm. Thus, the highest attained second harmonic power at 400 nm reached 1.5 W with the input (fundamental) power at the entrance to the frequency doubler being 4.1 W (green pump power 18.5 W), and it was as high as 700 mW when pumped with 12.5 W of green radiation.

It is necessary to note that such comparatively elevated levels of the second harmonic output power were generated in the course of this work on traditional non-linear crystals LBO. The use of periodically-poled crystals may deliver better efficiency of conversion, but, as a rule, at substantially lower radiation powers. Utilisation of such crystal in single-pass configuration at wavelength 421 nm resulted in Ref [12] in only 0.3 mW at the pump Ar laser power of 13 W. There are definitely numerous examples of more efficient conversion of Ti:Sapphire laser radiation into the blue range with the help of periodically-poled crystals. Nevertheless, the attained absolute power levels are substantially lower than those achievable in external cavities with LBO crystals.

3 CONCLUSIONS

The present paper discusses laser systems on the basis of Ti:Sapphire laser with powerful pump (12.5–18.5 W) and efficient external radiation frequency doublers for generation of powerful radiation at the level of 1–1.5 W in the 390–425 nm range, featuring instantaneous line widths of less than 10 kHz. These systems are used for cooling of atoms such as dysprosium (421 nm), ytterbium/erbium (399/404 nm), and others. Presented tandem configurations on the basis of Ti:Sapphire lasers and external frequency doublers have proven themselves as reliable and efficient sources of powerful wavelength-tuneable blue radiation with ultra-narrow line width.

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