RESONANTLY ENHANCED FREQUENCY DOUBLING OF A CONTINUOUS-WAVE YTTERBIUM-DOPED FIBER LASER

LUKAS ROSKOT[1,2], MARTIN SMRZ[1], ONDREJ NOVAK[1], TAISUKE MIURA[1]

[1]HiLASE Centre, Institute of Physics AS CR
Dolni Brezany, Czech Republic

[2]Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Czech Republic

DOI: 10.17973/MMSJ.2019_12_2019108

lukas.roskot@hilase.cz

A single-mode ytterbium-doped continuous-wave fiber laser operated at a wavelength of 1030 nm is designed and utilized for frequency doubling at 515 nm in a periodically poled lithium niobate (PPLN) crystal. The standard single-pass of the PPLN results in a conversion efficiency of only 2 % due to the low intensity of the continuous-wave laser even though optimal focusing into the PPLN is used. Because the second harmonic (SH) power depends quadratically on the input power, the intensity of the 1030 nm beam needs to be increased. Therefore, the beam enters an external resonant enhancement cavity with a high quality factor. The waves are trapped inside the resonant cavity and superimposed resulting in an increase of intracavity power by an estimated factor of 24. SH conversion efficiency of over 51 % is achieved after placing the PPLN inside the enhancement cavity. This is more than 25 times higher than for the single-pass case showing high potential of this method which is easily scalable to watt-level powers. 515 nm beams with watt-level power can be used e.g. to pump titanium sapphire lasers, which generate femtosecond laser pulses that can be used for precise micromachining.

KEYWORDS

fiber laser, frequency doubling, enhancement cavity, periodically poled lithium niobate

1 INTRODUCTION

Fiber lasers, that is lasers with the active medium being an optical fiber with a rare-earth ion-doped core, find increasingly greater utilization in a broad spectrum of applications. Owing to the use of very small fiber core diameters, such lasers can provide very intense and high-quality beams with a nearly unlimited length of the active medium enabling very high average powers in the continuous-wave (cw) regime. Typical industrial uses include cutting, welding, marking and tempering. In these applications, fiber lasers either compete with or have replaced other solid-state lasers in recent years [Zervas 2014]. Additionally, thanks to the high beam quality, their beams can be focused very tightly making them suitable for use in areas requiring high precision. An example is the fiber laser scalpel. Fiber lasers also find extensive use in telecommunications, where they are readily compatible with standard telecom fibers. Depending on the used ion in the active medium, fiber lasers can generate light in various parts of the optical spectra, most often in the near infrared. By frequency doubling the output of these lasers it is possible to obtain visible light. For instance, an ytterbium-doped fiber laser operating at 1030 nm can be used to generate green light at 515 nm which, when powerful enough, can be useful for e.g. pumping titanium sapphire lasers [Kumar 2012, Samanta 2011], which generate femtosecond pulses that may be used for micromachining [Bruneel 2010]. While other means of pumping are possible, e.g. using frequency doubled neodymium-doped lasers, they are often less efficient, not compact, and expensive.

Frequency doubling or second harmonic generation (SHG) is a nonlinear process that is possible to occur in crystalline media lacking inversion symmetry and exhibiting χ^2 (second-order susceptibility) nonlinearity. When a sufficiently intense monochromatic laser beam enters such a material it induces a nonlinear polarization wave which oscillates with twice the fundamental frequency. According to Maxwell's equations, this polarization wave generates an electromagnetic field with this doubled frequency [Boyd 2007]. This can result in a substantial energy transfer from the first to the second harmonic wave, provided some key conditions are met. For an effective conversion the fundamental and frequency doubled wave have to be in phase while propagating through the crystal. This is possible only when the phase velocity is the same for both waves; we say the two waves need to be phase-matched. The second-harmonic field contributions generated at different locations in the nonlinear crystal then coherently add up throughout the crystal. This cannot be accomplished in isotropic dispersive materials. The most common method for achieving phase-matching is to exploit birefringent crystals. In these the phase velocity depends not only on the wavelength of the radiation, but also on the direction of beam propagation and polarization relative to the optical axis of the crystal. Waves propagating through a birefringent uniaxial crystal are called ordinary and extraordinary, depending on the linear polarization direction. While for ordinary waves the phase velocity remains the same for all input directions, extraordinary waves propagate with a different phase velocity depending on the propagation angle. By selecting the right polarization and input angle of the fundamental beam, one can achieve phase-matching.

A less usual, but very convenient method is to utilize crystals that have a periodically modulated sign of the nonlinearity. By manufacturing such a crystal with an appropriate modulation period, it is ensured that the fundamental and second harmonic wave are never completely out of phase and at least a partial constructive interference of the second harmonic wave contributions in all positions inside the crystal is guaranteed. This technique is called quasi-phase matching. Here, all beams typically have the same polarization and the crystal axis is oriented in a way to utilize the highest nonlinear coefficient, which can be more effective than birefringent phase-matching [Hum 2006].

Single-pass SHG conversion efficiency for cw lasers is usually in the range of a few percent, unless powers of tens of watts are used [Kumar 2009]. Because the efficiency scales linearly with input fundamental power in periodically-poled crystals, it is beneficial to use a high average power laser or to somehow increase the power inside the crystal. One of the possibilities of achieving this is to place the crystal inside the laser resonator. Because the light resonates and adds up inside, the intracavity power is much higher than at the output of the laser and the conversion efficiency is therefore increased. Similarly, one can also build an external resonator and place the crystal inside [Khripunov 2014]. This approach has the advantage of not requiring any modifications to the laser resonator itself and thus preventing any power instabilities that may be caused by placing the crystal there (the so-called 'green problem') [Baer 1986]. On the other hand, there are also certain complications that arise when this approach is chosen. It is necessary to ensure the external resonator is stable and its length does not change due to thermal or other effects otherwise the resonance condition for the fundamental beam would not be satisfied. Additionally, the output beam of the laser has to be mode-matched to the mode of this new resonator. Beam parameters such as its diameter, divergence, and waist position need to be the same. Finally, the reflectivity of the input mirror of the resonator must be carefully chosen. Its transmission coefficient needs to equal the coefficient of losses inside the resonator. This condition is called impedance-matching [Kozlovsky 1988]. Only when this prerequisite is satisfied, will there be zero reflection at the resonator input and the light will be coupled inside. This is due to the fact that the reflected radiation then destructively interferes with the radiation exiting the resonator.

In this work we present a simple and compact fiber-laser design and its utilization for efficient second harmonic generation. We experimentally study the widely used single-pass method with the more complex but significantly more efficient resonant enhancement approach and compare them in terms of conversion efficiency. While the single-pass conversion efficiency is only 2 %, the resonantly enhanced conversion efficiency is much higher, above 50 %.

2 FIBER LASER DESIGN

The layout of the designed cw fiber laser is depicted in Fig. 1. The active medium is a 20 cm long single-mode ytterbium-doped fiber pumped by a single-mode laser diode operating at the wavelength of 976 nm and delivering 677 mW of maximum pump power. The absorption of the active fiber at the pump wavelength is 1500 dB/m. The pump light is coupled via a wave-division multiplexing coupler (WDM) into a compact 3 m long resonator. To prevent any damage to the laser diode, it is protected by an isolator that blocks radiation that may be reflected back into the laser diode. At the rear end of the resonator, light is coupled out of the fiber and reflected by a thin-film polarizer which ensures that the laser light is linearly polarized. Here it is reflected by a highly reflective mirror and coupled back into the resonator via a pigtailed fiber collimator. The reflectivity of the output coupler of the laser was optimized in order to maximize the laser output power.

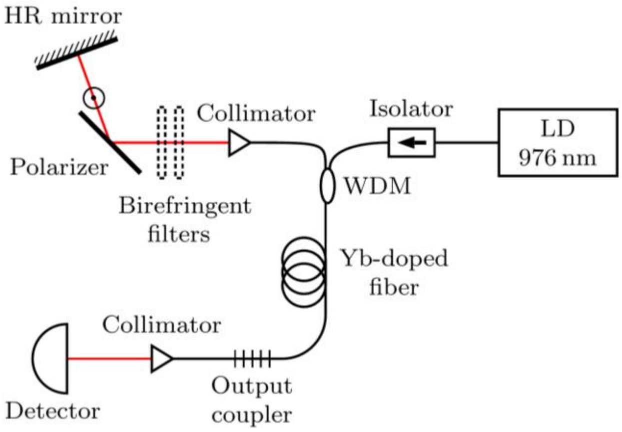

Figure 1. Experimental layout of the fiber laser. HR – highly reflective, WDM – wave-division multiplexing coupler, LD – laser diode.

The process of optimization is documented in Fig. 2. With a 98 % reflective mirror only 19 mW of power was coupled out of the resonator while for an 85 % reflective mirror it was 100 mW. The highest power of 286 mW was obtained by using a narrow bandwidth fiber Bragg grating (FBG) with 10.5 % reflectivity for 1030.1 nm as the output coupler. The corresponding optical efficiency is 42.2 %.

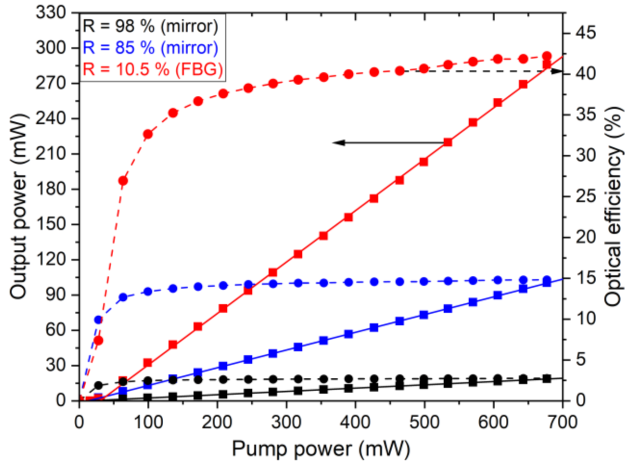

Figure 2. Laser output power and optical efficiency in dependence of the pump power. Solid lines are linear fits of measured data.

The measured spectrum of the laser is in Fig. 3(a). It is centered at 1030.1 nm with a full width at half maximum (FWHM) of 20 pm which is at the resolution limit of the spectrometer. We expect the actual spectral width to be much narrower. The beam profile is in Fig. 3(b) and has a Gaussian shape.

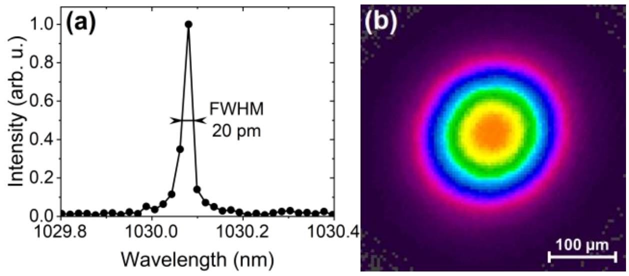

Figure 3. Measured spectrum (a) and beam profile (b) of the fiber laser.

Due to the high spectral selectivity of the FBG, only a few longitudinal modes are present in the laser resonator. Because of that, intermodal interference with frequency of about 100 MHz is noticeable resulting in periodic short-term power instabilities in the output power (average power peak-to-peak fluctuations of 1.5 %). In order to mitigate these effects, one 0.5 mm and one 3.5 mm thick calcite birefringent spectral filter (birefringent filters in Fig. 1) are added inside the resonator next to the polarizer. This results in a stable, single longitudinal mode operation, although the maximum output power is lowered to 193 mW. While the resonator without filters was used for the single-pass harmonic generation, the enhanced generation was carried out with the filters inside the laser.

3 SECOND HARMONIC GENERATION RESULTS

A 20 mm long MgO-doped (5 %) periodically poled lithium niobate (PPLN) crystal made by Covesion Ltd. is used for the second harmonic frequency generation. It is suitable for frequency doubling of cw beams thanks to its high effective nonlinear coefficient of 14 pm/V. The aperture of the crystal is 0.5x0.5 mm and both faces are anti-reflection coated for 1030 and 515 nm. The PPLN is kept in a temperature-controlled oven.

3.1 Single-pass generation

The experimental layout for the single-pass second harmonic generation measurement is in Fig. 4. The beam exits the laser and its polarization is adjusted using a set of two half- and one quarter-wave plate. A focusing lens (f = 50 mm) is used to focus the beam inside the crystal. The 4σ diameter of the beam in the center of the crystal is 68 µm, which corresponds to the optimum given by the theory of SHG by a focused beam [Boyd

1968]. The residual fundamental beam is filtered out by a shortpass filter so only the frequency doubled beam is detected.

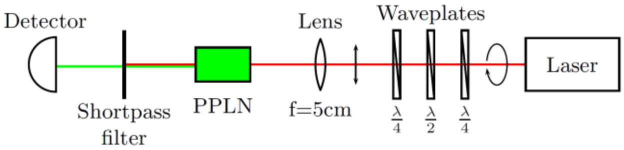

Figure 4. Setup of the system for single-pass second harmonic generation. Linear and elliptical arrow indicate the polarization state of the beam.

Because the poling period is temperature-sensitive the temperature of the crystal was optimized in order to achieve optimal quasi-phase matching and highest conversion efficiency. The dependence of the second harmonic power on the crystal temperature is in Fig. 5(a). Measured data closely follow the theoretical sinc² dependence [Boyd 2008]. For 286 mW of input power the maximum attained second harmonic power is 5.7 mW with the temperature kept at 69 °C. As can be seen in Fig. 5(a), a change in temperature of 0.7 °C results in the output power being halved indicating significant temperature sensitivity of the quasi-phase matched SHG process. Fig. 5(b) shows the dependence of the second harmonic power on the input fundamental power. The conversion efficiency achieved for 286 mW of input power is 2 %.

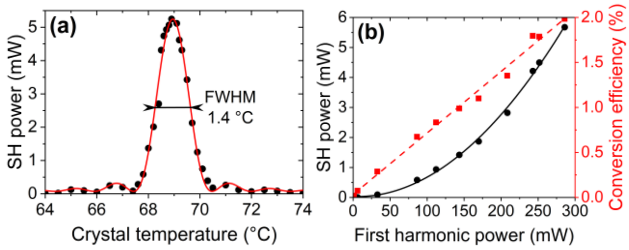

Figure 5. Dependence of the second harmonic power on crystal temperature with a sinc² fit (a) and dependence of second harmonic power and conversion efficiency on first harmonic power (b) with a parabolic fit (black line) and a linear fit (red line) of the measured data.

The measured spectrum of the second harmonic is in Fig. 6(a). It is centered at approximately 514.9 nm with a FWHM of 0.1 nm which is again at the resolution limit of the used spectrometer meaning the actual width is much narrower. The beam profile can be seen in Fig. 6(b).

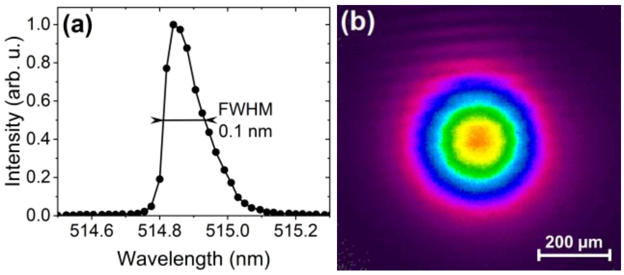

Figure 6. Measured spectrum (a) and beam profile (b) of the second harmonic.

3.2 *Resonantly enhanced generation*

In order to increase the conversion efficiency, an external resonator for the fundamental wavelength was designed and the PPLN crystal was placed inside. The layout of the resonator is shown in Fig. 7.

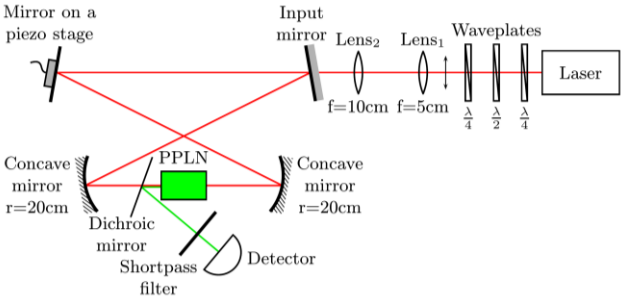

Figure 7. Layout of the external resonator for enhanced second harmonic generation.

It is a 149 cm long ring cavity formed by four mirrors – a partially reflective flat input mirror, a flat mirror on a piezo stage and two concave mirrors (20 cm radius of curvature). A ring cavity ensures the second harmonic is generated only in one direction. A bow-tie arrangement of the mirrors is implemented in order to minimize the influence of astigmatism on the beam shape. The size and divergence of the laser beam is adjusted using two lenses (f = 5 cm and f = 10 cm) in order to match the mode of the resonator. The PPLN is placed between the concave mirrors where the 4σ beam diameter is 110 µm. Because the length of the resonator needs to be constant, the mirror on the piezo stage is used to manually correct any slight length variations caused by thermal or other environmental effects. The second harmonic beam is coupled out of the resonator by a dichroic mirror that is transparent for the fundamental beam and reflective for the frequency doubled beam.

As stated in section 2, the laser for this measurement operated at a maximum power of 193 mW. The dependence of second harmonic power and conversion efficiency on input power is shown in Fig. 8 and Fig. 9, respectively, measured for different reflectivity values of the input coupler. The optimum value was found to be 90 %. Even a relatively small variation of 5 % in mirror reflectivity results in a drop in the conversion efficiency of 20 %. As can be seen, the reflectivity is a crucial parameter and has to be carefully optimized. For the optimal reflectivity and maximum input power of 193 mW, 99 mW of second harmonic power was generated resulting in a conversion efficiency of 51.3 %, i.e. more than 25 times higher than for the single-pass case. By measuring the leakage through the mirror on the piezo stage and using the available mirror specifications, the intracavity power was estimated to be 4.6 W, which corresponds to an increase of power by a factor of 24. Intracavity conversion efficiency was 2.2 %, i.e. only slightly higher when compared to the single-pass measurement. This can be attributed to the difference in the beam diameter inside the PPLN, which was considerably larger than the optimal 68 µm in the case of the resonantly enhanced generation measurement.

Spectrum and beam profile of the second harmonic were also measured and confirmed to be identical to those shown in Fig. 6(a) and (b).

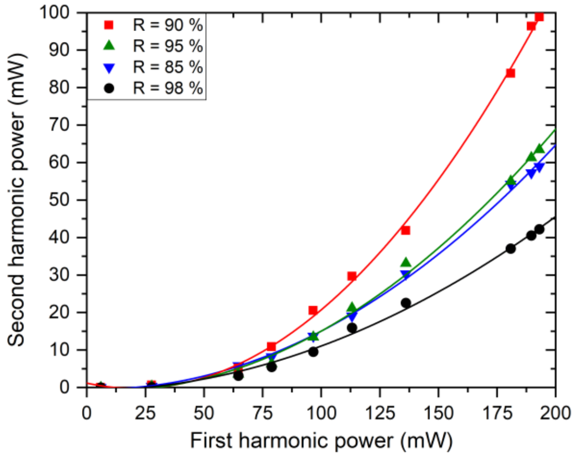

Figure 8. Dependence of the second harmonic power on input power for different reflectivity of the input mirror. Solid lines are parabolic fits of measured data.

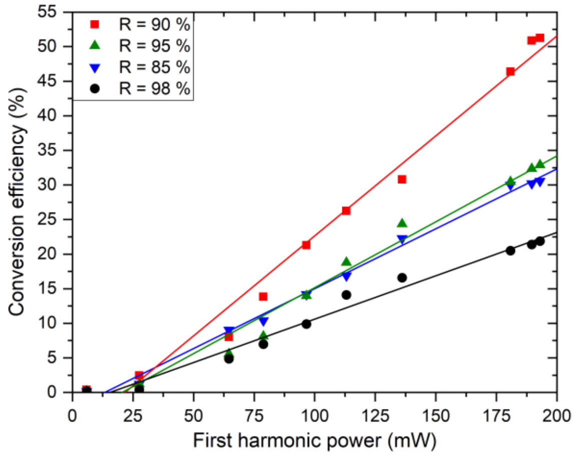

Figure 9. Dependence of the conversion efficiency on input power for different reflectivity of the input mirror. Solid lines are linear fits of measured data.

4 CONCLUSIONS

In this work we have presented a simple design of a 1030 nm Yb-doped fiber laser and its utilization for efficient second harmonic generation in a PPLN crystal. The standard single-pass method resulted in 5.7 mW of generated second harmonic power which corresponds to a 2 % conversion efficiency. In order to increase the efficiency, an external resonator was designed to increase the power of the fundamental beam. By placing the crystal inside this cavity, we were able to obtain a considerably higher second harmonic output power of 99 mW. The conversion efficiency is 51.3 % which is more than 25 times higher than in the single-pass case.

As can be seen in Fig. 8, the output power shows no sign of saturation which enables straightforward scalability of the whole system towards higher powers. The laser output power can be increased e.g. by using a multi-mode pump diode and double-clad active fibers in the laser. The presented method of frequency doubling can result in a second harmonic beam with watt-level power. Such a system could be readily used in e.g. pumping of titanium sapphire lasers, certain interferometric applications, or Raman spectroscopy.

ACKNOWLEDGMENTS

This work was co-financed by the European Regional Development Fund and the state budget of the Czech Republic (project HiLASE CoE: Grant No. CZ.02.1.01/0.0/0.0/15_006/0000674) and by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 739573. This work was also supported by the Ministry of Education, Youth and Sports of the Czech Republic (Programmes NPU I Project No. LO1602, Large Research Infrastructure Project No. LM2015086), and by the Czech Science Foundation (GACR) under project No. GA16-12960S.

REFERENCES

[Baer 1986] Baer, T. Large-amplitude fluctuations due to longitudinal mode coupling in diode-pumped intracavity-doubled Nd:YAG lasers. Journal of the Optical Society of America B, September 1986, Vol.3, No.9, pp 1175-1180. ISSN 1520-8540

[Boyd 1968] Boyd, G. and Kleinman, D. Parametric Interaction of Focused Gaussian Light Beams. Journal of Applied Physics, July 1968, Vol.39, No.8, pp 3597-3639. ISSN 0021-8979

[Boyd 2008] Boyd, R. Nonlinear Optics. Burlington: Academic Press, 2008. ISBN 978-0123694706

[Bruneel 2010] Bruneel, D. et al. Micromachining of metals with ultra-short Ti-Sapphire lasers: Prediction and optimization of the processing time. Optics and Lasers in Engineering, March 2010, Vol.48 No.3, pp 268-271. ISSN 0143-8166

[Hum 2007] Hum, D. and Fejer, M. Quasi-phasematching. C. R. Physique, March 2007, Vol.8, No.2, pp 180-198. ISSN 1631-0705

[Kozlovsky 1988] Kozlovsky, W. et al. Efficient second harmonic generation of a diode-laser-pumped CW Nd:YAG laser using monolithic $MgO{:}LiNbO_3$ external resonant cavities. IEEE Journal of Quantum Electronics, June 1988, Vol.24 No.6, pp 913-919. ISSN 0018-9197

[Kumar 2009] Khripunov, S. et al. Variable-wavelength second harmonic generation of CW Yb-fibre laser in partially coupled enhancement cavity. Optics Express, March 2014, Vol.22 No.6, pp 7046-7051. ISSN 1094-4087

[Kumar 2009] Kumar, S. et al. High-power, single-frequency, continuous-wave second-harmonic-generation of ytterbium fiber laser in PPKTP and MgO:sPPLT. Optics Express, August 2009, Vol.17 No.16, pp 13711-13726. ISSN 1094-4087

[Kumar 2012] Kumar, S. et al. Single-frequency, high-power, continuous-wave fiber-laser-pumped Ti:sapphire laser. Applied Optics, January 2012, Vol.51 No.1, pp 15-20. ISSN 2155-3165

[Samanta 2012] Samanta, G.K. et al. High-power, continuous-wave Ti:sapphire laser pumped by fiber-laser green source at 532 nm. Optics and Lasers in Engineering, February 2012, Vol.50, No.2, pp 215-219. ISSN 0143-8166

[Zervas 2014] Zervas, M. and Codemard, C. High Power Fiber Lasers: A Review. IEEE Journal of Selected Topics in Quantum Electronics, April 2014, Vol.20, No.5, pp 219-241. ISSN 1558-4542

CONTACTS:

Bc. Lukas Roskot
HiLASE Centre
Za Radnicíi828, Dolni Brezany, 252 41, Czech Republic
lukas.roskot@hilase.cz, www.hilase.cz