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Passively Q-switched Nd:YAG pumped UV lasers at 280 and 374 nm

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ABSTRACT

Pulsed UV lasers at the wavelengths of 374 and 280 nm are realized by cascaded second harmonic generation (SHG) and sum frequency generation (SFG) processes using a Nd:YAG laser at 1123 nm. The Nd:YAG laser is longitudinally pumped and passively Q-switched, and it has a high peak power of 3.2 kW. The UV peak powers at 280 and 374 nm are 100 and 310 W, with pulse lengths of 6 and 8 ns, respectively. Spectral broadening of 374 nm laser by stimulated Raman scattering is studied in single mode pure silica core UV fiber. Realizations of UV lasers enabling compact design at 280 and 374 nm wavelengths are demonstrated.

1. Introduction

Compact UV-light sources can be used in, e.g. spectroscopy, bioanalysis and micromachining. Pulsed UV light sources make it possible to extend the spectroscopic analysis to the time resolved regime. One advantage of passively Q-switched solid state lasers is the possibility to produce high peak powers. This enables studies of low sample volumes and high signal levels when compared to the semiconductor light sources in the UV range.

We present here realizations of solid state UV-lasers producing pulsed output at wavelengths of 374 nm and 280 nm. For 374 nm light, the 1123 nm laser is frequency doubled, followed by SFG of light at the wavelengths of 1123 nm and 561 nm. The fourth harmonic generation is done by cascaded frequency doublings. The passively Q-switched IR pump laser makes use of the low gain transition of the $Nd{:}Y_3Al_5O_{12}$ (Nd:YAG) crystal at 1123 nm. We also studied spectral broadening of the 374 nm laser output in pure silica core single mode UV fiber. Light at 280 nm can be used to excite fluorescence in natural biofluorophores like tyrosine and tryptophan [1]. This enables study of proteins using their intrinsic fluorescence and its decay, giving information on system dynamics and structural changes. Pulsed UV source allows not only studies of fluorescence spectroscopy and microscopy but also study of kinetics and sensing [2]. In addition, some complex biological compounds can be identified on the basis of the responses to 280 and 374 nm [3]. The wavelength of 374 nm is applicable, e.g. in photopolymerization. In the field of optoelectronics, pulsed UV sources can be used in life time measurements, e.g. to detect and image semiconductor quantum well structures emitting in blue and near UV spectral ranges [4].

Earlier, SHG of the Q-switched laser source emitting at 1123 nm was demonstrated using a Cr:YAG saturable absorber [5]. However, to our knowledge, this laser has not been converted to UV light. Reports on 280 nm lasers have been obtained with the help of one or several external resonators [6,7]. These setups are complex and require sophisticated electronics whereas our approach enables building a compact laser. Furthermore, we are able to create a peak power in a range of 100 W at 280 nm and 300 W at 374 nm. Compared to commercial semiconductor lasers at 375 nm, the peak power is over three orders of magnitude higher. This high power is needed here in obtaining a broadened spectrum in the UV wavelength range. Earlier, a broadband UV source was demonstrated by pumping with a dye laser in the work of Lin and Stolen [8] and with a nitrogen laser at 337 nm by Bartula et al. [9].

2. Setup

The general layout of the laser is depicted in Fig. 1. The pump light is provided by a fiber coupled laser diode emitting at

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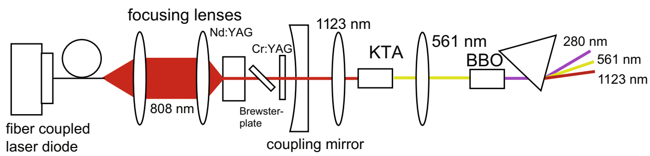

Fig. 1. Schematic picture of the setup. For the 374 nm laser the BBO crystal is replaced the BIBO crystal.

808 nm with the maximum power of 4 W, fiber core diameter of 100 μm and N.A. of 0.22. The output from the fiber is collimated and focused into the laser crystal with a pair of aspheric lenses with focal lengths of 11 and 15.4 mm. As a result, the width of the pump beam is around 140 μm (FWHM) which is on the same order as the theoretical mode diameter of 150 μm (FWHM) for the used physical cavity length of 18 mm. The dimensions of the laser crystal are $3 \times 3 \times 3$ mm^3. The first surface is a dielectrically coated with high-reflection at 1123 nm, anti-reflection at 808 nm, and high-transmission ($T > 80\%$) at the wavelengths of 1064 and 1318 nm. The second surface is anti-reflection (AR) coated for 1123 nm. High enough transmission for the high gain transitions at 1064 and 1318 nm is critical for the laser operation in order to choose the wanted laser transition at 1123 nm. The laser crystal is cooled by a thermoelectric cooler with the laser mount temperature being approximately 20 °C. The Q-switch is an AR coated Cr^{4+}:YAG crystal with an unsaturated transmission of 96% at 1123 nm. The radius of curvature of the output coupling mirror is 15 cm. The curved surface is coated for a reflectivity of 90% at 1123 nm and for high-transmission ($T > 90\%$) at 1064 and 1318 nm. The planar surface is AR coated for 1123 nm. Polarized output of the laser is achieved with a Brewster plate inside the laser cavity.

The IR light is focused with an AR coated lens with the focal length of 40 mm into a 5 mm long KTA crystal where SHG takes place. The lens is placed at a distance of 16.5 cm from the laser output coupling mirror. The resulting focus size is 26 μm × 27 μm (FWHM) which is close to the optimum of 28 μm [10]. The phasematching parameters for the SHG and SFG processes are presented in Table 1. The polarization direction for SFG is not perfect since the angle between the directions of the polarizations corresponding to the fundamental and second harmonics due to the type II SHG process is 45° with the optimum for SFG being 90°. However, KTA crystal is chosen for SHG because the performance of SHG for 1123 nm is very good due to high nonlinearity (3.25 pm/V) and small walk-off (3 mrad). The BIBO crystal orientation is chosen so that the polarization of the yellow light is optimal for the conversion since the power at that wavelength is lower than the IR power. For SHG the small walk-off is essential since it should be possible to focus the beams with different wavelengths to the same spot. A type I SHG would be perfect in terms of polarization for the following SFG process. A prominent of such crystals would be BIBO which however has both lower nonlinearity of 2.73 pm/V and significantly higher walk-off of 17 mrad when compared to KTA. A lens with an AR coating for the visible wavelengths and with a focal length of 40 mm focuses the light into the BBO and BIBO crystals for 280 and 374 nm lasers, respectively. The resulting focus size for the 561 nm beam is 25 μm (FWHM). This is also the optimum focus for the 280 and the 374 nm, conversions [10]. The UV light is filtered for power measurements using a Schott glass filter UG11 whose transmission is verified at the wavelengths of interest with a PerkinElmer LAMBDA 950 spectrophotometer.

The light beam at 374 nm is coupled into a pure silica core single mode fiber. Due to the high walk-off in the UV conversion, the elliptical beam is focused into the fiber with two cylinder lenses. The lens is uncoated and made out of fused silica. A lens with a focal length of 12.7 mm is used to focus into the direction of no walk-off where the beam quality is also better, whereas in the direction of the walk-off, the focusing is done by a lens with the focal length of 8 mm.

Table 1
Phasematching parameters for the second, third and fourth harmonic processes [10].

Process Crystal	λ_1 (nm) + Walk-off (mrad)	λ_2 (nm) =	λ_3 (nm)	Length (mm) d_{eff} (pm/V)
SHG	1123(e)	1123(o)	561(e)	5
KTA	2.35	0	3.0	3.25
SFG	1123(e)	561(e)	374.1(o)	6
BIBO	59.6	62.3	0	3.83
SHG	561(o)	561(o)	280.5(e)	10
BBO	0	0	84.5	1.82

3. Results

Typical pulse parameters are presented in Table 2 and the pulse energy conversion efficiencies in Table 3. The parameters are measured with the absorbed pump power of 2.16 W which was 75% of the incoming power. Average power as a function of the absorbed pump power is presented in Fig. 2. When the UV laser power measurements are performed, the background power leaking through the UV filter is subtracted from the measurement results by turning the nonlinear crystal so that it there is no phasematch. The losses due to the unoptimal polarization and those caused by the focusing lens are taken into account in calculating the conversion for 374 nm in order to make a comparison to the theoretical simulation. A practical challenge of the SFG process is the focusing of the beams with different wavelengths to the same position both in the transverse and longitudinal directions. The experimental conversion of 7.6% is relatively close to the theoretical value of 11% [10]. The simulation was done by using the measured pulse parameters and with the measured losses. An oscilloscope trace of the laser pulses at 1123 nm, 561 nm, 374 nm and 280 nm is presented in Fig. 3.

The beam quality parameter M^2 measurement results at 561 nm, that are performed by calculating the second moment of the beam intensity, show nearly diffraction limited beam quality with M^2 values of 1.1 and 1.2 to the nonwalk-off and walk-off directions. The measurements are made with a beam camera (Beamstar Fx-50) using a 4× beam expander. For the 374 nm laser, the similar measurements give the results of 1.3 and 1.7 for the nonwalk-off and walk-off directions, respectively. The cylindrical lenses are used to focus the beam. For the 280 nm beam, the M^2 parameter values are 2.4 and 2.8 for the nonwalk-off and walk-off directions, respectively. The beam intensity to the camera at

Table 2
Pulse parameters for pulses at wavelengths λ: average power P_{ave}, time between the pulses T_{per}, pulse energy E, pulse width FWHM T_p and peak power P_p.

λ (nm)	P_{ave} (mW)	T_{per} (μs)	E (μJ)	T_p (ns)	P_p (kW)
1123	282	142	40	12	3.2
561	55	156	8.6	8	1.0
374	16	155	2.5	8	0.31
280	3.8	161	0.61	6	0.10

Table 3
Pulse energy conversion efficiencies.

Conversion	1123 to 561	1123 to 280	561 to 280	1123 + 561 to 374
Efficiency (%)	21	1.5	7.1	7.6

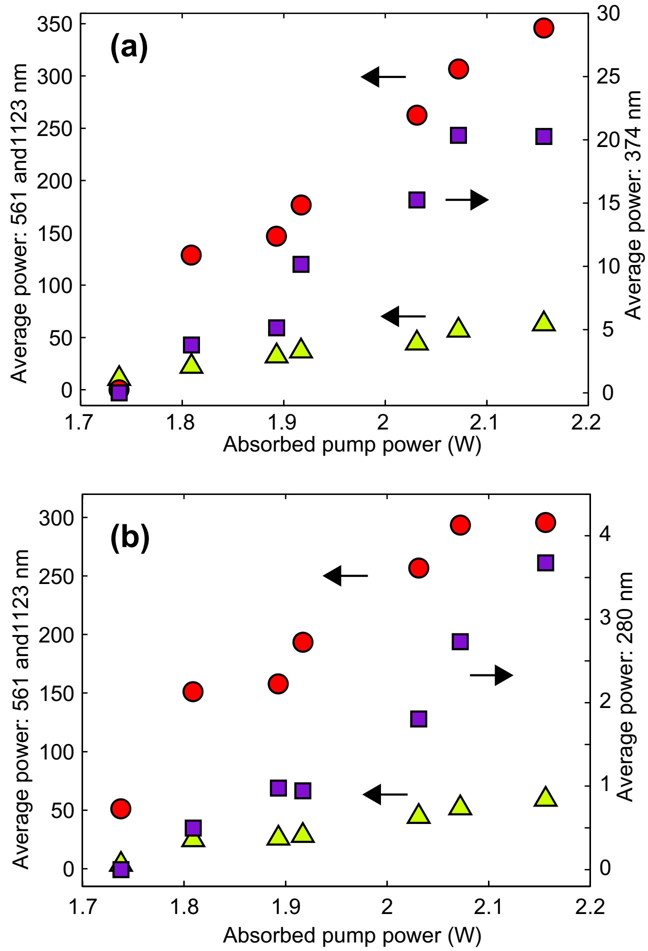

Fig. 2. Average laser powers of the a) 374 nm laser and b) 280 nm lasers are presented as a function of the absorbed pump power. In figure a) average power is shown at 1123 nm (circles), 561 nm (triangles) and 374 nm (squares). In figure b) average power is shown at 1123 nm (circles), 561 nm (triangles) and 280 nm (squares).

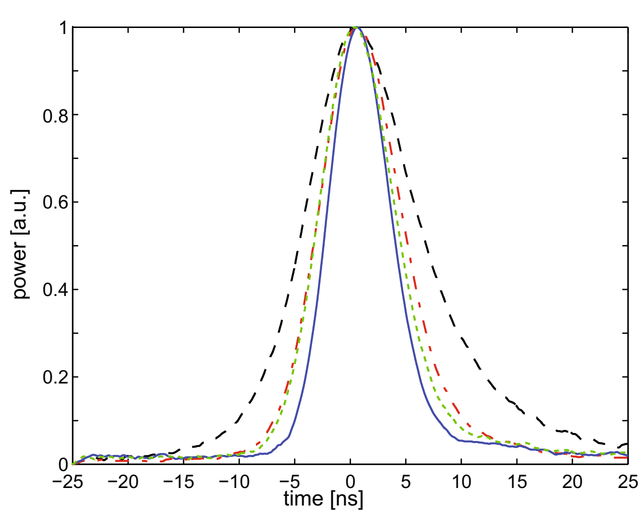

Fig. 3. Normalized time traces of the laser pulses at 1123, 561, 374 and 280 nm (dashed, dash dotted, dotted and solid, respectively).

280 nm was attenuated by controlling the intensity of the yellow beam. This should however not affect the results noticeably since the conversion is in any case low. The beam is focused with a lens with a focal length of 10 cm.

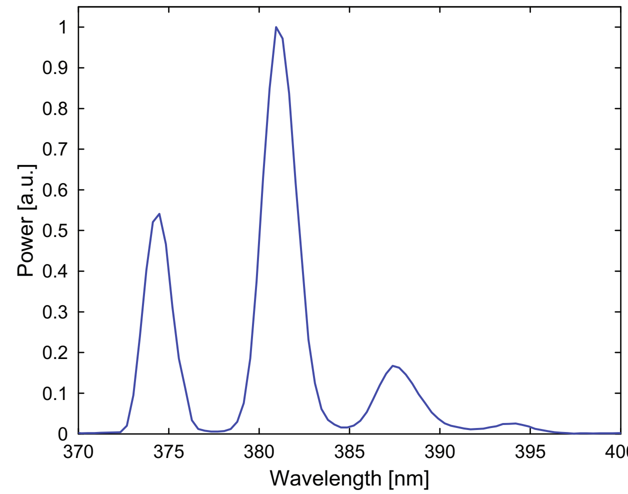

Fig. 4. A spectrum of the 374 nm laser after the 30 m of pure silica single mode fiber.

We experimented UV light spectral broadening by simulated Raman scattering at 374 nm wavelength in a silica core fiber (StockerYale NUV-320-K1) with the length of 30 m. Raman peaks with the frequency separation of 14 THz are observed. The generated spectrum is presented in Fig. 4. The power coupled into the fiber is approximately 15% of the incoming power. The losses in the fiber with the length of 30 m are in the order of 2 dB according to the manufacturer data. A decent coupling efficiency to a fiber with the 2 μm core confirms the relatively good beam quality observed in determining the M^2 value. A comparison to the spectra reported by Bartula et al. [9] reveals that we obtained a lower number of Raman peaks despite higher pulse energy (around 300 nJ) and peak power (around 40 W) coupled into the fiber. The use of a longer fiber would result into a wider spectrum but also to a lower transmission. The longer pump wavelength strongly affects the spectral broadening as the Raman gain scales roughly with the inverse third power of the wavelength [11]. The losses at the wavelength of 280 nm are far too high for spectral broadening with the used fiber.

4. Conclusions

A method to realize UV lasers at 374 nm and 280 nm was demonstrated. A pump laser for the SHG and SFG processes is a Nd:YAG laser at 1123 nm. A Cr:YAG crystal is used as a passive Q-switch and the SHG is performed in KTA crystal. Nonlinear conversions to 374 and 280 nm light were performed using BIBO and BBO crystals, respectively. The peak powers at 280 and 374 nm are 100 and 310 W, and pulse lengths 6 and 8 ns, respectively. The spectral broadening in a pure silica core fiber using the 374 nm laser as a pump is demonstrated.

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