Watts-level frequency doubling of a narrow line linearly polarized Raman fiber laser to 589 nm

D. Georgiev, V. P. Gapontsev

IPG Laser GmbH, Burbach, Germany

A. G. Dronov, M. Y. Vyatkin

NTO IRE-Polus, Vvedenskogo sq.1, Fryazino, Russia

A. B. Rulkov, S. V. Popov, J. R. Taylor

Femtosecond Optics Group, Imperial College, London SW7 2BW, England
s.popov@ic.ac.uk

Abstract: A single-mode, linearly polarized, 1118 nm ytterbium fiber laser was applied to pumping of a short fiber length, polarization-maintaining Raman cavity, resulting in a 0.4 nm linewidth, 23 W CW source at 1179 nm. Efficient, single-pass frequency doubling of the Raman source in MgO doped PPLN to 589 nm was demonstrated with CW power levels in excess of 3 W. No beam quality degradation was observed due to photorefraction at pump power densities up to 2 MW/cm^2. The proposed approach can be readily extended to Watt-level generation of any desired wavelength in the 560 to 770 nm range.

OCIS codes: (190.2620) Frequency conversion; (140.3550) Lasers, Raman; (190.4370) Nonlinear optics, fibers.

References and links

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Wavelength diversity and Watt-level average power, single spatial mode visible laser sources are becoming an indispensable requirement for numerous advanced medical, spectroscopic and material processing applications where resonant absorption and excitation properties of laser-matter interaction are exploited. Until now a restricted choice of CW operational wavelengths has been available in the visible range from fundamental or doubled frequency solid state, diode, gas or fiber lasers, with a particularly limited choice of high, Watts level, power CW sources in the range from 560 to 770 nm.

Versatile generation in the range of fundamental wavelengths from 1120 to 1550 nm can be achieved with all-fiber format pump sources exploiting Raman gain of predominantly Ge doped silica fibers pumped by CW Yb fiber lasers around 1μm wavelength. To date CW Raman generation and amplification in isotropic fibers with levels in excess of 30W have been demonstrated and high power commercial Raman lasers are readily available [1]. A number of attempts [2, 3] to construct and apply Raman lasers to second harmonic generation were undertaken where control of the inherently broad linewidth and polarization of isotropic fiber Raman lasers resulted in the second harmonic output power to 10mW level. Because Raman gain is polarization-sensitive [4], linearly-polarized Raman generation can be realized in birefringent fibers with polarization discrimination of Raman gain; the highest power, linearly polarized Raman source reported to date [5] had an output power level of 4.7 W at 1120 nm with extinction ration of 24 dB and linewidth of 0.9 nm.

In this Letter we report on an all-fiber configuration employing a single-Raman shift of an 1118 nm linearly polarized ytterbium pump to 1178 nm, which allowed dramatic enhancement of the generated power level while maintaining a narrow, sub-nanometer Raman generation linewidth in a polarization preserving format. Output powers at 1178 nm as high as 23 W with 0.4 nm linewidth have been obtained. We also applied this CW fiber source to the generation of 3W of visible radiation around 589 nm by employing highly nonlinear, periodically poled, MgO-doped $LiNbO_3$. 12% efficiency was achieved in this robust single-pass SHG configuration.

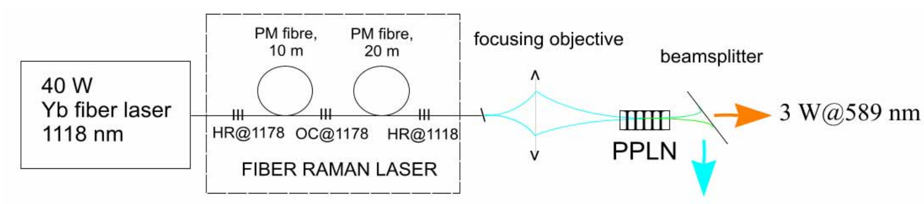

Fig. 1. 3 W 589 nm generation with frequency doubled, linearly polarized Raman laser.

The experimental configuration is shown in Fig. 1. To realize a single Raman shift generation at 1178 nm, we designed and built a 40 W single transverse mode linearly-polarized CW Ytterbium laser, with the operation wavelength extended to 1118 nm. The cladding-pumped laser cavity was formed by fiber Bragg gratings and a 26 m long Yb doped fiber stage with Yb concentration of 7000ppm. At 40 W average power the linewidth of the pump was 2.5 nm and a polarization extinction ratio of better than 15 dB was achieved. The output of the pump laser was spliced in polarization maintaining format to a seed Raman fiber laser. The 10 m long cavity of the seed laser was formed by two narrowband fiber Bragg grating directly written in the polarization-maintaining Ge-doped 7 μm core diameter, single mode nonlinear fiber. The additional 20 m length of this fiber was used as an amplifier of the seeded signal. A double-pass pump configuration was arranged by employing the highly-reflective broadband 1118 nm Bragg grating facilitating efficient Raman amplification in the short length fiber Raman amplifier. Due to the short length of the Raman gain fiber, Self Phase Modulation (SPM)-induced frequency broadening of the signal was reduced in comparison with the conventional cavity fiber Raman lasers. With the linearly polarized pump, similar to [5], discrimination of the polarization dependent Raman gain was sufficient to produce 23 W linearly polarized output at 1178 nm with the polarization extinction ratio in excess of 15 dB.

Figure 2(a) illustrates the dependence of the 1178 nm signal linewidth (FWHM) on the output power. Due to SPM induced broadening at higher powers, the Stokes line has nearly 50% of the spectral power located outside the -3 dB bandwidth at 23 W of output power. The short time stability of the high power Raman was analyzed with a fast photodetector and RF spectrum analyzer showing less than 2% fluctuations.

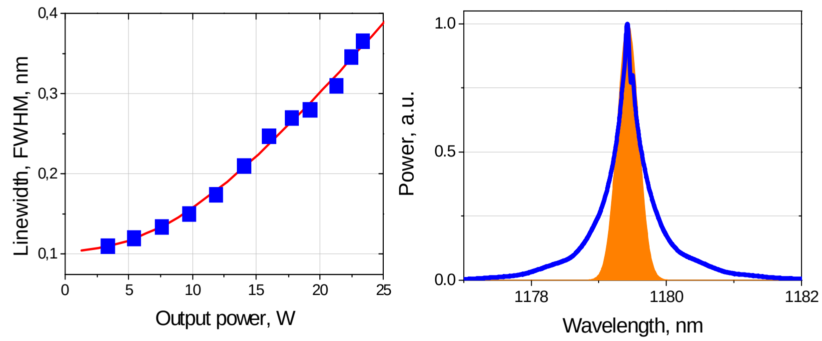

Fig. 2. (a) Evolution of the linewidth (FWHM) of the high power, linearly polarized 1178 nm output; (b) The output spectrum (blue) at 23W output power and Gaussian profile (orange) line of identical width added for comparison.

The 23 W CW output with 0.37 nm linewidth was frequency doubled in a periodically poled, MgO-doped, lithium niobate crystal in a single-pass configuration. The choice of the material was dictated by the high effective nonlinearity and low susceptibility of MgO doped PPLN to optical damage due to photorefraction and visible induced infrared absorption at our operational CW power levels. The PPLN crystal acquired from HC Photonics had a 50/50 poling ratio with a 9.23 µm period for first order quasi-phase-matched SHG at 1178 nm. The phase matching temperature of the crystal was about 130ºC, and the measured temperature quasi-phasematching (QPM) curve width was 3.4ºC. The input facet of the crystal was antireflection-coated for the fundamental wavelength. Confocal fundamental beam focusing was optimized to obtain a maximum of the frequency doubled power. With an 8 mm long PPLN crystal a single-pass SHG efficiency of 12.3% was reached and 3.03 W at 589 nm was generated. The effect of the fundamental line broadening on the second harmonic generation efficiency can be seen in Fig. 3, where the theoretically expected parabolic dependence of the SH emission on the pump, in conditions of low pump depletion, tended to linear after the pump power reaches 3 W.

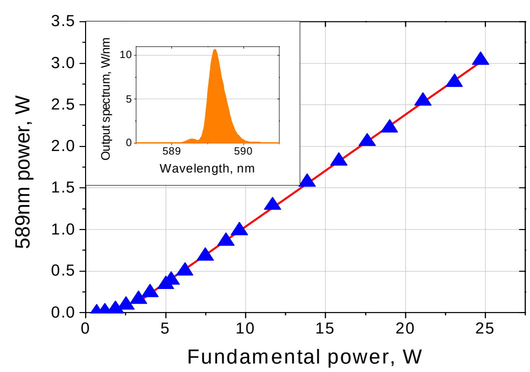

Fig. 3. Power dependence of 589 nm CW second harmonic generation in 8mm long MgO PPLN. Inset shows a typical SH spectrum with 0.25 nm bandwidth at 2.3W 589 nm power level.

At the optimal focusing conditions in the 8 mm crystal, the pump beam waist diameter was measured as 40 µm which corresponded to a 4.5 mm confocal length in the crystal and to 0.6 nm QPM bandwidth. This bandwidth value is larger than the pump Raman laser linewidths measured at -3 dB level, Fig. 1(a), and relates to the fact that significant power of the pump is located outside the 3 dB level band, Fig. 2(b). Taking this into account, to estimate the second harmonic generation efficiency, we calculated the amount of fundamental power within the 0.6 nm band. Figure 4 shows the power of the second harmonic generated versus this fundamental power.

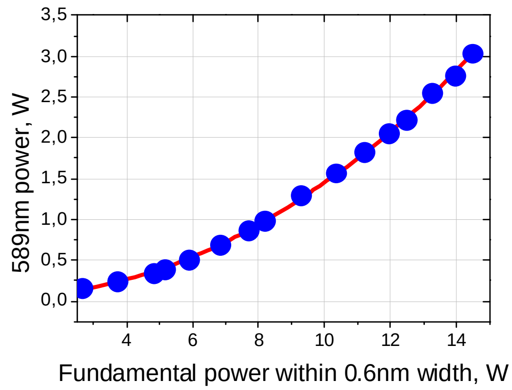

Fig. 4. Second harmonic power versus the fundamental power within 0.6 nm QPM bandwidth.

A fit to the data in Fig. 4 was used for estimating the normalized conversion efficiency η [6]:

$$\eta = \frac{P_2}{P_1^2 L} = \frac{8\omega^3 d_{33}^2 h_{mm}(0, L/b)}{\pi^3 n_\omega n_{2\omega} \varepsilon_0 c^4} \tag{1}$$

where P_1, P_2 are the fundamental and second harmonic powers respectively, L - the crystal length, ω - fundamental frequency, d_{33} - diagonal tensor component of the PPLN second order nonlinearity, b - the confocal focusing length in the crystal and $h_{mm}(0,L/b)$ – Boyd-Kleinman focusing factor [6] whose value is close to unity for the given focusing conditions. The experimentally obtained η value of 1.62 %/(W·cm) corresponds to d_{33} of 24 pm/V, which is in a good agreement with the value of 27±20% pm/V for congruent MgO doped $LiNbO_3$ reported elsewhere [7,8]. This confirms validity of the above assumptions and the approach which can be used to assess second harmonic efficiency in similar configurations.

The beam quality of the second harmonic radiation was monitored with a BeamMap beam profile monitor. No degradation of the measured value M^2 <1.1 throughout the whole range of output powers was observed, up to 1.9 MW/cm^2 and 120 KW/cm^2 power densities for fundamental and second harmonic respectively. Notwithstanding, a measurable thermal load was recorded at 3 W 589 nm output from MgO: PPLN which led to 1.3°C shift of the QPM temperature to 128.5°C. Several days long endurance tests (over 100 hrs) showed no variation of the conversion efficiency or spatial beam quality of the second harmonic beam.

Further power scalability of the proposed configuration can go through the routes of using polarization combining of the fiber based visible sources, employing single-frequency seeding with Brillouin scattering suppression of a short length Raman amplifier, or by using sum frequency generation of linearly polarized, narrow line Raman fiber source at 1.3 µm and ytterbium fiber laser at 1μm taking into account the quantum defect and required ratio of fundamental powers for SFG process.

In conclusion, we demonstrated a novel narrow-bandwidth high-power linearly polarized all-fiber Raman source capable of generating up to 23 W CW power with narrow, down to 0.37 nm, emission linewidth. The source was applied to generation of 3.03 W single transverse mode 589 nm visible radiation in a short-length, periodically-poled, magnesium-doped lithium niobate crystal. The demonstrated simple and robust configuration has 2.5% electrical to optical efficiency, and the approach can be readily extended to CW generation of any desired wavelength in the 560 to 770 nm range.

Acknowledgments

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