Watt-level Nanosecond 589 nm Source by SHG of a Cascaded Raman Amplifier

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Abstract: We present a power-scalable nanosecond source operating at 589 nm by frequency-doubling a cascaded Raman amplifier that is pulse-pumped by an ytterbium-fiber master oscillator power amplifier system and seeded with a narrow linewidth CW signal.

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1. Introduction

Laser sources operating in the yellow-green spectral region (550–600 nm) are of vital importance for fluorescence-based imaging techniques in the life sciences as the absorption and emission features of many key fluorophores lie in this region. Additionally, absorption resonances of molecules such as oxyhaemoglobin and atoms such as barium, ytterbium and sodium give rise to applications in ophthalmology, dermatology and scientific research (e.g. spectroscopy and laser guide star). Unfortunately, the main sources of direct laser emission in this region are too impractical for use in non-specialist laboratories, therefore, nonlinear frequency conversion of near-infrared (NIR) laser sources is the most common route to obtaining yellow-green radiation. Of the many possible NIR laser sources, those based on Yb:fiber are ideally suited to nonlinear frequency conversion since they are power scalable whilst maintaining excellent beam quality, spectrally and temporally versatile, highly efficient, compact and have low maintenance requirements.

The frequency-doubling of Yb:fiber master oscillator power amplifier (MOPA) schemes into the green is a well established technique that has been scaled to average powers up to 700 W [3]. It is difficult to operate high-gain Yb:fiber MOPA systems beyond 1100 nm, however, due to the larger emission cross-section at shorter wavelengths that results in issues with amplified spontaneous emission (ASE). Stimulated Raman scattering in optical fibers can be used to efficiently frequency-downshift the output of Yb:fiber systems but the broadband nature of the Raman gain spectrum results in the formation of Raman ASE with a bandwidth of several nanometres. This bandwidth can severely limit the second-harmonic generation (SHG) conversion efficiency if it exceeds the spectral acceptance bandwidth of the SHG crystal [3]. This is a particular issue if the fundamental has modest peak-power, since the high nonlinear coefficients of periodically poled (PP) crystals are required for efficient SHG. The quasi phase-matching utilized with PP crystals results in a far narrower spectral acceptance bandwidth in comparison to birefringent phase matching.

In recent work, we have shown that Raman amplifiers can be used to efficiently frequency-downshift the output of Yb:fiber MOPA systems with spectral bandwidths that are suitable for efficient SHG using PP crystals [1, 2]. The Raman amplifiers were seeded with a narrow linewidth CW signal and pulse-pumped with a Yb:fiber MOPA system. Since Raman gain is only available within the window of the pump pulses, the temporal properties of the Raman amplifier output are determined by the pump pulses; whereas, the spectral properties are predominantly determined by the seed signal. In this contribution, we use the output of a Yb:fiber MOPA pumped Raman amplifier to pulse-pump a second CW-seeded Raman amplifier, which is frequency-doubled to 589 nm with parameters that are well suited to biophotonic applications such as stimulated emission depletion (STED) microscopy.

2. Experimental Results

2.1. Cascaded Raman Amplifier

The schematic of the cascaded Raman amplifier is shown in Fig. 1. The 1064 nm seed pulses were generated by a picosecond pulse board (PPB), which incorporated a distributed feedback (DFB) laser diode and picosecond pulse generator (PPG) on an integrated circuit board (QD Laser). A Mach-Zehnder amplitude modulator (MZAM) was used to shape the optical pulses, driven by a second PPG that shared a common clock signal. The pulses were pre-amplified in a double-clad polarization-maintaining (PM) ytterbium-doped fiber amplifier (YDFA) before being amplified up to 15 W using a commercial YDFA (IPG Photonics). The output from the YDFA collimator head (CH) was optically isolated (ISO) before being coupled into the Raman amplifier. It is worth noting that the Yb:fiber MOPA is duration-tunable and it can be spliced to the Raman amplifier, as in previous work [1, 2], to obtain a fiber-integrated system.
The cascaded Raman amplifier was comprised of two distinct stages (Fig. 1). In the first stage, the output of the Yb:fiber MOPA was spectrally combined with the output of an 1120 nm CW Raman fiber laser (RFL) in a PM fused-fiber wavelength division multiplexer (WDM) that was spliced to a 1.2 m length of PM Raman fiber (OFS Fitel). Since the output of the RFL was randomly polarized, a three-paddle polarization controller (PC) was used to optimize the polarization for most efficient Raman amplification. In the second stage, the 1120 nm output of the first stage was spectrally combined with an 1179 nm DFB laser diode in a second PM WDM, which also served to remove any residual 1064 nm pump light. The output of the second WDM was spliced to a 1.9 m length of PM Raman fiber, the output of which was angle-cleaved to eliminate feedback and collimated using an AR-coated aspheric lens.

Figure 2(a) shows the optical spectrum of the first Raman amplification stage, before the second WDM, for a Yb:fiber MOPA pump peak-power of 1 kW with 300 mW of RFL signal power. The integrated spectrum revealed that the 1120 nm amplified signal accounted for 85% of the total power, corresponding to an average power of 1.6 W at a repetition rate of 1 MHz, resulting in an amplifier efficiency of 57%. When the second Raman amplifier stage was pumped with this output and seeded with 40 mW of CW 1179 nm signal, the amplified 1179 nm signal accounted for 75% of the spectral output [Fig. 2(b)], corresponding to an average power of 1.0 W and an amplifier efficiency of 60%. The amplified 1179 nm signal had a 3 dB spectral bandwidth of 0.01 nm, limited by the resolution of the optical spectrum analyzer, and a pulse duration of 1.9 ns [Inset Fig. 2(b)].

2.2. Frequency-doubling

The output of the 1179 nm cascaded Raman amplifier was frequency-doubled using a 20 mm long, 5 mol.% MgO-doped periodically poled congruent lithium niobate (PPLN) crystal. The crystal was poled with a single 9.27 µm pitch grating, corresponding to a 3 dB spectral acceptance bandwidth of 0.16 nm for an 1179 nm signal at the quasi phase-
matching temperature of \(\sim 130^\circ\text{C}\). The crystal was AR-coated for the fundamental and second-harmonic on the input side but the output side was uncoated. A half waveplate (HWP) was used to align the polarized output of the cascaded Raman amplifier to the extraordinary axis of the PPLN crystal for type-0 phase-matching. The collimated output of the cascaded Raman amplifier was focused into the center of the PPLN with an optimized \(1/e^2\) diameter of 61 \(\mu\text{m}\), corresponding to a Rayleigh range of 5.4 mm in the crystal.

Figure 3(a) shows the generated 589 nm second-harmonic (SH) power and conversion efficiency as a function of the fundamental power from the output of the cascaded Raman amplifier at a pump repetition rate of 6 MHz. The SH power is corrected for the 14.6\% Fresnel reflection of the SH on the output facet of the crystal, which can be eliminated with an appropriate AR-coating. A maximum 589 nm power of 1.13 W was generated for a cascaded Raman amplifier output of 6.52 W, corresponding to a conversion efficiency of 17\%. It is worth noting that the power of the cascaded Raman amplifier output that was within the spectral acceptance bandwidth of the PPLN crystal was only \(\sim 20\%\) for an output power of 6.52 W, so the effective conversion efficiency was \(\sim 85\%\). The SHG conversion efficiency increase with fundamental power is close to exponential, rather than the expected \(\tanh^2(\sqrt{P_0})\) relationship, since the proportion of the cascaded Raman amplifier output at 1179 nm increased as the Yb:fiber MOPA pump power increased.

![Fig. 3](image)

Fig. 3. (a) SH power and conversion efficiency as a function of fundamental average power at 6 MHz repetition rate. Inset: optical spectrum of the SH. (b) Sampling optical oscilloscope traces of the 589 nm pulses with increasing fundamental power at 1 MHz repetition rate.

The 589 nm output pulses for several cascaded Raman amplifier output powers at a pulse repetition rate of 1 MHz are shown in Fig. 3 (b). It was observed that at the lowest fundamental power shown, the 589 nm pulse had the same features of the 1179 nm pulse (Inset Fig. 2). As the fundamental power was increased, the 589 nm peak-power saturated at \(\sim 86\) W and as a result the top of the pulse broadened at the fundamental power of 1.32 W, which gave the highest SHG efficiency. Further increases in the fundamental power resulted in the 589 nm peak-power at the centre of the pulse, corresponding to the position of the highest instantaneous power of the fundamental, decreasing monotonically. This was evidence that back-conversion of the SH was occurring, confirming that the SHG conversion efficiency was primarily limited by the spectral acceptance bandwidth of the PPLN crystal.

3. Conclusion

In conclusion, a maximum average power of 1.13 W of 589 nm was generated by frequency-doubling the output of a pulse-pumped cascaded Raman amplifier in a PPLN crystal. The 589 nm pulse duration was 1.9 ns with a pulse energy of 188 nJ, which was limited by the low proportion of the cascaded Raman amplifier output within the spectral acceptance bandwidth of the PPLN crystal. Future work will seek to improve the power spectral density of the cascaded Raman amplifier output and a PP lithium tantalate crystal will be used to scale the average power of the 589 nm source.

References