620 nm Source by Second Harmonic Generation of a Phosphosilicate Raman Fiber Amplifier

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Abstract: We demonstrate a nanosecond-pulsed 620 nm source through frequency doubling a 1240 nm phosphosilicate Raman fiber amplifier. The source emits up to 213 mW of average power, and is repetition rate and pulse duration tunable.

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1. Introduction

Fiber-based, nanosecond-pulsed sources in the red spectral region are useful for a number of biophotonics imaging applications, including stimulated emission-depletion microscopy (STED) [1]. Typical Raman fiber-based sources operating in this region utilise multiple Raman shifts in silica fiber pumped by ytterbium-doped fiber (Yb:fiber) systems operating around 1 μm, followed by second harmonic generation (SHG) in a bulk crystal such as lithium triborate or lithium niobate [2, 3]. An alternate method is to first frequency double Yb:fiber systems to the green, before repeatedly Raman shifting in silica fiber [1]. In both methods, multiple Raman shifts are required to generate red light. Each Raman shift decreases the overall system efficiency due to the inelastic nature of the Raman scattering process.

A single shift architecture provides a simple route to increasing overall system efficiency compared with techniques involving multiple Raman shifts. Here, we report a Yb:fiber laser pumped fiber-based Raman amplifier for generating repetition-rate tunable, nanosecond light at 620 nm. Specifically, we employed a phosphosilicate fiber as the Raman gain medium. Phosphosilicate fiber exhibits Raman gain at shifts of both 13.2 THz and 39 THz from the pump [4]. By exploiting the latter shift, we converted directly to 1240 nm from a 1064 nm pump, rather than employing the multiple shifts required in standard silica fiber. This light can be frequency doubled using poled nonlinear crystals, generating a source with ideal characteristics for biophotonics imaging applications.

2. Results

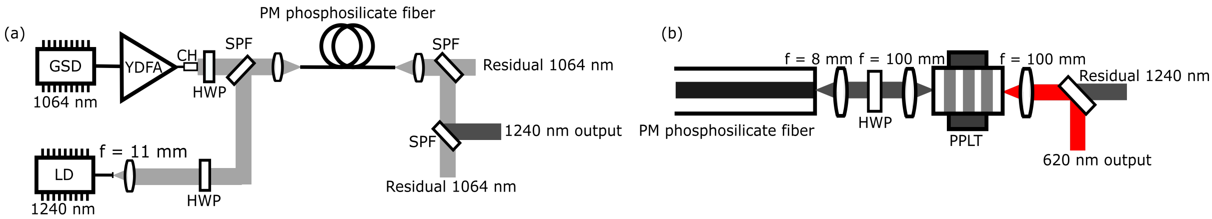

Fig. 1. (a) Schematic of the 1240 nm phosphosilicate Raman fiber amplifier. GSD, gain switched diode; YDFA, Yb-doped fiber amplifier; CH, collimator head; LD, laser diode; HWP, half-wave plate; SPF, short pass filter. (b) Set-up for SHG in periodically-poled lithium tantalate (PPLT).

A 1064 nm gain-switched laser diode providing pulses of 1.5 ns at 20.6 MHz was amplified in a polarisation-maintaining (PM) Yb:fiber amplifier (IPG Photonics) to an average power of 19.7 W (Fig. 1 (a)). A maximum of 14.7 W was coupled into 21.5 m of PM phosphosilicate fiber (FORC P-SM-5-PM), along with 120 mW of continuous-wave (CW) light at 1240 nm from a fiber Bragg grating stabilized laser diode (FBG-LD). A maximum of 95% of the total spectral power was at 1240 nm when 10 W of power was measured at the phosphosilicate fiber output, as shown in Fig. 2 (a), which also shows the 1240 nm power as a function of phosphosilicate fiber output power. However, at a maximum 1064 nm input power of 14.7 W, ≈85% of the total Raman-shifted spectral content was at 1240 nm, resulting in a maximum of 11.7 W of 1240 nm power. The drop in the spectral content at 1240 nm at higher 1064 nm powers was due to the onset of cascaded Raman shifts: from 1240 nm to 1310 nm due to the 13.2 THz shift, and from 1240 nm to 1480 nm due to the 39 THz shift. The length of phosphosilicate fiber used, as well as the peak power of the 1064 nm source, was crucial to efficiently converting to 1240 nm without

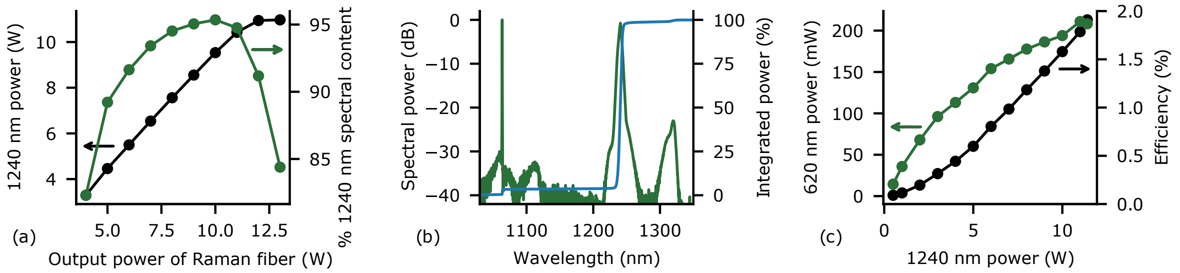

Fig. 2. (a) Generated 1240 nm power and % spectral content at 1240 nm against output power of the phosphosilicate fiber where (b) is the spectrum and integrated power at the highest % 1240 nm spectral content. (c) Generated 620 nm power and conversion efficiency against 1240 nm power.

further cascading. Ongoing work aims to optimize the length of phosphosilicate fiber to maximise the generated spectral power at 1240 nm as a function of input 1064 nm power. The output spectrum and integrated power of the phosphosilicate fiber at the highest spectral proportion of 1240 nm can be seen in Fig. 2 (b).

The generated 1240 nm pump was used for single pass SHG in a 20 mm long anti-reflection coated, periodically-poled, stochiometric lithium tantalate (PPLT) crystal with a poling period of 12.1 µm (Fig. 1 (b)). The crystal was held at a constant temperature of 149.7 °C in a brass oven and had a spectral acceptance bandwidth (SAB) for SHG at 1240 nm of 0.224 nm. The highest recorded conversion efficiency was achieved with a beam waist of 63 µm. Initially, 1.5 ns pulses at a repetition rate of 5 MHz produced a maximum output power of 50 mW with a 1240 nm power of 2.3 W at the crystal face. Increasing the repetition rate to 20.6 MHz produced a maximum output power of 213 mW with a 1240 nm power of 11.7 W, corresponding to a conversion efficiency of ∼1.8%. The generated 620 nm power and efficiency can be seen in Fig. 2 (c). The low conversion efficiency was due to the broad spectral linewidth of the generated 1240 nm light, which had a full width at half maximum (FWHM) of 4.8 nm at maximum power. The large linewidth arose because of undesirable nonlinear effects such as self-phase modulation in the long length of phosphosilicate fiber, and because of the large seeding linewidth of the FBG-LD, which had a FWHM of 0.86 nm. The spectral power at 1240 nm which was contained within the SAB for SHG in PPLT was found by integrating the spectrum across the SAB. The power contained within this bandwidth implied a conversion efficiency within the SAB of up to 50%, in line with our expectations for SHG in PPLT based on previous results [5]. Ongoing work will optimize the SHG conversion efficiency by using a 1240 nm FBG-LD with a narrow spectral FWHM of 0.08 nm, and an optimized length of phosphosilicate fiber, which will be reported.

3. Conclusions and Outlook

We have demonstrated a fiber-based architecture for generating repetition-rate tunable, nanosecond-pulsed red light. Our scheme was based on frequency shifting a Yb:fiber based system in a phosphosilicate Raman fiber amplifier, followed by SHG in a PPLT crystal. With 1.5 ns pulses at a repetition rate of 20.6 MHz, and using a CW signal provided by a 1240 nm FBG-LD, as high as 95% of the total spectral power was contained in the first Raman shift at 1240 nm. Subsequent frequency doubling in PPLT generated 213 mW average power at 620 nm, limited by the spectral linewidth of the generated 1240 nm. Ongoing work will employ a narrow linewidth seed and optimize the Raman fiber length to improve conversion efficiency to 620 nm, before deploying the source for applications in STED microscopy. Once optimized, we expect to generate multi-Watt-level power in the red with a tunable pulse duration. The increased efficiency due to using only one shift in phosphosilicate Raman fiber provides an attractive, simple way of improving the efficiency of current nanosecond-pulsed, fiber-based red sources.

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