Watt-level 743 nm source by second-harmonic generation of a cascaded phosphosilicate Raman fiber amplifier

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Abstract: We demonstrate a nanosecond pulsed 743 nm source through second-harmonic generation of a cascaded phosphosilicate Raman fiber amplifier system operating at 1485 nm. The amplifier is pumped by a 1240 nm phosphosilicate Raman fiber amplifier and seeded with a continuous-wave 1485 nm diode. This 1485 nm light is used for second-harmonic generation in periodically poled lithium niobate. Greater than 1 W of average power is generated at 743 nm with a corresponding pulse energy of 220 nJ at a repetition rate of 5 MHz. The source displays excellent beam quality ($M^{2}_{x,y} \leq 1.18$) with ideal parameters for biomedical imaging applications.

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1. Introduction

Pulsed deep-red sources with hundreds of picoseconds to few nanoseconds duration and MHz repetition rates are desirable for biomedical imaging applications such as stimulated emission depletion (STED) microscopy [1], and optical-resolution photoacoustic microscopy (OR-PAM) [2,3]. Such deep-red sources allow for greater penetration depths in tissue due to the weaker absorption of wavelengths $>650$ nm in blood [4]. In particular, for STED microscopy, sources with hundreds of nanojoules of pulse energy are preferable, as the enhancement in imaging resolution scales with the pulse energy of the depletion beam [5]. Depletion is most efficient using sources between 0.1–2 ns in duration [6], and by using repetition rates of several MHz, photobleaching of the fluorophores can be avoided, while maintaining a fast image acquisition time [7].

Currently available sources in the deep-red spectral region have numerous limitations. Super-continuum sources require spectral filtration, reducing optical efficiency and resulting in low pulse energies [7]. While diodes are commercially available in this region and have been used for STED microscopy [8], they suffer from limited pulse energies in single transverse spatial mode configurations. Ultrafast optical parametric oscillators have limited flexibility in their pulse duration, are costly, and have large laboratory footprints. Ultrafast titanium sapphire lasers are also widely-used in the 700–780 nm region, but obtaining the optimal pulse durations for STED microscopy requires pulse-stretching [9]. Frequency-doubled crystalline Raman sources have demonstrated Watt-level, nanosecond pulsed operation in the deep-red [10], but have kHz repetition rates and limited repetition rate tunability due to their Q-switched, solid-state pump lasers. Sources in this spectral region based on four-wave mixing in photonic crystal fiber (PCF) are also efficient [11], but require custom-manufactured PCFs.

Systems based on the second-harmonic generation (SHG) of pulsed fiber master oscillator power amplifiers (MOPAs) can provide an efficient method for reaching the visible and near-infrared spectral regions, but their coverage in the deep-red remains limited. Ytterbium-doped fiber (Yb:fiber) based sources at around 1030–1100 nm can be frequency-doubled to efficiently
generate light in the 515–550 nm spectral region with near diffraction limited beam quality [12], but these systems become difficult to implement at wavelengths ≥ 1100 nm due to excessive amplified spontaneous emission at shorter wavelengths. Erbium-doped fiber based sources can also be frequency-doubled to reach ~780 nm [13], but erbium-doped fibers have low emission cross sections below 1530 nm. Directly emitting, rare-earth-doped, fiber based sources in the 1100–1530 nm region are also lacking. Bismuth-doped aluminosilicate fibers do exhibit luminescence across the 1100–1300 nm region, but are not yet commercially available, and have insufficient gain ≥ 1200 nm to implement pulsed MOPA systems [14]. This leaves a spectral gap, between 550–765 nm, which is poorly served by SHG of directly emitting fiber MOPAs.

A combination of stimulated Raman scattering (SRS) in optical fibers, and SHG in periodically poled nonlinear crystals provides an effective method of extending the coverage of existing rare-earth-doped fiber lasers. With an Yb:fiber pump source, a combination of SRS followed by SHG provides a highly efficient method for accessing yellow-green wavelengths [15]. In silica fibers, the peak Raman gain occurs at a Stokes shift of 13 THz and multiple Stokes shifts (≥ 3 from an Yb:fiber pump system operating between 1030–1060 nm) are required to reach the red and deep-red spectral region (> 600 nm) after SHG. For unseeded SRS, the light generated at the Stokes wavelength has a large spectral bandwidth because of the broadband Raman gain, and this spectral bandwidth increases for multiple shifts due to competing nonlinear processes [16]. The subsequent SHG conversion efficiency is, therefore, reduced due to the finite spectral acceptance bandwidth of the crystals used [12]. The spectral bandwidth of the Stokes light can be reduced by seeding the SRS processes with a narrow bandwidth signal, but this becomes impractical in systems requiring many (> 2) shifts.

In phosphosilicate fiber, the Raman gain has peaks at a frequency downshift of both 13 THz and 40 THz [17]. By using phosphosilicate fiber as the Raman gain medium, wavelengths > 600 nm can be reached after SHG using fewer Raman shifts. Our previous work has shown efficient generation of 620 nm light using an Yb:fiber pump system followed by a single Raman shift in phosphosilicate fiber, and subsequent SHG [18]. In phosphosilicate fiber, when using an Yb:fiber pump system, only two shifts are required to reach the 700–765 nm spectral region after SHG.

Here we report, to the best of our knowledge, the first demonstration of a frequency-doubled, cascaded phosphosilicate Raman fiber amplifier system, expanding on work presented in [19]. A 1240 nm phosphosilicate Raman fiber amplifier system was cascaded to 1485 nm in a second phosphosilicate Raman fiber amplifier, seeded by a tunable, narrow-linewidth continuous-wave (CW) laser diode at ~1485 nm. An average power at 1485 nm of up to 4.2 W was generated with 1.6 ns pulses at 5 MHz repetition rate. This light was used for single-pass SHG in a periodically poled lithium niobate (PPLN) crystal, generating ≥ 1 W of average power at 743 nm. The source had near diffraction limited beam quality (M² ≤ 1.18) and ideal parameters for biomedical imaging applications such as STED microscopy.

2. Experimental setup

The schematic of the 1485 nm phosphosilicate Raman fiber amplifier and subsequent SHG is shown in Fig. 1. An in-house built phosphosilicate Raman fiber amplifier system operating at 1240 nm (described fully in [18]) was used to pump 25 m of polarization maintaining phosphosilicate fiber (FORC P-SM-5-PM). The fiber was seeded with linearly polarized, CW light at 1485 nm from a tunable external cavity diode laser (ECDL, NewFocus Velocity 6300) with a 3 dB spectral bandwidth of ≤ 30 pm (limited by the resolution of the optical spectrum analyzer). A maximum of 500 μW of seed power was coupled into the phosphosilicate fiber. The 1240 nm Raman amplifier had a full width at half maximum (FWHM) pulse duration of 1.6 ns [Fig. 2(a)], and a repetition rate of 5 MHz.

The length of phosphosilicate fiber was chosen to maintain high conversion into the 1485 nm Stokes line while minimizing detrimental nonlinear effects such as higher order Raman cascades.
The 1240 nm pump and 1485 nm signal were combined using a long-pass filter with a cut-on at 1300 nm (LPF, Edmund Optics LP1300, Fig. 1). Both pump and seed beams were linearly polarized, and a half-wave plate was used to align both beams to one of the principal axes of the phosphosilicate fiber to optimize the Raman gain. The generated 1485 nm light was filtered from residual 1240 nm light using an LPF.

The 1485 nm light was frequency-doubled in a periodically poled congruent lithium niobate (PPLN) crystal (HC Photonics SHRED-ME) (Fig. 1). The crystal was 25 mm long with a 1.0 x 7.9 mm$^2$ aperture. Both crystal faces were anti-reflection coated at 1485 nm (R < 0.5%) and 743 nm (R < 0.5%). The crystal had a poling period of 17.2 µm for quasi-phasematching SHG of 1485 nm and was held at a temperature of 141°C in a copper oven, corresponding to a spectral acceptance bandwidth of 0.38 nm using the Sellmeier equations in [20]. A half-wave plate and polarizing beamsplitter cube were used to control the incident 1485 nm power onto the crystal face, and a second half-wave plate was used to utilize type-0 phasematching (with all beams extraordinarily polarized).

The 1485 nm beam was focused into the crystal using a 63 mm focal length plano-convex lens, anti-reflection coated at 1485 nm. The focused 1/e$^2$ beam diameter in air was measured to be 55 µm using a pyroelectric scanning slit beam profiler. This corresponded to a peak 1485 nm intensity of ~40 MW/cm$^2$, and a Boyd-Kleinmann focusing parameter of $\xi = L/b = 3.7$ [21], where $L$ is the crystal length and $b$ is the confocal parameter. The generated 743 nm light was collimated using a 100 mm focal length lens, anti-reflection coated at 743 nm, and separated from the residual 1485 nm using a short pass filter with cut-off wavelength at 1100 nm (Thorlabs DMLP1100).
3. Experimental results and discussion

The phosphosilicate Raman fiber amplifier was pumped with up to 7 W of 1240 nm average power, with 1.6 ns duration pulses at a repetition rate of 5 MHz. The total output power from the phosphosilicate fiber was 4.5 W. Up to 4.2 W of 1485 nm power was measured after an LPF [Fig. 3]. At this power level, the integrated spectral content of the phosphosilicate fiber output in a 70 nm bandwidth centered at 1485 nm was 94% [Fig. 4(b)].

**Fig. 3.** Generated 1485 nm power (blue circles) and integrated spectral content across a 70 nm bandwidth centered at 1485 nm (orange squares, dashed) as function of 1240 nm pump power. Lines are a guide for the eye.

**Fig. 4.** Output optical spectrum of the 1485 nm phosphosilicate Raman fiber amplifier for a 1240 nm pump average power of 7 W where the phosphosilicate fiber was (a) unseeded and (b) seeded with 500 µW of 1485 nm light. The orange lines depict the cumulative, integrated spectral content as a function of wavelength. Inset: optical spectrum of the generated 1485 nm light (blue) with seed diode spectrum (orange). The 3 dB spectral bandwidth is also indicated.
Figure 3 shows that the 1485 nm power increased monotonically as the 1240 nm power increased. The integrated spectral content at 1485 nm, however, began to roll off at 1240 nm powers of ∼4 W. This roll off indicated a saturation in the conversion efficiency to 1485 nm. Beyond the 1240 nm pump powers used, energy transfer to the next Raman shift at 1589 nm would be observed, causing the conversion efficiency to decrease. Other nonlinear processes such as Raman-assisted four-wave mixing also occurred in the phosphosilicate fiber. This produced spectral features at 1180 nm and 1600 nm, which can be seen in the seeded output spectrum of the phosphosilicate fiber [Fig. 4(b)].

The phosphosilicate Raman fiber amplifier was highly efficient. With a 1240 nm pump power of 7 W, and a 1485 nm output average power of 4.2 W, the overall conversion efficiency was 60%. When accounting for a coupling efficiency into the phosphosilicate fiber of ∼75%, this corresponded to an internal conversion efficiency between 1240 nm and 1485 nm of ∼79%, just below the quantum-defect-limited conversion efficiency of 83%.

The 1485 nm pulses had a FWHM duration of 1.6 ns and adopted the temporal properties (and, hence, shape) of the 1240 nm pump system [Fig. 2(b)], as the Raman gain is only available in the window of the 1240 nm pump pulses. The maximum generated 1485 nm average power was 4.2 W, corresponding to a pulse energy of 830 nJ.

Using a 1485 nm seed dramatically improved the conversion efficiency into the Stokes line at 1485 nm. Figure 4(a) shows the unfiltered optical spectrum at the output of the phosphosilicate fiber (sampled with a multimode fiber, Thorlabs FG050LGA, using an optical spectrum analyzer, Ando AQ6317B) for a 1240 nm pump power of 7 W in the unseeded case, as well as the integrated spectral content as a function of wavelength. In this case, the majority of the spectral content was at 1240 nm and 1310 nm (the first 13 THz Raman shift from 1240 nm). Here, less than 1% of the light was found to be in a 70 nm bandwidth centered on 1485 nm. Moreover, the bandwidth of the generated 1485 nm light was broad, with a 3 dB bandwidth of 3 nm. In comparison, Fig. 4(b) shows the spectrum for the seeded output of the phosphosilicate fiber at the same 1240 nm pump power. In this case, 94% of the output spectral content was contained in a 70 nm band at 1485 nm, with a 3 dB bandwidth of 0.11 nm. This bandwidth is narrower than the spectral acceptance bandwidth for SHG of 1485 nm in the PPLN crystal used for this experiment (0.38 nm).

A significant pedestal around the 1485 nm signal was also present in the phosphosilicate fiber output spectrum at maximum power due to other nonlinear effects such as four-wave mixing between the 1485 nm signal and multiple wavelengths around 1310 nm. The broadening of the 1485 nm light was dependent on the length of phosphosilicate fiber used, in conjunction with the 1240 nm peak power. There was a trade-off between minimizing deleterious nonlinear effects, and maintaining high conversion to 1485 nm.

The linearly polarized, high power spectral density output of the cascaded phosphosilicate Raman fiber amplifier system was used for single pass SHG in PPLN. The generated second-harmonic output power and conversion efficiency as a function of 1485 nm power can be seen in Fig. 5, which also shows the spectrum of the generated light at 743 nm. The 743 nm light has a 3 dB spectral bandwidth of 0.2 nm. A maximum average power of 1.08 W was generated at 743 nm for a 1485 nm power of 4.00 W, corresponding to a maximum conversion efficiency of 27%. The maximum pulse energy at 743 nm was 220 nJ.

The SHG conversion efficiency of 27% is lower than conversion efficiencies obtained in previous PPLN-based frequency-doubled fiber amplifiers [22]. This was due to the broad pedestal present in the spectrum of the 1485 nm light and, hence, the large proportion of light at 1485 nm contained outside the spectral acceptance bandwidth for SHG. By reducing the length of fiber used in the phosphosilicate Raman fiber amplifier, it may be possible to reduce the effects of spectral broadening and, therefore, reduce the fraction of light contained within the pedestal at 1485 nm. This could allow for a higher SHG conversion efficiency to be obtained.
nm pulses can be seen in Fig. 2(c), and had a FWHM duration of 1.3 ns, which is well suited to STED microscopy [7]. The beam quality of the generated 743 nm light was measured using a pyroelectric scanning slit beam profiler. The $4\sigma$ beam diameter was measured through the focus of a 100 mm focal length plano-convex lens and can be seen in Fig. 5(b), along with Gaussian fits to the beam caustics. The beam had an $M^2$ of 1.18 in both the vertical and horizontal axes, close to diffraction limited in both dimensions. The inset in Fig. 5(b) shows a CCD camera image of the collimated beam. The ellipticity of the beam was measured to be $\sim 0.9$.

The 1240 nm pump system was also run at a pulse duration of 0.9 ns and repetition rate of 5 MHz. The shorter pulse duration was achieved by varying the duration of the 1064 nm input pulses for the 1240 nm amplifier (where the 1240 nm system is fully described in [18]). These 1064 nm pulses were delivered by a diode that was gain-switched using a tunable-duration electrical pulse generator. Shortening the electrical pulse duration resulted in shorter output pulses. Up to 580 mW of 743 nm average power was generated, corresponding to a maximum conversion efficiency of 26% [Fig. 6(a)]. This was approximately equal to the 27% conversion efficiency obtained for a similar 1485 nm peak power in the longer pulse case. The generated 743 nm pulses had a FWHM spectral bandwidth of 0.3 nm [inset, Fig. 6(a)] and a measured
FWHM pulse duration of 0.8 ns [Fig. 6(b)]. This resulted in a pulse energy of 120 nJ. No significant difference in beam quality was observed, with the generated 743 nm beam having $M_x^2 = 1.06$ and $M_y^2 = 1.02$. We have, therefore, demonstrated that varying the pulse duration of our phosphosilicate Raman fiber amplifier system does not compromise the SHG conversion efficiency.

4. Conclusion

We report an architecture for generating MHz repetition rate, nanosecond pulsed light at 743 nm, building upon our previous work to generate nanosecond pulses at 620 nm [18]. An in-house built 1240 nm phosphosilicate Raman fiber amplifier was cascaded to 1485 nm with up to 60% efficiency in a second phosphosilicate Raman fiber amplifier, producing up to 4.2 W of 1485 nm light with a pulse duration of 1.6 ns at 5 MHz repetition rate.

The high power, narrow-bandwidth output of this phosphosilicate Raman fiber amplifier was used for single-pass SHG in PPLN to generate up to 1.08 W of light at 743 nm, with a maximum conversion efficiency of 27%. The 743 nm light had a pulse energy of 220 nJ with a pulse duration of 1.3 ns and near diffraction limited beam quality ($M^2 \leq 1.18$). The technique was performed at a second 1240 nm pulse duration, generating up to 580 mW of 743 nm light, with a pulse duration of 0.8 ns and a pulse energy of 120 nJ. An SHG conversion efficiency of 26% was obtained, demonstrating the temporal versatility of our phosphosilicate Raman fiber amplifier architecture.

Previous work has shown that this technique is flexible in repetition rate [23], and can be fully fiber integrated [24]. By varying the 1240 nm pump wavelength, and seed diode wavelength, this technique could also be easily adapted to generate light between 700–780 nm, allowing access across this spectral region based on Yb:fiber MOPA systems.

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Data availability. Data underlying the results presented in this paper are available in Ref. [25].

References