Fiber-integrated frequency-doubling of a picosecond Raman laser to 560 nm

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Abstract: We report the development of a fiber-integrated picosecond source at 560 nm by second harmonic generation of a Raman fiber laser. A picosecond ytterbium master oscillator power fiber amplifier is used to pulse-pump a Raman amplifier, which is seeded by a continuous wave distributed feedback laser diode operating at 1120 nm. The pulse train generated at 1120 nm is frequency-doubled in a fiber-coupled periodically-poled lithium niobate crystal module, producing 450 mW of average power at 560 nm with a pulse duration of 150 ps at a repetition rate of 47.5 MHz. The near diffraction-limited ($M^2 = 1.02$) collimated output beam is ideal for super-resolution microscopy applications.

OCIS codes: (140.3550) Lasers, Raman; (230.4320) Nonlinear optical devices; (190.4370) Nonlinear optics, fibers.

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1. Introduction

Compact, turn-key sources of picosecond radiation at 560 nm are in great demand for many fluorescence-based imaging techniques, including stimulated emission depletion microscopy (STED) [1], semiconductor characterization and biochemical analysis [2]. Pulsed semiconductor laser diodes operating at this wavelength have recently become commercially available but they suffer from limited average output power with an elliptical output beam and low degree of polarization. In contrast, fully fiber-integrated systems are known to be a good solution in applications requiring high average power and excellent beam quality.

The lack of efficient actively-doped silica fibers emitting in the visible spectral region has fueled intense research and commercial effort towards the use of second-harmonic generation (SHG) to extend the wavelength coverage of fiber lasers into the visible and near-visible [3]. Single-pass SHG in periodically-poled crystals is a compact and efficient technique for frequency-doubling fiber lasers, however, the use of bulk optical components negates the alignment and maintenance-free nature of fiber-integrated systems [4].

In this contribution, we report the frequency-doubling of a picosecond Raman fiber laser operating at 1120 nm, using a fiber-coupled periodically-poled lithium niobate crystal module. The high average power and excellent beam quality of this small-footprint source, emitting at 560 nm, make it an ideal tool for fluorescence-based imaging applications.

2. Picosecond Raman fiber laser at 1120 nm

Although direct pulsed emission of Yb-fiber lasers has been demonstrated at 1120 nm [5], the larger emission cross-section at shorter wavelengths severely limits performance due to gain competition, giving rise to excessive amplified spontaneous emission (ASE) and parasitic lasing. It is therefore technologically challenging to develop efficient, high signal to noise ratio amplifiers for this wavelength [6]; because of this, commercial off-the-shelf amplifiers are not currently available.

In contrast, well developed [7] Yb-fiber lasers operating around 1070 nm can be used to pump highly efficient Raman amplifiers operating at 1120 nm [8]. However, the long gain fiber lengths required with continuous wave (CW) pumping make it difficult to preserve narrow spectral linewidth pulsed signals, due to nonlinear spectral broadening through self-phase modulation (SPM).

Our approach circumvents this issue by pulse-pumping a Raman amplifier, seeded by a CW signal, with a ytterbium master oscillator power fiber amplifier (Yb-MOPFA) system. Due to the virtual energy states involved in Raman amplification, there is no energy storage in the gain medium. Therefore, gain is only available in the window of the pump pulse and hence the pulse characteristics of the pump source are imposed on the CW seed signal, generating a train of picosecond pulses at 1120 nm.

The use of a small mode-field diameter, germanium-doped Raman gain fiber gives a higher nonlinearity and an enhanced Raman gain coefficient over standard single-mode fiber. This, combined with a high peak-power pump source, enables short gain fiber lengths to be used, reducing the nonlinear phase shift acquired by the signal. This is important for maintaining the narrow spectral linewidth of the seed signal, necessary for efficient frequency-doubling in periodically-poled crystals.

The Yb-MOPFA was seeded by a commercial passively mode-locked Yb-fiber laser (Fianium), operating at 1064 nm (Fig. 1). The oscillator produced 7 ps, near transform-limited,

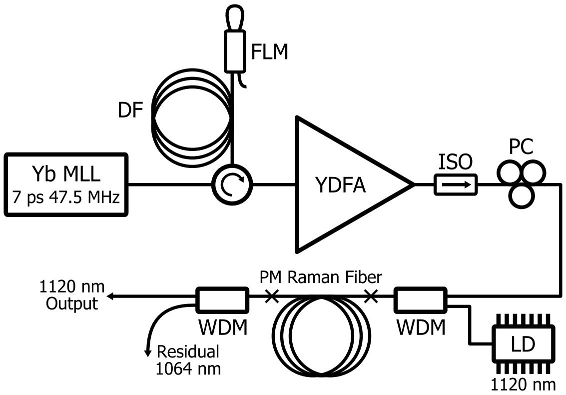


Fig. 1. Schematic of the picosecond Raman fiber laser. Yb MLL, ytterbium mode-locked laser; DF, dispersive fiber; FLM, fiber loop mirror; YDFA, ytterbium-doped fiber amplifier; ISO, isolator; PC, polarization controller; LD, laser diode; WDM, wavelength division multiplexer.

sech^2 pulses at a repetition rate of 47.5 MHz. To enable amplification to high average powers, the oscillator's pulses were stretched to 350 ps [Fig. 2(a)] by double-passing a 1.25 km length of normally dispersive fiber using an optical circulator and fiber-loop mirror. Due to the high nonlinearity of the normally dispersive fiber (OFS Raman Fiber), the oscillator's spectrum was broadened through SPM [Fig. 2(a) inset], which enhanced the rate of dispersive broadening of the pulses.

The temporally-stretched oscillator pulses were directly amplified in a commercial multi-stage Yb-fiber amplifier (IPG Photonics) with a gain of 45 dB and a saturated output power of 10 W. An optical isolator was spliced to the output of the amplifier, to protect it from backwards propagating Raman ASE generated by the Raman amplifier. Since the Yb-MOPFA was constructed from isotropic fiber, a three-paddle polarization controller was spliced to the isolator

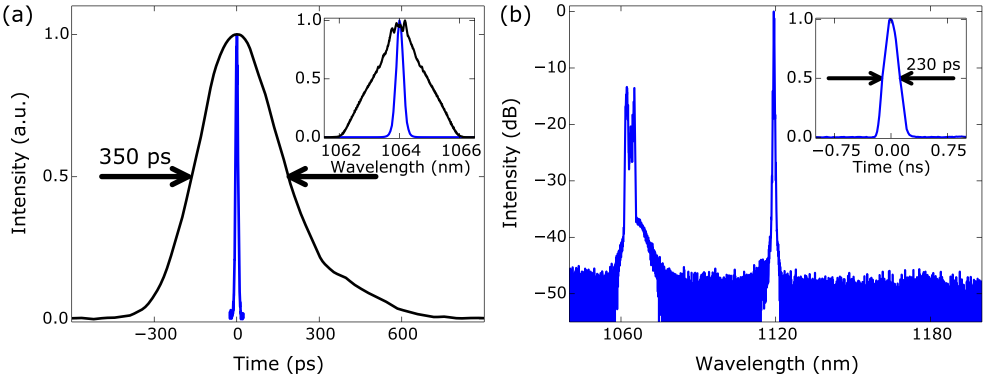


Fig. 2. (a) Sampling optical oscilloscope trace of the stretched mode-locked oscillator pulse (black) and autocorrelation trace of the original oscillator output (blue). Inset: optical spectrum of the stretched (black) and original (blue) oscillator pulses. (b) Optical spectrum of the output of the Raman amplifier. Inset: sampling optical oscilloscope trace of the filtered 1120 nm pulses.

to provide complete control over the randomly polarized output of the amplifier.

The pulsed 1064 nm pump radiation from the Yb-MOPFA was spectrally combined with a CW 1120 nm signal from a fiber-pigtailed distributed feedback laser diode (QD Laser, Inc) in a polarization-maintaining (PM) wavelength division multiplexer (WDM). The laser diode had an average output power of 30 mW and operated with a single longitudinal mode, corresponding to a spectral linewidth of < 10 MHz. A 10 m length of PM Raman fiber (OFS PM Raman Fiber) was used as the Raman gain medium and a second PM WDM was spliced to the output of the Raman fiber to filter residual pump light.

Figure 2(b) shows the optical spectrum of the Raman amplifier output for an average power of 2.22 W, with 80% of the power contained in the 1120 nm signal, equivalent to 1.78 W. The corresponding output power of the Yb-MOPFA pump was 5.2 W, giving a conversion efficiency of 34%, taking into account the input power of the 1120 nm seed signal. The conversion efficiency was limited by the excess loss of the two WDMs (0.9 dB) and the two splice losses to the small-core Raman fiber (1 dB). The 3 dB spectral linewidth of the 1120 nm signal in Fig. 2(b) is 0.29 nm, which was significantly broader than the seed signal due to SPM in the excessive length of Raman fiber. This effect could be mitigated by performing a cut-back on the Raman fiber to optimize the output linewidth for a given pump peak-power.

The 1120 nm signal had a pulse duration of 230 ps [Fig. 2(b) inset] at the pump repetition rate of 47.5 MHz, with no observable pedestal on a sampling optical oscilloscope with a dynamic range of 30 dB (Hamamatsu OOS-01). The reduction in duration from the Yb-MOPFA pump pulses was expected due to the nonlinear nature of the Raman amplification. The use of PM fiber in the Raman amplifier and the polarizing nature of Raman amplification enabled the 1120 nm signal to be amplified with an output PER of 14 dB.

3. Frequency-doubling using fiber-coupled PPLN module

The frequency-doubling optical setup was packaged in a compact and robust fiber-coupled module measuring $120 \times 40 \times 26.5$ mm, greatly reducing the footprint of the source (Fig. 3). The design of the module was based on a previous iteration for generation of 780 nm light, highlighting the wavelength flexibility of the concept [9].

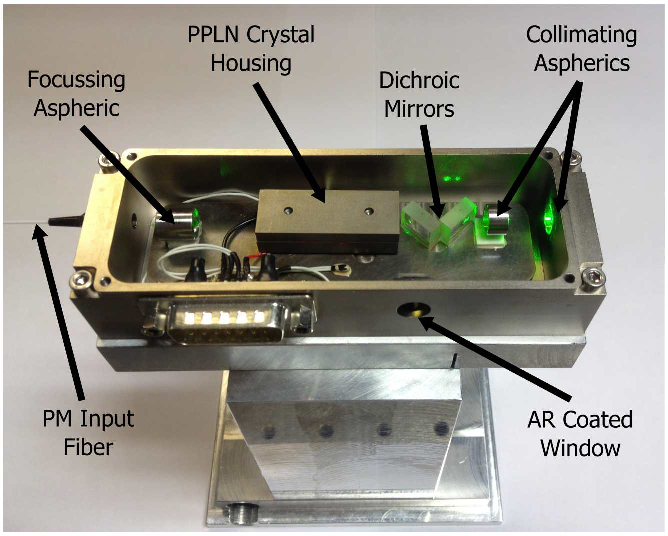


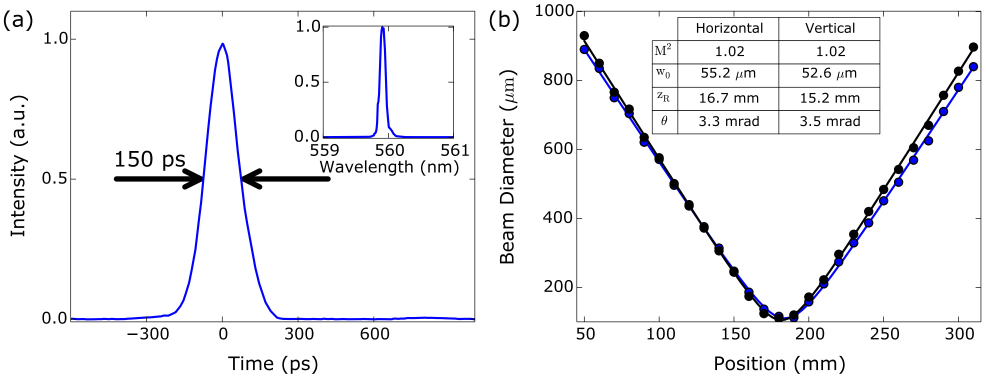
Fig. 3. Photograph of the fiber-coupled frequency-doubling module.

Inside the module, a 15 mm long 5% MgO-doped congruent lithium niobate crystal, held in a metal housing, was bonded to a thermoelectric cooler (TEC).The crystal had a thickness of 1 mm, a width of 3 mm and a manufacturer quoted effective nonlinear coefficient of > 14 pm/V. The crystal was poled with a single 8.06 μm pitch grating, giving a phase-matching bandwidth of 0.176 nm for the fundamental wavelength of 1120 nm. The crystal was anti-reflection coated on the input and output facets for both the fundamental and second-harmonic wavelengths.

The PM980 input fiber to the module was focused to a waist of 30 μm at the center of the crystal using an $f = 2.95$ mm aspheric lens. The ratio of the crystal length to the confocal parameter was 2.97, which was close to the optimal Boyd-Kleinman focusing condition of 2.84 [10]. The slow-axis of the input fiber was aligned to the extraordinary axis of the crystal to maximize the SHG efficiency. After the crystal, the residual 1120 nm pump power was directed out of the module through an AR-coated window using an orthogonal pair of 45° dichroic mirrors. The generated second-harmonic was collimated to a diameter of 1.1 mm using an $f = -10$ mm and $f = 20$ mm telescopic pair of aspheric lenses. All of the optical components and the TEC controlled crystal housing were bonded to a baseplate that was temperature controlled using three TECs in series. The individual temperature control of the crystal and the baseplate ensured the phase-matching temperature could be maintained with a precision of ± 0.1 °C without perturbing the alignment of the optical setup. The calculated full-width half-maximum temperature acceptance bandwidth of the crystal was 1.8 °C, which with the precision of the temperature control sets an upper limit on the SHG power stability of $< 1\%$.

The Raman fiber laser described in the preceding section was fusion spliced to the input fiber of the frequency-doubling module. A maximum average power of 450 mW of 560 nm was generated for 1.78 W of 1120 nm, giving a conversion efficiency of 25% at the optimum phase-matching temperature of 74.4 °C. The conversion efficiency was predominantly limited due to the fact that the 1120 nm pump bandwidth (0.29 nm) exceeded the spectral acceptance bandwidth of the crystal (0.176 nm). Integrating the pump spectrum over the spectral acceptance of the crystal revealed that only 45% of the 1120 nm power, equivalent to 0.8 W, was available for SHG, giving an effective 56% SHG conversion efficiency.

The 560 nm pulse duration was 150 ps [Fig. 4(a)] at a repetition rate of 47.5 MHz, which is ideally suited to STED microscopy applications [11]. The estimated maximum peak power intensity of the generated 560 nm signal was ~ 4.5 MW/cm^2, which was approaching the



	Horizontal	Vertical
M^2	1.02	1.02
w_0	55.2 μm	52.6 μm
z_R	16.7 mm	15.2 mm
θ	3.3 mrad	3.5 mrad

Fig. 4. (a) Sampling optical oscilloscope trace and optical spectrum (inset) of the 560 nm frequency-doubled module output. (b) Measured beam caustic of the collimated module output focused by an $f = 200$ mm lens with the Gaussian beam fit parameters (inset).

photorefractive damage threshold limit of 5% MgO-doped PPLN [12]. Further scaling of the 560 nm average power would require looser focusing to ensure the second-harmonic peak intensity remained below the photorefractive damage threshold. The spectral linewidth of the 560 nm signal was measured to be < 0.1 nm, limited by the resolution of the optical spectrum analyzer [Fig. 4(a) inset]. A CCD camera was used to measure the beam diameter of the collimated module output focused by an f = 200 mm lens [Fig. 4(b)]. A Gaussian fit of the beam caustic revealed a near-diffraction limited beam, with an $M^2 = 1.02$ and an ellipticity of 0.95.

4. Conclusion

In conclusion, we have demonstrated a small footprint, turn-key fiber-integrated source of picosecond pulses at 560 nm, a key wavelength for many fluorescence-based imaging techniques. By pulse-pumping a Raman amplifier, which was seeded by a narrow linewidth DFB laser diode, we efficiently converted 1064 nm picosecond radition from a Yb-MOPFA to 1120 nm. The 1120 nm pulse train was frequency-doubled to 560 nm in a robust and compact fiber-coupled PPLN module. The source generated 450 mW of 560 nm light with a pulse duration of 150 ps at a repetition rate of 47.5 MHz. The circular (ellipticity 0.95) collimated output beam of the module had near diffraction-limited beam quality ($M^2 = 1.02$). This source is an ideal tool for applications such as STED microscopy, which require high peak-power, picosecond pulses with excellent beam quality.