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Pushing the tuning limits of femtosecond Yb-based solid-state lasers to 1 µm: a Yb:YVO_4 laser tunable down to 1004 nm

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We have obtained what we believe to be the shortest fs tuning wavelength (1004 nm) from a Yb-based solid-state laser system. As the working horse, we have chosen Yb:YVO_4 due to its blueshifted gain spectrum. While using a single 10 W 952 nm diode for pumping and a semiconductor saturable absorber mirror (SESAM) for mode-locking, we have achieved 266 fs long pulses with up to 1.24 W of output power around 1021 nm. Using an intracavity birefringent filter, the central wavelength of the fs pulses could be tuned smoothly between 1004–1038 nm and 1009–1061 nm while employing the E//a and E//c axis of the material, respectively. By using an additional hard aperture to increase the modulation depth, we have also attained 100 fs level pulses in the 1012.5–1019 nm range, which shows the suitability of the system in seeding cryogenic Yb:YLF-based amplifiers.

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Many applications in ultrafast science require fine-tuning of the central wavelength of the femtosecond laser sources, e.g., for on-resonance excitation of chemical mechanisms or for optimum in-band seeding of amplifier systems. Our effort to develop high-energy and high-repetition rate cryogenic Yb:YLF systems [1,2] also necessitates a broadband seeder source with a central wavelength of around 1017 nm (the gain peak for E//a axis) [3], a challenging central wavelength to obtain from fs oscillators [2]. For this purpose, we have investigated several alternatives as seeders, such as fiber-based Yb lasers [4], Cr:LiSAF lasers [5], and Yb:YLF lasers [6]. With fiber lasers, building sub-500-fs systems is challenging due to the inherent high nonlinearity of fiber systems. Moreover, reaching these short wavelengths requires the usage of specially gain fibers that are not always polarization-maintaining, which induces sensitivity to polarization fluctuations. As a result, our search for an optimum seeder source is still ongoing, as an ideal seeder must simultaneously meet the ease of use, compactness, and long-term stability requirements and should provide sufficient pulse energy at the desired central wavelength with a wide enough spectral bandwidth.

In the case of Yb-based laser gain media, the strong overlap of absorption and emission bands makes tuning their output challenging at short wavelength regions, especially in mode-locked operation [6–16]. In earlier work, using Yb:YLF, we could push the fs tuning range of the oscillator down to 1019 nm [6], which is a good result among the Yb-based systems (Fig. 1), but the wavelength is not yet short enough for seeding the cryogenic Yb:YLF amplifier chain.

Considering the other promising alternatives, in this work, we focused our attention on Yb:YVO_4, as it has one of the most blueshifted gain spectra among all the Yb-based solid-state laser gain media [17–22]. Earlier mode-locking [18] and regenerative amplifier [23] work with Yb:YVO_4 gain media already indicated its potential for generating/amplification of fs pulses close to the 1 µm region. Here, we extend upon earlier results (Table 1); as far as we are aware, we report: (i) the first detailed mode-locked tuning results with Yb:YVO_4, and (ii) the shortest fs tuning wavelength obtained from any Yb-based solid-state laser gain media to date. Our results also clearly demonstrated the suitability of Yb:YVO_4 in generating broadband fs pulses around 1017 nm, confirming its usefulness in seeding cryogenic Yb:YLF amplifiers [1,2].

Figure 2 shows a schematic of the Yb:YVO_4 laser system used in the mode-locking experiments. A single-emitter multimode diode (MMD, LDX-3A10-960-C from RPMC Lasers), capable of delivering a maximum pump power of 10 W at 952 nm, is used as the pump source. The MMD output is first collimated by a 4.5 mm focal length aspheric lens (f_1). Then, a cylindrical lens with a focal length of 50 mm (f_z, acting on the fast axis) is placed after the collimator to reduce the diode beam astigmatism. Later, an achromatic doublet with a focal length of 75 mm (f_2) is used to focus the pump beam inside the gain medium. For the laser cavity, an X-type resonator configuration is employed,

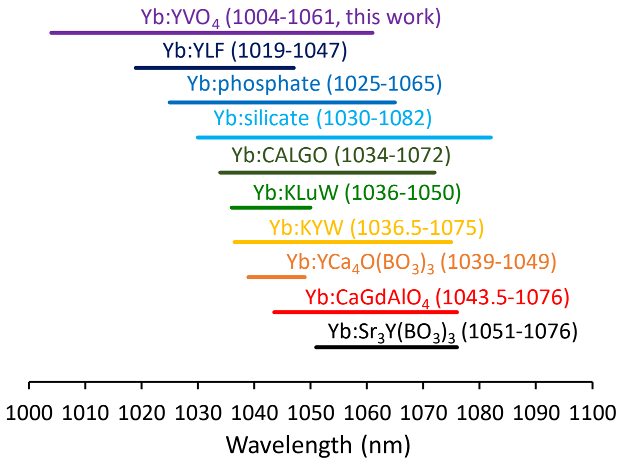

Fig. 1. Summary of mode-locked tuning ranges demonstrated with Yb-based solid-state laser gain media: Yb:YLF [6], Yb:phosphate [7], Yb:silicate [7], Yb:CALGO [8,13], Yb:KLuW [9], Yb:KYW [10,12,14], Yb:YCa$_4$O(BO$_3$)$_3$ [11], Yb:CaGdAlO$_4$ [15], Yb:Sr$_3$Y(BO$_3$)$_3$ [16].

Table 1. Summary of Mode-Locking Results of Yb:YVO$_4$

Lasing Conf.	Avg. Power (mW)	Pulse Width (fs)	Central Wavelength (nm)	OC (%)	Ref.
E//c	300	120	1021	3	[18]
E//c	54	61	1050	1	[19]
E//c	1000	80	1040	3	[20]
E//c	820	123	1029	5	[a]
E//a	1240	266	1021	5	[a]
E//c	~300	~400	1009-1061	1	[a]
E//a	~200	~600	1004-1038	5	[a]
E//a	200-600	290-110	1012.4-1019	5	[a]

[a] Results obtained in this work.

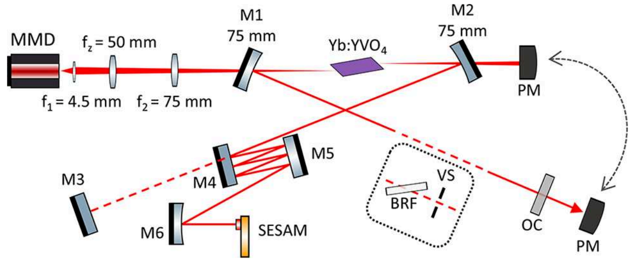

Fig. 2. Experimental setup of the diode-pumped Yb:YVO$_4$ laser used in the experiments. MMD, multimode diode; M, cavity mirror; SESAM, semiconductor saturable-absorber mirror; f, focusing lens; BRF, birefringent filter; VS, variable slit; OC, output coupler; PM, power meter.

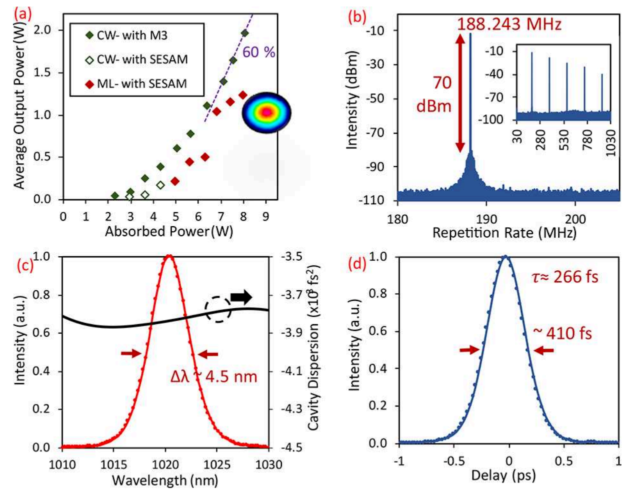

Fig. 3. Summary of mode-locking performance of the Yb:YVO$_4$ laser in E//a axis with a 5% OC, for the 266 fs long 1.24 W average power pulses around 1021 nm at a repetition rate of 188.2 MHz. Measured (a) efficiency curves, (b) microwave spectrum, (c) optical spectra, and (d) autocorrelation.

consisting of two curved high reflectors with a radius of curvature of 75 mm (M1, M2), a flat high reflector (M3), and a flat output coupler (OC). Mirrors M1–M3 are highly reflective in the 1010–1200 nm range and possess a transmission window between 800 and 970 nm. Two different output couplers with transmission of 1% and 5% are used in the experiments. A variable slit (VS) is inserted near the output coupler to control the transverse output mode of the laser in the tangential axis. For tuning the central wavelength of the mode-locked pulses, a 2 mm thick off-surface optical axis crystal quartz birefringent filter (BRF) with a diving angle of 25° is inserted at Brewster's angle near the output coupler [24]. As the laser gain media, two Brewster–Brewster cut crystals optimized for lasing in the E//c and E//a axes were tested. Both Yb:YVO$_4$ crystals are doped with 2.6% Yb and have a length of 5 mm and an aperture of 2×2 mm^2. The crystals are mounted with indium foil in a water-cooled copper heat spreader. The cooling temperature of the heat spreader is set to 10°C. The laser output and pump power were measured using the Ophir Optronics FL250A-BB-35 power meter (PM).

For mode-locking experiments, to achieve soliton pulse shaping, mirrors M4–M5 with negative group delay dispersion (GDD) are inserted (Fig. 1). We have carefully adjusted the number of bounces on the mirrors to acquire the desired amount of dispersion. For the short pulse generation, a combination of dispersive mirrors with a GDD of −50 fs^2 (970–1120 nm), −150 fs^2 (980–1100 nm), and −500 fs^2 (1000–1060 nm) are used. Mode-locking is initiated and sustained by a SESAM, which is placed at a secondary focus generated by the curved mirror M6 (ROC: 200 mm). The commercial SESAM (BATOP, SAM-1040-1.5-1 ps) has a company-specified modulation depth of 0.9%, a non-saturable loss of approximately 0.6%, a reflectivity range of 1000–1070 nm, a relaxation time constant of 1 ps, a damage threshold of 4 mJ/cm^2, and a saturation fluence of 50 μJ/cm^2.

We start presenting our experimental results with the high-power mode-locked lasing configuration (Fig. 3), where we have employed the E//a axis of YVO$_4$ and a 5% OC. In a continuous-wave (CW) operation, using the high reflector M3, an output power level of up to 2 W is achieved at around 1023 nm with a slope efficiency of 60%. Then, using the dispersive mirrors (M4, M5), the net cavity dispersion is set around −3800 fs^2. In this configuration, the laser started to operate in the stable self-starting CW mode-locked regime already at an absorbed pump power level of 4.9 W, where the average output power was 210 mW (Fig. 3(a)). At the maximum absorbed pump power of 8 W, the Yb:YVO$_4$ laser produced 266 fs pulses (assuming sech^2 shape) with 1.24 W of average power at a repetition rate

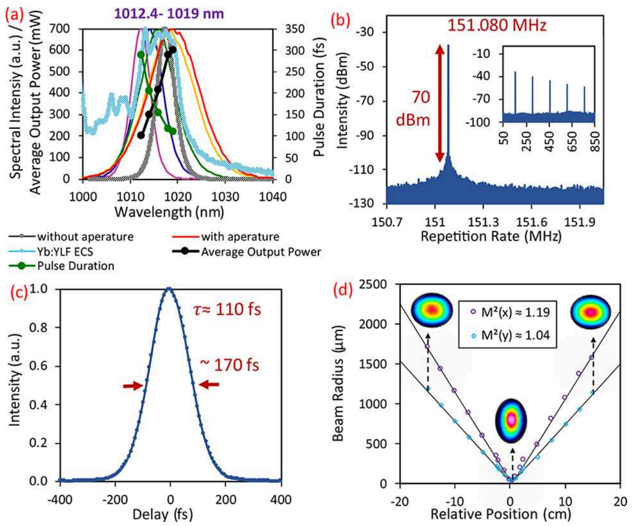

Fig. 4. Summary of mode-locked tuning performance of the $Yb:YVO_4$ laser in E//a axis with an 5% OC, for the shortest 110 fs long 600 mW maximum average output power pulses around 1016 nm. (a) Measured optical spectra of fs pulses along with the Yb:YLF emission cross section (ECS) in its E//a axis at 78 K. Measured (b) microwave spectrum, (c) autocorrelation trace, and (d) caustic of the laser output beam.

of 188.2 MHz. The spectrum was centered around 1021 nm and had an FWHM of 4.5 nm (Fig. 3(c)), corresponding to a time–bandwidth product of 0.344. The pulse energy and peak power were 6.6 nJ and 21.8 kW, respectively. The laser output had a single transverse mode output beam profile at the maximum output power of 1.24 W, as shown in the inset figure in Fig. 3(a). Note that, in a similar configuration, this time by employing the crystal cut for the E//c axis, we have also achieved 123 fs pulses with 820 mW of average power around 1029 nm from the $Yb:YVO_4$ laser (Table 1).

As the next step, to obtain shorter pulses, the net cavity dispersion is decreased and set to be around $-1800\ fs^2$. Moreover, we have also fine-adjusted the width of the slit near the OC to improve the bandwidth of the femtosecond pulses. Basically, the modulation depth of the SESAM (0.9%) was not large enough to push the bandwidth of the ML pulses to the desired level. Hence, we have used an additional modulation depth created by hard-aperture Kerr-lens mode-locking to balance the gain filtering effect, which enabled us to push the pulse widths down to 100 fs level. Figure 4(a) shows the optical spectra of the fs pulses obtained with and without the usage of Kerr-lens hard aperture. The spectral width, which was around 5 nm without the aperture, could be extended up to 12.5 nm. Furthermore, via simple fine alignment of cavity end mirrors (SESAM and OC for our case), we could adjust the central wavelength of the fs pulses in the 1012.4–1019 nm range. In Fig. 4(a), the emission cross section of Yb:YLF gain medium in the E//a axis at cryogenic temperatures is also shown, and we see that the central wavelength of the pulses from the $Yb:YVO_4$ oscillator could be tuned to cover the Yb:YLF gain window effectively. In this configuration, the mode-locked pulses with the broadest optical spectrum had an average output power of 600 mW and a repetition rate of 151.08 MHz (Fig. 4(b)). The pulse duration is measured as 110 fs (Fig. 4(c)), indicating a time–bandwidth product of 0.4. The corresponding pulse energy and peak power were 4 nJ and 31.8 kW, respectively. To verify the suitability of the system for efficient seeding of a regenerative amplifier, we have also measured the beam quality parameter (M^2) of the $Yb:YVO_4$ laser output. In Fig. 4(d), the inset pictures show the beam profiles at the left and right extremes and at the focus. The laser output had a single transverse mode beam profile with an M^2 of 1.19 and 1.04 for horizontal (x) and vertical (y) axes, respectively. Note the output beam is slightly astigmatic, which could be optimized by fine-adjusting the incidence angles of the intracavity laser beam on the curved mirrors of the laser cavity.

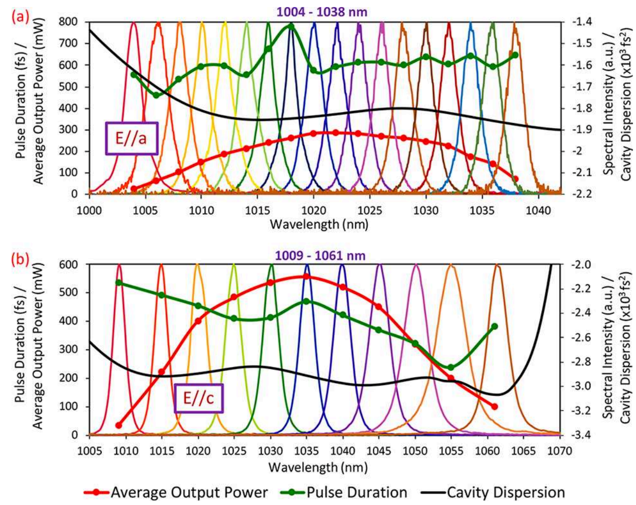

Fig. 5. Sample optical spectra from the mode-locked $Yb:YVO_4$ laser showing tunability of central wavelength of the mode-locked pulses from (a) 1004 nm to 1038 nm and (b) 1009 nm to 1061 nm using the E//a and (b) E//c axes, respectively.

To test the ultimate femtosecond tuning capability of the system, we have returned back to the long pulse configuration by modifying the cavity dispersion level. A 2-mm thick off-surface BRF is also inserted into the cavity at Brewster's angle to adjust the central wavelength of the pulses. Figure 5 summarizes fs tuning results obtained with $Yb:YVO_4$ while employing its (a) E//a and (b) E//c axis, respectively. Mode-locking tuning experiments were performed at around $-1800\ fs^2$ net cavity dispersion level, at an absorbed pump power of 8 W using a 5% OC for the E//a axis (Fig. 5(a)), and at around $-2900\ fs^2$ net cavity dispersion level, at an absorbed pump power of 5.6 W using a 1% OC, for the E//c axis (Fig. 5(b)). For both cases, the repetition rate of the laser was around 150 MHz. As we can see from Fig. 5(a), the central wavelength of the pulses could be tuned smoothly in the 1004–1038 nm range while employing the E//a axis. The average pulse duration over the tuning range did not fluctuate much and stayed around 600 fs. The average power of the laser was above 250 mW in the central region around 1020 nm but decreased to below 50 mW at 1004 nm due to increased losses of the cavity mirrors and SESAM and decreased gain of the material. To our knowledge, this is the shortest fs tuning central wavelength ever obtained from any Yb-doped solid-state mode-locked laser (Fig. 1). Compared to earlier fs tuning results with Yb:YLF gain media (1019–1047 nm), the tuning range is extended 15 nm more into the shorter wavelength region. We believe that the obtained short-wavelength limit could be pushed down below 1 µm in future studies by employing custom-designed mirror sets and SESAM for this wavelength range. In the case of mode-locked tuning with the E//c axis, the central wavelength of the fs pulses could be tuned smoothly between 1009 and 1061 nm (52 nm overall tuning range). From 1009 to 1055 nm, the pulse duration slightly decreased from around 580 to 240 fs, leading to an average pulse duration of approximately 400 fs. Mode-locked average powers were as high as 500 mW around the central tuning region near 1035 nm but decreased to below 100 mW around both edges. In future studies, using a lower loss gain element along with a SESAM optimized for longer wavelengths, we believe that the tuning range of the fs pulses could be extended to longer wavelengths beyond 1061 nm.

To summarize, in this work, we have investigated the femtosecond tuning behavior of mode-locked Yb:YVO_4 oscillators for the first time to understand its suitability in seeding cryogenic Yb:YLF amplifier chains around 1017 nm. An overall fs tuning range covering the 1004–1061 nm region has been demonstrated, only limited by the specifications of off-the-shelf optics used in this study. The initial results we present here already show that, among the Yb-doped solid-state lasers, Yb:YVO_4 is the few that is suitable for an efficient operation near the 1 μm region.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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