Scaling the repetition rate of thulium-doped ultrafast soliton fiber lasers to the GHz regime

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Abstract: GHz high repetition rate compact sources with femtosecond pulse durations and stable performance can enable a wide range of applications. In this paper, several high repetition rate ultrafast thulium fiber lasers with repetition rates varying between 532 MHz to 1.25 GHz are demonstrated with femtosecond pulse durations down to 426 fs. An approach of maintaining comparable pulse energies while scaling the repetition rates allows high quality femtosecond mode-locking performance with low noise performance in thulium soliton lasers for the first time.

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1. Introduction

High repetition rate thulium (Tm)-doped fiber lasers [1] with femtosecond pulses are attractive for applications such as high speed optical sampling [2,3], frequency metrology [4–8] or optical arbitrary waveform generation [9]. Specifically, for frequency comb applications in spectroscopy or high precision metrology, a higher repetition rate provides a wider frequency tooth spacing, which can support more power in each individual line, thus boosting sensitivity and the signal-to-noise [4–6]. However, to achieve fundamentally mode-locked laser operation at high repetition rates, the cavity design has to be miniaturized through reducing the fiber length. This in turns implies that short sections of highly doped gain fiber on the order of a few cm's are needed that can support the right balance between group velocity dispersion and nonlinear generation, mostly in form of self-phase modulation, to generate femtosecond pulse durations. Fiber based high repetition rate technology platforms are attractive due to their compactness, their robust performance metrics, high spatial beam quality and the ease of integration for fiber-based sensors and communication systems, minimizing alignment sensitivity and environmental noise compared to free-space solid state or optically pumped semiconductor gain laser configurations. The feasibility of achieving GHz repetition rates in fundamentally mode-locked fiber lasers with femtosecond pulse durations has been demonstrated in ytterbium based lasers with wavelengths around 1 µm [10] up to 5 GHz [11], and in erbium fiber lasers with wavelengths around 1.5 µm [12–17] up to 19.4 GHz [16]. While harmonic mode-locking [18–21] and external repetition rate multiplication through interleavers [22,23] or Fabry-Perot filtering [4–6,24] can form a pathway towards high repetition rates, the stability and noise properties of fundamentally mode-locked lasers are usually superior. While good progress has been made towards high repetition rate thulium fiber lasers, so far passively mode-locked high repetition rate Tm-doped fiber lasers with a few picosecond pulse duration have been demonstrated based on mostly custom-made gain fibers and customized components, up to repetition rates of 1.6 GHz [25–27], 982 MHz [28] and 535 MHz [29]. Harmonic mode-locked Tm laser systems above 400 MHz operating at higher multiples of the fundamental repetition rate have featured mostly longer picosecond pulse durations [21,30–33] and repetition rates up to 14.5 GHz [31] have been demonstrated. Good thermal management [15], repetition rate scaling [34] and different pulsation regimes [17,25] have been outlined as key areas to address to achieve long-term stable laser operation.

In this paper, we present for the first time to the best of our knowledge, a systematic scaling of Tm mode-locked lasers from repetition rates of 531.9 MHz up to 1.25 GHz in a laser cavity based on commercially available components. The full laser performance is characterized, including a detailed noise analysis. The mode-locking threshold occurs for similar soliton pulse energies, providing a pathway to scale the repetition rate while maintaining comparable optical performance, presented here up to a repetition rate of 1.25 GHz. While previous research on high repetition rate Tm laser have recorded pulse durations in the picosecond regime [25,26,29], pulses around 600 fs pulse duration are demonstrated at GHz repetition rates with low noise and timing jitter.

2. High Repetition Rate Laser Cavities

To enable high repetition rates within a compact cavity, a linear fiber laser configuration with a highly absorbing gain fiber is designed based on soliton mode-locking, as illustrated in Fig. 1(a). Utilizing a heavily doped Tm gain fiber (Nufern, SM-TSF-5/125), with a peak absorption of 340 dB/m at 1560 nm, four different fiber laser cavities are designed. This approach varies from conventional shortening of the gain fiber to obtain higher repetition rates. Instead, the gain fiber is kept at a constant length of 7 cm that is optimized for pump absorption, for all high repetition rate fiber designs to enable similar gain and pump power dynamics. The gain fiber is spliced to various lengths of single-mode fiber SMF-28e+ of 12.2 cm, 7.5 cm, 3.5 cm and 1.1 cm in order to scale the fundamental repetition rate of the laser, resulting in four cavities with a total lengths of 19.2 cm, 14.5 cm, 10.5 cm and 8.1 cm, respectively. The set-up picture of the shortest gain fiber with an 8.1 cm long cavity is shown in Fig. 1(b). With an estimated group velocity dispersion for the gain fiber of -840 fs^2, the net cavity dispersion varies between -9502 fs^2 to -1621 fs^2 for the different laser configurations. The passive fiber end of the cavity is butt-coupled to a saturable Bragg reflector (SBR, BATOP GmbH) with a modulation depth of 12% and a saturation fluence of 65 μJ/cm^2 for self-starting mode-locking operation. The other end of the cavity is coupled to a 10% output coupler. The laser is core-pumped at a wavelength of 1565 nm. An external dichroic mirror is used to separate the pump and output light.

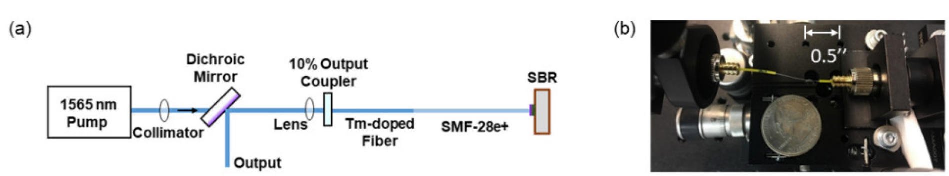

Fig. 1. (a) Compact linear soliton laser fundamentally mode-locked with repetition rate between 532 MHz to 1.25 GHz based on the total cavity length. SBR: saturable Bragg reflector. (b) Image of 1.25 GHz laser with a 8.1 cm-long fiber cavity and a US quarter coin next to it for comparison.

3. Results and Discussion

High repetition rate ultrafast pulses at 531.9 MHz, 704.3 MHz, 974.4 MHz and 1.25 GHz are achieved, and all laser cavities are analyzed and compared with regards to their optical performance. For the 19.2 cm long cavity laser with a repetition rate of 531.9 MHz, a coupled pump power value of 204 mW sets the mode-locking threshold to generate single pulse mode-locking with an average output power of 7.0 mW. As shown in Fig. 2, the intracavity pulse energy increases linearly from 160 pJ to 376 pJ (corresponding to 16.1 mW of output power) for a coupled pump power up to a value of 427 mW. The mode-locking threshold corresponding to an intracavity pulse energy of 160 pJ for the 531.9 MHz laser is comparable to the lasers with repetition rates of 704.3 MHz, 974.4 MHz and 1.25 GHz. For a pulse energy of 170 pJ, the average output power of the 531.9 MHz laser is measured to be 7.1 mW. Based on this value, the output power for the 704.3 MHz, 974.4 MHz and 1.25 GHz laser for the same pulse energy is expected to amount to 9.4 mW, 13 mW and 16.7 mW. This corresponds well to the measured output power values of 9.5 mW, 13.3 mW and 17.1 mW for the 704.3 MHz – 1.25 GHz lasers, respectively. From the mode-locking threshold, all four studied high repetition rate fiber lasers show a linear increase in pulse energy and output power for higher coupled pump power values, see Fig. 2.

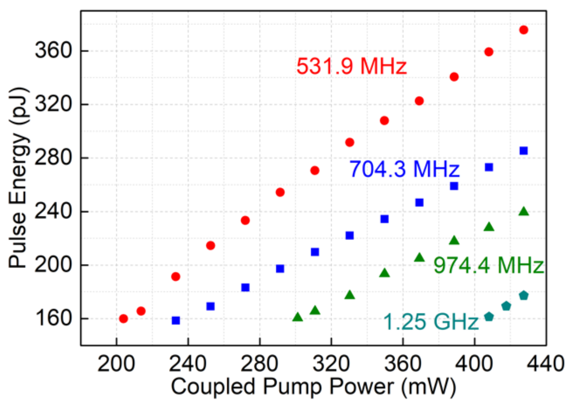

Fig. 2. (a) Mapping of the intracavity pulse energy with regards to the coupled pump power indicates that similar soliton energies are required to initiate mode-locking for fundamentally mode-locked ultrafast fiber lasers with repetition rates between 531.9 MHz and 1.25 GHz.

While the mode-locking threshold pulse energy is comparable for all four laser systems, systematic studies and comparison of the optical laser performance are conducted in Fig. 3 for the lasers with a repetition rate of 531.9 MHz, 704.3 MHz and 974.4 MHz. As shown in the first row of Figs. 3(a)-3(c), the lasers operate at a center wavelength of 1958 nm, 1950 nm and 1940 nm at the mode-locking threshold, respectively. For the higher repetition rates, the laser automatically operates at shorter center wavelengths, where improved overlap with the maximum of the gain curve and slightly reduced losses at the saturable absorber are provided. Thus, at the mode-locking threshold the optical bandwidth for comparable pulse energies increases slightly with the higher repetition rate cavities supporting slightly shorter pulses, as shown in Fig. 3 (first row). When studying the behavior of each laser individually, the center wavelength of the optical spectrum is getting red-shifted with higher pump powers, leading to higher peak intensities, broader spectral generation and shorter pulses. For the particular state of the 531.9 MHz laser, the full width at half maximum (FWHM) of the optical spectrum broadens from 4.4 nm to 10.3 nm for coupled pump power values from 204 mW to 427 mW, while the center wavelength shifts from 1957.8 nm to 1962.8 nm. For these states, output power values between 7 mW to 16.1 mW are measured, which correspond to transform-limited pulse durations from 914 fs to 393 fs, based on a hyperbolic sech pulse shape. The spectral bandwidth of the 704.3 MHz laser varies between 4.6 nm and 7.8 nm when the coupled pump power increases from 233 mW to 427 mW, resulting in output power values between 9 mW to 16.2 mW. The center wavelength shifts from 1950.2 nm to 1953.9 nm, corresponding to transform-limited pulse durations between 870 fs down to 516 fs in Fig. 3(b). For the 974.4 MHz laser, the pulse is centered around 1940 nm to 1941.8 nm with an optical spectrum FWHM varying between 4.9 nm and 6.7 nm, corresponding to transform-limited pulse durations from 914 fs to 595 fs. These states are induced for coupled pump power between 301 mW to 427 mW, where output power values between 12.6 mW up to 18.8 mW are measured.

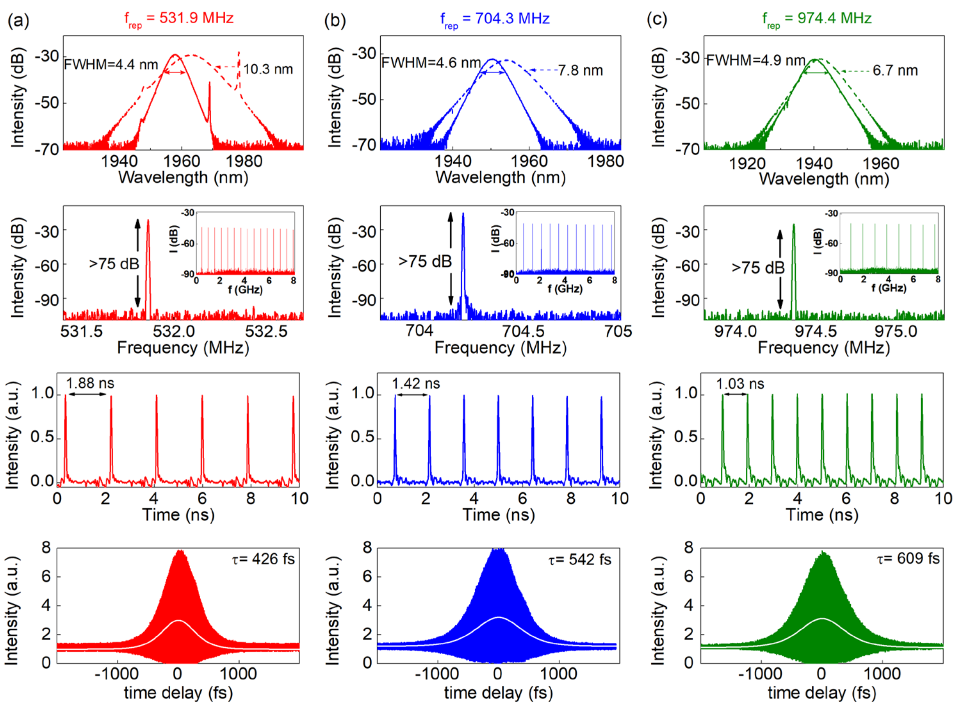

Fig. 3. Tm fiber lasers at a repetition rate of (a) 531.9 MHz, (b) 704.3 MHz and (c) 974.4 MHz. First row: The optical spectrum is measured at the mode-locking threshold (solid line) and for the highest observed pulse energy (dashed line). Second row: RF spectrum of the fundamental repetition rate. The insets show the RF spectral traces for an 8 GHz span. Third row: Measured oscilloscope traces. Fourth row: Interferometric autocorrelation traces of pulses correspond to FWHM of 10.3 nm, 7.8 nm and 6.7 nm in the optical spectrum.

In the additional rows of Fig. 3, the radio frequency (RF) and temporal behavior of the lasers is studied. The signal-to-noise ratio (SNR) of the fundamental RF peak, as shown in the second row of Fig. 3, is greater than 75 dB, measured with a resolution bandwidth (RBW) of 3 kHz, indicating high noise suppression. The stability of all three configurations is confirmed by the uniform RF spectral traces in a frequency range of 8 GHz (RBW of 100 kHz), shown as insets. The oscilloscope traces (third row in Fig. 3) feature uniform pulse trains with pulse spacing of 1.88 ns, 1.42 ns, and 1.03 ns, respectively, corresponding to the cavity length and confirming the high single pulsing stability. Autocorrelation traces for the broadest spectrum of each of the respective lasers are measured with a home-built interferometric autocorrelator, which is based on two-photon absorption in an amplified silicon detector, as displayed in the fourth row of Fig. 3. The measured pulse duration corresponds to 426 fs, 542 fs and 609 fs based on a sech shape with a deconvolution factor of 1.54 for the laser cavities at a repetition rate of 531.9 MHz, 704.3 MHz and 974.4 MHz, respectively. These values agree well with the transform-limited pulse durations of 393 fs, 516 fs and 595 fs, indicating minimal uncompensated dispersion. The time-bandwidth product (TBP) of the measured pulses is calculated to be 0.342, 0.331 and 0.329 for the 531.9 MHz, 704.3 MHz and 974.4 MHz lasers, respectively, which is close to the limited TBP for a sech^2 pulse which is ~0.315. The higher the repetition rate, the better agreement with the transform-limited pulse duration is obtained due to a reduced overall dispersion. From the characterization of the three lasers in both the spectral and temporal domain, all presented lasers achieve comparable performance with same amount of gain fiber.

The laser configuration can be further scaled to a repetition rate of 1.25 GHz. For a coupled pump power of 408 mW, the 1.25 GHz laser starts mode-locking at a center wavelength of 1941 nm with a FWHM optical spectral bandwidth of 4.8 nm, as shown in Fig. 4(a). A femtosecond pulse train is generated with an average power of 16.3 mW. This laser operation point is close to the observed mode-locking threshold for the lower repetition rate lasers. For the 1.25 GHz cavity, 17.9 mW of average power is obtained for the maximum coupled pump power of 427 mW. The optical spectrum is centered at a wavelength of 1941 nm with a FWHM of 5.4 nm, as shown in Fig. 4(a). Stable mode-locking operation is confirmed by the RF spectrum in a frequency range of 8 GHz (inset of Fig. 4(b)) and the fundamental RF peak has a SNR greater than 75 dB. Uniform pulse trains are measured in the temporal domain, cf. Fig. 4(c). The observed pulse spacing of 0.79 ns corresponds well with the cavity length. The autocorrelator pulse duration is measured as 741 fs, very close to the transform-limited pulse duration of 733 fs, see Fig. 4(d), leading to a TBP of 0.318. For the higher repetition rate lasers, the broader spectral bandwidth states can currently not be generated with the given configuration due to limited available pump power, but they should scale accordingly. Thus, similar performance improvements with shorter pulse energies are expected for higher pump powers so that pulse durations down to 400 fs with GHz repetition rates can be supported. By reducing the gain fiber length further, it should be possible to induce even higher repetition rates above 1.5 GHz.

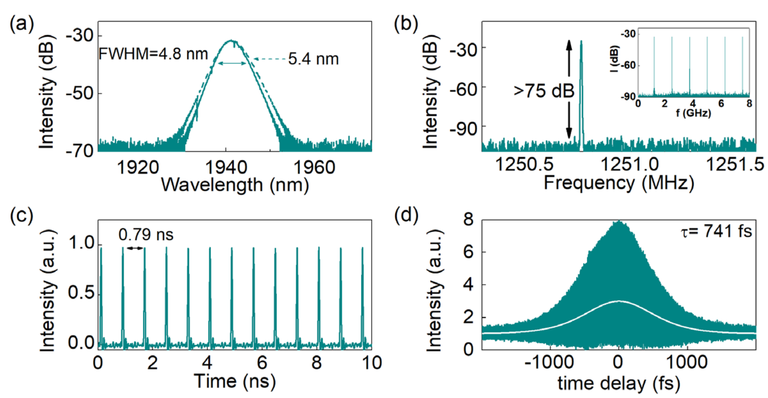

Fig. 4. Characterization of pulse train with a repetition rate of 1.25 GHz. (a) The optical spectrum is measured at the mode-locking threshold (solid line) and for the highest observed pulse energy (dashed line). (b) RF spectrum of the fundamental repetition rate. The insets show the RF spectral traces for an 8 GHz span. (c) Measured oscilloscope traces. (d) The measured interferometric autocorrelation trace results in a pulse duration of 741 fs.

Previously high repetition rate soliton mode-locked demonstrated Tm ultrafast fiber laser systems relied on home-made Tm-doped fiber that enabled repetition rates up to 1.6 GHz [25,34], 982 MHz [28] and 535 MHz [29]. The Tm-doped fibers featured core diameters of 8.6 μm [25,34] and 10 μm [27] correspondingly, resulting in longer reported pulse durations of 1 ps and 7.9 ps, correspondingly. Output powers of 4.5 mW for 10% output coupling (with a pump power threshold of 107 mW) at 1.6 GHz and 26 mW for 15% output coupling (with a pump power threshold of 390 mW) for 0.5 GHz were presented. In the system here, the pulses obtained from our lasers are fairly close to transform-limited. The smaller core gain fiber with a core diameter of 5.5 μm facilitates higher focusing and higher nonlinearity so that femtosecond pulse durations can be achieved directly from the laser cavity. For a relative low pump power mode-locking threshold, good optical performance with output powers up to 18.8 mW is demonstrated for 10% of output coupling.

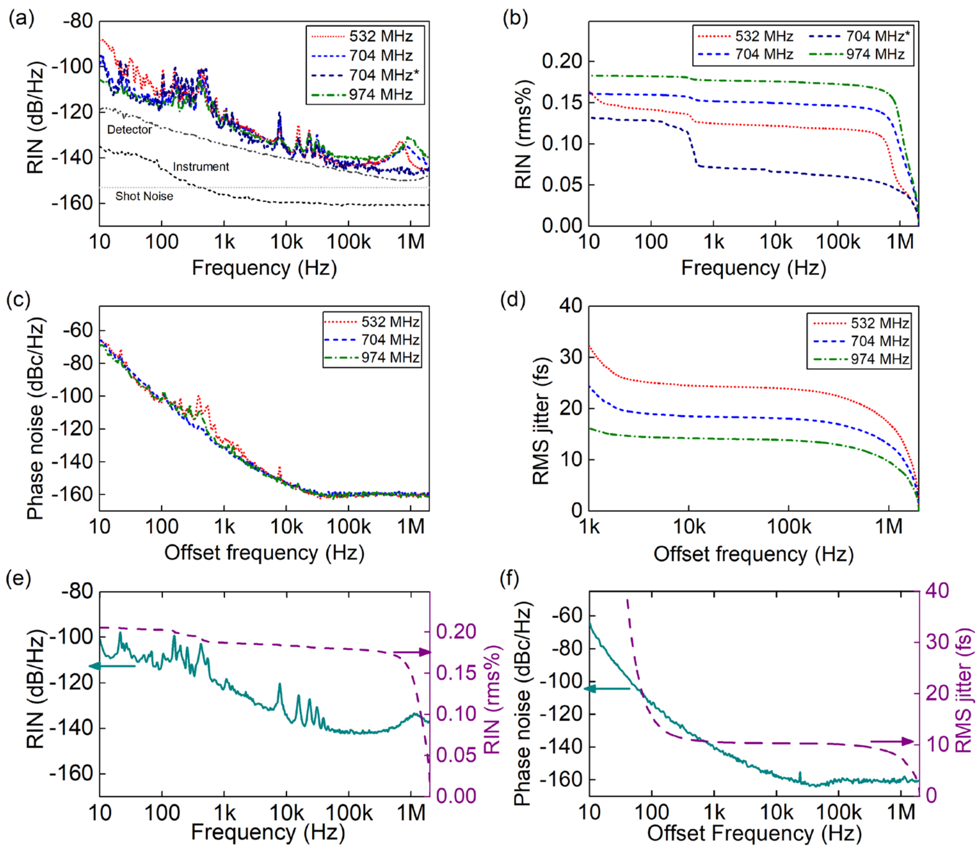

Fig. 5. (a) Relative intensity noise (RIN) of mode-locked fiber laser with a repetition rate of 531.9 MHz (red dotted), 704.3 MHz (blue dashed) and 974 MHz (green dashed dot). RIN of 704.3 MHz laser without hump around 1 MHz is shown (navy short dashed, 704.3MHz*). (b) Integrated RIN of 0.13 %, 0.15 % and 0.18 % respectively [1 kHz, 2 MHz]. The integrated RIN is reduced to 0.07 % for a measurement with a pulse energy of 280 pJ labeled as 704.3 MHz*. (c) Single side-band (SSB) phase noise of lasers from 10 Hz to 2 MHz. (d) Integrated rms timing jitter of 32 fs, 25 fs and 16 fs [1 kHz, 2 MHz] respectively. (e) RIN of 1.25 GHz cavity. Integrated RIN of 0.19 % [1 kHz, 2 MHz] (purple dashed line). (f) SSB phase noise of 1.25 GHz laser. Integrated rms timing jitter of 11fs [1 kHz, 2 MHz] (purple dashed line).

To investigate the output intensity fluctuations of the lasers, the relative intensity noise (RIN) is measured over the frequency range from 10 Hz to 2 MHz, as shown in Fig. 5(a) for 531.9 MHz, 704.3 MHz and 974.4 MHz and in Fig. 5(e) for 1.25 GHz. All meausrements are conducted for an intracavity pulse energy of 170 pJ. The RIN of the photodetector is both above the RIN of instrument (black dashed line) and shot noise (grey dotted line) at a value of −153 dB, but the detector response limits the overall noise measurement for frequencies of 3 MHz and higher. The RIN measurements of the lasers with repetition rates of 531.9 MHz (red dotted lines), 704.3 MHz (blue dashed line), 974.4 MHz (green dashed dot line) and 1.25 GHz (dark cyan solid line) demonstrate good stability, resulting in rms RIN values of 0.13 %, 0.15 %, 0.18 % (Fig. 5(b)) and 0.19 % [1 kHz to 2 MHz] (Fig. 5(e) purple dashed line) respectively, partly limited by the pump noise. Thus, relaxation oscillations from the erbium amplifier around 10 kHz and below 1 kHz are directly imprinted onto the RIN spectrum. Overall, the RIN measurements of all three lasers, recorded for a pulse energy of 170 pJ, show a similar trend, including the humps around 10 kHz due to the noise from the EDFA. With the shorter cavity length, the integrated RIN increases slightly for the free-running system. In the RIN curve a small hump appears around 1 MHz, which is reduced in the same system for higher pulse energies. This is demonstrated for two versions of the 704.3 MHz laser, one labeled with a star* in Fig. 5(a). The latter measurement corresponds to a pulse energy of 280 pJ, which leads to a reduction of the integrated RIN down to 0.07 % compared to 0.15 % for the interval [1 kHz to 2 MHz]. To compare the noise behavior across all lasers for the same pulse energy, a value close to the mode-locking threshold was chosen. However, this measurement indicates that enhanced performance for all lasers can be achieved for higher pulse energies where the mode-locking can be slightly more stable. The integrated RIN amounts to 0.16%, 0.16 %, 0.18 % and 0.21 % for the repetition rate of 531.9 MHz, 704.3 MHz, 974.4 MHz and 1.25 GHz, respectively, when integrating down to 10 Hz. Some of the lower frequency noise can be further suppressed if electronic feedback and stabilization is implemented.

The single sideband (SSB) phase noise of the fundamental repetition rate (531.9 MHz, 704.3 MHz, 974.4 MHz and 1.25 GHz) phase noise of the three lasers is measured with a pulse energy of 160 pJ, as shown in Fig. 5(c) and Fig. 5(f). The timing jitter is integrated from 2 MHz down to 1 kHz and results in an integrated jitter of 32 fs, 25 fs, 16 fs and 11 fs respectively, as presented in Fig. 5(d). With a higher pulse energy for the 704.3 MHz cavity, the integrated jitter can be reduced to 20 fs. This represent a remarkable low timing jitter for high repetition rate lasers. Taking into account the slight shift in center wavelength and pulse duration between the three laser configurations, this trend agrees well with analytical predictions, showing an inverse relationship with the repetition rate for this particular scenario.

4. Conclusion

In a straightforward and compact laser cavity based on soliton mode-locking, passively mode-locked, high repetition rate femtosecond Tm doped fiber lasers with fundamental repetition rates up to 1.25 GHz are demonstrated. By using equal lengths of a highly doped gain fiber (7 cm) for optimized pump absorption, the laser cavities are scaled by the length of passive fiber included in the cavity. Thus, the optical performance of four cavities with fundamental repetition rates of 531.9 MHz, 704.3 MHz, 974.4 MHz and 1.25 GHz is analyzed in great detail, demonstrating that comparable optical performance can be achieved. Unique to this approach is that similar mode-locking thresholds around an intracavity pulse energy of 160 pJ are achieved. While the higher repetition rate fiber laser performance is limited by available pump power in the current set-up, the presented pulse durations can be decreased further with higher pump power so that this provides a scalable approach to generating femtosecond high repetition rate fiber lasers. Additional shortening of the gain fiber is expected to support cavities beyond 1.5 GHz repetition rates with femtosecond pulses, good output power and low noise performance. This can fuel high speed communication, metrology and spectroscopy applications.

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