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Mode-Locking Dynamics in an All-PM Figure-Nine Tm-Doped Fiber Laser

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Abstract: We report a study on pulse dynamics in figure-nine Tm-doped all-polarization maintaining fiber laser. We analyzed laser operation from self-starting with multi-pulse dynamic to single-pulse operation by decreasing the pump power from the mode-locking threshold. By choosing a reliable setting of waveplates, our laser was generating pulses at the central wavelength of 1985 nm with a half-width of the spectrum, pulse duration, and pulse energy equal 6.4 nm, 650 fs, 177 pJ for the output port and 19.2 nm, 1279 fs, 57 pJ for the reject port in the single-pulse state. In the multi-pulse state, we recorded optical spectra, temporal waveforms, and average power at both exit ports. By analyzing temporal traces and output to reject port ratio power, we can distinguish between eight states of operation which follow an exact pattern. In the case of the single-pulse regime, we performed a further laser characterization, including relative intensity noise.

Keywords: fiber laser; mode-locked laser; soliton; nonlinear amplifying loop mirror

1. Introduction

Recent advances and development of Tm-doped fiber lasers have been primarily driven by potential applications of intense and ultrashort pulses at the emission wavelengths in the range of 1.7 to 2.1 µm, which are spectroscopy, material processing, laser surgery, and nonlinear mid-IR generation [1]. Different materials containing Tm³⁺ ions are used as dopants for an active medium in solid-state lasers. In particular, disordered host crystals such as Tm:CALGO, Tm,Ho:CALYO and Tm,Ho:CNGG have been shown to provide smooth and broad emission bands, essential for mode-locked (ML) operation [2–4]. On the other hand, fiber lasers operating at 2 µm are the subject of considerable development as they are compact, maintenance-free, and environmentally stable if polarization-maintaining (PM) architecture is incorporated. Among the commonly used Tm-doped fibers it is worth highlighting two types: Tm-doped single-clad fiber and Tm,Ho-co-doped fiber with a double cladding. Both types can be highly doped with Tm₂O₅ and can be used for continuous wave (CW) and pulsed lasers as well as for amplifiers at 2 µm. The co-doped fibers take advantage over single-clad fibers as energy transfer from Tm³⁺ to Ho³⁺ ions provides a more efficient absorption of pump power. This is the equivalent of a popular Er,Yb-co-doped fiber and is allowing for a higher doping and uniform pump absorption along the fiber to prevent overheating. However, care should be taken to properly design the fiber layers, especially the cladding, to allow both an even distribution of radiation in it and the transfer of the pump from it to the core [5]. Therefore, a typical cladding cross-section has an octagonal shape. Such Tm,Ho-co-doped fibers can be found in both non-PM and PM designs.

Passive methods of ML operation require a saturable absorber (SA) or its equivalent for in-phase synchronization of many longitudinal laser modes [6]. Various material-based SAs such as semiconductor saturable absorber mirror (SESAM) [7], carbon nanotubes [8–10], graphene [11–14], graphene oxide [15], topological insulators [16–18], transition metal dichalcogenides [19,20], and black phosphorus [21] have been used in Tm-doped ML lasers.
At least as much interest is contemporarily devoted to Kerr-lens mode-locking [22] as well as additive pulse mode-locking techniques (APM) [23] such as nonlinear polarization rotation (NPR) [24], nonlinear optical loop mirror (NOLM) [25], and nonlinear amplifying loop mirror (NALM) [26]. APM operation results from coherent interferometric addition of pulses with different phases which depend on their intensity. A phase difference may be the result of any of the following factors: (a) birefringence; (b) a nonlinear phase shift; (c) phase bias. Birefringence-dependent shift is caused by the propagation of each pulse in a different polarization state of a birefringent medium. Effects of birefringence can be omitted once PM architecture, which allows working with linearly polarized beams, is applied. The nonlinear phase shift is induced by a self-phase modulation experienced by the pulses with different intensities propagating in a nonlinear medium via the optical Kerr effect [27]. A phase bias is a power-independent phase shift that can be introduced by a non-reciprocal phase shifter (NRPS) [28]. The usual implementation of NRPS consists of at least one Faraday rotator and a set of waveplates. Such a component shifts the transmission curve of the cavity enabling self-starting operation and is used mainly in all-PM NALM-based lasers in figure-nine configuration [26,29–31]. Shifting the transmission leads to a maximum of the roundtrip transmission for lower intensities and in the case of figure-nine lasers, the most common bias is $-\pi/2$. Liu et al. demonstrated the effect of bias values on the self-starting threshold and the phase noise, concluding that $-\pi/2$ provides the lowest self-starting threshold and highest phase noise value [32]. NALM-based lasers have some advantages over other ML techniques in terms of relatively lower intrinsic noise [33], robustness [34,35], and a lack of coupling between phase and amplitude noise [36]. The latter makes them an ideal candidate in applications such as optical frequency combs. Figure-nine lasers with two exit ports, the output port, and the reject port possess significant differences in the relative amplitude noise (RIN) values between both exit ports [37]. In particular, the output port transmitted by a polarization discriminator possesses lower RIN values than the portion of the radiation that was reflected from it. Moreover, the rejected pulses tend to have a rather complicated optical spectrum and spectral phase [38]. In contrast, our recent studies have shown that for a laser operating in the net-zero dispersion regime (stretched-pulse), both ports can have a flat spectral phase [31]. In the net-normal dispersion regime (dissipative soliton) the reject port can overperform the transmitted port if proper spectral filtering and dispersion map is used [39]. Unlike lasers designed with material-based SAs, NALM-based lasers require a relatively high pumping power to initiate the mode-locking [28,40]. The laser firstly operates in a multi-pulse regime, and then lowering of the pump power is required to obtain single-pulse operation. Multiple pulses propagating in a single cavity tend to interplay with each other. In solitonic fiber lasers, several phenomena of interaction between several pulses are presented [41] such as soliton rains [42,43], soliton molecules [44], multisoliton states such as tightly bunching of soliton molecules [45], and noise-like pulses generation [46]. Tightly bunched solitons separation can be either dense or coarse indicating, in turn, the stability or instability of the state [47]. The second important element from the point of view of the dynamics of the laser operation is polarization. A number of works in which dynamics of laser in the multi-pulse state was manipulated have employed polarization controllers (PCs) and non-PM fiber architecture for this purpose. This resulted in the non-arbitrary laser settings required to operate in a given state as the PC had to be tuned to switch between states. However, in an all-PM laser based on NALM, the dynamics of operation does not depend on polarization since it is linear. Moreover, in their case, there is no concern about damaging the laser since it consists of fibers and optical components, exclusively. This makes the figure-nine laser an interesting test bed for analyzing pulse propagation dynamics in anomalous dispersion regime. Here we present an all-PM NALM-based fiber laser operating around the central wavelength of 1985 nm. We placed a NRPS in the linear arm of the cavity, which simplified the setup in contrast to previously presented oscillators with NRPS placed in the NALM loop. Thanks to the figure-nine configuration, we can observe pulses leaving the oscillator from both output and reject ports. Using the high pumping power ($P_{\text{pump}}$) necessary for
self-starting pulsed operation, we characterize the dynamics of the mode-locked laser from the multi-pulse states down to the single-pulse regime. We show that it is not possible to obtain instantaneous single-pulse operation after turning on the pump of the oscillator. The starting procedure of a NALM laser always requires an overdrive of the pump power to initiate multi-pulse mode-locking, and then gradual lowering of the pump to achieve single-pulsing. We observed eight different operating states of the laser which were controlled solely by the pumping power of the active fiber of the oscillator. We distinguished between these states using both time waveforms and the ratio of average output power between output and reject port.

2. Experimental Setup

The experimental setup is depicted in Figure 1. The all-PM Tm-doped oscillator was optically pumped by a self-made CW laser operating at 1565 nm. The pumping laser was based on a pair of fiber Bragg gratings with reflectivity of 10% and 99%, 2.5 m of Er/Yb-codoped double-clad fiber (Nufern SM-EYDF-6/125), and a multimode fiber-coupled laser diode operating at 976 nm (BWT K976AB2RN-9.000W). The pumping laser delivered up to 1.8 W to the oscillator via the PM wavelength division multiplexer (PM WDM). The entire Tm-doped oscillator was composed exclusively of PM fibers and components. The fiber part of the laser incorporated 1560/2000 nm PM WDM, asymmetrically placed 35 cm of PM highly doped active fiber (Nufern PM-TSF-5/125, $\beta_2 = -20.0 \text{ ps}^2/\text{km}, \text{TDF}$) [11]. We used a C-band Panda-type PM fiber (Nufern PM1550-XP, $\beta_2 = -76.0 \text{ ps}^2/\text{km}, \text{SMF}$) as a passive fiber in the entire cavity [11]. The linear arm was connected with the loop via a fiber-based polarization beam combiner (PBC) and consisted of a reflective-type NRPS. The former combined beams from the loop segment into the free-space segment in two orthogonal polarizations. The latter introduced intensity-independent phase bias between beams via a set including a Faraday rotator (FR), a quarter-wave plate (QWP$_1$), and a half-wave plate (HWP). The fast axis of each of the wave plates corresponds to an angle of zero degrees. In addition, the fast axis of the fiber entering the collimator is parallel to the fast axis of the plates in the zero degrees setting. By adjusting the angle of these waveplates, we changed phase bias, modulation depth, and the ratio of light reflected by the free-space polarization beam splitter (PBS), thus constituting a reject port [48]. By using QWP$_2$ placed between the end mirror and PBS, we controlled the amount of light returning to the loop part and the amount of laser radiation leaving the output port. The total length of the oscillator was 404.5 cm, including 23.0 cm of the free-space segment. Both active and passive fibers possessed anomalous dispersion in the region around 1985 nm, resulting in the net group delay dispersion of approximately $-0.091 \text{ ps}^2$. Regarding the asymmetry of the active fiber placement, between the beginning of the Tm-doped fiber and the end of the collimator there were about 97.0 cm and 226.5 cm for clockwise and counterclockwise directions of propagation, respectively, as shown in Figure 1.
Figure 1. Experimental setup of all-PM NALM-based Tm-doped fiber laser. WDM: wavelength division multiplexer; PBC/PBS: polarization beam combiner/splitter; TDF: Thulium-doped fiber; FR: Faraday rotator; QWP: quarter-wave plate; HWP: half-wave plate; M: mirror, NRPS: non-reciprocal phase division multiplexer; PBC/PBS: polarization beam combiner/splitter; TDF: Thulium-doped fiber; FR: Faraday rotator; QWP: quarter-wave plate; HWP: half-wave plate; M: mirror, NRPS: non-reciprocal phase shifter.

3. Results

In the process of examining the setup, we found several wave plate settings that enabled self-starting ML operation. Once the given setting was found, the wave plates were not tuned, and as the threshold of $P_{\text{pump}}$ was reached, self-starting operation with the central wavelength ranging from 1950 up to 1990 nm proceeded. Different wave plate settings resulted in different central wavelengths of the generated pulses since the phase shift introduced by NRPS depends on the wavelength [30]. For various settings, the $P_{\text{pump}}$ threshold of ML ranged from about 800 mW to about 1860 mW and depended mainly on the setting of the QWP$_2$. Unfortunately, not every setting leads to single-pulse operation by decreasing the $P_{\text{pump}}$. For this reason, we present the results acquired for the angle settings as follows: $\theta_{\text{QWP}_1} = 28.5^\circ$, $\theta_{\text{HWP}} = 90.0^\circ$ and $\theta_{\text{QWP}_2} = 82.5^\circ$, which provided repetitive self-starting and effortless achievement of the single-pulse operation. In this setting, $P_{\text{pump}}$ needed for self-start and single pulse were 980 mW and 405 mW, respectively. We used the following instruments to characterize the source: an optical spectrum analyzer (Yokogawa, Tokyo, Japan, AQ6376, OSA), a 3 GHz radio frequency (RF) spectrum analyzer (Rohde and Schwarz, Munich, Germany, FPL1003), a 6 GHz digital oscilloscope (Agilent, Santa Clara, CA, USA, DSO90604A), an InGaAs high-speed photodiode (Discovery Semiconductors, Trenton, NJ, USA, DSC2-50S), an optical power and energy meter (Thorlabs, Newton, NJ, USA, PM400 and Thorlabs S405C), and an autocorrelator (APE GmbH, Berlin, Germany, pulseCheck 50 USB, AC). To characterize RIN, we used a setup consisting of a 200 MHz oscilloscope (Rohde and Schwarz RTA4004), an InGaAs fixed gain amplified detector (Thorlabs PDA10D2, PD), and a 4 MHz low-pass filter. The results of single-pulse operation at a $P_{\text{pump}}$ of 405 mW are shown in Figure 2. For the output port, the laser emits pulses centered at 1985 nm with 6.4 nm of the full width at half maximum (\(\Delta \lambda\)) bandwidth (without taking into account the Kelly’s sidebands [49]), 650 fs pulse duration and 177 pJ energy. From the reject port, pulses with 19.2 nm \(\Delta \lambda\), 1.28 ps and 57 pJ were generated. The \(\Delta \lambda\) was determined including the dip inside the spectrum (visible in Figure 2b).
To investigate the noise properties, we measured the RIN of the free-running laser and integrated it in the range from 10 Hz to 488 kHz. The results are shown in Figure 3. Integrated RIN in this range is 0.29% and 0.98% for output and reject port, respectively. As our setup was not stabilized either thermally or via electronic locking methods, the RIN levels were relatively high compared to other ultrafast oscillators employing NALM in figure-nine architecture [26,30,37,50]. However, our goal was to compare integrated RIN values between exit ports for the solitonic laser operating at around 2000 nm. In the case of the reported oscillator, the integrated RIN value is over 3 times lower for the output port than in the case of the reject port. Interestingly, the output port reigns supreme over the reject port in all measured parameters but the optical spectrum bandwidth, which was 3 times narrower. The difference in characteristics between ports can be explained by the operating principle of the APM technique in which the coherent addition of pulses can, in a way, be treated like a Mach–Zehnder interferometer. The intensity-dependent phase changes to be experienced by pulses counterpropagating in the amplifying loop as a result of self-phase modulation. The phase shift in the nonlinear medium is selected so that the pulse maxima interfered constructively causing an increase in pulse intensity. This causes the transmitted pulses (output port) to have a higher peak power value. On the other hand, the non-transmitted part (reject port) consists of this radiation that interfered destructively. Since pulse slopes are characterized by lower peak power than the central peak, the radiation at the reject port generally takes the form of two local maxima between which there is a dip, which is the case with our oscillator [27,38]. The results are consistent with earlier studies, mainly with lasers operating at 1000 and 1550 nm [30,38,51]. It can be noticed that the highest increase in RIN value covers the frequency range below 25 kHz, similarly to the laser presented in [52].

Figure 2. Measured single-pulse operation characteristics. Optical spectrum at the output (a) and reject (b) port. Autocorrelation trace with sech² fit at the output (c) and the reject (d) port. RF spectrum of the first harmonic (e) and the broad spectrum of harmonics in the 3 GHz span (f), measured with resolution bandwidth 50 Hz and 1 kHz, respectively.
The combination of an artificial SA with a negative GDD value and an all-PM configuration resulted in the ability to control the dynamics of laser operation with a change of $P_{\text{pump}}$ exclusively without changing the settings of the absorber itself. This situation is typical for ML lasers based on artificial SAs such as NALM or NOLM. Self-starting occurs with relatively high $P_{\text{pump}}$, thus leading to multi-pulse operation. Then, as a result of decreasing the value of the $P_{\text{pump}}$, transitional stages of operation are produced to reach a single pulse in the cavity as the last step. To monitor the dynamics of the laser over the entire range of $P_{\text{pump}}$, we analyzed oscillograms and optical spectra for each $P_{\text{pump}}$ value. We decided to present these results for the output port as it was particularly steadier than the reject port in terms of RIN value. Given the use of all-PM and NALM configurations, we ensured the lack of polarization state influence on the dynamics. This allowed us to reach states that are purely pumping power-driven. We recorded 8 different states of pulse operation whose transitions occurred after exceeding a certain value of $P_{\text{pump}}$ and were characterized by a slight hysteresis. However, the reproducibility of changes between states and the patterned response of the system to pump manipulation aroused our interest and resulted in an attempt to investigate its behavior. The results of our observations are shown in Figure 4.

The dynamic of pulse-state changes was not repeatable, meaning each time the laser was turned on, the transition from multi-pulse to single-pulse operation was not identical, but it followed a certain pattern. In high $P_{\text{pump}}$ states ($750 \text{ mW} < P_{\text{pump}} < 980 \text{ mW}$) the laser pulse operation changes in time without modulation of $P_{\text{pump}}$. The three states obtained from the self-starting power to around 750 mW are characterized by packets of pulses irregularly spaced between the fundamental pulses given by round-trip-time. We have been able to observe three different patterns of 8 pulses of similar amplitude (black waveform in Figure 4), 1 main pulse and 6 additional ones (red), and 1 main and 5 additional pulses (green), successively. Interestingly, upon closer analysis of the divergence times in pulse positions (over 11 consecutive round trips) we did not note significant pulse drift for the 980 and 750 mW $P_{\text{pump}}$ (Figure 5). The stability of the separation indicates the previously observed phenomenon of densely bunched solitons, although in previous work, changing between states most often also requires changing the pumping power of the active fiber [46,47]. This means that our laser generates a condensed soliton phase state on a small time scale.
Figure 4. Optical spectra (left) and recorded oscillograms (right) for eight different laser operating states corresponding to given pumping power.

Figure 5. Successive temporal traces show a lack of drift among pulses in states: (a) 8 pulses; (b) 5 + 1 pulses.

With a decrease of $P_{\text{pump}}$ below 750 mW, we observed states in which individual pulses traveled at equal and fixed intervals between each other. We first noticed a condition in which three additional pulses appear whose amplitudes are close to the fundamental pulse and propagate at a distance of about 5.8 ns from each other. The triple-pulse emerged at 566 mW of $P_{\text{pump}}$ and exhibited a pulse separation of 2.0 ns. This state was significantly rare, only occurring once every 20 courses of pump decrease. The double-pulse operation occurred at around 450 mW of $P_{\text{pump}}$ and was far more common. Here the pulse separation was equal to about 2.8 ns. Since the distances between pulses in all the described states were not constant, none of them can be classified as harmonic mode-locking. The last among observed states was a single-pulse operation. After reducing the $P_{\text{pump}}$ below double-pulse operation (428 mW), we have been reaching single-pulse with CW spectral component located at 1972 nm. The CW component was close to the first-order Kelly sideband on the shorter-wave side. Further reduction of power to 405 mW resulted in the disappearance of the CW component. Measured optical spectra were unstable for higher $P_{\text{pump}}$ and changed rapidly irregularly. With the decrease of pump power, the center wavelength
shifted unpredictably in both directions. However, for weaker pump powers (<474 mW) the direction of movement of the center wavelength was towards shorter wavelengths, with a sudden “jump” towards longer wavelengths when the single-pulse operation (without CW) was achieved. Important notice is that the optical spectra of other stable states such as double or triple pulses remained stable during each run. A very interesting detail is visible during the double-pulse and 1 + 3 pulses operation of the laser, where the optical spectrum exhibits an increase in the number and compaction of Kelly sidebands. The Δλ of measured spectra has remained consistent along the entire measurement, although the broadest spectrum at output port was recorded for single-pulse (on par with the state of 5 + 1 pulses) and equal to 6.4 nm, while the narrowest spectrum belonged to the state of 1 + 4 pulses. The Δλ of the optical spectra on the reject port also was not significantly fluctuating and approximated 19 nm.

For the next step of analyzing the dynamics of laser operation as a function of P_{pump}, we used the power division ratio between the two exit ports. The states of operation were not repeatable every time. However, during observation, we came across a kind of schematic of laser operation which was dependent on the state of self-start dynamics, i.e., the state of operation after self-start dictated the pattern in which the dynamics of laser operation changed up to a single pulse. The results presented in Figure 6 correspond with the measurements in Figure 4. Since we did not want to consider the hysteresis of the system which has already been analyzed in other works [53,54], we decided to measure the split ratio in the case of gradual reduction of P_{pump} from self-start to a single pulse, and thus within one complete measurement. Analyzing the values of this distribution ratio, it can be found that as the P_{pump} decreases, the difference between the average power measured at the output port versus the power measured at the reject port increases. The only minor deviation is the border between the state of 1 + 6 pulses and the state of 1 + 5 pulses. Despite the higher average power at the output port in each operating state, the relative advantage ranges from 1.5 dB to 5.5 dB over the reject port. One can clearly see the difference between the various states which is highlighted by the power ratio. Certainly, its value is higher for smaller P_{pump}, i.e., fewer pulses in the cavity. Interestingly, for single-pulse operation, the difference in output power increases by more than 1 dB compared to single-pulse operation with an additional CW component.

![Figure 6. The power ratio between output and reject port.](image-url)
4. Discussion

The ability to evaluate pulse dynamics as a function of $P_{\text{pump}}$ in all-PM artificial SA-based ML fiber laser has become even more needed now with the rapid development of robust setups and their industry-level applications [26,34,55]. Unlike many previous works [42–46,53,54,56], we focused on studying the dynamics of a laser with a linearly polarized beam in which the only variable at fixed parameters of the SA is $P_{\text{pump}}$. We were able to isolate the dynamics of laser operation from the polarization state of the beam, thus neglecting the non-arbitrary introduced by a PC. To obtain informative data about our laser in the single-pulse regime, we characterized a number of its properties shown in Figures 2 and 3. Pulse durations directly from the oscillator were 650 and 1279 fs for output and reject port, respectively. Based on measurements of optical spectra and autocorrelation, time-bandwidth product 0.316 and 1.859 values were derived for output and reject port, respectively. Assuming the typical shape of a conventional optical soliton, we found that pulses from the output port were very close to the limit defined by the transform while pulses from the reject port had a non-zero chirp. Additional noise analysis confirmed both the comparatively satisfactory noise properties of the oscillator and the differences in performance between the output and reject ports. The 0.29% result for the output port is comparable to other lasers operating at similar wavelengths and using similar ML mechanisms [52,57]. It implies that the presented laser can be used in the future as a low-noise seed laser for ultrashort pulse amplification systems [58]. On the other hand, in order to maximize the energy of the generated pulses, it would be necessary to replace the active single-clad fiber with Tm,Ho co-doped fiber with a double-clad. Holmium ions used as a sensitizer would provide higher efficiency of pumping. Regarding a further integration of the setup, it would eliminate the free-space optics components and could significantly reduce the inherent noise level which, in the case of our laser, increases very rapidly for frequencies below 25 kHz.

In the second part of our investigation, we studied the pulse dynamics. As NALM-based lasers require a high $P_{\text{pump}}$ for self-starting, we focused our attention on possible scenarios of multi-pulse ML operation. We demonstrated eight different states that, despite similar optical spectra, differed in the relationship between the average power at the two ports and the waveforms recorded on the high-speed photodiode. Solitons propagating together in a cavity can self-organize, or the distances between them can change between passes through the cavity. We observed states that are not stable in the long term, but solitons form a condensed phase in the short term. Interestingly, in states with lower $P_{\text{pump}}$, we could observe additional solitons equidistant from each other. By analyzing the power ratio between the output and reject port, we were able to distinguish both the different states of laser dynamics and, more importantly, the changes between these states. This technique cannot determine precisely how many pulses are propagating in the cavity at any given time, but it can be a diagnostic clue for figure-nine architecture lasers. From the perspective of repetitive laser self-starting, knowledge of potential intermediate states can be crucial. Transitions between different states can introduce disturbances in the dynamics (e.g., collisions) which can cause loss of ML. From a practical point of view, the most desirable is a single-pulse operation (perhaps even with a CW component) immediately for $P_{\text{pump}}$ threshold. Unfortunately for NOLM/NALM-based lasers, this is not achievable in anomalous dispersion. While this behavior is common in dissipative systems such as net-normal and stretched-pulse regimes [29,31], lasers in the soliton regime tend to transition into multi-pulse mode due to the area theorem limiting single soliton energy [59]. In the context of the Tm-doped fiber laser, this is one of the key issues, because both passive and active fibers in the spectral range around 2000 nm have anomalous dispersion which causes the formation of optical solitons unless dispersion compensation is applied [25,60,61]. Without the use of specially designed normal dispersion fibers or intra-cavity compressors, any laser based on artificial SA will exhibit dynamics similar to that presented in this paper. Such dispersion management is a preferable tool to avoid build-up dynamics for lasers with artificial saturable absorbers such as NALM as self-starting in the form of a single pulse.
with a CW component is observed in both stretched-pulse and net-normal regimes [29,31]. At the same time, shifting the regime towards net-zero dispersion broadens the optical spectrum, allowing pulses of the shortest possible duration and the highest peak power while providing the narrowest carrier to envelope phase linewidth.

5. Conclusions

In summary, we have demonstrated an all-PM Tm-doped femtosecond fiber laser based on figure-nine architecture. We characterized the single-pulse operation state as well as the workflow from launch to achieve a single pulse. We have developed a laser oscillator layout operating at a repetition rate of 52.4 MHz and generating pulses at the central wavelength of 1985 nm with a half-width of the spectrum, pulse duration, and pulse energy of 6.4 nm, 650 fs, 177 pJ for the output port and 19.2 nm, 1279 fs, 57 pJ for the reject port in the single-pulse state. We established a plurality of intermediate states that are related to each other by varying the number of pulses propagating in the cavity and the ratio of the average power measured at the two exit ports. In the single-pulse mode, our oscillator provides sub-picosecond pulses with hundreds of pJ of energy per pulse from the output port, which in the next stages of our laser system development can be amplified and used as a seed for nonlinear conversion.

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