Recent advance of high-energy ultrafast mode-locked oscillators based on Mamyshev mechanism with different starting modes

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Abstract The nonlinear effect of fiber limits the further increase in pulse energy, and Mamyshev oscillator shows outstanding advantages in managing nonlinearity in waveguide medium, which is now associated with high peak power and high pulse energy. The potential applications of these laser sources based on Mamyshev mechanism have facilitated aggressive research and innovative ideas by researchers around the world. Here, we focus on the mode-locked principle and starting dynamics of Mamyshev oscillator. The review of Mamyshev technology is summarized from two starting modes of seed source injection and self-starting. Initial research and significant progress in this field, plus new insights and challenges of Mamyshev oscillator for ultrafast fiber laser technology are analyzed. © *2022 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.61.12.120901]

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1 Introduction

High-energy ultrafast mode-locked lasers hold great potential in many applications including nonlinear microscopy,[1,2] laser micro-machining,[3,4] and frequency comb.[5,6] Compared with the active mode-locked operation, passive mode-locked technology is simpler and more effective to generate ultrashort pulses. To obtain ultrashort pulse output, real material-based saturable absorbers (SAs) and artificial SAs especially based on the fiber nonlinearities have been employed as an efficient approach to realize mode-locking operation in ultrashort lasers.[7–9]

The material-based SAs, such as semiconductor saturable absorber mirrors[10,11] and various kinds of low-dimensional materials,[12–16] have become the most prevalent SAs in mode-locked fiber lasers. However, they have relatively low damage thresholds and lifetimes, which will limit the output performance of lasers. In recent years, nonlinear multimode interference technology based on graded-index multimode fiber overcomes existing deficiencies of the present SAs, however, it requires a seriously specific length of nonlinear multimode fiber.[17–19] nonlinear polarization evolution (NPE) has low environmental stability,[20–22] and nonlinear amplifying loop mirror cannot be easily self-starting.[23–25] Because the modulation depth of these traditional SAs is difficult to exceed 70%, all the above mode-locked devices belong to the non-ideal SAs. Recently, the excellent performance of the Mamyshev oscillator has attracted lots of attention. The Mamyshev oscillators have unique stepped transmission curves with very high modulation depths, which are necessary for high-energy mode-locked lasers.

This paper reviewed the recent advance of Mamyshev mode-locked technology. The theoretical principle of Mamyshev oscillator was first introduced. Then, we reviewed the latest technology innovation path of Mamyshev oscillator from two starting modes of seed source injection and self-starting. In addition, the self-starting technologies were divided into several types, including pump modulation mechanism, filter-tuning mechanism, the method of adding a

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starting arm, and NPE-based mechanism. The comparison between different techniques from the perspective of the parameters was also analyzed and discussed. Finally, we pointed out the limitations of Mamyshev mode-locked technology and its development direction in the future.

2 Theoretical Principle of Mamyshev Oscillator

The concept of mode-locked laser based on NL frequency broadening and spectral filtering effect was proposed as early as 1994, but it did not attract enough attention at that time.[26] In 1998, Mamyshev from Bell Laboratories described the simple all-optical regeneration technique based on NL frequency broadening and spectral filtering effect.[27] He defined this structure as an optical regenerator, and this so-called Mamyshev oscillator drew lessons from the pulse regeneration technology of Mamyshev regenerator (MR) in optical communication. When MRs were used during signal transmission in optical communication, the purpose was to improve signal quality and avoid severe signal attenuation.

The MR consist of a spectral filter and a segment of NL fiber, and its working principle[28] is shown in Fig. 1. When the launched pulse with central frequency of ω_0 propagates through a NL medium, it will experience self-phase modulation (SPM), leading to spectral broadening. After that, it will encounter a bandpass filter with central frequency of ω_f that is offset from the pulse's central wavelength ω_0. Crucially, the offset means the filter has little overlap with the initially launched spectrum, restricting the passed light to only that which is newly generated with central frequency of ω_f through SPM.

As shown in Fig. 2(a), the typical Mamyshev oscillator consists of two cascaded MRs. When gain fibers and output couplers are added between the two MRs, the distinction between the two

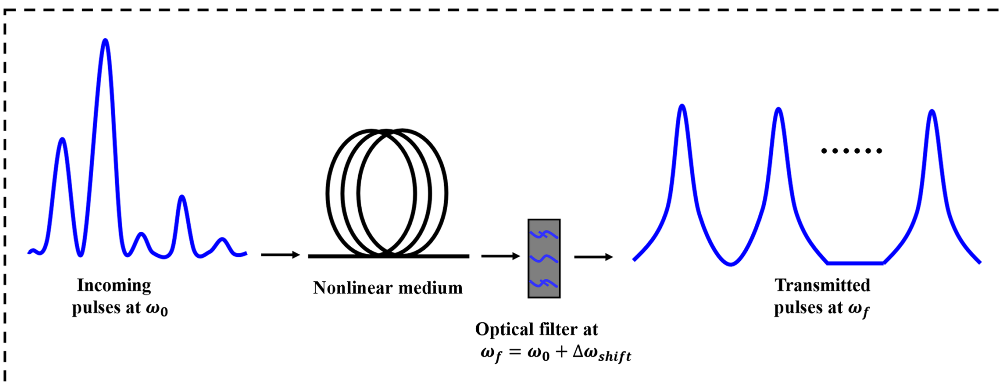

Fig. 1 Schematic of a single-pass MR.[28]

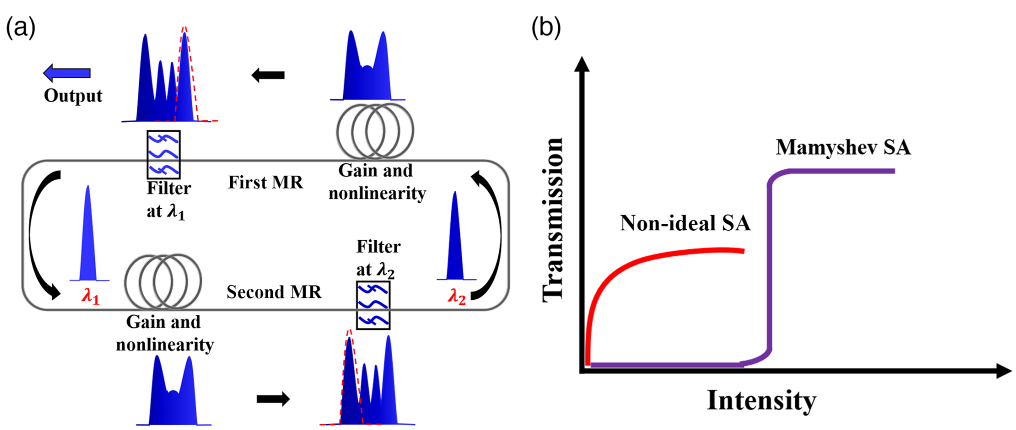

Fig. 2 (a) Schematic of a Mamyshev oscillator[29] and (b) comparison of Mamyshev SA and traditional non-ideal SA.

arms (first MR and second MR) in the cavity becomes obvious. A key feature of Mamyshev oscillator is that the transmission curves of filter1 and filter2 are offset and do not overlap. The high-intensity pulse produces sufficiently large spectral broadening and NL phase in each arm to bridge the spectral interval between the two filters. The low-intensity pulses produce insufficient SPM to pass through the offset filters, which effectively suppresses noise continuous wave (CW) lasing. Pulse tends to stabilize during repeated passes through two cascaded transmission spectrum offset filters. In this process, the transmittance of the cascaded MR system is related to the light intensity, so this system can act as an effective SA. Mamyshev oscillator ultimately produces a step-wise transfer function that passes high-intensity pulses while extinguishing those below a certain intensity threshold.[28] Figure 2(b) shows the transmittance curves of Mamyshev SA and traditional non-ideal SAs, respectively. The filtering characteristics of the former are nearly perfect. Theoretically, the modulation depth of the laser can reach 100% if the offset ranges of the two filters do not overlap.

Based on the above analysis, the pulses experience pulse amplification, spectral broadening, and spectral filtering processes in the Mamyshev oscillator. Finally, mode-locked pulses with high peak power and short pulse duration are obtained. It must be admitted that the Mamyshev oscillator is excellent at suppressing noise, however, the reverse problem will also arise: that of enabling starting. At present, there are two ways to start the Mamyshev laser, seed-source starting and self-starting. The next section focuses on the latest research results of fiber Mamyshev oscillators based on different startup modes.

3 Mamyshev Oscillator Based on Seed-Source Starting Mode

Due to the high suppression of CW lasing for the Mamyshev oscillator, it is extremely difficult to achieve a self-starting mode-locked state from noise. External seed source is a common method to realize the startup of Mamyshev oscillator. After realizing stable mode-locked, the seed source can be closed, and the oscillator can continue to work steadily.

In recent years, the research of Mamyshev oscillator mainly focused on Yb-doped oscillator. In 2015, Regelskis et al. demonstrated a polarization maintaining (PM) Yb-doped Mamyshev oscillator based on SPM and alternating spectral filtering. As shown in Fig. 3, the starting lasers can be achieved by injecting initial seed pulses through the output1/seed port. Pulses with the energy up to 2.8 nJ at 1060 nm were achieved experimentally and the pulse width reached the order of femtosecond (fs) after being compressed by the grating.[30]

The peak power of multi-megawatt level was achieved in the Mamyshev oscillator in 2017. Numerical simulations revealed the process of the pulse evolution and indicated that (after external linear compression) peak powers up to 10 MW were possible from an ordinary single-mode fiber. Experimentally, the laser yielded stable pulse trains with the pulse-width of 40 fs, the peak power of 1 MW, and the pulse energy of 50 nJ.[31] At the same time, Fu et al. demonstrated a fiber amplification system based on a gain-switched diode seed. The MR achieved the pulse compression and improved laser coherence. The laser can generate nearly transform-limited 140-fs pulses with 13-MW peak power—an order-of-magnitude improvement over previous gain-switched diode sources.[32] In 2019, Repgen et al. presented a Mamyshev oscillator-amplifier system, as shown in Fig. 4(a). The spectrum of Mamyshev oscillator and amplifier, shown

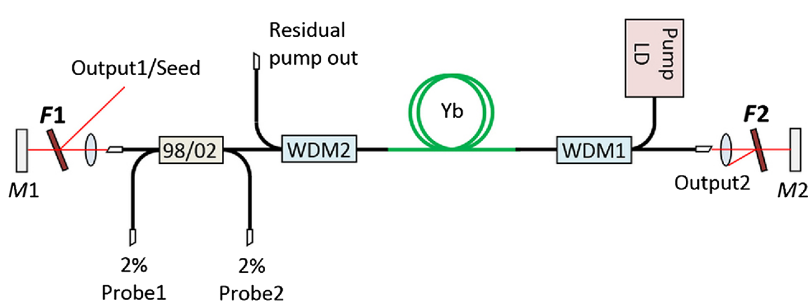

Fig. 3 Schematic diagram of the ultrashort pulse fiber generator.[30]

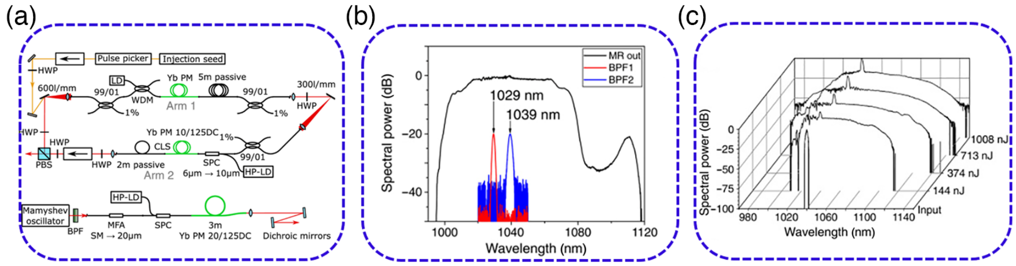

Fig. 4 (a) experimental setup of the Mamyshev oscillator and the amplification arm; (b) output optical spectrum and the transmission spectra of the BPFs of Mamyshev oscillator; and (c) the optical spectrum of the input and the amplified signal of the amplification arm.[33]

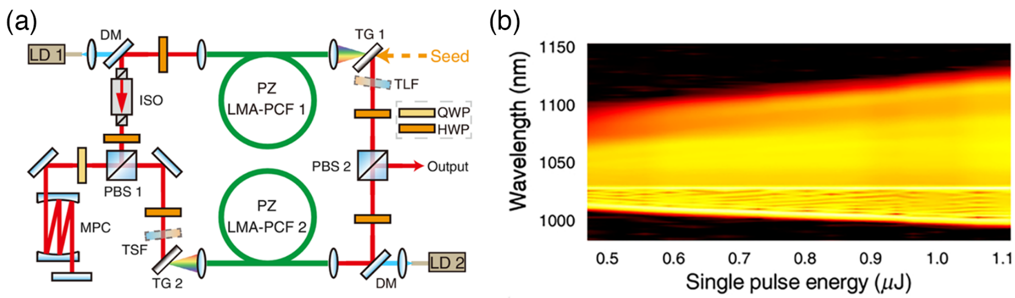

Fig. 5 (a) Schematic of the polarizing LMA-PCF Mamyshev oscillator and (b) evolution of the output spectrum with the increase of pulse energy.[34]

in Figs. 4(b) and 4(c), is very smooth without a sign of NL distortions. For the Mamyshev oscillator, the output power is about 332 mW and the single pulse energy is about 31 nJ. By balancing the gain-narrowing effect with SPM during amplification, the pulse width after compression and the corresponding pulse energy are sub-50 fs and 1 μJ, respectively.[33] For higher energy laser output, Liu et al. demonstrated a high-peak-power Mamyshev oscillator based on the Yb-doped single-mode polarizing large-mode-area photonic crystal fibers (LMA-PCF).[34] As shown in Fig. 5(a), arranged filters were used properly, and the Mamyshev oscillator directly reached 9 W of average power at an 8 MHz repetition rate, corresponding to 1.1 μJ pulses. The output pulses are extracavity de-chirped down to 41 fs with 13 MW peak power. Figure 5(b) shows the evolution of the output spectra. As the single-pulse energy increases with the pump power, the pulse spectrum broadens monotonically.

Gain competition is a difficult problem in traditional multi-wavelength lasers, because sharing gain fiber will lead to crosstalk between wavelengths. In 2020, Li et al. designed a synchronous spectral overlapping multi-wavelength pulsed fiber laser based on Mamyshev cavity. The laser uses a multi-stage cascade MR, and multiple laser light waves with different wavelengths occupy different modules respectively. This single-cavity ring structure solved the problems of gain competition and difficulty in synchronization output of traditional multi-wavelength lasers. Through numerical simulation, the output of four wavelengths with the central wavelength of 1035, 1040, 1045, and 1050 nm were achieved, as shown in Fig. 6.[35]

The micromachining efficiency of the material surface treatment process usually depends on the number of laser pulses in the pulse window, so controlling the repetition rate of the oscillator is very important for the emerging laser pulse micromachining. It seems beneficial to achieve the harmonic mode-locking (HML) regime in the Mamyshev oscillators, as it could help to scale up the pulse energy in conjunction with high repetition rates and short pulses, as well as help to achieve better environmental stability. In 2020, Piechal et al. presented the first observation of HML in the all-PM-fiber Mamyshev oscillator. The laser emitted 2 nJ pulses with repetition rate up to 229 MHz at 14th harmonic, limited by available pump power.[36] Additionally, they discussed the mechanism of HML in detail, and the HML mode was found to be caused by gain depletion and recovery effect. The oscillator's repetition rate was tunable from 16 to 305 MHz,

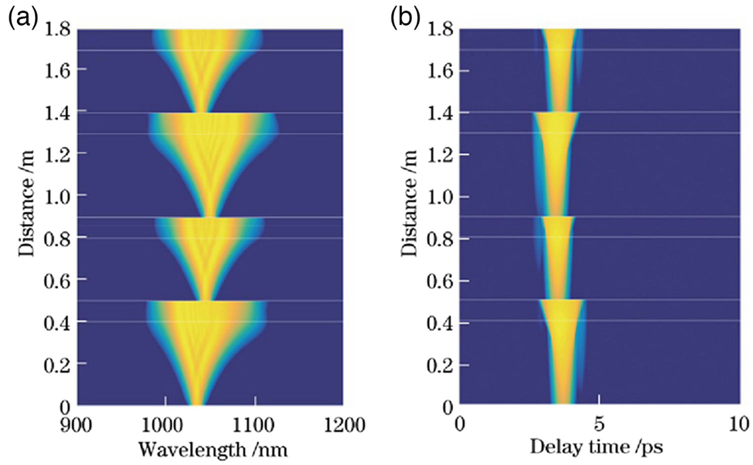

Fig. 6 The pulse evolution diagram of multi-wavelength laser.[35] (a) The spectrum evolution of multi-wavelength laser; (b) the time domain evolution of multi-wavelength laser.

where the repetition rate of 305 MHz was the 19th HML pulses.[37] At the same time, Poeydebat et al. also presented the experimental demonstration of high-order HML of an all-fiber Yb-doped Mamyshev oscillator. The maximum pulse energy of 2.8 nJ was obtained with an uncompressed pulse width of ∼30 ps. The oscillator generates pulses with an average power of more than 100 mW at the fundamental mode-locked repetition rate (7.7 MHz), and 1.3 W at the 14th harmonic (107.8 MHz).[38,39] Techniques for higher-order harmonic mode locked from Mamyshev oscillators remain to be explored.

A variety of special fibers are used in Mamyshev oscillators as NL media for SPM. In 2021, Wang et al. reported an all-fiber Yb-doped Mamyshev oscillator with a segment of 10/125 double-cladding fiber. The maximum output power of 787.3 mW with the single pulse energy of 83.5 nJ was achieved at a repetition rate of 9.43 MHz. The pulse duration could be compressed to 56 fs by a grating pair, corresponding to the peak power of 1.15 MW.[40] In the same time, Repgen et al presented a Mamyshev oscillator that completely consist of commercially available standard step-index fibers with output pulse energies in the range of 0.5 μJ, an optical spectrum ranging from 1010 to 1060 nm, and an externally compressed auto-correlation duration of fewer than 100 fs. To handle the high pulse energies, a few-mode gain fiber (20-μm core diameter) in the second arm of the oscillator was applied.[41] In the next work, a special fiber with a larger core diameter was used for the Mamyshev oscillator. Lin et al. demonstrated a Maymshev oscillator based on a 25-μm core diameter Yb-doped fiber. The presence of higher order mode (HOM) in the LMA Yb-doped fiber could disrupt stable mode-locking and significantly reduce the maximum pulse energy. Therefore, the LMA Yb-doped fiber was coiled with a bending diameter of ∼7 cm and two SMFs were employed as intracavity spatial-mode filters and were placed on either side of the LMA Yb-doped fiber to suppress HOMs. The Mamyshev oscillator directly emits pulses with a peak power of ∼5.6 MW that can be compressed to ∼59 fs, corresponding to a single pulse energy of 625 nJ.[42] The team improved the experimental setup by placing two core diameters SMF with core diameters of 10 and 6 μm behind the grating to form two intracavity spatial mode filters, further suppressing the oscillation of higher-order modes. The pulses could be externally de-chirped to ∼58 fs, leading to a peak power of ∼13 MW at a repetition rate of 14.01 MHz.[43] In 2022, Haig et al. presented a spatiotemporal mode-locked Mamyshev oscillator. The design featured a single-mode arm in the cavity that supported the multi-mode evolution by providing spatial filtering, compensating modal dispersion, and exerting some control over the modal content in the multi-mode arm. Comparison of simulations with experiments indicated that spatiotemporal mode locking (STML) with varying degrees of spatiotemporal coupling was enabled by NL intermodal interactions and spatial filtering, along with the Mamyshev mechanism. This work represented the first exploration of STML in an oscillator with a Mamyshev SA.[44] In the same time, the Mamyshev oscillator again developed new output pulse characteristics. Cao et al. reported experimental and numerical observation of pulsating dissipative solitons in a Mamyshev oscillator operating around 1030 nm. The pulsation was observed in both single-pulse and DS molecule states by controlling the filter separation. Single-shot spectra measured by the dispersive Fourier transform method further enabled the observation of spectral bandwidth breathing and soliton explosion in the pulsation. In addition, pulsation lasting nine round trips and a chaotic pulsation state were observed. The results enriched pulsating DS dynamics and reveal the impact of filter separation on the stability of Mamyshev oscillators.[45,46] Optical vortex beams carrying orbital angular momentum are subject to ever increasing attention due to their relevance and potential for widespread practical application in areas such as optical communications,[47] high-resolution microscopy,[48] quantum information,[49] and macro-/nano-particle manipulation.[50] Lin et al. first realized mode-locked vortex optical output based on the Mamyshev oscillator of few-mode PM Yb-doped fiber in 2022. To achieve intracavity transverse spatial mode selection, the combination of a pair of QWPs and a q-plate with appropriate rotation angles forms an orbital angular momentum (OAM) beam converter that converts a linearly polarized Gaussian-shaped beam into a linearly polarized OAM beam with a controllable topological charge of $l = \pm 1$, or vice versa, as shown in Fig. 7. The ultrafast pulses carrying OAM were successfully generated with an average output power of 5.72 W at 24.35-MHz repetition rate, corresponding to a single pulse energy of 235 nJ. The chirped pulses could be compressed to 76 fs outside the cavity with a pulse peak power of 2.2 MW.[51] Mamyshev oscillator is further developing toward a variety of pulse forms and different transverse modes.

In addition, Er- and Tm-doped Mamyshev oscillators have also been studied. To understand the physical mechanisms in Mamyshev oscillators, Xu et al. investigated the multi-pulse dynamics in an Er-doped fiber Mamyshev oscillator by utilizing the dispersive Fourier transform technique in 2020. It was observed that multi-pulse modes such as bound and randomly distributed states adjust the pump power of the two arms. Due to the unique step-like saturable absorption characteristics of the Mamyshev oscillator, the multiple pulses with significantly different intensities could be still stabilized.[52] In 2022, Zheng et al. were demonstrated an all-fiber Mamyshev oscillator with 83 fs short pulse-duration that the sub-90 fs pulse output was first observed directly from the Mamyshev oscillator output coupler without extra compression. The mode-locked operation was easily initiated when the power of the two pumps exceeded 33.9 and 28.8 mW, respectively.[53] In 2022, Zheng et al. demonstrated an all-fiber Mamyshev oscillator with repetition rate of 6.55 MHz, 20-dB spectral bandwidth of 78.2 nm. The pulse duration of 72 fs and peak power of 86 kW were achieved from output coupler device directly without extra compression.[54] This is by far the shortest pulse duration, the highest peak power Er-doped Mamyshev oscillator. In 2020, Repgen et al. presented experimental results about the generation of ultrashort pulses in the 2 μm wavelength region by a fiber Mamyshev oscillator for the first time. It emitted pulses with energies of 3.55 nJ at 15 MHz with spectral bandwidths of 48 nm.[55] In 2021, the group applied ultra-high numerical aperture fibers with normal dispersion to achieve up-chirped pulses in an anomalous dispersive Tm-doped gain fiber. With that design, mode-locked pulses with energies of 6.4 nJ were obtained at a repetition rate of 16 MHz. The auto-correlation pulse duration could be compressed to 195 fs.[56]

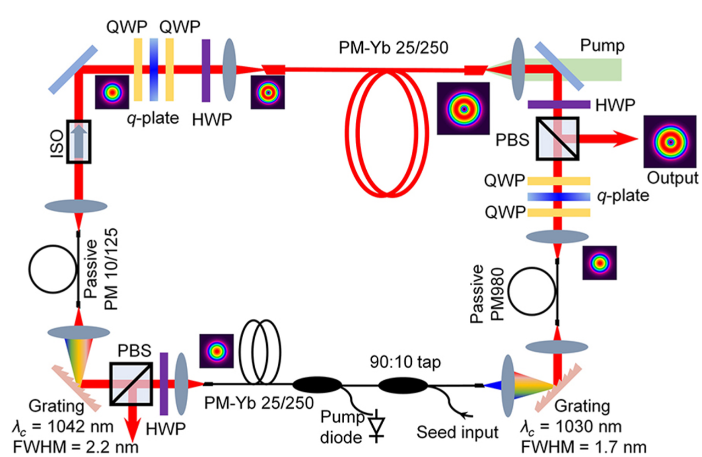

Fig. 7 The Mamyshev oscillator of femtosecond optical vortex beams.[51]

Table 1 The latest key advance of some typical Mamyshev oscillators with seed source injection start mode.

Pulse energy	Peak power	Uncompressed pulse width	Compressed pulse width	Repetition frequency	SNR	Laser typer	Ref
			Yb-doped lasers				
2.8 nJ	15 kWa	3.1 ps	180 fs	14.52 MHz	60 dB	Hybrid	30
50 nJ	1 MW	6 ps	40 fs	17 MHz	80 dB	Hybrid	31
1 μJ	13 MW	—	41 fs	8 MHZ	60 dB	Hybrid	34
31 nJ	0.62 MWa	—	<50 fs	10.84 MHz	76 dB	Hybird	33
2.8 nJ	16.5 kWa	—	170 fs	16 MHz	>70 dB	All fiber	36
2.7 nJ	15.1 kWa	—	179 fs	16.3 MHz	70 dB	All fiber	37
2.5 nJ	—	~26 psa	—	7.7 MHz	>60 dB	All Fiber	38
83.5 nJ	1.15 MW	20.1 ps	56 fs	9.43 MHZ	65.8 dB	All Fiber	40
625 nJ	5.6 MW	5 ps	59 fs	12.8 MHz	–	Hybird	42
1.2 μJ	13 MW	—	58 fs	14 MHZ	76 dB	Hybird	43
235 nJ	2.2 MW	—	76 fs	24.35 MHz	70 dB	Hybird	51
—	—	4.6 ps	—	11.81 MHz	70 dB	Hybird	46
			Er-doped lasers				
—	—	2.9 ps	—	6.87 MHz	54 dB	Hybird	52
0.1 nJ	—	83 fs	—	5.54 MHz	—	All fiber	53
—	86 KW	72 fs	—	6.55 MHz	58 dB	All fiber	54
			Tm-doped lasers				
3.55 nJ	17.1 kW	5 ps	208 fs	15 MHz	84 dB	Hybird	55

[a]Value either calculated, estimated, or read out from a graph, not given directly in the publication.

Today, the peak power of Mamyshev oscillator has reached a megawatt level, which is comparable to that of commercial solid-state lasers. Table 1 gives typical output characteristics of some Mamyshev oscillators with seed source injection start mode in recent years. To achieve the highest pulse energies to date, an even larger filter separation was usually required, which made it difficult for the Mamyshev oscillator to self-starting. Thus, Mamyshev oscillators with seed source injection start mode were usually used, it also has its disadvantages, considering starting the laser requires an ultrashort external seed pulse, which significantly diminishes the attractiveness of the Mamyshev oscillator with seed source injection starts mode as a practical device.

4 Self-Starting Mamyshev Oscillator

As we all know, Mamyshev oscillator can overcome the limitations of NL effects. In fact, only if the nonlinearity is correctly managed, for example, by increasing the filter separation, high-energy, wave-breaking-free pulses can be generated. However, the resulting suppression of low-intensity fluctuations also hinders starting the oscillator from noise. Most studies have focused on how to improve the pulse energy, and these Mamyshev oscillators above all require an external seed source to start, which significantly diminishes the attractiveness of the Mamyshev oscillator as a practical device. As shown in Fig. 8, the Mamyshev oscillators based on different self-starting methods are summarized. These self-starting mode-locked technologies have been proposed, such as modulating pump, tuning filter, adding a starting arm, and utilizing an NPE-based SA to start mode-locked state.

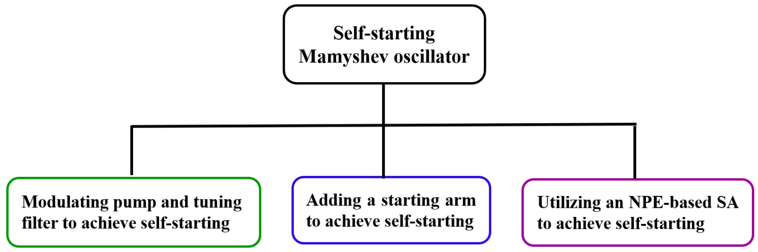

Fig. 8 The different self-starting methods of Mamyshev oscillators.

4.1 *Modulating Pump and Tuning Filter to Achieve Self-Starting*

To achieve the goal of offering excellent performance without requiring an external coherent seed pulse, a self-starting Mamyshev oscillator can be achieved by modulating the pump. This method can be divided into two steps: (a) the filter passbands should be overlapped to initiate lasing and pulse formation; (b) the filter separation should be subsequently increased for evolution to a high-energy single-pulse state. This strategy based on modulation of the pump power allows the noise in the cavity to temporarily the pass filter and be fed back. The detailed starting process[57] is shown in Fig. 9, (1) the laser requires overlapped filter passbands; (2) the pump modulation should be turned on and off to obtain a (possibly multi-pulsing) stable mode-locked state; and (3) the filter separation and/or pump power should be increased to reach a high-energy mode-locked state.

In 2017, Samartsev et al. presented an environmentally stable all-fiber self-starting mode-locked ring oscillator. They used 20-kHz modulation, which produces Q-switching and utilized crossed bandpass transmittance filters in ring architecture to discriminate against CW lasing. Broadband pulse evolves from cavity noise under amplification, after passing each filter, causing strong spectral broaden. It generated transform-limited spectrally flat pulses of 1- to 50-nm width at 6- to 15-MHz repetition rate and pulse energy 0.2 to 15 nJ at 1010 to 1080-nm CW laser. But the researchers of IPG Photonics Corporation were not fully aware at that time that this was the Mamyshev oscillator derived from cascaded regenerators.[58] However, Q-switching state, happening at low modulation frequency, doesn't provide reliable starting. In 2018, Želudevičius et al. presented a thorough investigation of features for a linear Mamyshev oscillator setup. The influence of fiber chromatic dispersion and other parameters of the circuit for stable pulse generation and the characteristics of generated pulses are described by numerical calculations and confirmed by experiments. It is also shown that self-starting can be achieved by setting the filter overlap and increasing the gain of the amplifier under both normal and negligible dispersion settings.[59] In 2020, Chen et al. demonstrated the startling dynamics of a linear Mamyshev oscillator for the first time, which is started by the modulation of a pump. They

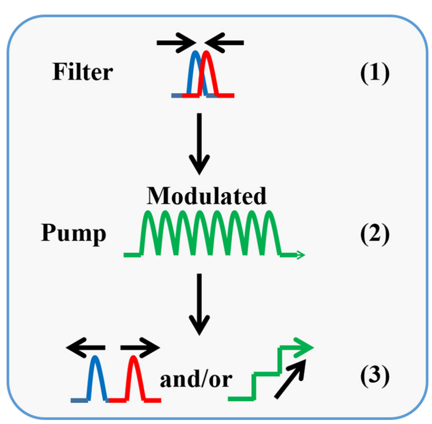

Fig. 9 The starting process of self-starting Mamyshev oscillator with pump modulation and a moving filter.

found a new modulated mode-locked state only at >70-kHz modulation frequency and achieved reliable starting. For this linear-cavity Mamishev oscillator, the success rate for starting is over 99%, and damage from stimulated Brillouin scattering (SBS) is completely avoided. The group further studied the starting dynamics of the linear fs Mamyshev oscillator. As shown in Fig. 10(a), a new design with two Faraday rotators was applied to suppress SBS, and a reliable starting method was realized by a combination of pump modulation and shifting filters. The starting process was automated, with full electronic control. The laser delivered 21 nJ pulses with the pulse duration of 65 fs, and the spectral bandwidth of single-pulse reached 90 nm, which was shown in Fig. 10(b). As shown in Fig. 10(c), the mode-locked state showed 83 dB contrast in its RF spectrum.[57,60] In the same year, the timing jitter and the relative intensity noise of a ring Mamyshev oscillator, operating in the fundamental mode-locked regime, were investigated experimentally. The dependence of output pulse characteristics on fiber dispersion, nonlinearity, small-signal gain coefficient of the gain fiber, and filter bandwidth is investigated systematically. Poeydebat et al. found that both the timing jitter and the intensity noise spectra are related to the output power with noise increase close to the loss of the mode-locked state.[61] In 2021, Bednyakova et al. performed a detailed investigation of influence of spectral filtration on the output field dynamics of the ring-cavity Mamyshev oscillator. Floquet stability analysis was used to verify the self-priming possibility and to predict the repetition rate of pulse trains due to Faraday instability. It is demonstrated that a gradual increase of the spectral filters separation leads to rich transient dynamics between multi- and single-pulse generation regimes, including hysteresis phenomena and formation of soliton molecules. In further research, pump power should also be considered as a tunable parameter, leading to even more complicated dynamics.[62] In 2021, Han et al. were investigated systematically the dependence of output pulse characteristics on fiber dispersion, nonlinearity, small-signal gain coefficient of the gain fiber, and filter bandwidth. And Mamyshev fiber oscillator is established with Yb-doped fiber to confirm the credibility of simulation results. An average power of 130 mW is obtained, with a pulse energy of 8.6 nJ.[63] In 2022, Haig et al. have demonstrated a new variation of Mamyshev oscillator that requires only one gain segment and reliably self-starting from pump modulation. This oscillator generates 70 nJ pulses that can be compressed externally to 41 fs. The PM fiber makes

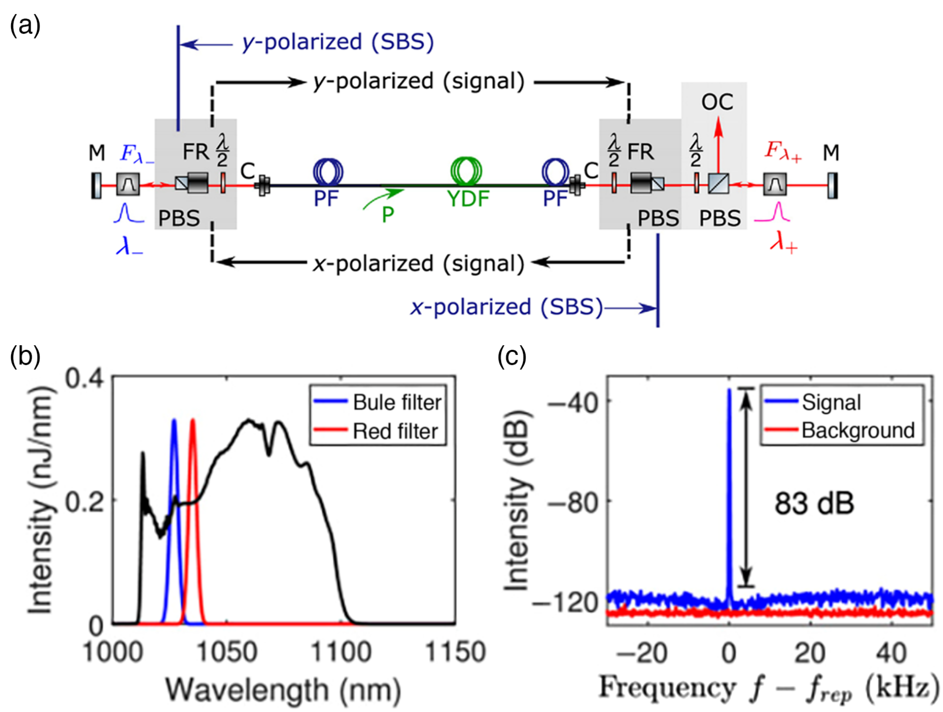

Fig. 10 (a) Schematic of a damage-free linear Mamyshev oscillator with Faraday rotators; (b) spectra of delivered pulses and corresponding filters; and (c) RF spectrum $f_{rep} = 16.1$ MHz.[57]

the laser robust to environmental perturbation, and the design gives a route toward fully fiber-integrated oscillators with pulse energy approaching 100 nJ.[64] In 2022, the group demonstrated for the first time a ring Mamyshev oscillator with a passive arm that enables self-starting operation. The laser generates 110-nJ pulses that compress to 40 fs and 80 nJ with a grating pair The peak power of 1.5 MW is 20 times higher than previous all-fiber self-starting lasers.[65] In 2019, Wang et al. numerically analyzed the pulse pattern formation in 2-μm thulium-doped Mamyshev fiber oscillators, associated with the dissipative Faraday instability (DFI). The periodic frequency detuning of the cavity induces Faraday instability, which further induces the noise to trigger the pulse formation. The steady-state regimes are significantly affected by the frequency detuning between the filters. Regular patterns form via the DFI mechanism when the frequency detuning is decreased to a certain threshold. And the investigations could benefit the applied field of mid-IR multi-GHz frequency comb generation, as well as enhance the understanding of the DFI mechanisms in laser physics.[66]

4.2 *Adding a Starting Arm to Achieve Self-Starting*

Besides pump modulation method above, there is another simple and reliable method for starting Mamyshev oscillator that could generate pulses with megawatt level peak power. The oscillator includes a starting arm, which can create a fluctuating field to start the mode-locked state. The first arm acts mainly as a lower-energy feedback loop for the second arm. Once the Mamyshev oscillator started, the starting arm would be closed and the mode-locked state was stable. When the oscillator restarted, the mode-locked state can be restored by reconnecting the starter arm. With the incorporated starting cavity, the oscillator is self-seeded and environmentally stable in the mode-locked state.

In 2018, Sidorenko et al. demonstrated a fiber Mamyshev oscillator, which can be started by simply flipping a mirror to engage a starting arm. The schematic of the starting arm is shown in Fig. 11(a). An oscillator with this feature generates 35 fs and 190 nJ pulses, for 3-MW peak power. The starting arm and the self-seeding mechanism do not diminish the steady-state mode-locked performance. Numerical simulations suggest that the pulse energy can ultimately be increased up to ∼500 nJ, and the pulse duration can be below 30 fs, resulting in 20-MW peak power.[67] In 2019, Olivier et al. took the first step to extend the operating wavelength of the Mamyshev oscillator to 1.5 μm again. For this fs erbium-doped fiber Mamyshev oscillator, its pulse energy can reach the nano-joule level. The schematic of the starting arm is shown in Fig. 11(b), stable mode-locked is achieved by starting the oscillator through a nonlinear polarization rotation mode-locked mechanism and bypassing one of the filters. The stable pulse trains were generated with energy up to 31.3 nJ, which is comparable to the highest achieved by previous ultrafast Er-doped fiber lasers. The pulses are de-chirped to around 100 fs via a grating compressor.[68] In 2020, Boulanger et al. designed a 1.5 μm PM fiber Mamyshev oscillator based on fiber Bragg grating filters, which can initiate the mode-locked state by adding an external starter arm with SA or another perturbation-inducing mechanism. At the main output, this oscillator generates 31-nJ pulses that can be compressed externally to a duration of 116 fs by a grating pair.[70] In the same year, the group presented a linear cavity self-polarizing PM Mamyshev oscillator at 1550 nm. The cavity filters are chirped fiber Bragg gratings with a Gaussian reflectivity

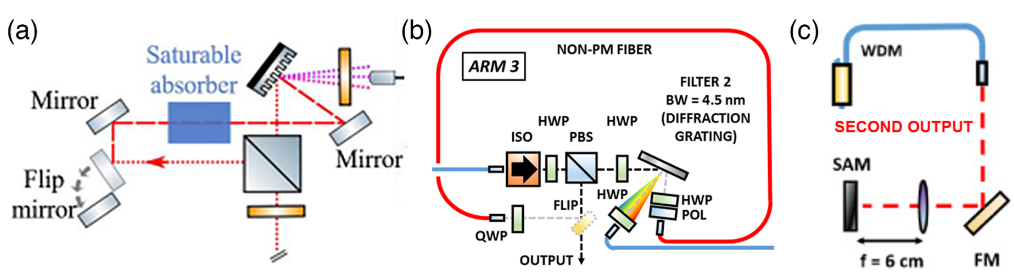

Fig. 11 Schematic of the starting arms: (a) the starting arm containing a SA; (b) the starting arm containing a NPE structure; and (c) the starting arm containing a SAM.[67–69]

profile allowing for larger bandwidth, greater reflectivity, and dispersion control. The mode-locked state is initiated with an external SAM as a starting arm, which is shown in Fig. 11(c). The de-chirped pulses are obtained with a pulse width of 108 fs and with a pulse energy of 21.3 nJ.[69]

Although the self-starting arm does not require reducing the filter separation, mechanical movement of the flipped mirror is undesirable and cannot sustain thousands of movements without optical misalignment, which is not conducive to a wide range of applications.

4.3 *Utilizing an NPE-Based SA to Achieve Self-Starting Mechanism*

Expect for the two above methods to achieve self-starting, we can also utilize an NPE-based SA to achieve self-starting for the Mamyshev oscillator. The starting mode can be triggered easily adjusting the waveplates of NPE-based SA or by adjusting the laser cavity's polarization controller (PC). No external seed pulse laser or auxiliary starting arm is needed to induce mode-locked, and once it is obtained, the pulse train is stable for several hours and can be maintained over a wide range of pump power.

In 2019, Ma et al. demonstrated a Mamyshev oscillator by inserting a high NL PCF in the cavity, which generated a few cycle pulses (five cycles) with broad spectrum (~400 nm). The average output power is 62 mW, and the pulse energy is 3.5 nJ at 17.5 MHz. The autocorrelation showed that pulse duration was about 17 fs after being de-chirped by a 300 lines/mm grating pair. It was also the broadest spectrum generated directly from a mode-locked fiber laser with the shortest de-chirped pulse duration at that time.[71,72] In 2021, Yan et al. experimentally demonstrated an all-normal dispersion Yb-doped fiber Mamyshev oscillator, which was shown in Fig. 12. In the first arm, two $\lambda/2$ plates, a $\lambda/4$ plate, and a PBS serve as an NPE-based SA. The starting of mode-locked operation could be triggered easily by adjusting the waveplates or just by increasing the pump power under suitable parameters of the waveplates and filter spectral separations. Multiple dynamic patterns of pulses were observed including single pulses, bound pulses, and HML pulses at different pump powers and filter spectral separations.[73] Although self-starting is desirable in general, it requires NPE, which relies on non-PM fibers that are subject to environmental perturbations.

In 2019, Luo et al. demonstrated an all-fiber mode-locked laser based on the Mamyshev mechanism operated at 1559 nm. This structure could realize starting mode-locked easily by adjusting the PC or shaking the fiber in the laser cavity. Pulses with maximum energy of 18 nJ and width 230 fs were obtained, which was the highest pulse energy currently available in all-fiber Er-doped mode-locked fiber lasers.[74] As shown in Fig. 13, the Mamyshev oscillator

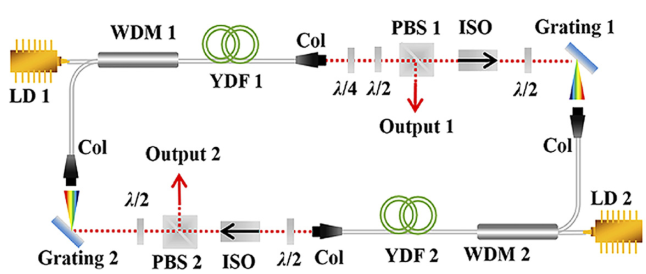

Fig. 12 Schematic of the Yb-doped Mamyshev oscillator based on NPE.[73]

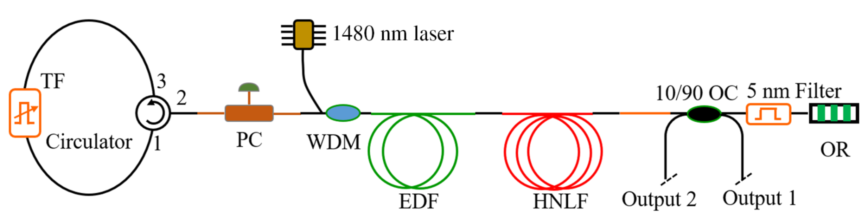

Fig. 13 Mode-locked Er-doped laser based on Mamyshev mechanism.[75]

Table. 2 Output characteristics of some typical self-starting Mamyshev oscillators.

Pulse energy	Peak power	Uncompressed pulse width	Compressed pulse width	Repetition frequency	SNR	Laser typer	Ref
			Yb-doped lasers				
21 nJ	0.32 MWa	—	65 fs	—	83 dB	Hybird	60
8.6 nJ	—	4.16 ps	—	15.18 MHz	~60 dB	Hybird	63
70 nJ	1.7 MWa	—	41 fs	18 MHz	90 dB	Hybird	64
80 nJ	1.5 MW	—	40 fs	—	—	All fiber	65
190 nJ	3 MW	4 ps	35 fs	—	75 dB	Hybird	67
3.5 nJ	0.2 MWa	—	17 fs	17.5 MHz	—	Hybird	72
			Er-doped lasers				
21.3 nJ	95 kW	—	108 fs	8.93 MHZ	95 dBa-	Hybird	69
18 nJ	78.2 kWa	—	230 fs	3.18 MHz	60 dB	All fiber	74
—	—	10 ns	—	0.74 MHz	63 dB	All fiber	75
31.3 nJ	126 kW	—	93 fs	7.35 MHz	70 dBa	Hybird	68
31 nJ	120 kW	—	116 fs	9.25 MHz	—	Hybird	70

[a]Value either calculated, estimated, or read out from a graph, not given directly in the publication.

structure was further modified and a highly NL optical fiber was inserted into the mode-locked fiber laser. A supercontinuum was generated in the range of 1330 to 2030 nm. This is the first intracavity supercontinuum generation in an all-fiber mode-locked laser based on the Mamyshev mechanism.[75]

Thus, the self-starting Mamyshev oscillators above offer simplicity of construction, robust operation, compactness, and require no extra components than the Mamyshev oscillators with seed-source injection starting mode. Table 2 gives the output characteristics of some typical Mamyshev oscillators with the self-starting mode in recent years.

5 Conclusion

As a new mode-locking mechanism, there are many unknown theories and performances of Mamyshev oscillator that deserve further exploration. We have investigated the principle and structure of Mamyshev oscillators with different starting modes. Figure 14 shows the timeline of major advances in the development of the Mamyshev oscillator around the world in recent years. To date, the Mamyshev oscillator can achieve peak power over 10 MW and pulse energy

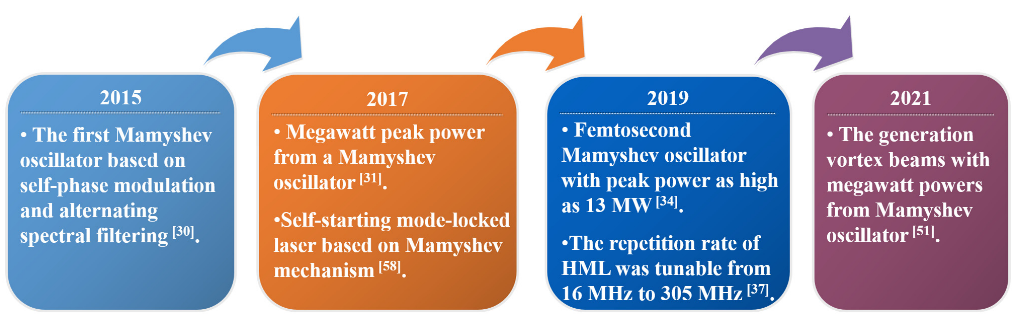

Fig. 14 Major advances of Mamyshev oscillators.

above μJ while maintaining pulse duration in the order of fs. Compared with the traditional mode-locked laser, the mechanism of Mamyshev oscillator is more complex. The cascaded MRs are implemented into the cavity to provide a stronger ability to suppress noise and CW light, which can achieve higher pulse energy and higher coherence degree. Although most of previous Mamyshev oscillators incorporate free-space components, the all-fiber Mamyshev oscillator system has realized starting of mode locking at present, which achieved the output limit of single-mode fiber in the single pulse energy and peak power. Compared with the traditional mode-locked fiber lasers, the pulse peak power of Mamyshev oscillator increase by an order of magnitude.

In the future, all the performance of Mamyshev oscillators will achieve breakthrough from the following aspects: First, the linear-cavity structured Mamyshev oscillators offer simplicity and compactness. In addition, they require fewer components than ring-cavity structured ones. However, to date, linear-cavity structured Mamyshev oscillators with a maximum pulse energy of 21.3 nJ and a minimum pulse width of 65 fs, have not come close to the performance achieved by ring-cavity designs. Breaking through the limits of the linear-cavity will simplify the structure of Mamyshev oscillators and make them more widely used. There are relatively few studies on Mamyshev oscillators based on Er- and Tm-doped, compared with Yb-doped lasers. It is necessary to pay attention to the research of mid infrared Mamyshev oscillator. Finally, special techniques have to be applied to initiate mode-locked state of Mamyshev oscillators, among which are including a seed laser, modulating a pump power, tuning offset filter, adding an external starting arm, adjusting wave plates or PCs. However, these methods sacrifice the mode-locked pulse output performance and laser stability to some extent. Therefore, the start-up technology of the Mamyshev oscillator needs to be further optimized. As we look to the future, we see research value in Mamyshev oscillators, both for laser optimization and for exploration of application areas.

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