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REVIEW

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Ultrafast Raman fiber laser: a review and prospect

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Abstract

Ultrafast Raman fiber laser has been proved to be an effective method to obtain ultrafast optical pulses at special wavelength. Yet, compared with conventional rare-earth doped counterparts, it is challenging for Raman fiber lasers to generate pulses with high pulse energy and short pulse duration. Here, we review three categories of ultrafast Raman fiber laser technologies and give detailed discussions on the advantages and challenges of each. In regards to mode-locking, different saturable-absorbers-based fiber lasers are compared and their common problem resulting from long cavity length are discussed. In terms of synchronously-pumping, several approaches to match the repetition rate of pulsed pump with the length of Raman fiber cavity are discussed, while the technical complexity of each method is analyzed. Moreover, the recently developed technology termed as nonlinear optical gain modulation (NOGM) is introduced, which turns out to be a simple and quality solution to generate high-energy femtosecond pulses with wavelength agility. Compared with the others, NOGM gathers various advantages including simple structure, long-term stability, high pulse energy and short pulse duration, which may effectively promote application expansion of ultrafast Raman fiber laser in the near future.

Keywords: Ultrafast lasers, Raman fiber lasers, Mode-locking, Synchronously-pumping, Nonlinear optical gain modulation

Introduction

Ultrafast lasers, which can generate optical pulses with duration from picosecond to femtosecond range, have been long proposed and studied since the time not far from the first laser demonstration by Maiman [1, 2]. Compared with their continuous-wave (CW) counterparts, ultrafast lasers have advantages in many aspects including short pulse duration, high peak power, and broad spectral width. Therefore, the development of ultrafast laser sources has been considered to have huge scientific impact for the past few decades [3–5].

In recent years, ultrafast fiber lasers have attracted great interest because of their compact structure, good beam quality, easy operation and cost efficiency [6, 7]. In addition, on account of flexible control of nonlinearity and dispersion in optical fibers, ultrafast fiber lasers have also become an ideal platform for studying various pulse shaping mechanisms and ultrafast phenomena [8, 9]. Rare-earth doped fibers are usually used as gain media in ultrafast fiber lasers. However, restricted by the emission spectra of rare earth ions, lasing could only be achieved in discrete spectral ranges. This limits the impact of ultrafast fiber lasers in the applications such as bioimaging, basic scientific research and optical metrology, where pulses with special wavelengths are required [10, 11]. Therefore, driven by those potential applications, it is highly demanded to extend the output spectral range of ultrafast fiber lasers.

Several existing technologies based on nonlinear optical effects in optical fibers can expand the output wavelength of ultrafast fiber lasers, including four wave mixing [12], self-phase modulation [13] and supercontinuum generation [14] et al. Yet, most of them have distinct drawbacks, such as limited spectral tuning range, low spectral power density and critical requirements for dispersion engineering of optical fibers. Compared with them, Raman scattering in optical fibers can effectively overcome the above-mentioned shortcomings. Once pump laser with appropriate wavelength is provided, laser output at any target wavelength within the transparent window of conventional optical fibers can be achieved with high conversion efficiency in near-infrared regime [15–18]. The Raman pulse wavelength could be extended into mid-infrared, or even far-infrared, by using special fibers, for example gas-filled hollow core fibers [19, 20]. Thus, ultrafast Raman fiber lasers have been considered as an outstanding solution to generate ultrafast pulses with wavelength agility. Such lasers have the potential to produce high power laser pulses at special wavelength, which may expand applications in industry and biomedical field as well as for scientific research [21–26]. Besides wavelength agility, Raman fiber lasers have some other advantages, compared with rare-earth doped ones, such as lower quantum defect, higher damage threshold and free of photodarkening [27].

Many methods have been developed with regard to ultrafast Raman fiber lasers, including mode-locking, synchronously-pumping and nonlinear optical gain modulation (NOGM). With the rapid progress in both numerical and experimental demonstration, ultrafast Raman fiber lasers have reached the point where the technology with ever-improving maturity could be used beyond laboratory to excite application blooming in the near future. In this paper, we review the most recent progress in ultrafast Raman fiber lasers. The scope of the paper is mostly focused on three major technologies to generate ultrafast Raman pulses in optical fibers. In Sect. 2, mode-locked Raman fiber lasers with various saturable absorbers are reviewed, and their existing major technology bottlenecks are summarized. In Sect. 3, we overview some works on synchronously-pumped Raman fiber lasers, which can produce high quality ultrafast Raman pulses with some sacrifice on technical simplicity. In Sect. 4, we summarized our recent works on the NOGM-based Raman fiber laser, which has been proved to be a simple and effective approach to generate femtosecond Raman pulses with high pulse energy. In Sect. 5, we overview the most representative applications of ultrafast Raman fiber lasers and give prospect for the developing direction of future technology.

Mode-locked Raman fiber laser

Like conventional rare-earth doped ultrafast fiber lasers, ultrafast Raman pulses can also be obtained by mode-locking. In the study of active mode-locked Raman fiber lasers, acousto-optic modulator was used to offer periodic modulation in a Raman fiber oscillator, in which Raman pulses with duration of few nanoseconds was achieved [28]. The output pulse duration can be optimized to tens of picoseconds by combining with passive mode-locking [29]. As a more commonly used mode-locking methods, passive mode-locking with saturable absorbers (SA) in cavity can provide passive modulation periodically with a modulation frequency that matches with cavity length. This method does not require additional acousto-optic modulators, and to a large extent maintains the simplicity advantages of fiber lasers. The working principle of SA is shown in Fig. 1 The transmission of a SA is intensity dependent: CW laser and pulses with low intensity would experience large loss, while pulses with high intensity would enjoy high transmission. Therefore, in the temporal domain, CW component would be eliminated and pulses would be established. Meanwhile, in the spectral domain, phases between different longitudinal mode would be intrinsically locked. Various SAs have been applied in passive mode-locked Raman fiber lasers, most of which can be classified into two categories: material-based SAs and artificial SAs. Table 1 summarizes the representative performances of mode-locked Raman fiber lasers in recent years.

Material-based saturable absorber

Material-based SAs are widely used to initialize and stabilize ultrafast pulses in fiber oscillators [43–46]. The performance of various material-based SAs has been investigated in Raman fiber lasers, including semiconductor saturable absorber mirror (SESAM) [30], carbon nanotube [31–33] and graphene [34]. For example, Chamorovskiy et al. demonstrated a 1590 nm mode-locked Raman fiber laser, whose experimental setup is shown in (Fig. 2a) [30]. The laser employed a SESAM as the SA and a piece of 450 m long single mode fiber to provide adequate Raman gain in the condition of CW pump. Although pulsed operation was achieved, the generated pulse train has a strong intensity variation (Fig. 2b), indicating poor inter-pulse stability. Castellani et al. reported another 1670 nm ultrafast Raman fiber laser mode-locked by carbon

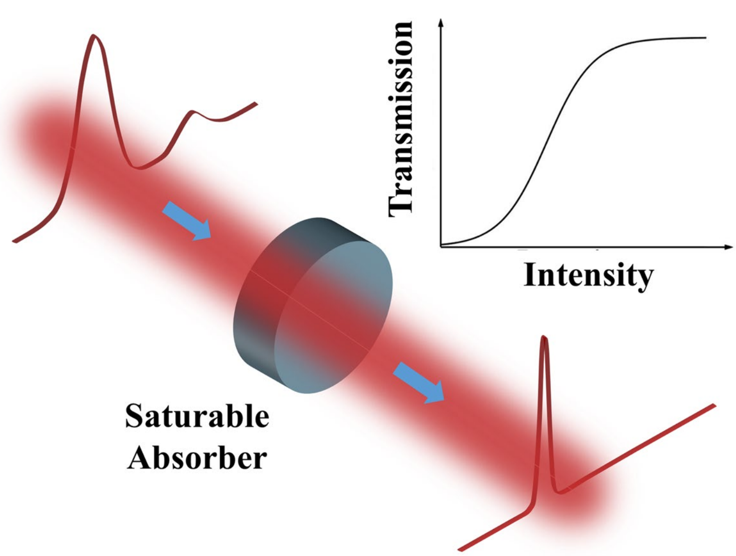

Fig. 1 Principle of SA in mode-locked lasers. The transmission of a SA is intensity dependent: CW laser and pulses with low intensity would experience large loss, while pulses with high intensity would enjoy high transmission

Table 1 Representative performances of mode-locked Raman fiber lasers

Laser	Center wavelength	Pulse Energy	Pulse Width	Repetition Rate	SNR of the RF spectrum
Active mode-locking [28]	1178 nm	15 nJ	2 ns	391 kHz	62 dB
Active–passive hybrid mode-locking [29]	1120 nm	20 nJ	50 ps	395 kHz	N/A
Material-based SA: SESAM [30]	1590 nm	N/A	2.7 ps	220 kHz	N/A
Material-based SA: nano-tubes [31]	1670 nm	3 nJ	2 ps	1.72 MHz	30 dB
Material-based SA: nano-tubes [32]	1120 nm	20 nJ	236 ps	2.88 MHz	30 dB
Material-based SA: nano-tubes [33]	1312 nm	0.1 nJ	2 ns	870 kHz	N/A
Material-based SA: Gra-phene [34]	1180 nm	150 nJ	200 ns	400 kHz	56 dB
Artificial SA: NPR [35]	1380 nm	N/A	2 ps	300 kHz	N/A
Artificial SA: NPR [36]	1651 nm	290 nJ	890 ps	378 kHz	41 dB
Artificial SA: NPR [37]	1600 nm	193 nJ	180 ps	275 kHz	65 dB
Artificial SA: NPR [38]	1120 nm	0.7 nJ	1 ps	2.47 MHz	85 dB
Artificial SA: NOLM [39]	1410 nm	15 nJ	N/A	660 kHz	N/A
Artificial SA: NOLM [40]	1534 nm	22 nJ	6 ps	64 kHz	N/A
Artificial SA: NOLM [41]	1120 nm	64.1 nJ	25 ns	733 kHz	66 dB
Artificial SA: NOLM [42]	1115 nm	1.23 nJ	63 ps	1.23 MHz	85 dB

nanotubes, as shown in Fig. 3 [31]. A long fiber cavity (over 100 m) was also necessary in their design. The output pulses can be compressed to 2 ps with 1.4 kW peak power. Yet, the radio frequency (RF) spectrum had a signal-to-noise ratio (SNR) of merely 30 dB, also indicating poor pulse stability (Fig. 3b).

In the above-mentioned works, Raman fiber lasers mode-locked by material-based SAs have unsatisfactory performance when compared with their rare-earth doped counter-parts. The main performance defects, as summarized in Table 1, are mainly concentrated on large pulse width and poor pulse stability, indicated by the low SNR of their RF spectrum. The unsatisfied performance is resulted from the fact that Raman gain is a nonlinear process with extremely fast response. Usually, the response time of Raman scattering in optical fiber is shorter than the recovery time of material-based SAs. Therefore, under CW pumping condition, real-time Raman effect will take place when the SA is bleached. As a result, laser pulses would be stretched, while spontaneous Raman component would be generated and amplified between adjacent laser pulses, which seriously degrades mode-locking performance. Therefore, although material-based SAs are easy to be implemented into Raman fiber lasers, their slow recovery time is the main barrier for achieving high quality Raman mode-locking. This problem could be overcome by using artificial SAs.

Artificial saturable absorber

Compared with material-based SAs, artificial SAs are almost instantaneous, having a response time of femtosecond, which is even shorter than the response time of Raman process in optical fibers. Therefore, artificial SAs can be functionalized in the whole Raman gain process, and thus have the potential to generate mode-locked Raman pulses

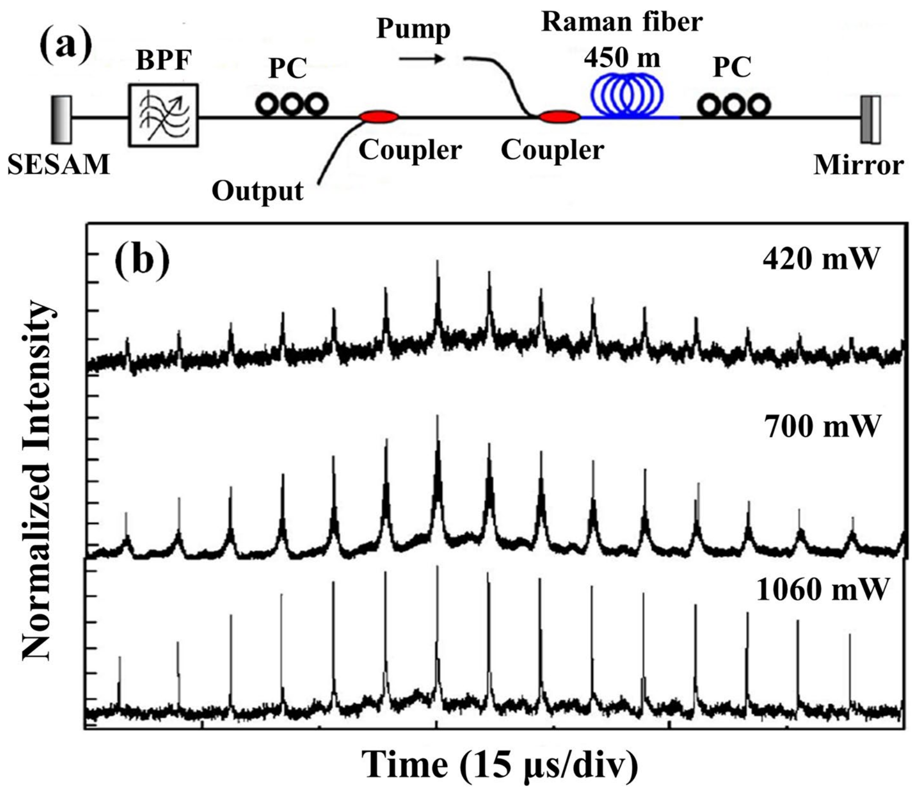

Fig. 2 (**a**) Scheme of the SESAM-based mode-locked Raman fiber laser, BPF: bandpass filter; PC: polarization controller. (**b**) Raman pulse train under different pump power [30]

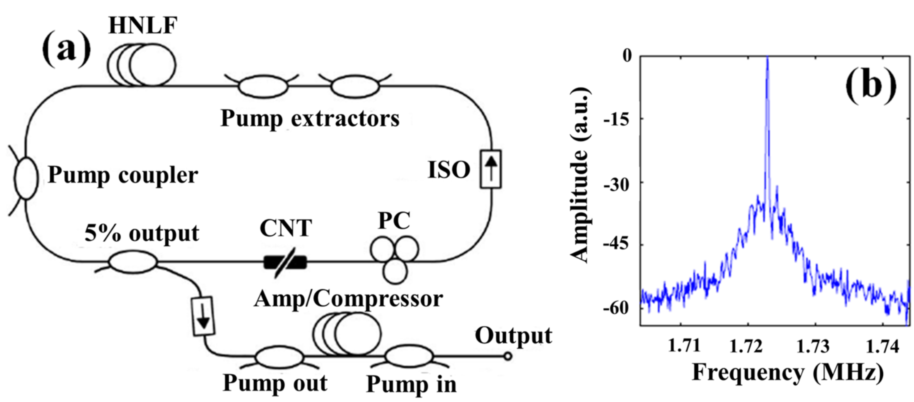

Fig. 3 (**a**) Scheme of the carbon-nanotubes-based mode-locked Raman fiber laser. (**b**) RF spectrum of the Raman pulses [31]

with high stability. Most widely used artificial SAs in the mode-locked fiber lasers are nonlinear polarization rotation (NPR) and nonlinear optical loop mirror (NOLM).

Nonlinear polarization rotation

NPR is a method based on the Kerr nonlinearity in the non-polarization-maintaining (PM) fiber [47]. The intensity-dependent nonlinear phase shift would result in variation

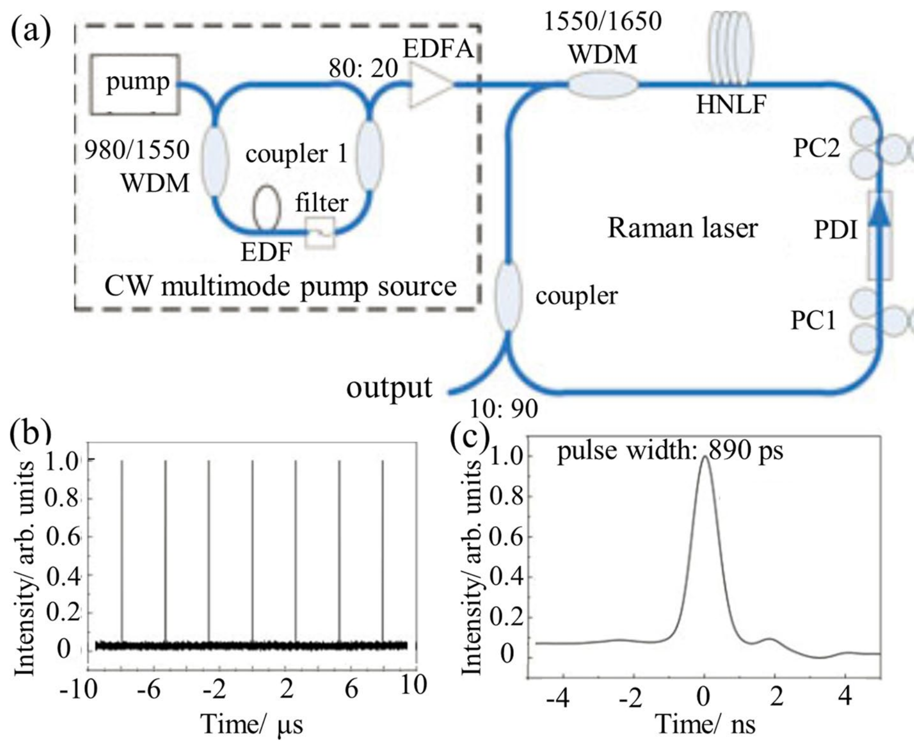

Fig. 4 (**a**) Scheme of the NPR-based mode-locked Raman fiber laser with a HNLF cavity. (**b**) Pulse train and (**c**) expanded temporal characteristic of the Raman pulses [36]

in polarization state as a function of light intensity. If a polarizer is aligned with the polarization state of high intensity light, laser pulses would experience lower loss compared with CW light. Therefore, NPR could act like an effective fast SA. NPR mode-locked Raman fiber lasers have been well studied and reported by many research groups [35–38]. For example, Kuang et al. demonstrated a passively mode-locked Raman fiber laser based on NPR with a high nonlinear fiber (HNLF) cavity [36]. In their laser setup, as shown in (Fig. 4a), NPR is functionalized by two polarization controllers (PC) and one PM isolator with fast-axis blocked. The pump is a 1539 nm CW laser, which was coupled into Raman gain medium (500 m long HNLF) to generated 1650 nm Raman pulses. The Raman laser can generate 890 ps pulses (Fig. 4c) with pulse energy up to 290.7 nJ. Yet, the large pulse width and low SNR of the RF spectrum (~40 dB) are unsatisfactory, which limits its impact for many potential applications.

In order to shorten the pulse width and improve the pulse stability, our group demonstrated another NPR-based mode-locked Raman fiber laser with several improvements in the laser design, as shown in (Fig. 5a) [38]. First, an amplified spontaneous emission (ASE) pump source was applied to replace traditional fiber oscillator pumps. Since SRS is a nonlinear effect with fast response time, the temporal characteristic of the pump laser would be inherited by its Stokes component directly. Thus, a pump laser with poor temporal stability would degrade the performance of a mode-locked Raman fiber laser. Compared with fiber oscillators, ASE sources have much lower intensity fluctuation, and thus are more suitable to serve as the pump for mode-locked Raman fiber laser. Secondly, an all-fiber Lyot filter was embedded into the cavity to trigger the dissipative

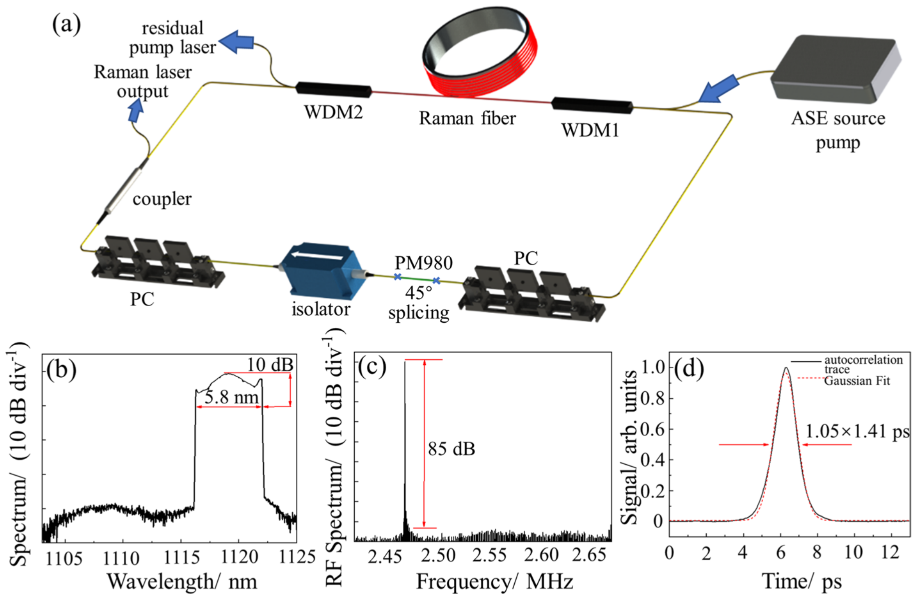

Fig. 5 (**a**) Scheme of the NPR-based mode-locked Raman dissipative soliton fiber laser with an ASE pump source. (**b**) Spectrum, (**c**) RF spectrum and (**d**) autocorrelation trace of the Raman pulses [38]

soliton (DS), which is a more stable attractor and could have higher pulse energy than conventional soliton [8]. Last but not least, we shortened the cavity length by applying a piece of 70 m long fiber with high Raman gain coefficient as the gain medium. With all these efforts combined, the laser can produce stable 1120 nm Raman pulses with a spectrum bandwidth of 5.8 nm (Fig. 5b) and a pulse duration of 1.05 ps (Fig. 5d) at a repetition rate of 2.47 MHz. A SNR as high as 85 dB (Fig. 5c) is measured in the RF spectrum, which suggests excellent temporal stability compared with other reported works.

Yet, due to NPR's working mechanism, non-PM fiber is usually necessary in an NPR-based oscillator, the performance of which is sensitive to environmental changes such as temperature and humidity. Thus, NPR is rarely considered to be a potential candidate to achieve long-term stable mode-locking. Although many efforts have been made to achieve all-PM NPR [48], such attempt is more difficult to be implemented in Raman lasers with a long fiber cavity. The poor long-term stability has limited their impact for many applications and strongly motivated research into alternative approaches to generate long-term stable mode-locked Raman pulses.

Nonlinear optical loop mirror

As another kind of artificial SA, NOLM is a method which can achieve mode-locking with all-PM fiber structure. NOLM is usually based on a 2×2 fiber coupler. Two arms of the coupler are connected to form a fiber loop mirror. Once a laser beam is injected into the fiber loop from the input port, it will be divided into two with opposite propagation direction. They would accumulate different nonlinear phase shift when propagating through the loop mirror. The nonlinear phase shift difference is intensity-dependent, and thus would result in variation in transmission/reflection as a function of light intensity. If the coupling ratio of the 2×2 fiber coupler and the length of the fiber loop are properly designed, laser pulses would have higher transmission than CW light and the oscillator

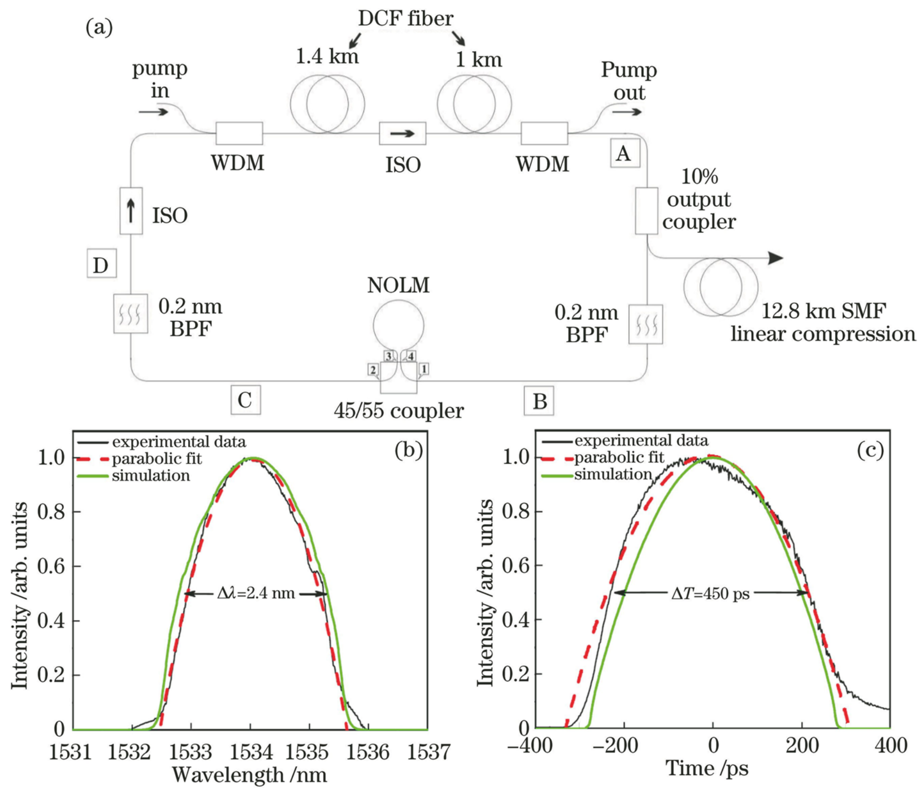

Fig. 6 (**a**) Scheme of the non-PM NOLM-based mode-locked Raman fiber laser. (**b**) Spectral and (**c**) temporal characteristics of the Raman pulses [40]

would prefer to work in pulsed regime [49]. NOLM-based mode-locked Raman fiber lasers have also been investigated for couple of years [39–42]. For example, a NOLM-based mode-locked Raman fiber laser, which can generate parabolic pulses (similaritons), was studied numerically, and realized experimentally [40]. As shown in (Fig. 6a), the NOLM is constituted by a 45/55 coupler whose two ends are looped together with 727 m of HNLF to promote the nonlinear phase shift difference. The pump is a 1435 nm CW laser, which was coupled into a 2.4 km long dispersion compensating fiber (Raman gain medium) to generated 1534 nm Raman pulses. The laser can generate parabolic Raman pulses with a spectrum bandwidth of 2.4 nm (Fig. 6b), a pulse duration of 450 ps (Fig. 6c) and a pulse energy up to 22 nJ. Yet, this NOLM-based Raman fiber laser was built with non-PM fibers, which hinders the priority of NOLM over NPR in the sense of long-term stability.

The first all-PM NOLM-based mode-locked Raman fiber laser was developed later then by our group, which was presented in Fig. 7 [42]. A PM fiber coupler with a splitting ratio of 20:80 is adopted to connect the NOLM ring and the unidirectional ring. In the unidirectional ring, an 80 m long PM Raman fiber (OFS Optics Inc.) was used as the Raman gain medium and an all-fiber Lyot filter was embedded into the cavity to trigger the DS solution. In order to promote the interpulse stability, a 1064 nm ASE source with low intensity fluctuation was applied to serve as the pump. The NOLM ring is constructed by 77 m long PM980 fiber. Benefited from the large splitting ratio of the

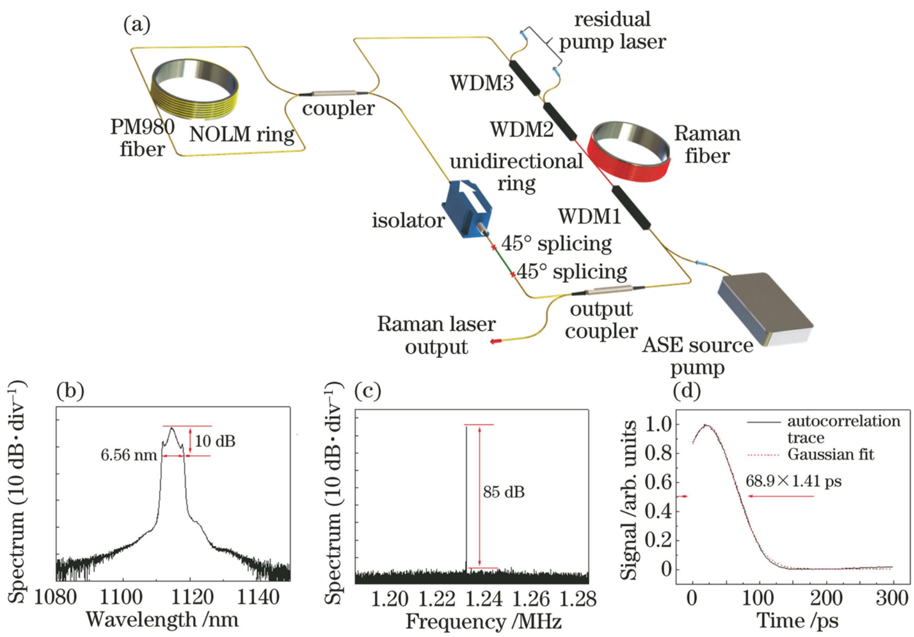

Fig. 7 (**a**) Scheme of the PM NOLM-based mode-locked Raman dissipative soliton fiber laser. (**b**) Spectrum, (**c**) RF spectrum and (**d**) autocorrelation trace of the Raman pulses [42]

PM fiber coupler, mode-locked operation could be self-started in the condition of much shorter NOLM fiber ring compared with other reported works. The laser could generate stable 1120 nm Raman pulses with a spectrum bandwidth of 6.6 nm (Fig. 7b) and a pulse duration of 69 ps (Fig. 7d) at a repetition rate of 1.23 MHz. A SNR as high as 85 dB (Fig. 7c) is measured in the RF spectrum, which suggests excellent temporal stability. Thanks to the all-PM configuration, the mode-locked operation could be maintained for weeks without performance degradation.

Despite much progress, the performance of mode-locked Raman fiber lasers is still not comparable to their rare-earth doped counterparts for the time being. One primary challenge is how to shorten the cavity length. As shown in Table 1, the repetition rates of the reported mode-locked Raman fiber lasers are all less than 3 MHz, which means their cavity lengths are either close to or longer than 100 m. Ultrafast pulses propagating in such a long fiber cavity would experience large dispersion and nonlinearity, which limits the pulse energy, broadens the pulse duration, and narrows the working regime of single pulse operation. However, in order to provide enough Raman gain, fiber cavity as long as tens of meters or even hundreds of meters is necessary under the condition of CW pump. Therefore, replacing CW pump with pulsed pump can be an effective solution to obtain Raman pulses with higher performance by shortening the cavity length while still maintaining adequate Raman gain.

Synchronously-pumped Raman fiber laser

Since Raman gain coefficient is intensity-dependent [50], replacing CW pump with pulsed one could effectively increase Raman conversion efficiency, so as to solve the problem of long fiber cavity length in the case of mode-locked Raman fiber lasers. Yet, when the pump is pulsed, a critical matching condition needs to be met in order to

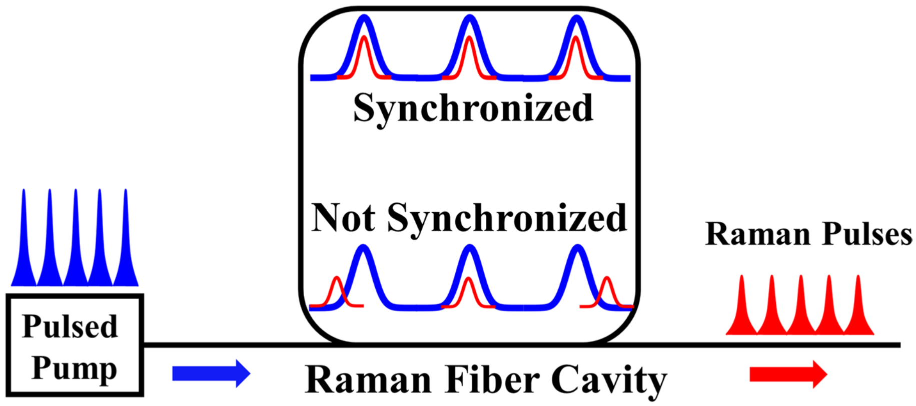

Fig. 8 Principle of synchronously-pumped Raman fiber laser. When the pump is pulsed, a critical matching condition needs to be met in order to achieve resonance enhancement, that is the repetition rate of the pulsed pump should match with the length of Raman fiber cavity

Table 2 Performances of some representative synchronously-pumped Raman fiber lasers

Laser	Center wavelength	Pulse Energy	Pulse Width	Repetition Rate	SNR of the RF spectrum
Fiber delay line [51]	1060 nm	12 nJ	400 fs	5 MHz	60 dB
Fiber delay line [52]	1080 nm	18 nJ	147 fs	43 MHz	55 dB
Fiber delay line phospho-silicate-fiber [53]	1240 nm	1.6 nJ	570 fs	15 MHz	70 dB
Fiber delay line phospho-silicate-fiber [54]	1270 nm	16 nJ	270 ps	19 MHz	N/A
Gain switched diode [55]	1120 nm	73 nJ	18 ps	12 MHz	60 dB
Self-synchronization [56]	1120 nm	6 nJ	36 ps	28 MHz	60 dB

achieve resonance enhancement, that is the repetition rate of the pulsed pump should match with the length of Raman fiber cavity. As can be seen in Fig. 8, only when this synchronization is satisfied can the generated Raman pulses coordinate with the pump and obtain the nonlinear optical gain continuously in the cavity. Because of this, such approach is named as synchronously-pumping. Table 2 summarizes the performances of some representative synchronously-pumped Raman fiber lasers in recent years.

In some early works, researchers tended to apply nanosecond pulses as the pump, in order to reduce the difficulty of synchronization [57–61]. Yet, it is hard to achieve few picosecond or even femtosecond Raman pulses under such long pump pulse duration. A breakthrough work was reported in 2014, in which a Raman DS was co-generated with a traditional DS by an Yb-doped mode-locked fiber laser [51]. Schematic of the laser are shown in (Fig. 9a). One distinct difference between this laser and the conventional ones is that a fiber delay line was inserted into the cavity to compensate the difference between the group velocities of DS and Raman pulses. Without the delay line, the generated Raman component could not be amplified persistently due to the walk-off between DS and Raman pulses. This would result in noise-like Raman pulses with a triangle-like shape spectrum (dashed line in (Fig. 9c)). By applying a delay line as Raman feedback loop, it will then be synchronously amplified by the DS circulating in the cavity. In the

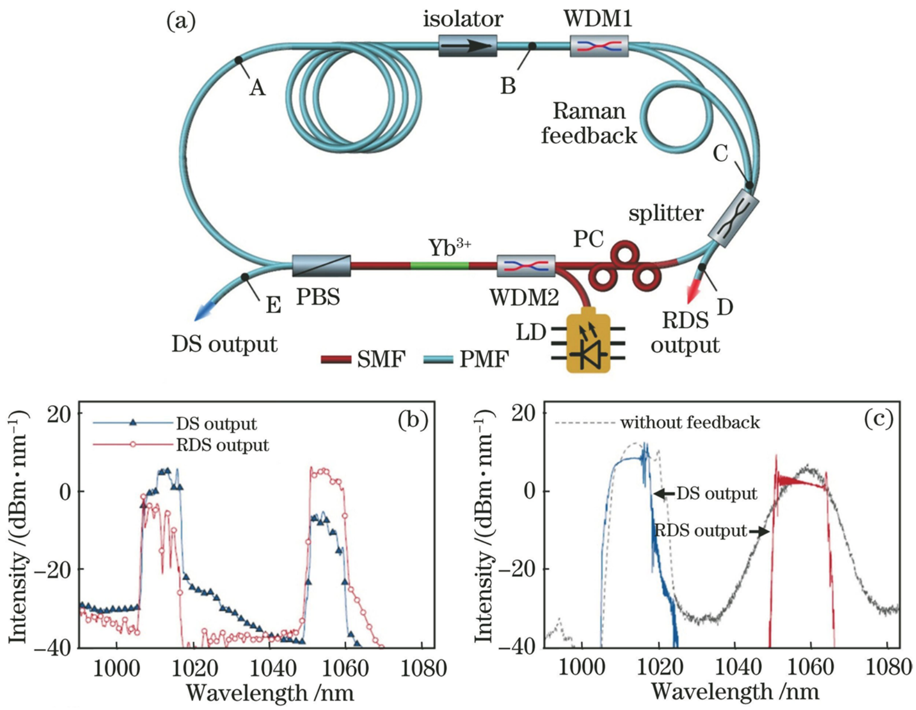

Fig. 9 (**a**) Scheme of the synchronously-pumped Raman fiber laser with pump and Raman pulses sharing a same cavity. (**b**) Measured and (**c**) calculated output spectra of the pump and Raman DS pulses [51]

synchronous condition, the noise is eliminated and the energy becomes concentrated in well-defined temporal and spectral ranges (red curve in (Fig. 9b, c). The generated Raman pulse has a spectrum bandwidth of ~ 10 nm and a pulse duration of ~ 400 fs at a repetition rate of 5 MHz.

In the above-mentioned work, the Yb-gain generated DS and Raman DS share the same fiber cavity. Inspired by this work, researchers demonstrated a high-power synchronously- pumped femtosecond Raman fiber laser by separating the Raman fiber cavity from the Yb-doped fiber oscillator [52]. In their demonstration (Fig. 10a), a 4.7 m long all-PM fiber Raman cavity is pumped by a high-power picosecond fiber laser mode-locked by SESAM. A PM fiber-coupled variable delay line was spliced inside the mode-locked oscillator for synchronization purpose with the Raman laser cavity. The Raman laser could produce highly chirped coherent pulses with energy up to 18 nJ, average power of 0.76 W and 88% efficiency. The pulses were compressed with a pair of transmission gratings to 147 fs. The performances of the Raman pulses with and without synchronization were also compared. The experimental results of spectrum, autocorrelation trace before and after compression are shown in (Fig. 10b, c and d) correspondingly. It has been proved that synchronization condition is essential for highly coherent Raman pulse generation. Without the proper temporal alignment of the pump and Raman pulses, only noise-like Raman pulses could be obtained. The overall performance of the reported femtosecond Raman fiber laser is comparable to most of the rare-earth doped ones, which can effectively meet the needs of many potential applications. Other than this work, the delay line assisted synchronously-pumped Raman fiber lasers were also reported using phosphosilicate-fiber to

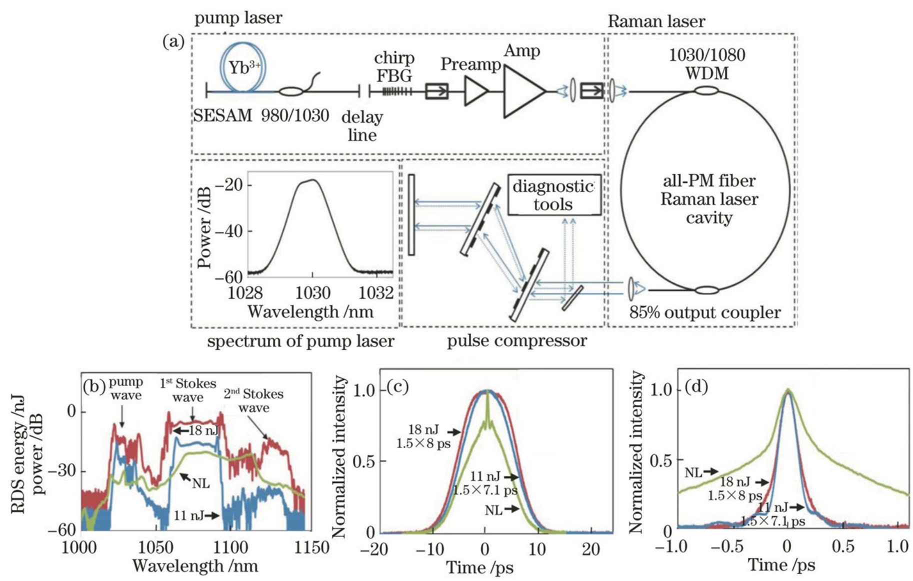

Fig. 10 (**a**) Scheme of the synchronously-pumped Raman fiber laser with a delay line. (**b**) Output spectrum. (**c**), (**d**) autocorrelation traces before and after compression [52]

increase Raman frequency shift [53, 54]. Although these results are promising, the involvement of delay line increases the cost and complexity of the system. Besides, the length of the Raman fiber cavity is sensitive to environmental temperature variation, which means the delay line needs to be feedback controlled in order to achieve long-term synchronization.

Apart from the delay line, another approach to achieve synchronously-pumping is by gain switched diode [55]. In the concept, the repetition rate of the diode pump could be continuously tuned by adjusting the electrical signal controlling the driver of the diode. The demonstrated synchronously-pumped Raman fiber laser based on gain switched diode is shown in Fig. 11. A 1066 nm distributed feedback (DFB) laser diode was driven by a gain-switched circuit board, so that pulse duration and repetition rate of the output pulses could be tuned in large ranges. Two stages of amplifiers are applied to scale up the average power of the pump to 1.2 W. The amplified pulses were then injected into a Raman fiber cavity with a length of ~ 10 m. When the repetition rate of the pump diode is fixed at 12.41 MHz, the synchronization condition is obtained and the laser could produce stable Raman pulses with a pulse duration of 78 ps, as shown in (Fig. 11b and c). However, the generated Raman pulses are not highly-coherent, which cannot be properly dechirped. This is resulted from the poor coherence of the pump pulses generated by the manner of gain switch. Therefore, in order to obtain highly-coherent Raman pulses, the technology of gain switched diode needs to be further developed and upgraded. Yet, compared with the mode-locked Raman fiber laser, the one reported in this work could achieve an optical conversion efficiency up to 80% with short gain fiber, which fully highlights the advantages of synchronously-pumping.

It can be concluded from the Table. 2 that, considering the state of the art, the output pulse energies of reported synchronously-pumped Raman fiber lasers are less

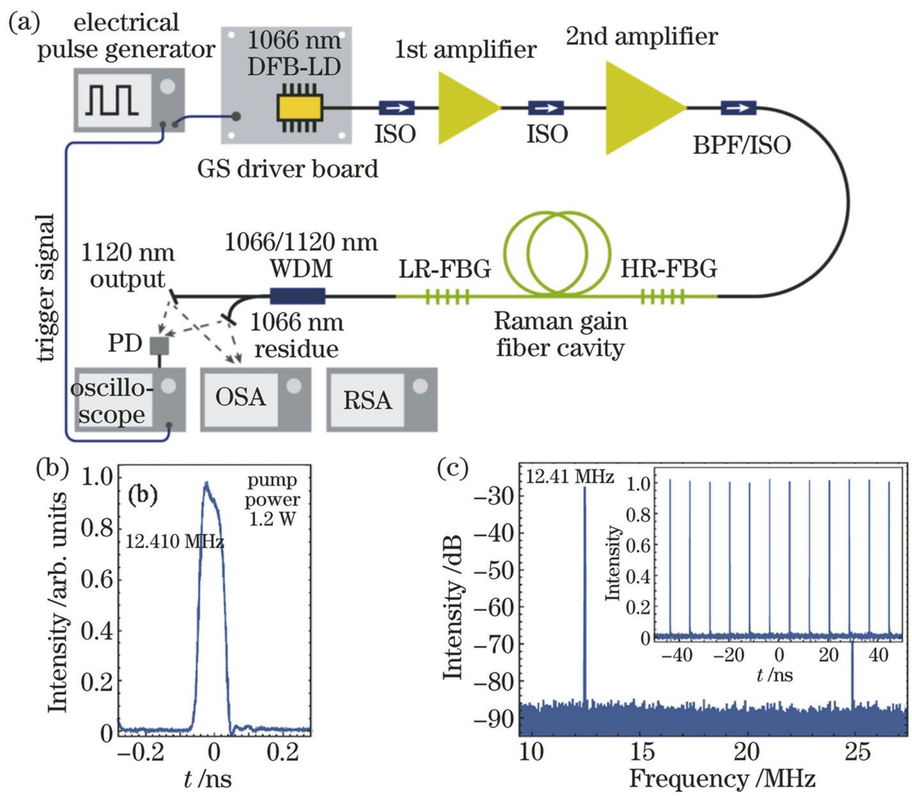

Fig. 11 (**a**) Scheme of the synchronously-pumped Raman fiber laser with a gain switched diode. (**b**) Temporal characteristic and (**c**) RF spectrum of the Raman pulses [55]

than 100 nJ. One direct solution to scale-up the output pulse energy of synchronously-pumped Raman fiber laser is by increasing the pump pulse energy. Yet, when the pump power exceeds a certain level, the energy would be transformed into high-order Stokes pulses. Therefore, one needs to reduce the cavity length so that the nonlinear effect would be just enough to restrict the energy within the 1st order Stokes pulses. Such attempt will ruin the synchronous condition between the repetition rate of the pulsed pump and the length of Raman fiber cavity. It is expected to obtain synchronously-pumped Raman pulses with pulse energy over 100 nJ by applying pulsed pump with both high pulse energy and high repetition rate. Yet, such high demands on the pump would increase both the complexity and cost of the overall system.

The above mentioned synchronously-pumping methods have a problem in common: that is the length and refractive index of optical fiber in Raman cavity will vary with temperature and humidity changing, which would result in repetition rate mismatching between pump and Raman pulses, and eventually lead to performance degradation in long-term operation. In order to solve this problem, one can use a servo system to feedback control and lock the pump pulses' repetition rate to the real-time length of the Raman fiber cavity. Yet, the involvement of active control unit would greatly increase the complexity of the system.

A simplified passive solution to achieve long-term synchronization without servo system was demonstrated recently [56]. The principle of the method based on distributed

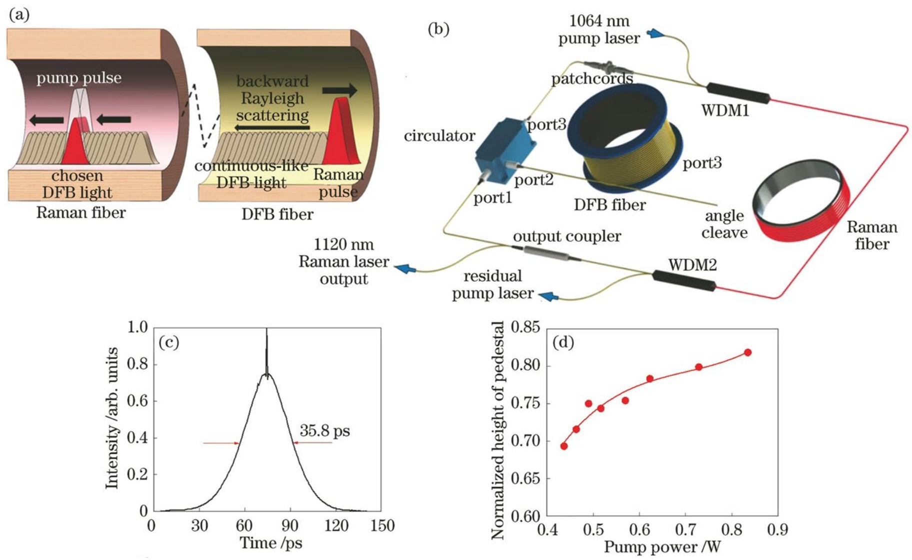

Fig. 12 (**a**) Principle of the self-synchronous Raman fiber laser based on distributed Rayleigh scattering. (**b**) Scheme of the Raman fiber laser. (**c**) Autocorrelation traces of the Raman pulse. (**d**) Normalized autocorrelation pedestal heights as a function of the pump power [56]

Rayleigh scattering and the corresponding laser setup are presented in (Fig. 12a and b) respectively. In the laser design, a picosecond pulsed pump laser is coupled into a piece of Raman fiber to generate Raman pulses. The Raman pulses are then injected into a long piece of single mode passive fiber via a circulator. Rayleigh scattering along this fiber would reflect part of the pulses back into the cavity. Since the Rayleigh scattering is distributed along the fiber, the feedback pulses overlap with each other and form a pulse continuum. The pump pulses would bump into part of the pulse continuum anyway, which eventually results in real-time self-synchronization. The autocorrelation trace of the generated random Raman laser pulse is shown in (Fig. 12c), which is a noise-like pulse with a sharp peak on a wide pedestal. The normalized height of the pedestal in the autocorrelation trace is higher than 0.5 and it will get larger with the increasing of pump power (Fig. 12d). This means that the noise-like Raman pulses emitted from the laser are partially coherent, and such coherence enhancement is related to the self-synchronization process. Moreover, the Raman pulses' performance with and without Rayleigh scattering feedback are compared with respect to slope efficiency and line width. Both results highlight the positive contribution of the self-synchronization process. The reported laser represents a new scheme for synchronously-pumped Raman pulse generation.

Nonlinear optical gain modulation

In terms of current technical maturity, it is still challenging to generate ultrafast Raman pulses with high pulse energy and short pulse duration in a compact and simple structure, no matter using mode-locking or synchronously-pumping. The impact of ultrafast Raman fiber laser is thus still limited in terms of applications. Therefore, developing a new technology that is superior to the old ones is of great scientific significance.

Traditional methods are mostly based on fiber oscillators to generate ultrafast Raman pulses. This brings problems such as involvement of long Raman gain fiber under CW pump; or synchronization difficulty under pulsed pump. The idea is whether oscillators can be replaced with single-pass amplifiers so that synchronization is not necessary under pulsed pump. In this regard, some exploratory works have been reported [62, 63]. As a representative one, amplified spontaneous Raman emission under picosecond pulse pumping is studied in detail both experimentally and numerically [63]. Yet, due to the poor coherence of spontaneous emission light, the generated Raman pulses are noise-like with partial coherence, which means they cannot be properly dechirped to femtosecond pulse duration.

In order to improve the coherence of the generated Raman pulses, one effective way is to replace the spontaneous Raman emission with a single frequency seed laser. Driven by this idea, our group proposed a novel method to transform single frequency CW laser into femtosecond-scale Raman pulses by NOGM [64, 65]. The concept of ultrafast Raman pulse generation by NOGM is illustrated in (Fig. 13a). The input signal is a single frequency CW laser, which is amplified and reshaped temporally and spectrally in a piece of optical fiber. The optical fiber, providing nonlinear optical gain by simulated Raman scattering, is pumped by ultrafast pulses. The ultrafast pump laser, served as a modulation driver, can offer an ultrafast nonlinear optical gain modulation to reshape the CW signal. In the temporal domain, the CW laser would be reshaped into pulsed laser; while in the spectral domain, the single longitudinal mode of the CW laser would be modulated and new spectral components would be generated by nonlinear optical effects, forming a shape of frequency comb. The repetition rate of the generated Raman pulses, or the comb line spacing, is exactly determined by the pulsed pump laser.

In the experiment, an 1121 nm single frequency laser is injected into a Raman fiber amplifier, which is pumped by a 1064 nm picosecond pulsed laser. With this simple and compact structure, the amplifier can generate stable and highly-coherent 1121 nm Raman pulses with a pulse energy of 25.7 nJ and a pulse width of 436 fs under an optical efficiency of 69.4%. As shown in (Fig. 13b), a broad spectrum with a 10 dB bandwidth of 9.5 nm is generated, whose center wavelength is aligned with the CW seed laser. Both oscilloscope trace (Fig. 13c) and RF spectrum (Fig. 13d) confirm that the repetition rate of the Raman pulses is exactly determined by the pump laser. The RF spectrum has a SNR of 80 dB, indicating a high pulse-to-pulse stability. Such high stability is directly inherited from the one of the 1064 nm all-PM figure-of-9 pump laser [66]. The NOGM laser was turned on and tested for days, and the performance of which remained highly consistent. According to the autocorrelation measurement (Fig. 13e), the Raman pulse has a Gaussian shape with a measured pulse width of 11.0 ps, which can be externally dechirped down to 436 fs. This confirms that the output Raman pulses are highly coherent. It has been proved that the high pulse coherence is originated from the single frequency seed laser. According to numerical simulations, further scaling the pulse energy to μJ-level is possible if the power of the pulsed pump could be increased.

In order to fill up all the spectrum gap left by the emission bands of rare earth doped fibers, cascaded Raman progress is necessary. Most recently, cascaded NOGM towards coherent femtosecond pulse generation with wavelength versatility has also been demonstrated [67]. The laser setup is presented in (Fig. 14a). In

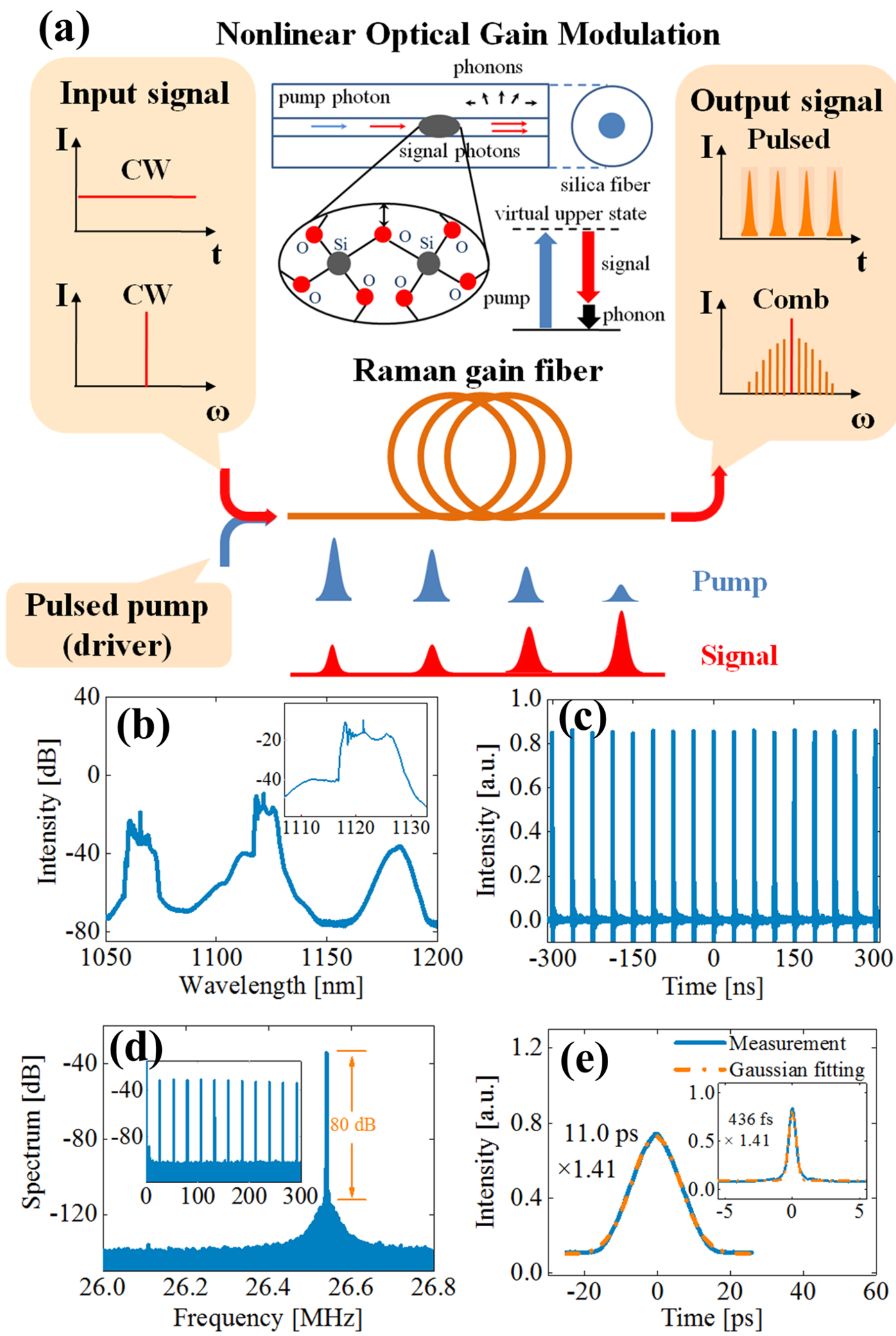

Fig. 13 Principle of NOGM (**a**); Characteristics of the experimental generated NOGM Raman pulses: (**b**) spectrum, (**c**) pulse train, (**d**) RF spectrum and (**e**) autocorrelation traces [64]

the demonstration, both 1121 nm and 1178 nm single frequency laser are injected into a Raman fiber amplifier, which is pumped by a 1064 nm picosecond pulse laser. The NOGM process, which transfers energy from 1064 to 1121 nm, and then to 1178 nm, is accomplished in this Raman fiber amplifier. The two-stage NOGM setup can generate 1178 nm pulses with a pulse energy of 76 nJ, a 10 dB spectral bandwidth of 10.6 nm (Fig. 14b) and a pulse duration of 621 fs (Fig. 14c) under an optical

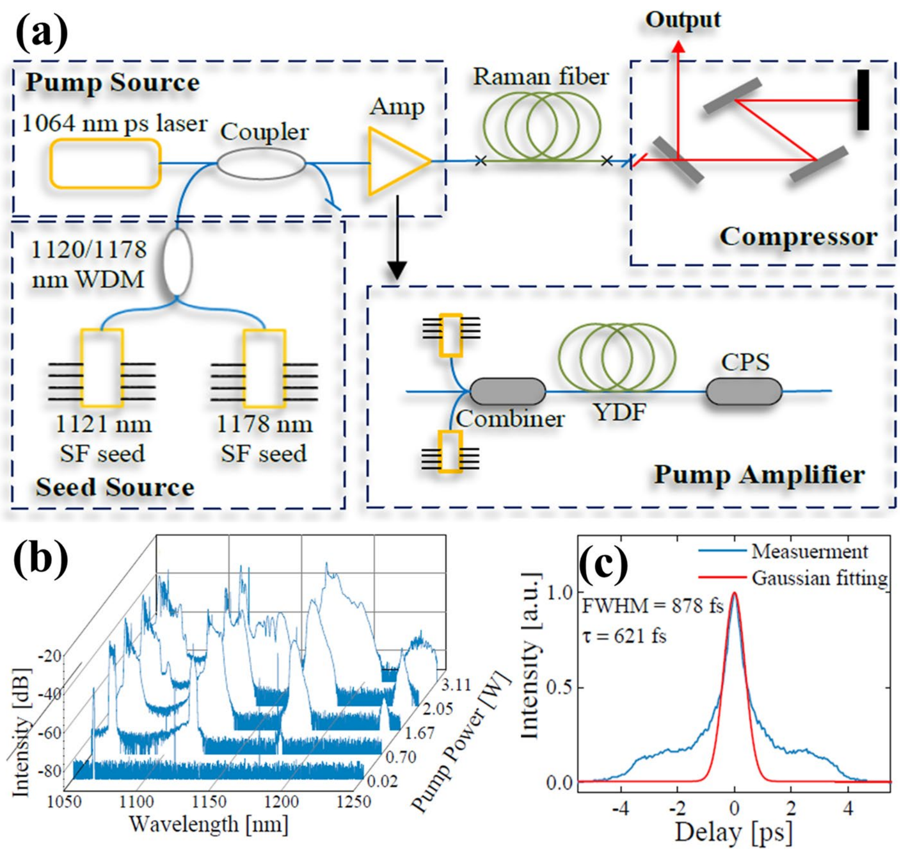

Fig. 14 (**a**) Scheme of the cascaded NOGM Raman fiber amplifier. (**b**) Spectrum under different pump power and (**c**) autocorrelation traces of the second order Raman pulse [67]

conversion efficiency of 65%. Numerical simulations revealed that walk-off effect between the pump and different order Stokes pulses is the main factor that limits the performance of high-order Stokes pulses. This indicates that by designing the NOGM amplifier with proper Raman fiber length, pump pulse energy and pump pulse duration to reduce the walk-off effect, high pulse energy and wavelength-agile femtosecond pulses can be obtained with higher conversion efficiency and shorter pulse duration.

The NOGM method can offer performance advantages over prior approaches. Compared with mode-locking, NOGM is not restricted by the long cavity length, which promotes the ability to produce pulses with high pulse energy and short pulse duration. Compared with synchronously-pumping, NOGM does not require strict synchronization between pump and Raman pulses, which offers a much simpler way to generate ultrafast pulses with high performance. Moreover, NOGM can generate Raman pulses with pulse energy scalability and wavelength expandability, which turns out to be a quality solution to generate high-energy ultrafast pulses with wavelength agility. Such laser sources may effectively promote technology landing and application expansion of the ultrafast Raman fiber lasers in the next few years.

Conclusion and prospect

Ultrafast Raman fiber lasers can effectively expand the wavelength range of conventional ultrafast fiber lasers, and thus have broad application prospects in industry and biomedical field as well as for scientific research, where ultrafast laser pulses with special wavelength plays important roles. For biomedical applications, two-photon excitation fluorescence microscopy has stimulated great research efforts in developing femtosecond sources in the wavelength of 1.3 μm and 1.7 μm [21–23]. These two wavelengths are located at the blank area, which cannot be covered by the emission band of most common used rare earth doped ions. For industrial applications, the processing of special materials, such as ceramics, glasses, and semiconductor wafers, calls for new demand for the demonstration of high-power ultrafast laser sources with special wavelength [24]. For scientific researches, optical frequency comb (OFC) has driven the rapid development of optical metrology for the past two decades. The development of OFC with high energy comb line at special wavelengths would further promote the expansion of OFC applications [25, 26]. For fiber communications, the development of high quality, cost-efficient ultrafast laser with special wavelength would extend applications from commonly-used band (C-band and L-band) to other developing bands, such as U-band (1625–1675 nm), which may effectively improve speed and bandwidth [68].

Figure 15 summarizes the performances of the most representative ultrafast Raman fiber lasers that has been reported in the sense of pulse energy and duration. At present, mode-locked Raman fiber lasers are still not comparable to their rare-earth doped counterparts in terms of pulse energy and duration, mainly because long optical fiber is necessary to provide adequate Raman gain under the condition of CW pump. Ultrafast pulses generated in a long fiber cavity would experience large dispersion and nonlinearity, which limits the pulse energy, broadens the pulse duration, and narrows the working regime of single pulse operation. This is the most critical issue that restricts the performance of mode-locked Raman fiber laser in the blue elliptical area, as shown in the middle part of Fig. 15. Recently, spatiotemporal mode-locking and multimode laser pumped Raman fiber lasers have been demonstrated [69, 70]. Both technologies apply graded-index fibers in their design. Therefore, the combination of these two technologies may address open scientific questions and pave the way toward spatiotemporal mode-locked Raman fiber laser with relatively short cavity.

As we can see from Fig. 15, the performance of synchronously-pumped Raman fiber lasers centers at the middle-top area of the figure (orange circle). Pulsed pumping can effectively solve the problem of long cavity length, and thus achieve femtosecond pulse operation. Currently, delay line based synchronously-pumping can produce Raman pulses with performance comparable to conventional rare-earth doped ultrafast fiber lasers. Yet, the involvement of delay line increases the cost and complexity of the system. The one using gain switched diode is a simpler solution to achieve synchronization. However, due to the poor coherence of gain switched pulses, only noise-like Raman pulses have been reported. One potential optimization scheme is using Mamyshev regenerator to improve the coherence of the pulses generated by gain switched diode [71]. As long as the gain switched pulse's coherence is comparable to the one generated by mode-locked oscillators, high performance Raman pulses could also be generated like the case of delay line.

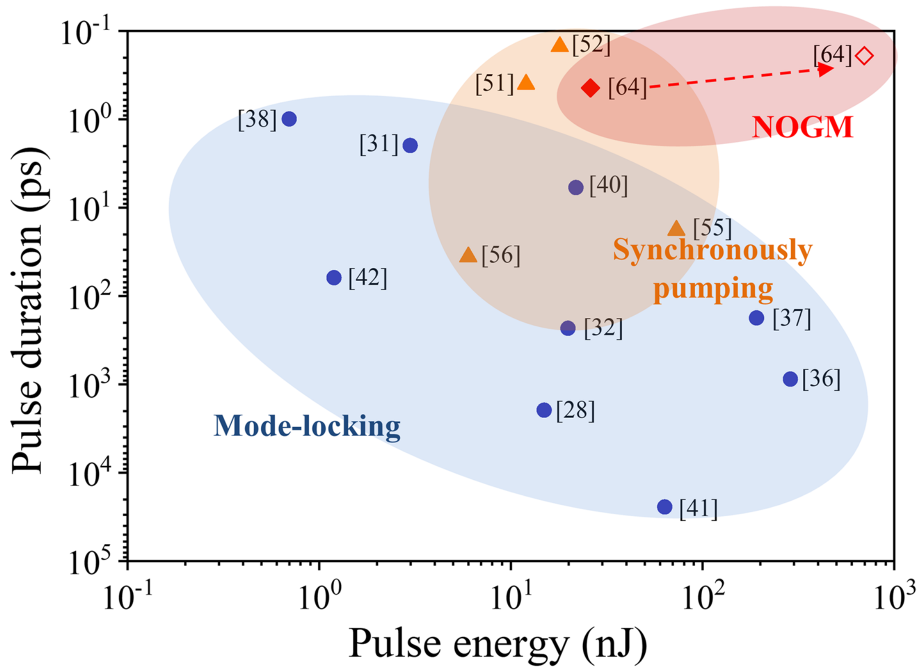

Fig. 15 Summary of the pulse energy and duration of the reported Raman fiber lasers, including mode-locking (blue circles), synchronously pumping (orange triangle) and NOGM (red diamond). The corresponding reference numbers of each work are marked nearby

It is worth emphasizing that both mode-locked and synchronously-pumped Raman fiber lasers are based on oscillators. Therefore, in order to balance dispersion, nonlinearity, gain and loss inside fiber oscillators, their conventional output pulse energies are limited to the level of nJ. Compared with mode-locking and synchronously-pumping, the method of NOGM avoids the oscillator structure, which gathers various advantages including simple structure, long-term stability, high pulse energy and short pulse duration. Simulations have confirmed that femtosecond Raman pulses with several MW peak power could be generated by NOGM with higher pump pulse energy than the one in Ref. 64, which means maximum pulse energy up to several-μJ could be achieved under all-fiber NOGM structure. This would further push the performance of NOGM pulses to the upper right corner of Fig. 15. Such high-quality ultrafast laser sources will effectively promote application expansion of ultrafast Raman fiber lasers. Future research into NOGM-based frequency comb may further enhance the influence of this technology in the near future. One primary technical challenge for NOGM is to limit the walk-off effect between pump and Raman pulses resulted from the dispersion in the cascaded set-up. The pulse walk-off would not only reduce conversion efficiency, but also lead to irregular pulse shape and nonlinear pulse chirp, which would eventually prevent us from obtaining Raman pulses with short pulse duration [67]. This walk-off issue could be eliminated either by designing the pump and Raman wavelengths around the zero-dispersion window of silica fiber, or applying a dispersion-managed set-up (two fiber segments with normal and anomalous dispersion respectively) in the Raman amplifier.

Another future challenge for ultrafast Raman fiber lasers would be studying their pulse dynamics. Compared with the ones from rare-earth doped ultrafast fiber laser, optical pulses generated by ultrafast Raman fiber lasers may experience more complex dynamic processes for both time and spectral domain, since nonlinear effects in Raman fiber laser are not only strengthened, but also plays multiple roles such as providing gain, broadening spectra and balancing the effect of dispersion. Although pulse dynamic behavior of rare-earth doped mode-locked lasers has been extensively investigated via the time-stretch dispersive Fourier transform technique for the past few years [9, 72], the temporal and spectral dynamics of different mode-locked Raman fiber lasers are still waiting for explore. As for synchronously-pumping and NOGM, some preliminary theoretical studies have been reported to study the dynamic conversion process between the pump and Raman pulses [51, 67]. Yet, detailed numerical simulations and experimental studies are expected for better understanding the pulse dynamic, which may promote system optimization.

Abbreviations

CW	Continuous-wave
NOGM	Nonlinear optical gain modulation
SA	Saturable absorbers
SESAM	Semiconductor saturable absorber mirror
RF	Radio frequency
SNR	Signal-to-noise ratio
NPR	Nonlinear polarization rotation
NOLM	Nonlinear optical loop mirror
PM	Polarization-maintaining
HNLF	High nonlinear fiber
PC	Polarization controllers
ASE	Amplified spontaneous emission
DS	Dissipative soliton
DFB	Distributed feedback
OFC	Optical frequency comb

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Not applicable.

Authors' contributions
JZ and YF conceived the manuscript. WP, WQ, XC and ZC performed part of experiments and analyzed data. JZ wrote the manuscript. JZ and YF revised the manuscript and supervised the project. All the authors read and approved the final manuscript.

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Availability of data and materials
Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Competing interests
The authors declare that they have no competing interests.

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