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Recent progress on the application of micro/nanofibers for ultrafast optics*

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Abstract: Ultrafast fiber lasers are indispensable components in the field of ultrafast optics, and their continuous performance advancements are driving the progress of this exciting discipline. Micro/nanofibers (MNFs) possess unique properties, such as a large fractional evanescent field, flexible and controllable dispersion, and nonlinearity, making them highly valuable for generating ultrashort pulses. Particularly in tasks involving mode-locking, dispersion and nonlinearity management, MNFs provide an excellent platform for investigating intriguing nonlinear dynamics and related phenomena, thereby promoting the advancement of ultrafast fiber lasers. In this paper, we present an introduction to the mode evolution and characteristics of MNFs followed by a comprehensive review of recent advances in utilizing MNFs for ultrafast optics applications including evanescent field modulation and control, dispersion and nonlinear management techniques as well as exploring nonlinear dynamical phenomena. Finally, we discuss the potential application prospects of MNFs in the realm of ultrafast optics.

Keywords: MNFs; Nonlinear dynamics; Dispersion; Ultrafast optics
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1 Introduction

The rapid pace of scientific exploration and industrial advancement requires ultrafast lasers with higher pulse energy, shorter pulse duration, and more importantly, a better understanding of the physics and mechanisms of power-scalable mode-locking and controllable intrapulse phase dynamics (Shi, 2022). Micro/nanofibers (MNFs), which are novel optical fibers with controllable dispersion and nonlinearity, have emerged as a constantly growing research platform for mesoscale optics and ultrafast laser dynamics (Tong et al., 2004; Zhang et al., 2012b; Li et al., 2014; Lou et al., 2014; Meng et al., 2015; Li et al., 2016; Cai et al., 2017; Li et al., 2019c; Huang et al., 2021a). Dispersion, along with its interplay with nonlinearity, is a crucial factor that influences pulse dynamics in

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mode-locked fiber lasers and can reshape the pulse in the time domain and spectrum (Walmsley et al., 2001; Woodward, 2018). Controlling the dispersion characteristics of traditional single-mode fibers (SMFs) is challenging due to the predominance of material dispersion. However, in MNFs, waveguide dispersion associated with the structural parameters of the fibers dominates, offering the opportunity for convenient dispersion regulation. Moreover, MNFs provide more compact structures and footprints when used for dispersion compensation (Li, et al., 2019c). MNFs also exhibit a large fractional evanescent field which can be conveniently coupled to nanomaterials decorated on the fiber's surface and greatly strengthen the light-matter interaction. These advantages have led to numerous studies on MNF-based sensors (Spillane et al., 2008; Shan et al., 2013; Lou, et al., 2014; Talataisong et al., 2018; Li et al., 2019b) and MNF-based saturated absorbers for mode-locked lasers (Luo et al., 2018; Liu et al., 2020).

The generation of an ultrashort pulse has promoted research on nonlinear dynamics and provides a powerful tool to manipulate the operating state of lasers (Huang, et al., 2021a). An essential component of nonlinear dynamics is soliton dynamics. Attaining control over dispersion is essential for steering nonlinear soliton dynamics (Billet et al., 2014). For example, self-similaritons generated by the interaction of self-phase modulation (SPM) and gain in the normal dispersion region can exhibit robustness to wave-breaking under high power conditions. Also, their characteristics of linear chirp and a broad, flat spectrum can lead to efficient pulse compression (Graini and Saouchi, 2022; Lidiya et al., 2022; Zhao et al., 2022). Details of other types of solitons, such as bright, dark, vector, dissipative, polarization domain wall, and other experimentally verified optical solitons in fiber lasers can be found in the review by Song et al. (2019). Soliton self-frequency shift (SSFS) (Alamgir et al., 2021) and dispersion wave (DW) (Brahms and Travers, 2023) are also attracting much attention and can be used to generate tunable ultrashort pulses. In addition, supercontinua (SC) which arise from a plethora of optical nonlinearity mechanisms, such as soliton fission, SSFS, four-wave mixing (FWM), and DW, have attracted much interest. The interplay between high nonlinearity, dispersion, birefringence, and other cavity parameters enables the generation of nonlinear dynamics and phenomena. Compared with photonic crystal fibers (PCFs), which are commonly used for research in nonlinear dynamics, MNFs show great potential: not only can the dispersion profile of MNFs be tuned by optimizing their structural parameters, but also the high refractive index contrast of MNFs provides much tighter confinement, leading to much higher nonlinear coefficients and the possibility of using nonlinear coating technology for further enhancement. Both characteristics are beneficial for research on nonlinear dynamics.

The characteristics of MNFs and their application to ultrafast optics are summarized in Fig. 1. The main factors in ultrafast optics are a large fractional evanescent field, controllable dispersion, and high nonlinearity. A large fractional evanescent field enhances the interaction between light and matter, making it suitable for nanomaterial carriers. Besides being used as a saturable absorber for mode-locking, MNFs can be used as highly nonlinear elements for studying nonlinear dynamics and phenomena when coated with highly nonlinear materials. Controllable dispersion and high nonlinearity are also crucial characteristics. Dispersion and nonlinearity affect the pulse dynamics inside the cavity, which can be used for mode-locking and the study of nonlinear dynamics. In mode-locking, the laser can operate in different states through the management of dispersion and nonlinearity. Regarding the study of nonlinear dynamics, this article primarily focuses on high harmonic generation, harmonic mode-locking, generation of noise-like pulses, and supercontinuum generation.

In this review, in Section 2 we introduce mode evolution in MNFs and highlight the pivotal characteristics of MNFs for ultrafast optics: large fractional evanescent field, dispersion, and

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nonlinearity. Then in Section 3, we illustrate the applications of MNFs, including evanescent field modulation and control, dispersion and nonlinear management, and nonlinear dynamics phenomena. Finally, in Section 4, we present prospects for the future application of MNFs in the field of ultrafast optics.

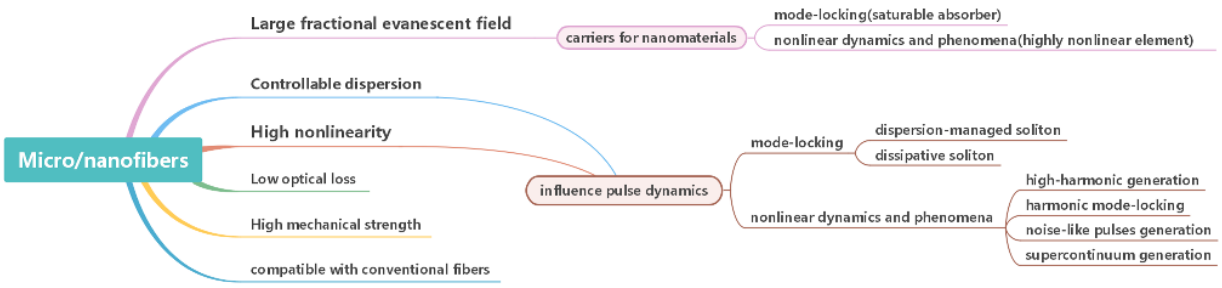

Fig. 1 Characteristics of MNFs and their application in ultrafast optics.

2 Optical properties of MNFs

Fig. 2a shows our homemade taper-drawing machine for fabricating commercial glass fibers into a specific MNF. The profiles of MNFs obtained from experimental measurement are in excellent agreement with theoretical prediction (Birks and Li, 1992), as depicted in Fig. 2b. Fig. 2c presents a schematic diagram of the fiber tapering. The diameter of the tapered fiber can be monitored in real-time by monitoring the transmittance of different wavelengths. The illustration is a photograph of our tiny homemade spectrometer, including a diagram and photograph of the coating.

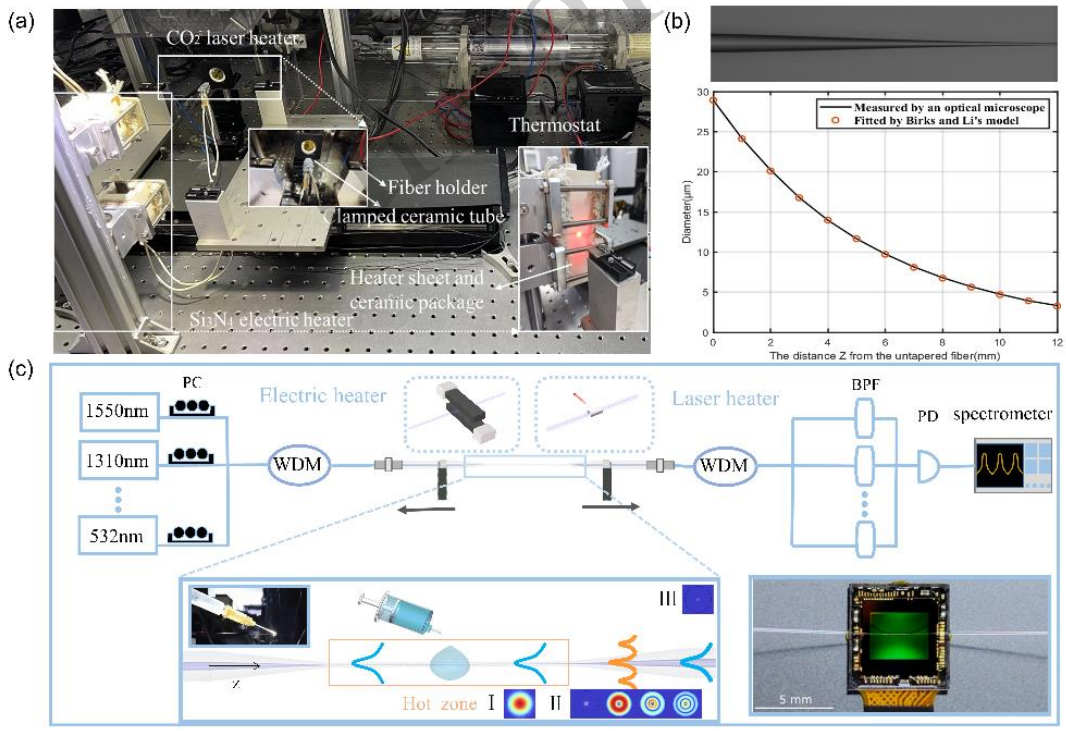

Fig. 2 Schematic of the MNF fabrication system. (a) The experimental setup for heat tapering. Two heaters are integrated

on the same displacement platform: one is a Si_3N_4 electric heater with a long hot zone and high-temperature stability, and the other is a CO_2 laser heater with an ultrashort hot zone. (b) The profile of an MNF with a heating zone of 5.5 mm and a 40-mm elongation, and the image of the MNF from an optical microscope. (c) A schematic diagram of fiber tapering. PC: polarization controller, BPF: band-pass filter, PD: photodiode. The evolution of the mode field at different diameters is also given. The illustration is a photo of our homemade spectrometer.

2.1 Mode evolution of MNFs

The tapering process not only creates a uniform waist region that matches the length of the hot zone but also establishes a taper transition region, (Fig. 2(c)). Within the taper transition region, as the diameter gradually decreases, the characteristics of mode evolution undergo a remarkable transformation. For example, the index of the fundamental mode gradually decreases, which may excite the generation of higher-order modes. However, when the diameter reaches a certain small size, the excited high-order modes are effectively suppressed. They either couple to the air through radiation modes or dissipate entirely, leaving only a few modes. Based on the leaked complicated random interference speckle in the taper transition region, we proposed a low-cost (the core components of the spectrometer cost less than US$15), scalable spectrum meter that has a picometer resolution and sub-millimeter footprint (Cen et al., 2023) (Fig. 2c, lower right). To comprehensively analyze and understand the transmission characteristics of MNFs, it is essential to consider both the taper transition region with variable diameters and the waist region with uniform diameters (see supplementary materials, Section 1).

2.2 Large fractional evanescent field

For MNFs with diameters close to or smaller than the wavelength of light, a large fraction of the energy can be confined within the evanescent field during its propagation along the fiber. The proportion of the evanescent field is influenced by factors such as the material, diameter, and transmission wavelength (Tong, et al., 2004). Strong confinement can reduce the mode field area and increase the nonlinear coefficient (Brambilla et al., 2009), so MNFs can be used as carriers of nanomaterials. In ultrafast optics, MNFs coated with nanomaterials can be used as saturation absorbers in mode-locking lasers and highly nonlinear elements in the study of nonlinear dynamics and phenomena.

2.3 Dispersion of MNFs

MNFs offer great potential in the field of ultrafast optics where controlling the dispersion is decisive (Li et al., 2019). The dispersion characteristics of MNFs are significantly affected by their diameters (see supplementary materials, Section 2).

In ultrafast fiber lasers, the pulse envelope propagates with the group velocity, and the group velocity dispersion determines the width of the pulse and affects the evolution of the pulse in the cavity. The group velocity dispersion (GVD) β_2 of MNFs is shown in Fig. 3a. This diameter-dependent engineering allows for precise control over the dispersion properties of MNFs. By manipulating the diameter of MNFs, it is possible to design the β_2 to be normal, anomalous, or zero. Additionally, the zero dispersion wavelength (ZDW) of MNFs experiences a redshift as the diameter increases, adding another degree of freedom for dispersion control and phase-matching. This becomes especially critical for nonlinear dynamical processes such as SC generation (Stark et al., 2012; Dubinskii et al., 2016).

2.4 Nonlinearity of MNFs

For MNFs, the nonlinear refractive index n_2 related to the third-order polarizability is no longer the same in the core and cladding, which makes the nonlinear coefficients of MNFs differ from the

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standard definition for traditional fibers (Agrawal, 2013):

$$\gamma = \frac{2\pi}{\lambda}\frac{\iint_{-\infty}^{\infty} n_2|F(x,y)|^4 dxdy}{(\iint_{-\infty}^{\infty}|F(x,y)|^2 dxdy)^2} \quad (1)$$

Fig. 3 b elucidates the remarkable disparity in the nonlinear coefficient γ between MNFs and conventional SMFs (HI1060), showing the potential for MNFs to exhibit orders of magnitude higher nonlinear coefficients. Furthermore, the use of coating technology further augments the already impressive nonlinear characteristics of MNFs, rendering them exceptionally well-suited for the generation and exploration of nonlinear phenomena. In addition, the nonlinear coefficient of MNFs reaches its maximum value when the diameter is about 75% of the transmission wavelength (Foster et al., 2004). Table 1 compares the dispersion and nonlinearity coefficients of different fibers, from which we can see the advantages of MNFs. Note that these comparisons are based on silica fibers and the use of alternative highly nonlinear materials may yield even higher nonlinear coefficients.

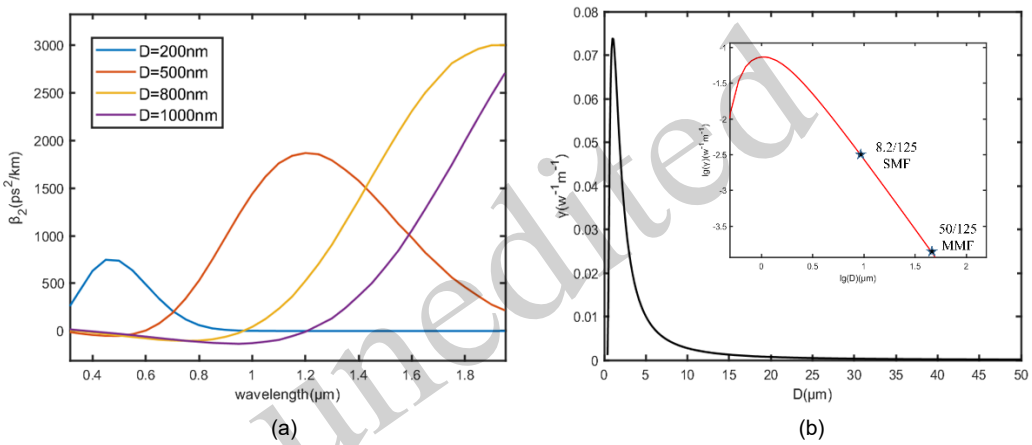

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Fig. 3 The characteristics of MNFs. (a) The group velocity dispersion of MNFs with different diameters. (b) Diameter-dependent γ of MNFs with a wavelength of 1550 nm in linear and log coordinates. The conventional SMF and multimode fiber (MMF) are also displayed for comparison.

Table 1 Comparison ofSMF, MMF, PCF, MNF (1550 nm)

Fiber types	Dispersion (ps^2/km)	Nonlinear coefficient ($w^{-1}m^{-1}$)	References
SMF	-15	3.81e-3	Agrawal (2013)
MMF	-20	1.15e-4	Agrawal (2019)
PCF1	2.17	0.011	Zhang et al. (2007)
PCF2	-150	0.025	Zhang et al. (2021)
MNF (d=1.2 μm)	100	0.07	Zhou, et al. (2021a)

In addition to the three main characteristics, the low optical loss, high mechanical strength, and compatibility with conventional optical fibers are also reasons why MNFs have potential applications

in ultrafast optics (see supplementary materials, Section 3).

Accordingly, benefiting from these characteristics, MNFs serve as an excellent platform for investigating ultrafast optics. For different nonlinear dynamics and phenomena, the requirements for dispersion and nonlinearity distribution in the entire cavity are different. These requirements can be obtained by solving the generalized nonlinear Schrodinger equation (GNLSE) to simulate the dynamic evolution of pulses within the cavity (Agrawal, 2013). The GNLSE is usually solved with distributed Fourier transform and finite difference method, and the physics-informed neural network is used to predict the complex nonlinear propagation process of pulses (Fang et al., 2022; Jiang et al., 2022). Based on the required total dispersion and nonlinearity, the values of dispersion and nonlinearity that the MNFs should provide can be determined. Consequently, MNFs with appropriate structural parameters can be chosen accordingly. Further modification can be achieved through coating to tailor their dispersion and nonlinearity characteristics.

3. Application of MNFs in ultrafast optics

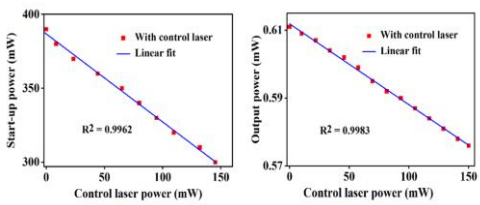
3.1 Component for ultrafast optical devices

In the realm of ultrafast optics, innovative strategies to generate ultrashort pulses are being explored, with mode-locking emerging as a crucial factor. The characteristics of MNFs, such as a high fractional evanescent field and diameter-dependent dispersion, make them a crucial component of passively mode-locked lasers.

3.1.1 Evanescent field modulation and control

Benefiting from a strong or rapid near-field interaction between light and nanomaterials, the nonlinearity of MNFs decorated with nanomaterials could be enhanced (Zhang et al., 2012a; Duan et al., 2015; He et al., 2016). Therefore, this composite structure can be exploited as a saturated absorber to generate ultrashort pulses (Luo, et al., 2018; Li, et al., 2019c; Liu, et al., 2020; Wang et al., 2020) and provide advantages over nanomaterials alone, such as a high optical damage threshold (Liu, et al., 2020). The commonly used nanomaterials include graphene (He, et al., 2016; Liu et al., 2016; Yang et al., 2016; Cai, et al., 2017; Wu et al., 2022), MXenes (Ahmad et al., 2021), topological insulators (Ahmad et al., 2022) or quantum dots (Du et al., 2017). Further information can be found in(Li, et al., 2019c; Liu, et al., 2020). In addition, the photo-thermal effect via the evanescent field along the MNFs could be greatly enhanced (Wang et al., 2016). By incorporating graphene on the surface of MNFs, the effective nonlinear index can be modified. Because the heat generated in graphene transfers to the MNFs, the graphene-decorated MNF becomes an effective tool for dynamically controlling the phase shift in ultrafast fiber lasers. Chen, et al. (2023) increased the thermal nonlinearity of graphene-decorated microfibers (GMFs) and the nonlinear phase shift difference between two counter-propagating beams by increasing the control laser power. This affects the self-starting performance of the laser, and the mode-locked threshold is linearly decreased Fig. 4a. The self-starting mode-locked threshold of the figure-9 fiber laser can be attained in a flexible pump power range. After achieving stable mode-locking operation, the output power of the mode-locked pulses can be adjusted when the control laser is turned on again, due to the difference in the nonlinear phase shift. The output power may either decrease linearly (as shown in Fig. 4b) or initially increase and then decrease, depending on the initial mode-locking state. To improve the speed of the phase shift difference control, the Kerr effect can also be used to achieve faster control of the phase shift difference, and the ultrafast laser can be used as the control laser.

The evanescent field also provides a platform



(a) (b)

Fig. 4 The mode-locking of a figure-9 fiber laser based on thermal nonlinearity of graphene-decorated MNF. (a) Start-up power at different control laser powers; (b) Output power with different control laser powers after the mode-locked operation(Chen et al., 2023).

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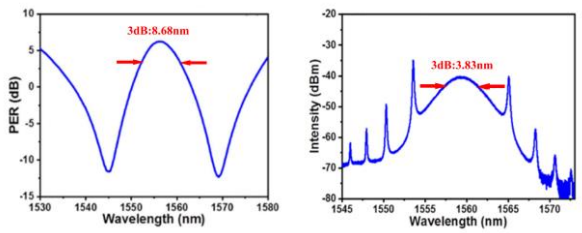
well-suited for coupling and interference between different modes, enabling MNFs to function as a polarization beam splitter (PBS) or polarizer due to the differences in optical paths among the modes. Zhang et al. (2015) obtained a polarizer based on MNFs by precisely controlling the partial overlap of two MNFs with equal lengths. Benefiting from the asymmetric transverse cross-section of the polarizer and large fractional evanescent field of MNFs, the overlap region exhibits significant birefringence, forming an effective polarizer. The transmission spectrum can be adjusted by altering the diameter of the MNFs and the length of the overlapping region. However, the fabrication of this polarizer involves rather delicate manipulation of equal length cleaving and precise stacking of the MNFs. To simplify the construction, Zhou, et al. (2021b) proposed an all-fiber PBS composed of two parallel coupled microfibers. They considered there are two different polarization states (TE and TM modes), each with a symmetrical supermode (even mode) and an antisymmetrical supermode (odd mode). Due to the interference between the symmetric TE mode and antisymmetric TM mode, the energy of the light is coupled to adjacent optical fibers through the evanescent field. When the length of the coupling region and the diameter of the MNF are set properly, the TE and TM modes will be separated. The characteristics of the MNF-Based PBS at 1.5 um wavelength bands are depicted in Fig.5. Soliton outputs were obtained experimentally. Zhou, et al. (2021b) pointed out that the birefringence effect



(a) (b)

Fig. 5 Mode-locked all-fiber laser based on MNF PBS. (a) The polarization extinction ratio spectra at the 1.5 μm band. (b) The spectrum of the mode-locked fiber laser at 1.5 μm (Zhou et al., 2021b).

increases with decreasing fiber diameter. Therefore, the polarization extinction ratio to wavelength decreases with decreasing fiber diameter of MNFs, which can affect the selection of diameter.

3.1.2 Dispersion and nonlinearity management

Dispersion and nonlinearity in the cavity play vital roles in pulse shaping and spectrum optimization in ultrafast lasers (Woodward, 2018). When a pulse transmits in MNFs, due to the small mode field area (MFA), it is easy to generate high power density, so nonlinear effects cannot be ignored. These nonlinear effects cause significant nonlinear phase accumulation, leading to pulse splitting, and limit the peak power of the ultrafast fiber laser. To balance or suppress these nonlinear effects, increasing the MFA to reduce the nonlinear coefficient is an effective approach. As a result, PCFs with large MFAs are rapidly being developed (Ranka et al., 2000; Akimov et al., 2003). Another solution is to manage the dispersion and nonlinearity, and MNFs are an attractive option in this regard.

There are two main advantages of using MNFs for dispersion and nonlinearity management. First, compared with dispersion compensation elements in free space (such as grating pairs), MNFs have compact and all-optical fiber structures. Second, MNFs have large and diameter-dependent dispersion, so the dispersion can be compensated accurately by tailoring their diameters. By managing the dispersion using MNFs, a laser can operate in a dispersion-managed soliton (Wang et al., 2018a; Yang et al., 2018) or a dissipative soliton (Li et al., 2018). A typical dispersion-managed mode-locked laser is described in Fig. 6. The MNF in the cavity is the dispersion delay line for dispersion compensation, and the MNF outside the cavity achieves further pulse compression.

The operating state of lasers is determined by the total dispersion within the entire cavity. In other words, when a specific output pulse is required, the dispersion that needs to be compensated is deduced by the total dispersion required for the entire cavity. By considering the relationship between the

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dispersion and the diameter of MNFs, the structural parameters of the MNFs can be determined. More detailed information on the applications of MNFs in mode-locked lasers can be found in (Li, et al., 2019c; Wang et al., 2019a; Liu, et al., 2020).

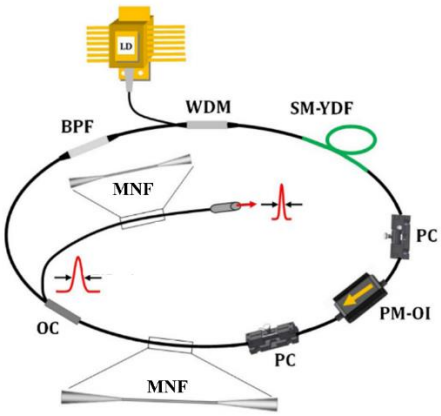

Fig. 6 A schematic diagram of a typical dispersion-managed mode-locked laser. LD: laser diode, PC: polarization controller, WDM: wavelength division multiplexer, YDF: ytterbium-doped fiber, OC: optical coupler, PM-OI: polarization maintaining optical isolator, GPC: grating pair compressor, BPF: bandpass filter (Yang, et al., 2018).

3.2 A platform for nonlinear phenomena and dynamics

Nonlinearity is a requirement for passive mode-locking, but too much nonlinearity can lead to pulse splitting and limit the output power. However, an appropriate level of nonlinearity can stimulate various nonlinear phenomena in mode-locked fiber lasers. Thus, MNFs with high nonlinearity provide an ideal platform for exploring nonlinear dynamics. Meanwhile, the study of nonlinear dynamics will promote the improvement of the performance of mode-locked fiber lasers (Grelu and Akhmediev, 2012; Liu, et al., 2020).

3.2.1 High-harmonic generation

The diameter-dependent dispersion character-istic of MNFs is suitable for parametric processes that require phase matching. Among these processes, the generation of high-order harmonics stands out, providing a convenient and efficient means of producing light of different wavelengths.

Grubsky and Savchenko (2005) derived a mathematical model of the third harmonic generation (THG) in MNFs and provided an expression of the conversion efficiency of the THG, as shown in Eq. (2):

$$\frac{P_3}{P_0} = 2(n_2|J_3|P_0)^2(\frac{k_0}{\delta\beta})^2 \qquad (2)$$

where P_0 and P_3 are the input fundamental wave power and the third harmonic power. J_3 is the nonlinear overlap integrals between them, k_0 is the propagation constant of the fundamental wave in vacuum, and $\delta\beta = \beta_3 - 3\beta_1$ is the propagation constant mismatch.

Eq. (2) shows that the improvement of THG conversion efficiency can be generally considered from the following aspects: reducing the phase mismatch; selecting a third-order mode with a large overlapping integral with the fundamental mode; choosing materials with a large nonlinear refractive index n_2. For MNFs, any mode of the third-harmonic wave, other than its fundamental mode $HE_{11}(3\omega)$, can be phase-matched with the fundamental mode of the fundamental wave $HE_{11}(\omega)$ by selecting an appropriate diameter, and the most efficient overlap is between $HE_{11}(\omega)$ and $HE_{12}(3\omega)$. Grubsky and Feinberg (2007) achieved an experimental conversion efficiency of 2×10^{-6} using MNF with a diameter of about 0.49μm and an effective length of 100μm, which is a factor of 3 lower than the theoretical value obtained from Eq.(2). They attribute the difference to slight diameter variations and not the optimal diameter. The conversion efficiency can be further improved when using longer MNFs, and the efficiency will reach 90% possibly in a 5cm MNF, but the inherent non-uniformities of MNFs along the length make it difficult to achieve such high efficiency in practice.

Nonadiabatic transmission of the third-harmonic generated in the high-order modes can also deteriorate the conversion efficiency and third-harmonic quality. Therefore, Ha et al. (2021) reduced the diameter of the cladding by introducing

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wet etching before fiber tapering and obtained an MNF that allowed simultaneous adiabatic transmission of multiple high-order modes and fundamental modes. Adiabatic transmission requires that the effective refractive index of high-order modes be distinguished. However, in the traditional tapering process, high-order modes become cladding modes, causing their effective refractive indices to become very similar. MNFs that support the simultaneous adiabatic transmission of different modes provide a good platform for THG. Ha, et al. (2021) obtained an improved third-harmonic conversion efficiency of 1.5×10^{-4} by using a 10-mm MNF drawn from a 17- μ m-thick cladding-etched fiber. They pointed out that the conversion efficiency could be further improved by increasing the length of the waist and improving the surface uniformity of MNFs.

Although Grubsky and Feinberg (2007) pointed out that phase mismatches included not only linear mismatches caused by refractive index but also nonlinear mismatches caused by nonlinear effects such as SPM and cross-phase modulation (XPM), they did not consider the nonlinear term in their practical calculations. Therefore, the conversion efficiency obtained by experiment is much lower than that in theory. Considering the nonlinear phase mismatch term, Jiang et al. (2018) took the diameter, length, and pump power of MNFs into consideration for iterative adaptive optimization to reduce the total phase mismatch, and achieved a conversion efficiency of several percent at peak pump powers lower than 2000 W with an MNF several centimeters long.

To further improve the efficiency of the THG, Jiang et al. (2017) introduced a method that involved a counter-propagating pulse train. The forward pump light was periodically modulated with the help of quasi-phase-matching technology. The forward pump light can be regarded as quasi-CW, the counter-propagating pulse train and the forward pumping light meet at every other coherence length L_c. That is, in the region satisfying the phase matching, a counter-propagating optical field did not exist, and in the region not satisfying the phase matching, a counter-propagating field existed and made the harmonic intensity zero, avoiding the transfer of harmonic energy to the pump. With this scheme, they further improved the conversion efficiency. They pointed out that the output harmonic power could be enhanced by several orders of magnitude by optimizing the parameters of the MNFs and input pulse.

In addition to the THG, the generation of higher harmonics is also expected. However, due to the limitation of high-order nonlinear polarizability, the generation of higher-order harmonics is usually realized by a cascade scheme. MNFs offer the potential for phase-matched four-wave mixing (FWM) by carefully controlling their dispersion, so they are suitable for cascade schemes for higher-order harmonics generation. The fourth harmonic (FH) and fifth harmonic (5H) in two MNFs using the FWM effect were achieved by Khudus et al. (2016).

In summary, in the generation of high-order harmonics, the controllable dispersion of MNFs plays a crucial role in phase matching. To achieve high conversion efficiency in high-order harmonic generation, it is necessary to minimize the phase mismatch between the fundamental and the harmonics. Additionally, further improvement in conversion efficiency can be achieved by using the nonlinear mismatch.

3.2.2 Harmonic mode-locking

Ultrafast lasers with high repetition rates (HRR) have great prospects in optical communication (Keller, 2003), micromachining (Yoshino, 2008; Kalaycioglu et al., 2018), and other applications (Denghui et al., 2021). The common techniques used to achieve a high repetition rate are to shorten the cavity length and use harmonic mode-locking (HML). Compared to simply shortening the cavity length, HML offers more flexibility and higher repetition rates. When the pump power is sufficient or the nonlinearity accumulated in the cavity is large enough, multiple pulses can propagate simultaneously in the cavity, achieving the state of

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HML. Consequently, some MNFs decorated with highly nonlinear nanomaterials have been proven to generate high-order harmonics with repetition rates up to GHz (Liu et al., 2014; Bogusławski et al., 2019; Wang et al., 2019b). Numerical results show that dispersion waves, gain depletion and recovery, and acoustic waves play crucial roles in the formation of HML during the early, middle, and later stages, respectively. The final stabilization of the HML state is achieved through acoustic resonance, which can capture pulses at a fixed temporal position (Liu and Pang, 2019). Acoustic resonance has discrete intrinsic frequencies and different gain factors which depend on the excitation mode and the diameter of the fiber. The small gain factor in SMF results in an unstable repetition rate and large pulse timing jitter (Kang et al., 2008). An MNF with a strong acoustic resonance effect is a more suitable scheme. MNFs of different diameters support different acoustic modes and thus have different acoustic frequencies. By designing the diameter, the acoustic frequency can be flexibly controlled (Cao et al., 2019). Huang et al. (2020) realized high-order HML of 2.3828 GHz and 1.7852 GHz by using an MNF with a waist length of 16 cm and a waist diameter of 1.56 μm, respectively. The repetition rates match well with the frequencies of R01 and TR21 acoustic modes, and this HML laser has high stability. An HML based on nonlinear multimode interference has also been proposed (Nazemosadat and Mafi, 2013). This nonlinear saturable absorption mechanism is realized by changing the coupling efficiency from MMF to SMF by controlling the incident optical power and has the advantage of being independent of the polarization state and a high damage threshold. Wang et al. (2022a) proposed a novel HML fiber laser based on a tapered single-mode fiber–multimode fiber–single mode fiber (SMS) ultrafast optical switch (The illustration in Fig. 7). As the diameter decreases, the self-imaging period is reduced, the dependence of nonlinear multimode interference mode locking on the length of MMF is eliminated, and the nonlinear coefficients improve, so the tapered SMS can easily achieve mode-locking operation. Fig. 7 shows the pump power is linearly correlated with the harmonic order, and the harmonic order for a diameter of 15 μm is higher than that for diameters of 30 μm and 40 μm under the same pump power.

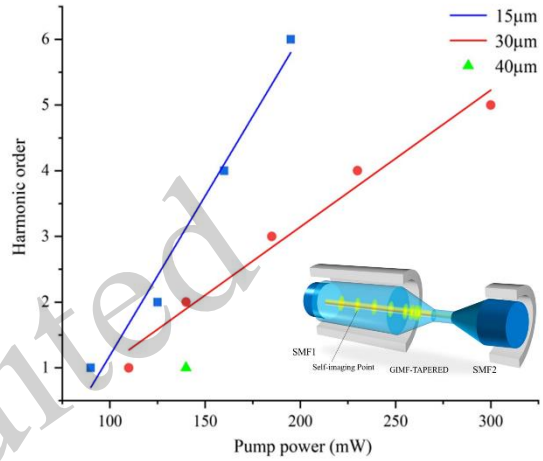

Fig. 7 Harmonic mode-locked fiber laser based on an SMS ultrafast optical switch. (a) Schematic diagram of the tapered SMS structure. (b) Relationship between pump power and harmonic order at different waist diameters of tapered SMS (Wang, et al., 2022a).

Generally, achieving a higher stability and repetition rate (>10 GHz) in a high-power HML can be attained by using a longer uniform waist and a smaller waist diameter, respectively.

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Dissipative four-wave mixing (DFWM) is a new scheme of mode-locking where the mode-locking pulse is obtained by adding multi-wavelength selective elements (such as comb filters) into the cavity and managing dispersion and nonlinearity (Li et al., 2019a; Zhou et al., 2022). The presence of the comb filter results in the growth of only a few modes, which transfer their energy to higher-order modes (the modes far from the center of the bandpass filter) by four-wave mixing. Due to the nature of the FWM process, all modes have a constant phase relationship, all sidebands are phase-locked, and the DFWM mode-locking can generate an ultra HRR (up to THz) (Schroder et al., 2009). The existence of the evanescent field provides the possibility of interference between different modes, so a knot resonator composed of MNFs can be used as a comb filter. Wang, et al. (2022b) used this filter by combining a graphene film to increase the nonlinearity and finally achieved adjustable higher harmonic mode-locked output. The diameter of the MNF knot resonator (MKR) can be altered to change the repetition rate. They obtained repetition frequencies of 323 GHz using an MKR diameter of 200 μm (Fig. 8a and 8b). To further improve repetition frequency, they further adjusted the polarization controller. By adjusting the polarization state, two main peaks appear, which further increases the repetition rate (Fig. 8c and 8d). They finally obtained a maximum repetition rate of 1.38 THz with the Lyot filtering effect and pointed out that the harmonic order equals the integer ratio of the free spectral range of the Lyot filter and MKR comb filter.

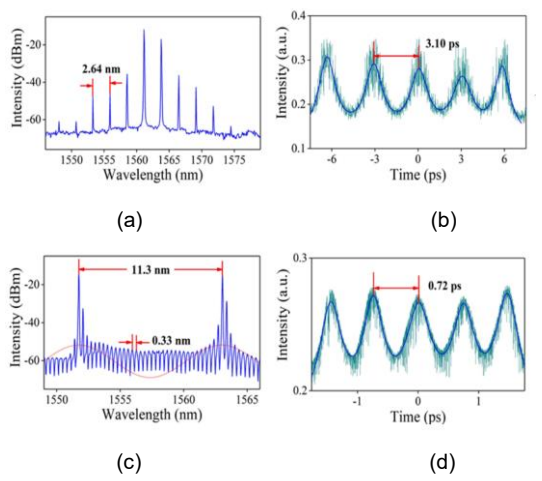

Fig. 8 Experimental results of the harmonic mode-locking with a micro-fiber knot resonator and Lyot filter. (a) The spectra and (b) the autocorrelation traces with an MKR diameter of 200 μm. (c) The spectra and (d) the autocorrelation traces with an MKR diameter of 1.6 mm after adjusting polarization states (Wang et al., 2022b).

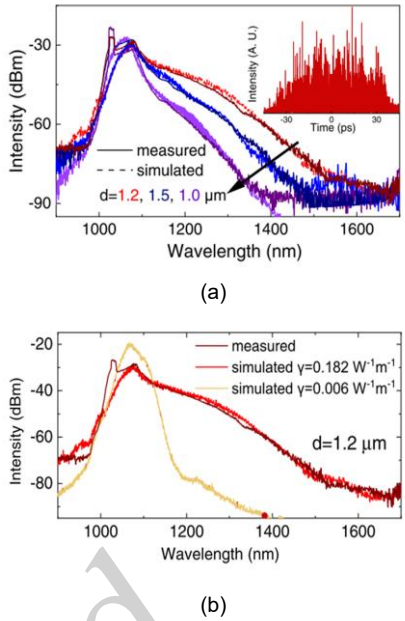

Fig. 9 Broadband spectrum NLPs based on MNFs. (a) Simulated and measured spectra for NLPs. The inset shows the simulated waveform with the 1.2-μm MNF. (b) Simulated spectra for NLPs for a 1.2-μm MNF, in which the nonlinear coefficients γ are assumed to be 0.182 $W^{-1}m^{-1}$ and 0.006 $W^{-1}m^{-1}$(SMF, HI1060). The measured spectrum (Zhou et al., 2021a) is also shown for comparison.

High-order harmonic mode-locking is obtained when the nonlinearity in the cavity is large. If the nonlinearity in the cavity continues to increase, unique multi-pulse patterns such as noise-like pulses and soliton rain may emerge (Huang et al., 2021b).

3.2.3 Noise-like pulse generation

Noise-like pulses (NLPs) arouse great interest due to their excellent properties of a broadband smooth spectrum and high pulse energy (Horowitz et al., 1997). In the net anomalous dispersion region, Tang et al. (2005) showed through numerical calculation that NLPs are caused by the soliton collapse effect and the positive feedback in the cavity. In areas of net normal dispersion, traditional soliton pulses cannot be generated, and the formation of

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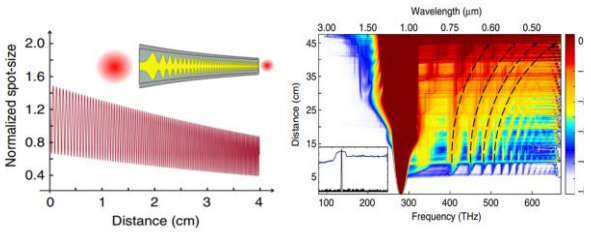
NLPs is due to the amplified dispersion wave and background noise. When the saturable absorber is oversaturated, the sharp increase in gain will cause the pulse peak power to become greater than the dispersive wave or the loss of the background noise. This results in fluctuations and instability of higher-order modes, which in turn results in the formation of NLPs (Jeong et al., 2014). In addition, studies have shown that NLP generation can be regulated through dispersion management and enhancement of nonlinear effects (Kang, 2000), which can be achieved by embedding MNFs in the cavity (North and Rochette, 2013; Wang, et al., 2018a; Li et al., 2020). Wang et al. (2018c) have obtained typical NLPs in the 1.5-μm band using a WS_2-deposited MNF as a saturable absorber. Their experimental results confirmed that the WS_2-deposited MNF is not only an excellent saturated absorber but also a highly nonlinear element in NLP generation. Based on the saturated absorption of a tungsten trioxide/polydimethylsiloxane-clad MNF, Abdul Hadi et al. (2022) generated an NLP with a spectral bandwidth of 22.8 nm, a maximum output power of 24.3 mW, and a repetition rate of 7 MHz. In addition to using coated MNFs, bare MNFs are also used to generate NLPs. Zhou, et al. (2021a) realized experimentally a wide spectrum NLP with a spectrum range of 1000-1600 nm using an MNF with a diameter of 1.2 μm. The output spectrum from using MNFs with different diameters is shown in Fig. 9a. Simulation results from solving the GNLSE and experimental results agree well. Fig. 9b verifies the effect of the large nonlinear coefficient of the MNF by comparing the output spectrum of an SMF and MNF. MNFs with different diameters have different dispersion, and the interplay of dispersion and nonlinearity enabled by MNFs is the key factor for the generation of broadband NLPs.

In the generation of NLPs in optical fibers, both dispersion and nonlinear distribution need to be considered. In terms of dispersion, the pump wavelength is expected to be at the anomalous region near the zero-dispersion wavelength, and the nonlinear coefficient is expected to be as large as possible in terms of nonlinearity. Therefore, it becomes necessary to use simulation to optimize the appropriate parameters for MNFs, achieving a balance between these two aspects.



(a) (b)

Fig. 10 SC generation based on a tapered MMF. (a) The simulation and (b) experimental results from a tapered MMF. Accelerated beating dynamics in a tapered multimode GRIN fiber (Eftekhar et al., 2019).

3.2.4 Supercontinuum generation

The generation of a supercontinuum (SC) is influenced by the reciprocal actions of dispersion and nonlinearity when an ultrashort pulse with high intensity is injected into a highly nonlinear fiber. SPM, XPM, SRS, FWM, and other effects will lead to spectrum broadening. Note that by tailoring their shape MNFs can fabricate and regulate the generation of SC.

Factors influencing SC generation in MNFs, such as fiber and pump pulse parameters, have been studied both in simulation (Foster et al., 2005; Kalli et al., 2010) and experiment (Birks et al., 2000). In terms of pump pulse parameters, theoretical (Zaytsev et al., 2013) and experimental (Chang et al., 2021; Luo et al., 2022) studies found that NLPs are effective pumping sources for the generation of SC spectra and are more effective at generating ultra-broadband SC than well-defined pulses (WDPs) (Chang et al., 2023). The femtosecond temporal durations make the peak powers of the inner structures much higher than the peak power of picosecond wave-packets, consequently inducing strong nonlinear optical effects for broadening the spectrum.

With increasing understanding of the SC

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generation process, attempts are being made to generate a flatter and broader spectrum by using dispersion-engineered fibers in which the dimensions and materials are carefully chosen.

In terms of the dimensions, in addition to selecting the appropriate length and diameter of the waist, the continuous change in taper diameter along the direction of propagation is attracting increasing attention. The taper offers the advantage of continuously modifying the phase-matching condition, allowing it to be satisfied for a wider range of wavelengths than a waveguide with constant dimensions would allow, making it a promising option for the generation of SC (Zhang et al., 2004; Chen et al., 2010).

In terms of the materials, to further expand an SC to the mid-infrared (MIR) band, chalcogenide MNFs are usually used, and the MIR SC is broadened to a wavelength beyond 5.0 μm(Yeom et al., 2008; Al-Kadry et al., 2014; Wang et al., 2018b). A broadband SC spectrum extending from 1.5 to 14.5 μm at −30 dB level has also been obtained by using the designed chalcogenide fiber taper with $AsSe_2$ glass as the core and As_2S_5 glass as the cladding (Saini et al., 2019).

In addition to the tapers obtained from SMFs and PCFs, tapered MMFs are promising avenues for the generation of SC. Periodic self-imaging, which is an important phenomenon in graded index (GRIN) fibers, affects the nonlinear propagation of optical pulses inside (Agrawal, 2019). The taper will accelerate spatiotemporal nonlinear dynamics (Fig. 10a). The oscillations experience an acceleration along the propagation direction, and as the diameter decreases, the spacing between the propagation eigenvalues increases, leading to an acceleration in intermodal collisions and energy exchange. The acceleration of intermodal collisions can affect the soliton fission mechanism and the subsequent generation of multimode solitons along with their Cherenkov radiation. In the normal dispersion region, the blue-shifted and red-shifted gain spectral bands that progressively drift away from the pump wavelength as the intermodal oscillations speed up, in turn leading to the generation of a markedly flat and uniform spectrum that extends over several octaves with large spectral power densities. As the input pulse travels through the taper section, there is an acceleration of intermodal collisions and newly generated sidebands move away from the pump, thereby sweeping the entire spectrum, resulting in a flat and uniform SC that spans over 2.5 octaves (Fig. 10a and 10b) (Eftekhar, et al., 2019). Some comparative results can be found in the supplementary material (Section 4).

In general, the generation of SC is a result of multiple nonlinear phenomena. To achieve a broader and flatter SC spectrum, optimizing the shape of MNFs is necessary. In the generation of SC, the number of zero-dispersion wavelengths, as well as the sign and value of dispersion, are important. By optimizing the structural parameters, the dispersion and nonlinearity profile can be precisely controlled, further enhancing the performance of the entire spectrum.

4 Conclusions and Outlook

In ultrafast optics, MNFs can be used as the main components of mode-locked lasers. They can be used as saturated absorption carriers for nanomaterials and also directly as saturated absorbers and polarizers for mode-locking. Secondly, their controllable dispersion and nonlinearity make them ideal for the dispersion and nonlinear management of ultrafast lasers, leading to improved output characteristics. In addition, MNFs present a versatile platform for studying nonlinear dynamics because of their significantly large and customizable nonlinear coefficient. This characteristic allows them to exhibit a variety of nonlinear effects, making them invaluable for research and applications in ultrafast optics. In addition to some of the applications mentioned above, MNFs hold great potential for application in many other fields. For example, in the field of nonlinear dynamics, MNFs drawn from MMFs with more complex spatiotemporal dynamics (Krupa et al., 2019; Mondal et al., 2020) have not been extensively studied. These complex dynamics offer the potential for a diverse range of nonlinear

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phenomena. However, the impact of tapering on nonlinear dynamics is not yet fully understood, and more comprehensive studies need to be conducted to better harness nonlinear effects in the future. The coatings and substrates associated with MNFs also need further study, as they play a key role in embellishing or protecting the MNFs. How the dispersion and nonlinearity properties of the coatings and substrates will affect that of the fibers may play a vital role in compact nonlinear systems. Finding new molecules with higher nonlinear coefficients could further strengthen the interaction between the strongly confined light fields and coatings or substrates, which might also be a novel way of boosting the performance of MNF-based devices.

Contributors

Xinying HE, Zhuning WANG, and Sijie PIAN investigated and summarized this paper. Xinying HE drafted the manuscript. Xinying HE, Yuhang LI, and Yaoguang MA, revised and finalized the paper.

Compliance with ethics guidelines

The authors declare that they have no conflict of interest.

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