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Recent progress on the applications of micro/nanofibers in ultrafast optics

Key words: Micro/Nanofibers (MNFs); Nonlinear dynamics; Dispersion; Ultrafast optics

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Motivation

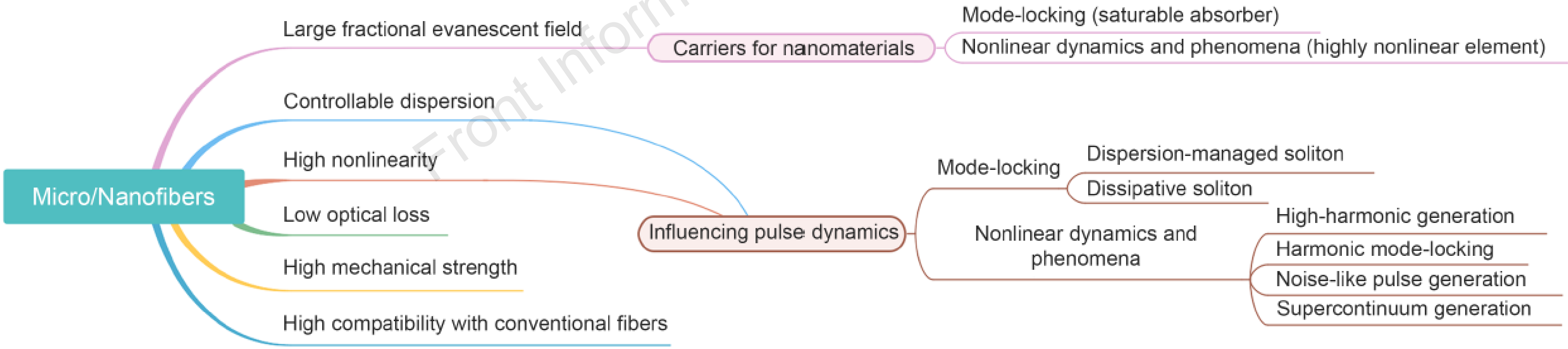
- Ultrafast fiber lasers are indispensable components in the field of ultrafast optics, and their continuous performance advancements are driving the progress of this exciting discipline. Micro/Nano-fibers (MNFs) possess unique properties, such as large fractional evanescent fields, flexible and controllable dispersion, and high nonlinearity which are valuable for generating ultrashort pulses.
- Dispersion, along with its interplay with nonlinearity, is a crucial factor that influences pulse dynamics in mode-locked fiber lasers and can reshape the pulse in the time domain and spectrum. However, in MNFs, waveguide dispersion associated with the structural parameters of the fibers dominates, offering the opportunity for convenient dispersion regulation.

Main idea

- Presented an introduction to the mode evolution and characteristics of MNFs.
- Provided a comprehensive review of recent advances in using MNFs for ultrafast optics applications including evanescent field modulation and control, dispersion and nonlinear management techniques, and nonlinear dynamical phenomenon exploration.
- Discussed the potential application prospects of MNFs in the realm of ultrafast optics.

Framework

The characteristics of MNFs and their applications to ultrafast optics are summarized. The main factors in ultrafast optics are a large fractional evanescent field, controllable dispersion, and high nonlinearity. MNFs can be used as highly nonlinear elements for studying nonlinear dynamics and phenomena when coated with highly nonlinear materials. Regarding the study of nonlinear dynamics, this article primarily focuses on high-harmonic generation, harmonic mode-locking, generation of noise-like pulses, and supercontinuum (SC) generation.



- Micro/Nanofibers
  - Large fractional evanescent field
    - Carriers for nanomaterials
      - Mode-locking (saturable absorber)
      - Nonlinear dynamics and phenomena (highly nonlinear element)
  - Controllable dispersion
  - High nonlinearity
    - Influencing pulse dynamics
      - Mode-locking
        - Dispersion-managed soliton
        - Dissipative soliton
      - Nonlinear dynamics and phenomena
        - High-harmonic generation
        - Harmonic mode-locking
        - Noise-like pulse generation
        - Supercontinuum generation
  - Low optical loss
  - High mechanical strength
  - High compatibility with conventional fibers

Fig. 1 Characteristics of micro/nanofibers (MNFs) and their applications in ultrafast optics

Method

The fabrication of MNFs with desired geometrical parameters holds paramount significance for their practical implementation in intricate ultrafast optics experiments. Real-time monitoring of the diameter of the tapered fiber ensures the smooth progress of the fabrication process.

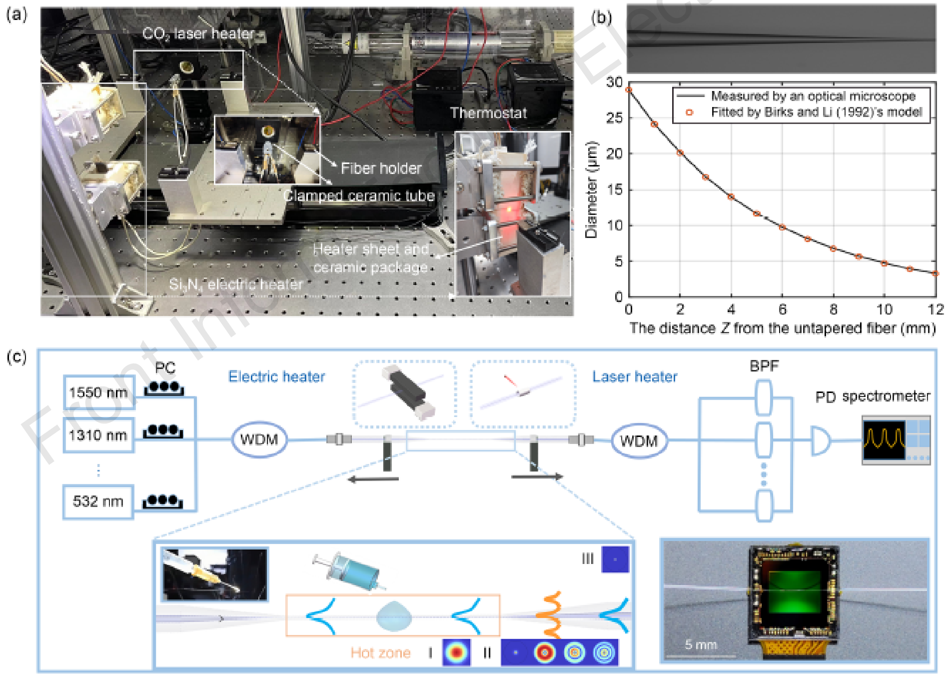


Fig. 2 Schematic of the MNF fabrication system: (a) experimental setup for heat tapering (two heaters are integrated on the same displacement platform; one is a Si$_3$N$_4$ electric heater with a long hot zone and high-temperature stability, and the other is a CO$_2$ laser heater with an ultrashort hot zone); (b) 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) schematic of fiber tapering. The evolution of the mode field at different diameters is also given. The illustration is a photograph of our homemade spectrometer (Cen et al., 2023). PC: polarization controller; BPF: band-pass filter; PD: photodiode; WDM: wavelength division multiplexer

Results

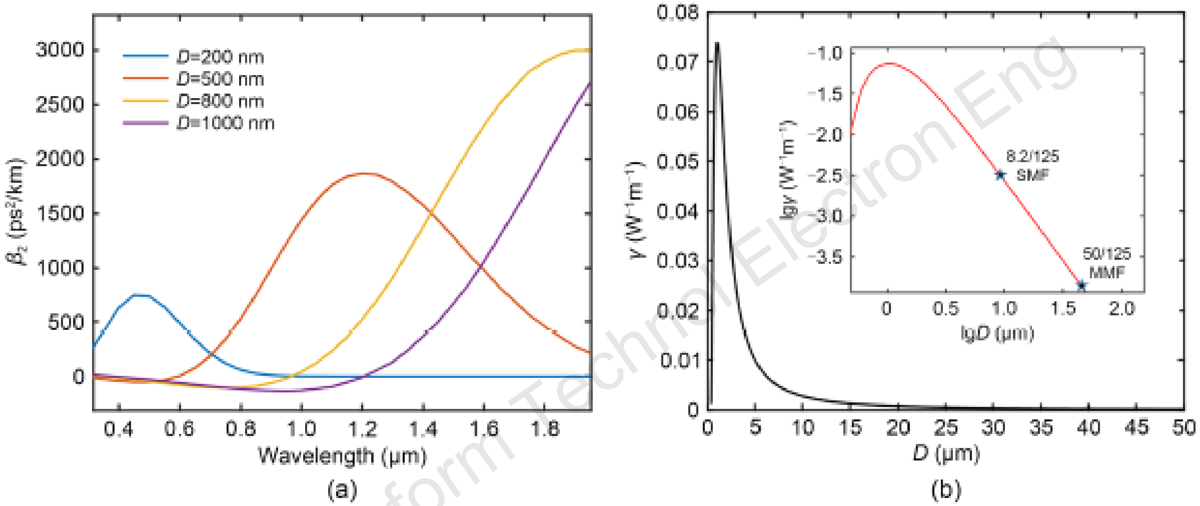


Fig. 3 **Characteristics of MNFs: (a) group velocity dispersion of MNFs with different diameters; (b) diameter-dependent γ of MNFs with a wavelength of 1550 nm in linear and log coordinates. The conventional single-mode fiber (SMF) and multimode fiber (MMF) are also displayed for comparison**

Nonlinear coefficient γ in MNFs

$$\gamma = \frac{2\pi}{\lambda}\frac{\iint_{-\infty} n_2 |F(x,y)|^4 \mathrm{d}x\mathrm{d}y}{\left(\iint_{-\infty} |F(x,y)|^2 \mathrm{d}x\mathrm{d}y\right)^2},$$

Results

Table 1 Comparison of SMF, MMF, PCF, and MNF (1550 nm)

Fiber type	Dispersion (ps^2/km)	Nonlinear coefficient ($W^{-1}m^{-1}$)	Reference
SMF	−15	3.81e-3	Agrawal (2013)
MMF	−20	1.15e-4	Agrawal (2019)
PCF1	2.17	0.011	Zhang X et al. (2007)
PCF2	−150	0.025	Zhang YC et al. (2021)
MNF (*d*=1.2 μm)	100	0.07	Zhou J et al. (2021)

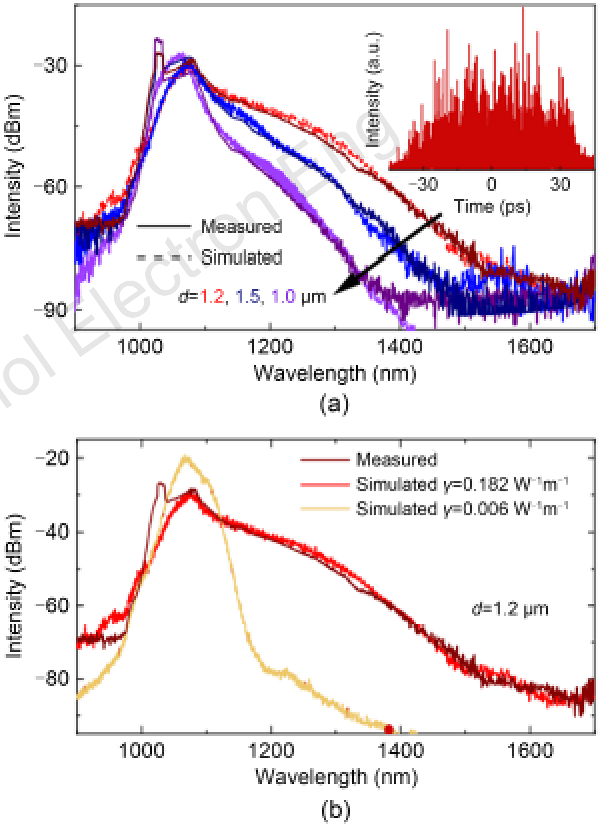


Fig. 9 Broadband spectrum noise-like pulses (NLPs) based on MNFs: (a) simulated and measured spectra for NLPs (the inset shows the simulated waveform with the 1.2-μm MNF); (b) simulated spectra for NLPs for a 1.2-μm MNF, in which the nonlinear coefficient γ is assumed to be 0.182 $W^{-1}m^{-1}$ (SMF)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

Conclusions

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. 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.

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Prof. Yaoguang MA is a Professor and Associate Dean of the College of Optical Science and Engineering of Zhejiang University. His research focuses on the study of light-matter interactions at mesoscopic scale, and micro/nano-techs stem from these interactions for advanced applications in photonic, electronic, and energy systems.