Several new directions for ultrafast fiber lasers [Invited]

WALTER FU,1 LOGAN G. WRIGHT,1 PAVEL SIDORENKO,1 STERLING BACKUS,2,3 AND FRANK W. WISE1,*

1School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853, USA
2Kapteyn-Murnane Laboratories Inc., 4775 Walnut St #102, Boulder, CO 80301, USA
3Colorado State University, ECE, 1373 Campus Delivery, Ft. Collins, CO 80523, USA
*frank.wise@cornell.edu

Abstract: Ultrafast fiber lasers have the potential to make applications of ultrashort pulses widespread – techniques not only for scientists, but also for doctors, manufacturing engineers, and more. Today, this potential is only realized in refractive surgery and some femtosecond micromachining. The existing market for ultrafast lasers remains dominated by solid-state lasers, primarily Ti:sapphire, due to their superior performance. Recent advances show routes to ultrafast fiber sources that provide performance and capabilities equal to, and in some cases beyond, those of Ti:sapphire, in compact, versatile, low-cost devices. In this paper, we discuss the prospects for future ultrafast fiber lasers built on new kinds of pulse generation that capitalize on nonlinear dynamics. We focus primarily on three promising directions: mode-locked oscillators that use nonlinearity to enhance performance; systems that use nonlinear pulse propagation to achieve ultrashort pulses without a mode-locked oscillator; and multimode fiber lasers that exploit nonlinearities in space and time to obtain unparalleled control over an electric field.

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The undeniable utility of a synchrotron into a widespread and routine capability—a synchrotron in locked lasers stand to transform nanoscience [2], or at more extreme wavelengths, turn the machines of today. Elsewhere, cheap and accessible x-ray sources driven by infrared, mode-might see femtosecond lasers being wheeled into doctors’ offices as easily as the ultrasound analytical tools of biologists are poised to become the clinical tools of surgeons. Even now, of this proliferation are difficult to overstate. With advances in nonlinear microscopy, the reliable, and affordable ultrashort pulse sources are expanding. The potential societal impacts laboratories. But the curve of technological demand is beginning to tip, as uses for compact, remain specialist instruments, operated largely by trained staff in universities and government have had tremendous impact in scientific applications, the ultrafast fiber lasers of today where they enable new forms of spectroscopy, metrology, and imaging. While such systems fiber lasers are becoming commonplace in chemistry, biology, and physics laboratories, there enable new forms of spectroscopy, metrology, and imaging. While such systems have had tremendous impact in scientific applications, the ultrafast fiber lasers of today remain specialist instruments, operated largely by trained staff in universities and government laboratories. But the curve of technological demand is beginning to tip, as uses for compact, reliable, and affordable ultrashort pulse sources are expanding. The potential societal impacts of this proliferation are difficult to overstate. With advances in nonlinear microscopy, the analytical tools of biologists are poised to become the clinical tools of surgeons. Even now, some techniques have already shown promise in clinical trials [1], and a not-so-distant future might see femtosecond lasers being wheeled into doctors’ offices as easily as the ultrasound machines of today. Elsewhere, cheap and accessible x-ray sources driven by infrared, mode-locked lasers stand to transform nanoscience [2], or at more extreme wavelengths, turn the undeniable utility of a synchrotron into a widespread and routine capability—a synchrotron in

1. Introduction

Nonlinearity is the traditional bane of physicists. We try our best to ignore it. We teach students to neglect it. We think up endless, clever ways to avoid it. But of course, without nonlinearity, there is no mode-locking. Without nonlinearity, there is no ultrafast science.

For most of their existence, the guiding philosophy behind ultrafast fiber lasers has been to minimize nonlinear effects. System design typically admits just enough nonlinearity to obtain short pulses, and no more. However, as the demand for larger peak intensities grows, this approach is becoming increasingly untenable.

At the same time, prospective applications for ultrafast lasers are on the rise. Mode-locked fiber lasers are becoming commonplace in chemistry, biology, and physics laboratories, where they enable new forms of spectroscopy, metrology, and imaging. While such systems have had tremendous impact in scientific applications, the ultrafast fiber lasers of today remain specialist instruments, operated largely by trained staff in universities and government laboratories. But the curve of technological demand is beginning to tip, as uses for compact, reliable, and affordable ultrashort pulse sources are expanding. The potential societal impacts of this proliferation are difficult to overstate. With advances in nonlinear microscopy, the analytical tools of biologists are poised to become the clinical tools of surgeons. Even now, some techniques have already shown promise in clinical trials [1], and a not-so-distant future might see femtosecond lasers being wheeled into doctors’ offices as easily as the ultrasound machines of today. Elsewhere, cheap and accessible x-ray sources driven by infrared, mode-locked lasers stand to transform nanoscience [2], or at more extreme wavelengths, turn the undeniable utility of a synchrotron into a widespread and routine capability—a synchrotron in

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a suitcase, to be optimistic [3]. Rather than jockeying for midnight shifts at million-dollar accelerators, biophysicists and materials scientists might perform the majority of their work from the comfort of their own labs. Meeting this remarkable demand for compact, powerful, and cost-effective ultrafast lasers will require more than simply engineering around known, linear constraints: it will require diving headfirst into all the possibilities that optical nonlinearities have to offer.

In this paper, we highlight work by our group and others that breaks from the pattern of avoiding nonlinearity, and instead explores lasers where nonlinearity is not only tolerated, but is in fact embraced. These successes in merging optical science with applied nonlinear dynamics have led to major improvements in fiber laser performance, with pulse energies increasing by multiple orders of magnitude. Perhaps more important than these performance improvements, however, is the number of qualitatively-new capabilities enabled by nonlinear fiber lasers. Nonlinearity is often eschewed for the complex and sometimes unintuitive dynamics that it can inject into otherwise simple, linear systems; nevertheless, this wealth of possibilities can also be the key to designing lasers to meet the equally diverse and innumerable ultrafast applications at hand.

Here, we present several areas that exemplify the theme of nonlinearity enabling both new performance levels and new capabilities. Faced on one hand with the field’s rapid advancement along multiple fronts, and on the other with the finite scope of this paper, we cannot be exhaustive in our discussion of this trend. We will restrict ourselves to three emerging areas, with the choices reflecting our point of view and biases. The structure of the paper is shown in Fig. 1. We first discuss the past and future of mode-locked oscillators, culminating in a new cavity design that harnesses an order of magnitude stronger nonlinearity than previous fiber lasers and reaps corresponding performance improvements. We then move on to prospects for nonlinearity-enabled ultrafast sources without a mode-locked laser, the ways and reasons this might be gainfully implemented, and the impact on the above applications. Finally, we discuss opportunities for extending nonlinear fiber systems to the highly multimode regime, and the advantages contained therein.

![Fig. 1. Outline of this paper, placed in historical context with the novel ideas and design elements that form a foundation for these results, and the applications that may follow. In the future, we see a variety of new source capabilities and features (listed from near- to long-term in descending order on the right) that may result from future combinations of these and other ongoing research directions.](image-url)
2. Beyond Ti:sapphire: Mamyshev oscillators

Currently, almost all ultrafast lasers are based on mode-locked oscillators in various broadband gain media. These oscillators may be directly employed in applications such as nonlinear microscopy, or they might supply seed pulses for parametric generators and amplifiers. The development of mode-locked oscillators with improved capabilities can therefore have major impact on applications. To see a dramatic example of this, one need look no further than the wide proliferation of ultrafast techniques after the appearance of mode-locked solid-state lasers [4,5].

While Ti:sapphire lasers currently dominate applications, fiber-based sources have begun to compete with them during the last few years. Fiber lasers are particularly suitable at high average powers, thanks to their excellent heat dissipation. Moreover, they offer robust, compact designs with lower costs than typically available with commercial, free-space laser systems. These factors, along with heavy investments into engineering high-power pump diodes and other major fiber laser components, contribute to making fiber lasers attractive for scientific, industrial, and clinical applications.

The most striking advances in ultrafast fiber laser performance have directly resulted from advances in understanding and controlling nonlinear pulse evolutions. This trend is depicted in Fig. 1, where the historical increases in the peak power of fiber oscillators are plotted according to the pulse evolution used. Today, research-grade oscillators have reached megawatt-level peak powers, on par with commercial solid-state lasers. However, the minimum duration of energetic pulses (~40 fs) still exceeds that of Ti:sapphire lasers, and of course, fiber lasers do not offer the broad wavelength tunability of Ti:sapphire.

Fig. 1. Historical increases in the peak power of fiber oscillators according to the pulse evolution used. Today, research-grade oscillators have reached megawatt-level peak powers, on par with commercial solid-state lasers. However, the minimum duration of energetic pulses (~40 fs) still exceeds that of Ti:sapphire lasers, and of course, fiber lasers do not offer the broad wavelength tunability of Ti:sapphire.

2.1 Limiting processes in high-performance fiber oscillators

Compared to solid state crystal lasers, fiber lasers feature much stronger dispersive and nonlinear effects (primarily the Kerr effect), arising from the small mode areas and long path lengths in the glass waveguide. The nonlinear phase accumulated through self-phase modulation (SPM), also known as the B-integral, is given by:
\[
\phi^{NL}(L) = \frac{\alpha}{c} \int_0^L n_2 I(z) dz
\]

where \( I \) is the peak electric field intensity, \( \omega \) is the field’s central angular frequency, \( c \) is the speed of light, and \( L \) and \( n_2 \) are the fiber’s length and nonlinear refractive index, respectively. When a pulse accumulates a nonlinear phase \( \phi^{NL} \sim \pi \), it will begin to distort if the process is not managed appropriately. Excessive nonlinear phase shift can cause a pulse in a cavity to either split apart (i.e., enter a multi-pulsing regime) or experience wave-breaking [26], or it may allow the growth of a significant continuous-wave (CW) background (a process termed CW breakthrough).

Mode-locking is generally initiated from noise and maintained by a suitable saturable absorber (SA). The SA promotes pulse formation by preferentially transmitting higher intensities, allowing random, initial fluctuations to evolve into short pulses above the background noise level. SAs based on absorption saturation in semiconductors [27], carbon nanotubes [28], or graphene [29], as well as effective SAs such as nonlinear polarization evolution (NPE) [30] and nonlinear loop mirrors [31,32], have all been employed in fiber oscillators. Unfortunately, none of these SAs is perfect. Material-based SAs are prone to damage in high-power fiber lasers, due to the need to operate near the damage threshold of the material [33,34]. On the other hand, the transmission-intensity curves of NPE and nonlinear loop mirrors do not increase monotonically, leading to pulse destabilization and multi-pulsing rather than a mode-locked state with a single, high-energy pulse [30]. As a practical concern, high-performance lasers based on NPE furthermore require the use of low-birefringence (i.e., non-polarization-maintaining) fiber, and are consequently sensitive to environmental perturbations. Nonlinear loop mirrors can be realized in environmentally-stable designs, but usually require precise control of the power splitting, which complicates saturation tuning and obtaining self-starting behavior. Finally, high-energy mode-locked fiber lasers require saturable absorption with very high modulation depth (often >70%) [35–37]. To date, this criterion has only been reliably met by NPE, with its attendant, aforementioned disadvantages.

Excessive nonlinear phase accumulation and the lack of high-contrast saturable absorbers combine to limit the performance of environmentally-stable laser designs severely, and motivate the development of new nonlinear propagation regimes and new cavity designs alike.

### 2.2 Brief overview of pulse-formation mechanisms

In this section, we briefly review established mechanisms of pulse formation in fiber lasers before turning our focus to the latest key advance, the Mamyshev oscillator. We encourage readers to visit our website [38] where animations that illustrate the different pulse evolutions are available.

When the net cavity dispersion of a laser is anomalous, solitons can form as a result of the balance between dispersive and nonlinear phases [39]. The relationship between this balance and the pulse parameters is described by the soliton area theorem, \( E \tau = 2|\beta_2|/\gamma \), where \( E \) is the pulse energy, \( \tau \) is the pulse duration, \( \beta_2 \) is the group-velocity dispersion (GVD) coefficient, and \( \gamma \) is the nonlinear parameter of the fiber [40]. This equation by itself only fixes the product of the pulse’s energy and duration; the maximum stable pulse energy is ultimately limited by the Kelly sidebands [41] that arise as the pulse’s duration decreases and its energy increases. In fiber lasers with a dispersion map, shorter and more-energetic pulses (dispersion-managed, or DM, solitons) can be generated. Such lasers incorporate both normally-dispersive and anomalously-dispersive sections, causing the pulses to alternately stretch and compress as they circulate in the cavity. The pulse width can evolve by an order of magnitude over each round-trip, significantly lowering the cavity-averaged peak power and
reducing the round-trip-integrated $\phi^{NL}$ for a given pulse energy. A more extensive discussion of soliton and DM soliton lasers is presented in [42,43].

While dispersion-managed solitons allow higher pulse energies than solitons, they are still ultimately constrained by the cavity-averaged soliton area theorem. An alternative pulse propagation regime was proposed in [44], where it was shown that a pulse with a parabolic intensity profile can propagate without wave-breaking and acquires a linear frequency sweep in the process. Such pulses preserve their shape during propagation—that is to say, they evolve self-similarly. Oscillators can generate such pulses through nonlinear, normally-dispersive propagation in passive fiber (passive self-similar lasers), or by way of a local nonlinear attractor in gain fiber (active self-similar, or amplifier similariton, lasers). Despite the self-similar regime’s resistance to optical wave-breaking, it is still susceptible to multi-pulsing and to CW breakthrough at high pulse energies and nonlinear phase shifts of $\phi^{NL} \sim 10\pi$. Detailed overviews of lasers based on self-similar pulse evolution are presented in [45,46].

In theory, the pulse energy in a self-similar oscillator scales up rapidly with increasingly normal net cavity dispersion [12]. Following this trend to its logical conclusion leads to the elimination of a cavity dispersion map, and the advent of the all-normal-dispersion (ANDi) cavity. By combining this new concept with an old one—intracavity spectral filtering—a new pulse evolution was born: the dissipative soliton [15]. Such pulses are analytic, cavity-averaged solutions to the cubic-quintic Ginzburg-Landau equation (CQGLE) with normal dispersion. Dissipative soliton lasers can support higher pulse energies than any other pulse evolution thus far discussed, but they remain fundamentally limited by nonlinear phase accumulation at $\phi^{NL} \sim 10\pi$. For an overview of dissipative solitons for mode-locked lasers, we refer to review papers [47,48].

2.3 Mamyshev oscillators

In the last few years, it has been shown that a new type of fiber oscillator can address the limitations described above. A so-called Mamyshev oscillator can be understood as a concatenation of two Mamyshev regenerators [49]. The operation of an individual Mamyshev regenerator has been well-studied: as a launched pulse propagates through a nonlinear medium (typically either passive or active fiber), it experiences SPM, leading to spectral broadening. It then encounters a bandpass filter that is offset from the pulse’s central wavelength. Crucially, the offset means the filter has little overlap with the initially-launched spectrum, restricting the passed light to only that which is newly-generated through SPM. As shown in Fig. 3, this mechanism can act as an effective saturable absorber, with low-intensity pulses producing insufficient self-phase modulation to be transmitted through the offset filter. Cascading this process (i.e., by repeating it with a different filter offset) can enhance the effect, ultimately producing a step-wise transfer function that passes high-intensity pulses while extinguishing those below a certain intensity threshold [50,51]. While the applications of this effect to high-power mode-locked lasers are clear in hindsight, the original and most longstanding use of the Mamyshev regenerator was in telecommunications as a pulse regenerator.
The Mamyshev oscillator is a natural continuation of the Mamyshev regenerator [23–25,52,53]. The idea of a mode-locked laser based on offset filters was actually proposed much earlier [54,55] but did not receive significant attention at that time. With the addition of gain fibers and output couplers between the Mamyshev regenerators, two distinct arms of the cavity become apparent (Fig. 4). A key feature of the resulting oscillator is that the centers of the two bandpass filters are offset, which prevents CW lasing. The cavity thus admits only high-intensity pulses, which experience large enough nonlinear phase and spectral broadening in each arm to bridge the spectral gap between the two filters and continue on to the next arm. In this manner, pulses can be stabilized by the repeated filtering despite propagating in a highly nonlinear regime, while noise and CW lasing are strongly suppressed. Effective saturable absorption from the Mamyshev mechanism obviates the need for other saturable absorbers such as NPE, permitting an all-polarization-maintaining (PM) cavity. Mamyshev oscillators have also been demonstrated in a fully fiber-integrated format, leading to even better environmental robustness [24].

The specific mode-locked state reached depends strongly on the spectral separation of the two filters. Larger separations require greater spectral broadening to traverse, thereby selecting for pulses with higher energy, greater bandwidth, and stronger nonlinearity even as the CW lasing threshold increases. For instance, with a filter separation of ~10 nm, a round-trip nonlinear phase as high as $\phi_{NL} \sim 60\pi$ has been observed, along with a corresponding, order-of-magnitude increase in the peak power obtained [25]. The power of the Mamyshev mechanism in stabilizing the pulse against noise and CW breakthrough is evident in this demonstration. In fact, the effective saturable absorber in so adept at suppressing noise that the opposite problem arises: that of enabling self-starting. Several methods for starting Mamyshev oscillators have been proposed, including allowing ASE to temporarily bypass one filter and be fed back [23]; modulating a pump diode [24]; and incorporating an auxiliary cavity [56]. In all of these examples, the aim is to briefly introduce a fluctuation into the cavity that is strong enough to sustain itself and seed pulse formation. High-performance mode-locked states can thereby be reliably accessed without requiring an external seed pulse.
Fig. 4. Schematic of a Mamyshev oscillator. The cavity comprises two Mamyshev regenerator (MR) arms, each containing a bandpass filter (BPF) at a different wavelength.

Compared to mode-locked fiber lasers that have undergone more systematic study, the Mamyshev oscillator presents a relatively-unexplored parameter space. Parabolic pulse evolution has been studied theoretically for picosecond pulse generation [57], and the generation of megawatt pulses has been partially attributed to parabolic evolution [25]. Seeking out other propagation regimes (for instance, Gaussian pulses [50,51]) remains important and interesting. Here, we would like to point out several promising directions for further work in this area.

1) An immediately evident feature of the Mamyshev oscillator is the ultrabroadband spectrum it can generate, courtesy of the unprecedented degree of nonlinearity tolerated by the pulse. Investigating the limits of this feature will be of obvious importance to generating still-shorter pulses while avoiding the power trade-offs that are endemic to typical, few-cycle mode-locked lasers. The generation of multi-megawatt, few-cycle pulses in a robust, compact setup will be useful for, e.g., time-resolved studies of ultrafast processes in atoms and molecules [58]. Taking this a step further, one could imagine optimizing the Mamyshev oscillator’s naturally broadband operation to generate coherent, octave-spanning pulses for applications requiring a phase-stabilized frequency comb.

2) In some cases, the central wavelength of a pulse can be just as important as its energy or duration. High-performance Mamyshev oscillators have thus far exclusively used ytterbium-doped fibers operating near 1 µm. Extending this breakthrough performance to new wavelengths will be key in enabling new applications based on this technology. A natural progression will be demonstrating high-energy Mamyshev oscillators in erbium- and thulium-doped silica fibers at ≈1.55 µm and ≈1.9 µm, respectively. Mid-infrared operation may also be possible, using either fluoride-based active fibers [59] or emerging, rare-earth-doped, chalcogenide fibers [60]. Doing so without sacrificing performance will be nontrivial, since at these wavelengths, fibers are either anomalously dispersive, or feature high nonlinearity as a byproduct of achieving normal dispersion. New pulse evolutions that can leverage nonlinearity in spite of anomalous dispersion may be needed in order to fully exploit Mamyshev oscillators at these wavelengths.

3) As a corollary to demonstrating Mamyshev oscillators in other gain media, the ultrabroadband nature of the Mamyshev oscillator suggests that using two different rare-earth-doped fibers in different arms of the same cavity might be possible. Candidates include oscillating between the 1030-nm gain window of ytterbium and the 920-nm line of neodymium [61], or between the 1550-nm line of erbium and the
recently-demonstrated, 1700-nm emission band of thulium [62,63]. In addition to the scientific interest in a single laser utilizing two different gain media, either of these combinations could cover a key wavelength for multiphoton imaging. Could this approach ultimately bridge the ytterbium and erbium gain windows, or the erbium band and the primary emission band of thulium? And if so, can the Mamyshev oscillator’s multiple outputs be spectrally combined to form a self-synchronized, band-spanning pulse? Given the huge nonlinearity tolerance of the Mamyshev oscillator, and the growing body of work on optimized self-phase modulation spectral shifting in fiber [64,65] and coherent supercontinuum generation [66], this outlandish possibility—a fiber oscillator providing 1000-nm-bandwidth pulses—appears at least accessible in principle.

4) While the Mamyshev regenerator uses SPM to shift between multiple bandpass filters, other nonlinear processes can be used. For example, the soliton self-frequency shift [67] can efficiently red-shift pulses across a large fraction of the near-infrared and even into the mid-infrared [68]. The soliton self-frequency shift has been demonstrated in a Mamyshev oscillator [69], but additional work is needed to stabilize a high-energy, single-pulse state. Due to the favorable scaling of the soliton area theorem at longer wavelengths, approaches such as this one may provide a route to the highest performance in the mid-infrared.

5) So-called giant chirp oscillators (GCOs) have been proposed as a means of simplifying chirped-pulse amplification (CPA) systems [70]. A long cavity with large normal dispersion generates high-energy, stretched pulses at low repetition rates, eliminating or reducing the need for additional preamplification, stretching, and pulse picking. Although typical GCOs suffer from poor bandwidth and compressibility, the large bandwidths and parabolic pulses emitted by a Mamyshev oscillator may provide a solution to these problems. A very high-energy, “giant-chirp Mamyshev oscillator” emitting pulses stretched to the nanosecond scale at low repetition rates could form an integral part of a state-of-the-art CPA system, greatly simplifying fiber or solid-state systems targeting millijoule energies for applications such as high-harmonic generation.

2.4 Conclusions
The history of mode-locked fiber oscillators is a story of advances in nonlinear pulse propagation leading to breakthroughs in laser performance. The Mamyshev oscillator is the latest leap in this pattern, delivering order-of-magnitude improvements in both the peak nonlinear phase and the peak power in an environmentally-stable design. These capabilities put Mamyshev fiber oscillators on par with typical Ti:sapphire oscillators except for in wavelength tunability, and potentially better in key metrics such as cost, size, and reliability. While we have suggested some research goals that may be of particular interest, we emphasize that avenues for future work on Mamyshev oscillators far outnumber what we can hope to discuss here. If the past is any indication, the demonstrated capabilities are only the beginning, and Mamyshev oscillators will continue to evolve to meet new performance levels and enable new applications.

3. Beyond mode-locking: nonlinear pulse generation
For some applications, having a mode-locked oscillator is essential. The coherence and noise properties of such devices are unrivaled by any other technology, and their raw performance will only improve as pulse propagation physics continues to develop. As has been discussed, the Mamyshev oscillator stands to address many longstanding issues with mode-locked fiber oscillators. However, mode-locked oscillators remain limited in certain ways. All lasers
require a means of initiating mode-locking and restoring it if it is lost, and even in reliably self-starting lasers, a given mode-locked state must be maintained during operation.

More fundamentally, mode-locked oscillators must operate at fixed, periodic, repetition rates defined by the cavity length. Often taken for granted by laser engineers, this can be a significant constraint in some cases: in micromachining, pulses must be synchronized to scanning optics that may change speed as they trace out various shapes; in deep-tissue nonlinear microscopy, maximizing the signal while simultaneously avoiding both nonlinear damage and thermal ablation requires independent optimization of the applied average power and peak power; and in functional neuroimaging, the region of interest may comprise just a few neurons sparsely distributed in a sample where full illumination would be harmful or inconvenient. Although pulse pickers can address these needs to some degree, they provide only a coarse level of control. Even systems that purportedly offer pulse-on-demand capabilities, as are common in micromachining, can only do so modulo the oscillator’s repetition rate, falling well short of being able to deliver pulses precisely when they are needed. Applications also exist that can benefit from pulse trains or bursts with repetition rates in the gigahertz range [71], a regime that standard fiber lasers have trouble accessing.

For these reasons, even the best mode-locked fiber lasers may sometimes prove lacking. In this chapter, we discuss alternatives: fiber systems that generate ultrashort pulses without starting from a mode-locked oscillator. We first review the major methods of producing pulses without mode-locking, and then turn our attention to how useful pulses can be obtained from such sources with the aid of strong nonlinearity.

3.1 Generating pulses without mode-locking

One straightforward method of generating short pulses is by launching long (nanosecond or longer) pulses into anomalously dispersive fiber, and filtering the ultrashort solitons that result from modulation instability [72]. Perhaps surprisingly, even the noisy, chaotic pulse bursts obtained via this approach have been successfully used for multiphoton imaging [73]. While evidently-controlled pulses are still preferable, this result reflects a common trend in ultrafast laser applications, where practical considerations spur unexpected laser source developments—sometimes prompting new features (e.g., tunability), and other times simply justifying a performance trade-off in exchange for a lower-cost or more reliable device. More deliberate methods that can deterministically generate individual, high-quality pulses can only increase the appeal of these cheap, but ill-controlled, sources (Fig. 5). For instance, a high-bandwidth intensity modulator can carve pulses out of a continuous-wave (CW) beam by attenuating the beam in a desired pulse sequence. Techniques with greater efficiency (up to unity in some cases) have been demonstrated using rapid amplitude or phase modulation schemes based on time-lenses [74–76], temporal zone plates [77], temporal holograms [78,79], or the temporal Talbot effect [80], followed by a dispersive delay line that compresses the modulated beam into a pulse train. The improved efficiency can reduce the number of amplification stages needed; however, these techniques generate a repetitive pulse train, rather than individual pulses, and are therefore less versatile than techniques such as direct intensity modulation. Furthermore, they can leave a residual CW background.

Short pulses can also be generated without an expensive, high-speed modulator. Some of the first work on non-mode-locked sources used seeded modulation instability, either by periodically modulating a CW beam or by beating two spectrally-separated CW beams against one another, and using soliton effects to convert the modulation to a high-repetition-rate, high-duty-cycle pulse train [81–84]. Self-similar propagation [85,86] and active pulse shaping [87] have been applied to similar systems. Gain-switched diodes offer another alternative: even a relatively slow current modulator can take advantage of the fast gain dynamics in an optical diode to generate ultrashort pulses on demand [88], although the pulses typically exhibit random fluctuations and incomplete coherence [89].
A primary shortcoming of mode-locking-free laser sources is the achievable pulse duration. Systems based on modulated CW light are limited by the bandwidth and power of electro-optic modulators and their drivers. Rarely do they produce pulses shorter than a few picoseconds, and more economical systems are limited to tens of picoseconds. Enhancement loops that compound the effect of a single modulator can improve this to the sub-picosecond regime, but they add complexity and sacrifice control over the pulse pattern and repetition rate [90]. While gain-switched diodes are not bound by the speed of an optical modulator, the natural rate of their internal photon-carrier dynamics is such that they, too, emit picosecond-scale pulses. Extending non-oscillator sources to the short pulse durations commonly associated with mode-locked oscillators (e.g., <300 fs) stands to greatly broaden their impact, and will allow a broad range of ultrafast applications to exploit their robustness and flexibility. The salient challenge, therefore, is to nonlinearly compress picosecond-scale pulses by multiple orders of magnitude in a manner that permits scaling to useful energies (e.g., microjoules or many nanojoules; see Fig. 2).

Simultaneously, the generated pulses must display low noise, although often not to the level displayed by typical mode-locked lasers. This poses another challenge, as nonlinear techniques generally magnify small, pulse-to-pulse fluctuations. One might wonder whether non-mode-locked sources can control these fluctuations in the long run without the optical feedback that stabilizes such processes in a mode-locked oscillator. The relative novelty of non-mode-locked sources that achieve comparable pulse parameters to their mode-locked brethren makes this an open question. As we will see, however, proper system design can help mitigate this concern and, in some cases, actually reduce noise through nonlinearity.

### 3.2 Compressing pulses from non-mode-locked sources

In anomalous-dispersion fiber, pulses can be adiabatically compressed as fundamental solitons. Following from the soliton area theorem, evolution in fibers incorporating amplification [91,92] or longitudinally-decreasing dispersion [93–95] produces transform-limited, sub-picosecond pulses. However, for standard fiber parameters, the soliton area theorem and higher-order effects limit this approach to sub-nanojoule energies. The reliance on anomalous dispersion also typically restricts soliton compression to wavelengths longer than ~1.3 µm, although this spectral range can be extended in photonic crystal fibers [96], hollow-core photonic bandgap fibers [97], and higher-order-mode fibers [98,99].

Normal-dispersion compression techniques have more success in scaling to high energies. By balancing nonlinearity and normal dispersion, a dispersive self-phase modulation (DSPM) compressor [100] can linearize the chirp across much of a pulse, allowing the pulse to be dechirped cleanly. However, the length of fiber needed to achieve the proper balance increases with the initial pulse duration. Thus, systems that start from long (~10-100 ps)
pulses often must compromise on pulse quality for practicality’s sake [101]. A better-controlled method is self-similar amplification, whereby pulses subject to gain, self-phase modulation, and normal dispersion asymptotically become parabolic, linearly-chirped pulses—so-called similaritons [44,102]. While this regime is most-commonly used for amplification, the exponential bandwidth growth and linear chirp makes it ideal for pulse compression as well. Furthermore, the asymptotic similariton acts as a global nonlinear attractor, making this technique applicable in principle to arbitrary seed pulses and potentially reducing noise [46,103]. Dispersion-decreasing fibers can replicate this phenomenon, exchanging the benefits of amplification for greater bandwidth and spectral flexibility [104]. Of course, self-similar evolution has limitations in practice. Although the similariton’s basin of attraction is infinite, the speed of the attraction depends on the seed parameters [105,106]. In typical fibers, a long or ill-shaped seed pulse might not reach the attractor within the finite fiber length. An arbitrarily long amplifier would resolve this in principle, but in practice, the onset of spontaneous Raman scattering and gain narrowing limit the maximum fiber length, and therefore the effective range of the attractor. These effects reduce the usefulness of this technique for the picosecond-scale durations and varied pulse shapes that mode-locking-free sources can generate.

Amplification following parabolic pre-shaping is related to self-similar amplification, but has several important differences [107]. Pulses in normally-dispersive fiber can transiently evolve to a nearly-parabolic state even in the absence of gain [108], and can be subsequently amplified in another fiber. The pulses need not be near the amplifier’s similariton attractor to benefit from their parabolic shape’s linearization of nonlinear phase: following amplification in the highly nonlinear regime, they can be substantially and cleanly compressed to the transform limit. While this is a powerful technique, the lack of a nonlinear attractor means that only pulses that are initially well-behaved (for instance, Gaussian or hyperbolic secant pulses near the transform limit) exhibit the necessary parabolic evolution. As a result, this technique can be unsuitable for the more complicated pulses that may be formed from non-mode-locked systems.

The Mamyshev regenerator from telecommunications can be a versatile tool for compressing and reshaping pulses [49]. As Fig. 6 illustrates, launching a pulse into a nonlinear fiber and then isolating newly-created spectral components with an off-center bandpass filter has a number of effects on the pulse, including reducing amplitude jitter [49,109], stripping amplified spontaneous emission [110,111], suppressing pedestals or background light [112–114], and enhancing intra-pulse coherence [50,51,115]. These effects are also accompanied by pulse compression by a modest factor (typically ~2-5), even for input pulse durations ranging from sub-nanosecond [116] to femtosecond timescales [64]. With an appropriate choice of bandpass filter, the output can be made transform-limited or linearly-compressible to the transform limit [109].
3.3 Prospects for short pulses without mode-locking: multi-stage compression

The problem of compressing pulses from non-mode-locked sources is compounded by the long initial pulse durations. The most powerful compression techniques require a balance between dispersion and nonlinearity (Fig. 7). Applying them directly to ~10-100-ps pulses can necessitate many kilometers of fiber (e.g., [85,94,117]). While such fiber lengths are common in telecommunications, they can have significant consequences for a high-energy pulsed laser system’s cost, footprint, and loss (particularly at wavelengths where fiber losses are higher). These restrictions can be particularly limiting for DSPM compressors, where using a more practical yet sub-optimally-short fiber length leads to pulses with a low-intensity pedestal rather than high-quality pulses [101]. This can be seen in Fig. 7, where, barring standout results, only compressors operating near the shaded regions tend to produce transform limited pulses.

If a more complex system is tolerable, using multiple different compressors in sequence can ameliorate the problem. For instance, the Mamyshev regenerator relies mainly on nonlinearity alone, which can be strengthened through amplification to permit spectral broadening in more reasonable fiber lengths [116]. Pulses may thereby be compressed and even amplified, while the Mamyshev regenerator’s normalizing effect on the pulse shape enables further shaping via more sophisticated techniques. The diverse properties of Mamyshev regenerators make them powerful front-line pulse shapers even beyond their compression capabilities: in systems seeded by gain-switched diodes, they can improve the intrapulse coherence and reduce amplitude fluctuations, especially when cascaded; in systems founded on intensity modulators, they can amplify the low-power pulse trains while curbing amplified spontaneous emission; and in systems based on amplitude/phase modulation of CW light, they can suppress the residual inter-pulse background even at non-uniform repetition rates. A Mamyshev regenerator following a DSPM compressor can also attenuate the pedestal produced by the latter, although interposing another nonlinear process before the Mamyshev regenerator will reduce its ability to dampen noise from the seed laser.
Fig. 7. Performance of various nonlinear compression schemes. Ovals indicate the approximate regime over which each technique typically produces transform-limited, pedestal-free pulses. Data are from [84–86,94,97,107,111,115,116,118–131].

An example that illustrates the multi-stage compression approach is recent work on a gain-switched diode source [115]. There, the combination of Mamyshev regeneration and amplification following parabolic pre-shaping led to pulse parameters that previously required an amplified, mode-locked oscillator. This result proved for the first time that, by taking advantage of fiber nonlinearities, non-mode-locked sources stand a chance of competing with mode-locked systems as application-relevant ultrafast lasers. While the demonstrated source exhibited pulse-to-pulse fluctuations as per the nature of the gain-switched diode seed, the observed energy jitter was already low enough to be acceptable for many applications. Further noise reductions might be accomplished by self-seeding [89,132,133] or injection seeding [134,135] the diode, although the former sacrifices fine control over the gain-switched diode’s repetition rate. Additional Mamyshev regenerators could be added in sequence in order to effect a more stepwise transfer function and funnel the pulses towards a uniform eigenstate [50,51]. While we are optimistic that sources based on gain-switched diodes may improve to eventually rival mode-locked lasers, it should be noted that many applications—for instance, micromachining [136] and multiphoton microscopy [73]—can be performed with significantly noisier pulses than even the source in [115].

Although the source in [115] lacked inter-pulse coherence—a hallmark trait of mode-locked oscillators, and a necessary one in comb-based applications—there is some evidence that even that feature might not be out of reach. Self-seeded gain-switched diodes have been shown to exhibit inter-pulse coherence [137], and an interesting question is whether injection seeding can accomplish the same. Given that gain-switched diodes have been shown to inherit coherence from an externally-seeding, pulsed, master laser, it seems plausible that an external CW seed might likewise confer inter-pulse coherence [138]. However, this remains to be experimentally verified for injection-seeded gain-switched diodes to compete with mode-locked sources in optical comb applications while retaining their pulse-on-demand capabilities.

It bears noting that the compression and amplification schemes described here for gain-switched diodes could be naturally adapted to modulated CW sources. Indeed, this may be a preferable alternative in some cases: pulses generated from a sufficiently quiet CW diode will inherit the diode’s long coherence time and low noise as a matter of course, without a gain-switched diode’s need for additional seeding. However, this approach is not without its disadvantages. The coherence and noise will still depend on the linewidth and stability of the CW diode, which will ultimately correlate strongly with the diode’s cost. In addition, the
degree of compression required will depend on the speed at which the diode can be modulated, necessitating a trade-off between the cost of fast driving electronics and the complexity of additional compression stages. As non-mode-locked systems with performance comparable to mode-locked lasers have only recently been demonstrated, it remains to be seen which approaches, if any, will have enduring and widespread impact. The decision to favor one method over another, along with the judgment of whether the simplicity and advantages of using a non-mode-locked seed outweigh the complexity of compressing the pulses, will ultimately come down to the needs of individual applications, and the resources available to them.

3.4 Prospects for short pulses without mode-locking: extreme dispersion engineering

As an alternative to the multi-stage compression schemes thus far discussed, the difficulties of shaping long pulses from non-mode-locked sources may be resolvable through appropriate dispersion engineering. Under the right conditions, the dispersion in a certain spectral range can be made extremely large, permitting soliton and self-similar evolutions in more practical fiber lengths. An example of this is near the mode cutoff in a higher-order-mode fiber, where dispersion nearly two orders of magnitude higher than that of typical fibers has been reported [98]. Even more powerful dispersion engineering can be performed near (but outside) the reflection band of a fiber Bragg grating (FBG) [139], where inscribed structures up to a meter long can boost the dispersion by more than six orders of magnitude [140–143]. Pulse compressors based on this technology have been proposed and demonstrated, including those using soliton and similariton evolutions [144–148], although the experimental demonstration of Bragg similaritons remains inconclusive [149]. Intriguingly, because the dispersion induced by the grating far exceeds the material or waveguide dispersion, this approach can be transposed to any wavelength of interest where fibers are available. This flexibility synergizes well with pulsed sources (mode-locked or otherwise) that can be designed at a variety of wavelengths in the near-infrared [150,151] or mid-infrared [152,153]. Concurrent development of spectrally-flexible gain media based on Raman scattering [154,155], four-wave-mixing [156], or semiconductor optical amplifiers [157,158] will help exploit this potential for applications where the source wavelength is critical.

Despite the power of dispersion engineering in a FBG, pulse propagation in such devices is complicated by several factors. Firstly, the strong group-velocity dispersion is accompanied by disproportionately stronger higher-order dispersion [159,160], which can cause soliton or similariton propagation to break down [145,147,161–164]. Secondly, the pulse evolution will be constrained by the nearby reflection band of the FBG. As per the Kramers-Kronig relations, the strength of dispersion increases with proximity to a sharp transmission or reflection feature, forcing a compromise between the induced dispersion and the pulse bandwidth. Finally, maintaining the same strength of nonlinearity (i.e., the same peak power) with much longer pulses necessitates proportionally high pulse energies, resulting in strong gain saturation during self-similar amplification [147,149]. Using a chirped FBG to effect a dispersion-decreasing fiber may alleviate this issue, as the varying dispersion behaves like amplification where the virtual gain is saturation-free [104]. One can envision such a device acting as a compact, passive pulse shaper, drawing long pulses from a simple pulse generator towards the similariton attractor for reshaping and compression (Fig. 8).
3.5 Conclusions

Generating ultrafast pulses without mode-locked lasers has the potential to enable new applications of femtosecond pulses, driven by qualitatively new kinds of nonlinear fiber light sources. To be sure, non-mode-locked lasers are unlikely to ever match mode-locked oscillators in every respect. Despite tremendous advances in optical and electro-optic pulse shaping, it is difficult to imagine what kinds of advances could replicate the pristine, broadband coherence of a finely-tuned oscillator. Nevertheless, for a significant number of applications, the full capabilities of a mode-locked oscillator are unnecessary, or may yet fall short. It is here where non-mode-locked sources will have a chance to shine: cases where simplicity and robustness are of primary importance, or where pulses need to be delivered at precise, aperiodic intervals. By taking advantage of a wide array of nonlinear pulse evolutions, non-mode-locked laser systems stand a chance of filling this niche with high-energy, ultrashort pulses in an unprecedentedly versatile format.

4. Beyond one dimension: multimode fiber lasers

In this section, we discuss potential new uses of multimode fibers for flexible high-power, ultrafast fiber lasers. First, we examine recent developments in the study of pulse propagation in multimode fibers. We identify several key effects that can influence future fiber laser designs, namely propagation in specific higher-order modes (HOMs), nonlinear beam cleanup, and spatiotemporal mode-locking (STML). In contrast with earlier sections, the study of multimode fiber in mode-locked lasers is just beginning. Questions consequently far outnumber answers. This section focuses on four pressing issues regarding the science and applications of multimode fiber lasers. These questions address applications in, for example, mid-infrared pulse generation, routes to environmental stability, and practical multimode fiber instruments. To ground these points and scientific directions in concrete applications, throughout this section, we examine several specific future applications in ultrafast and high-
power laser sources where the introduction of multimode techniques can lead to enhanced, or even fundamentally new, capabilities.

The first ultrafast fiber lasers utilized entirely anomalous-dispersion fibers [165,166], without any deliberate spectral filtering. Over time, the introduction of new elements—normal dispersion and spectral filtering—led to orders of magnitude higher performance: first through stable, higher-energy soliton lasers; then through dispersion-managed soliton lasers [9], self-similar [46] and dissipative soliton lasers [15]; and most recently through the Mamyshev oscillator [23–25]. Multimode fiber is another such element. Multimode fibers designed to support amplification of only the fundamental mode, usually called large-mode-area (LMA) fibers [167–170], are now widely used in ultrafast amplifiers. While they have also been used in oscillators [171–174], the requirements of HOM attenuation are much stricter there, and the demonstrated performance improvements are relatively modest compared to in amplifiers.

However, multimode fibers (MMFs) are much more than LMA fibers. Firstly, a MM fiber can support much larger modes than any single-mode or quasi-single-mode fiber (i.e., the effective mode area can be larger in a MMF than an LMA fiber). Secondly, the multiple modes provide additional degrees of freedom for dispersion engineering and for phase-matching various processes. Finally, the interaction of many transverse fiber modes leads to qualitatively new phenomena, which may in turn enable qualitatively new breeds of ultrafast lasers. Hence, compared to filtering and normal dispersion, multimode fiber is a much broader and more complex design element that is only just beginning to be explored.

4.1 Propagation in one or several higher-order modes

One line of development utilizes from one to a small number of HOMs [Fig. 9(a)]. Specific HOMs can be linearly stable (i.e., robust to disorder), provide large mode areas, and allow dispersion control [98,175–178]. Propagation in a HOM has enabled remarkable demonstrations, including the generation of high-energy, Raman-shifted solitons below and up to 1300 nm [96,99,179,180]. Propagation in multiple HOMs, meanwhile, allows for new four-wave mixing (FWM) and dispersive wave processes [181–185]. Conceptually, this research has been only one step removed from single-mode fibers: though the fibers used support many spatial modes, only a handful were populated at any given time. Nevertheless, we anticipate that the use of HOMs will advance further in coming years, both in terms of discovering new nonlinear phenomena [185] and reaching its exceptional performance potential [186]. Although further developments in the near-infrared and visible spectral regions are expected, applying this approach to mid-infrared source development is also very attractive. Extending what has been done in fused silica fibers to the mid-infrared using chalcogenide, fluoride, or gas-filled fibers, e.g., could have a transformative impact on the development of mid-infrared ultrafast fiber sources, not to mention supporting a versatile range of other processes [Fig. 10(a)]. For example, an anomalously-dispersive HOM within a chalcogenide step-index multimode fiber could support the generation of intense solitons shifted from ~2 μm to up to 13 μm.
Fig. 9. Key phenomena for multimode ultrafast lasers and future light sources based on multimode fiber. (a) Propagation in one or a small number of higher-order modes (HOMs) can provide, for example, a means of phase-matching different nonlinear processes (such as the intermodal four-wave mixing process shown as an example), or propagating long distances with controllable dispersion and large mode area. (b) Nonlinear beam cleanup causes an initially-multimode field to adjust into one dominated by the fundamental, Gaussian-like mode of the waveguide. (c) Spatiotemporal mode-locking can occur in laser cavities supporting multiple transverse modes. In the continuous-wave lasing state (left), the resonant lasing modes are complex, corresponding approximately to many transverse families of differently-spaced longitudinal modes. With spatiotemporal mode-locking (right), these modes nonlinearly lock together into phased frequency combs, resulting in coherent multimode pulses.

4.2 Spatiotemporal nonlinear multimode fiber optics

Spatiotemporal nonlinear multimode fiber optics is a more recent development [187–204]. These studies employ graded-index (GRIN) fibers, which feature smaller modal dispersion than step-index fibers. Consequently, ultrashort pulses in different modes can interact strongly. As the number of modes considered increases, the physics become increasingly well described by $3 + 1$ D (i.e., spatiotemporal) pulse propagation. Numerous surprising
phenomena have been observed, two of which are of particular relevance to ultrafast fiber lasers: Kerr nonlinear beam cleanup [Fig. 9(b)] and spatiotemporal mode-locking [Fig. 9(c)].

Fig. 10. Examples of future light sources based on multimode fiber. (a) By adjusting the initial modes excited, and with a low-power tunable visible source (e.g., filtered continuum from photonic crystal fiber), a multitude of nonlinear processes in a highly multimode chalcogenide or hollow-core fiber can be harnessed for generating tailored light from the visible into the mid-infrared. (b) Nonlinear beam cleanup may be used to improve the beam quality of very-high-average-power (e.g., ns-pulses or continuous-wave) fiber lasers amplified in multimode fiber, or suffering from thermal modal instability. (c) If spatiotemporal mode-locking can be understood and controlled, multimode lasers will provide a route to high-power ultrafast pulses, and a platform for full control of coherent electromagnetic fields in spacetime, frequency, and across many fundamental oscillation periods of the MM cavity. A hypothetical route to achieving this control is depicted, wherein modal multiplexing and demultiplexing are used so that each mode can be individually modulated, filtered, delayed, etc. before recombination.
4.2a Kerr nonlinear beam cleanup

Kerr nonlinear beam cleanup [195], or simply beam cleanup, is a process by which the Kerr nonlinearity causes a significant, irreversible transfer of energy from higher-order modes into the fundamental mode of a multimode waveguide. When the effects of disorder and dissipation are small, the observed irreversibility of the energy transfer is quite surprising. Since intermodal four-wave mixing is caused by the conservative Kerr nonlinearity, one might instead expect a continuous oscillation of energy back and forth between modes as the light propagates through the fiber. To explain why the energy transfers into the fundamental mode and remains there, we need to notice that the fundamental mode, being the most localized, accumulates nonlinear phase much faster than the HOMs. This difference in the nonlinear phase shift rate means that, as energy accumulates in the fundamental mode, its phase diverges increasingly rapidly from that of the HOMs, until eventually, the reverse FWM process does not occur [195,205]. Kerr nonlinear beam cleanup has proven to be a remarkably universal feature of nonlinear propagation in multimode fibers [190,194,196,198–201,206,207], and provides a means of obtaining high beam quality within a multimode fiber laser system. It also suggests a fiber-based saturable absorber similar to the Kerr lens, and with parallels to a number of previously-proposed fiber devices [208–211].

Although this article’s stated scope is ultrafast fiber lasers, many readers will notice an obvious application of nonlinear beam cleanup, namely for spatial mode improvement in multimode fiber lasers and amplifiers in the nanosecond through continuous-wave regime. Today, very high-power CW (and, to some extent, nanosecond-pulsed) fiber lasers based on MM fibers represent a large, growing market, with applications in laser cutting and welding in automobile construction. This market is currently much larger than that for ultrashort pulses [212]. As these types of fiber lasers reach ever-higher powers, they will encounter increasingly intractable nonlinear impediments. Consequently, taming or exploiting nonlinear multimode propagation will become both more necessary and more attractive. One well-known nonlinear instability is already relevant: the maximum average power of fiber lasers with single-mode beam quality is presently limited by the thermal modal instability within the amplifying fiber [213–217]. Beam cleanup appears to occur independently of the pulse duration [201], and could be implemented after a highly-multimode, continuous-wave amplifier [Fig. 10(b)]. An exciting alternative would be to realize the beam cleanup within a highly-multimode amplifier [199]. This could be more challenging however, since it would entail coupling between the thermal amplifier modal instability and Kerr cleaning, not to mention new gain fiber designs. In either case, since beam cleanup uses a nonlinear attractor, it could partially reverse the beam degradation caused by modal instability, or even avoid it in the first place. Although a deeper exploration would require more than this brief aside, we see many exciting applications of multimode nonlinear fiber optics in high-average-power fiber laser systems.

4.2b Spatiotemporal mode-locking

Spatiotemporal mode-locking (STML) is the locking of many spatiotemporal (3 + 1 D) modes into ultrashort multimode pulses [204]. This result seems to contradict the established fact that higher-order transverse mode content prevents high-power passive mode-locking [173]. In the multimode fibers considered earlier for mode-locked oscillators, the walk-off between transverse modes (i.e., the modal dispersion) is quite large, resulting in the formation of temporally separated sub-pulses. This ultimately limits the single-pulse energy. When the modal dispersion is small, however, pulses in different modes do not separate into sub-pulses, and instead can lock together into a high-power, ultrashort, multimode pulse. STML implies that fibers with larger mode areas may be used, and so higher-power ultrafast fiber lasers can be constructed. Dechirped pulses with peak powers as high as 1 GW may be within reach [204]. Since GW-class multimode lasers could maintain nearly the same compactness,
simplicity, and cost as single-mode fiber oscillators, this would bring ultrafast fiber lasers into entirely new application spaces (such as high-harmonic generation).

However, to focus on peak power alone would be a mistake. For one, the possibility of a GW fiber oscillator must be weighed against competing, non-fiber technology, or advanced fiber master oscillator power amplifier (MOPA) systems. For another, STML—and coherent, 3 + 1 D optical oscillators in general—represent an expansive space of possibilities for both laser physics and applications. What can be done with complete (spatial, spectral, and temporal, including over many cavity round-trips) control of coherent pulses and pulse sequences? What can be done using the internal dynamics of 3 + 1 D optical oscillators? We can speculate, but these questions echo earlier questions about the applications of ultrashort pulses. The most important realizations and applications of this kind of laser probably remain to be discovered.

With this admission of excited ignorance, we turn to open questions. Here we outline several important questions that are likely to determine the impact of multimode nonlinearities on ultrafast laser development. For the purposes of this article, the scope of these questions is kept narrow: we are primarily concerned with the development of practical, MMF-based laser sources. A broader introduction to the science of multimode nonlinear fiber optics and its relevance to other applications is given in [203].

4.3 Important questions

1. How can we control the excitation and exchange of different modes within multimode, fiber-integrated devices?

For many uses of MM fiber, we would like to excite specific modes or combinations of modes, or to induce a specific transfer of modes from one multimode fiber to another (or to/from single-mode fibers). Here, techniques and devices being developed for telecommunications applications of multimode fiber will be valuable. Long-period gratings [177,218], photonic lanterns [219,220], multi-plane light conversion [221], and so on may be useful. A more inspired, but also more difficult, approach would be to rely on nonlinear mode conversion [222–224], and to design the pulse evolution so that the desired excitations happen automatically. Coupled-core multicore fibers may meanwhile make this task much easier compared to single-core, multimode fibers.

Alternatively, incorporating one or more spatial light modulators (SLMs) into a multimode fiber laser cavity could be a complete solution. Spatial light modulators are now widely used to control light in space and time within multimode fibers [225–229]. On one hand, inserting one or more SLMs into a laser cavity would appear to increase its cost and complexity. For the time being, this is true. However, the growing demand for SLMs in applications of adaptive optics for astronomy, biomedical imaging, displays, etc., as well as for MM fiber telecommunications, offers prospects for high-quality fiber-integrated devices and significant cost reductions in the foreseeable future.

The use of SLMs will provide several additional practical benefits and capabilities. Integrated SLMs (either intracavity, or outside the cavity before a highly-MM delivery fiber) could provide closed-loop control over MM oscillators or amplifiers as a matter of course, permitting environmental stability on par with modern solid-state lasers. Furthermore, an SLM paired with a MMF can be used to control the spatiotemporal field at the output of the MMF. For example, an SLM might be used to create a transform-limited pulse after the MMF [230] and/or a Gaussian beam that is raster-scanned through space [228,229,231]. Of course, this requires spatiotemporal coherence—a STML laser, in which all transverse and longitudinal
modes have a fixed phase relationship, would work, while a spatially-incoherent, fluctuating MM laser would not. At the highest powers, SLMs may become less viable due to power handling limitations or damage. In this regime, deformable mirrors may be a fitting alternative [232].

The possibility of spatiotemporal control suggests a future MM laser with remarkable capabilities beyond any coherent light source considered before. Inside a MM laser, mode-locking can arise with much richer spatiotemporal behaviors than are possible with only a single spatial mode [204,233,234]. These behaviors follow naturally from the multitude of different repetition rates expected for the modes in isolation. As a result, full control over all the degrees of freedom in the MM optical oscillator would allow control of the spatiotemporal field emitted by the laser not only in the pulse frame, but also across many round trips [Fig. 10(c)]. A brute-force approach would involve numerous spatial light modulators inside the cavity, each optimized in an iterative fashion. However, steady advancements in telecommunications mode-division technology and integrated frequency comb devices suggest an alternative, more direct approach [depicted in Fig. 10(c)]. Using modal demultiplexing technologies, each spatial mode could be routed into a separate single-mode path, wherein its amplitude, phase and delay could be individually modified or modulated, thereby shaping the complex coefficients of each transverse mode’s individual frequency comb, while also permitting modal dispersion control. After recombination using a modal multiplexer within a multimode fiber, the coherently-combined, spatiotemporally-engineered field could be partially output-coupled before passage through a saturable absorber, followed by the modal demultiplexing and so on.

2. What kinds of pulse evolutions are supported in MM fiber lasers and amplifiers?

Section 2 reviewed nonlinear pulse evolutions in single-mode fiber lasers. While several implementations of MMF lasers have been demonstrated [204], it is natural to ask what other evolutions can exist in MMF lasers. For example, are MM dispersion-managed solitons, MM dissipative solitons, or MM amplifier similaritons possible? What behaviors may be observed with anomalous-dispersion MM solitons [189,192,202,207,235] within laser cavities? Alternatively, what about new pulse evolutions or types of solitary waves that are uniquely multimode, with no even approximate single-mode analogue? Considering how rich the physics of single-mode fiber lasers has turned out to be, it is simultaneously overwhelming and exciting to imagine what MM lasers may provide, in terms of both new physics and new capabilities.

While they are unlikely to provide major performance benefits over normal-dispersion lasers at 1 or 1.55 µm, multimode and HOM soliton lasers could have exceptional performance in the mid-infrared. For a given spatiotemporal size, MM solitons are stable with more energy than single-mode solitons [192,202], and like HOM solitons, they can have much larger spatial mode areas than solitons based on single-mode fiber. Realizing HOM or MM soliton lasers in the mid-infrared will, however, be somewhat challenging with modern technology. Advances in mid-infrared fiber devices, such as long-period Bragg gratings [236], could permit modal-dispersion managed MM or HOM soliton laser designs.

Nonlinear dynamics and stable pulse evolutions in multimode fiber lasers are likely to be much more expansive than in single-mode laser systems. While we expect that analogies with single-mode pulse evolutions will provide some initial intuition, the complexity of multimode systems lends itself to exciting new approaches. Both in
experiments and simulations, an efficient means of mining for useful phenomena will be the use of heuristic search, or machine learning, techniques. These have already yielded interesting results in the comparatively simple world of the single-mode fiber oscillators [237–241] and in passive or amplifier multimode fiber propagation [232,242], and should be even more useful in the voluminous parameter space of multimode fiber lasers. To some extent, these techniques could be viewed as higher-dimensional versions of the work that has already been done on polarization (i.e., using waveplates to control NPE) and spectral/dispersion (using SLM-based pulse shapers) control. Considering also the myriad recent advances in machine learning algorithms and graphical processing units for efficient high-dimensional calculations, there is much cause for optimism for this direction. Studies and designs of this kind would be naturally realized with the intracavity SLMs previously mentioned, as well as with intracavity dispersion control and spectral shaping. Ideally, the latter two should be realized either in a mode-resolved fashion (e.g., by multi-plane light conversion [221] to disperse the modes across the second dimension of a 2D SLM), or using at least one spatial dimension in addition to the frequency/time dimension.

3. How can environmental stability be achieved with multimode fiber lasers?

In GRIN fibers, higher-order mode groups contain increasingly many quasi-degenerate modes which can be sensitive to index perturbations, bending, and temperature changes. Even if the fibers are held fixed, it is unlikely that lasers based on standard, telecommunications GRIN fibers will achieve environmental stability. Faraday rotators could provide some degree of environmental stability [171,243] by cancelling out birefringence-related effects. This would be even more effective with very large, rod-like fibers, whose size would provide both low modal dispersion and relative immunity to changing physical deformations like bending. Self-organization effects such as beam cleanup are robust to disorder [195,200], granting lasers based on this effect some environmental robustness. The use of MM lasers as enhancement cavities to amplify external seeds could also improve this [198], while simultaneously mitigating spatiotemporal instabilities associated with beam cleanup.

Another potential solution is modal dispersion management (MDM) [244,245]. By using sections of MMF with opposite modal dispersions, or by using mode-multiplexing/demultiplexing to separately control the cavity length seen by each mode, the net modal dispersion in the cavity could be brought close to zero (or adjusted to different values as required). This would allow large local modal dispersion and propagation constant differences, and would therefore be compatible with many polarization-maintaining MM fiber designs. Even fibers with large modal dispersion and large propagation constant differences may be usable in multimode mode-locked oscillators if the net round-trip modal dispersion experienced by the pulse is small. In analogy with the group-velocity dispersion management used in dispersion-managed soliton oscillators, one could imagine a modal-dispersion-managed laser, e.g., as depicted in Fig. 11. While we expect that some forms of STML may be observable in cavities with large modal dispersion, STML will usually require low net modal dispersion. Therefore, modal dispersion management will allow more widely-available fibers like step-index MM fibers to be used for a variety of STML lasers. In addition, the strong breathing of the effective pulse duration could translate directly to higher peak power from stable pulses, much as the breathing of group-velocity-dispersion-managed solitons enhances their performance over their all-anomalous soliton brethren.
In addition, coupled-core multicore fibers may be very useful for multimode fiber lasers and amplifiers [174]. They may provide a straightforward and flexible means of designing multimode fibers with all the necessary features: low modal dispersion, large mode area, easy integration and mode control, and environmental stability.

Finally, while polarization and optical momentum have largely been overlooked throughout this section, it is worth briefly reminding the reader that HOMs in multimode waveguides can have very complex momenta and vectorial polarization properties compared to the typical lowest-order mode. These are especially relevant in the context of the large numerical aperture and strong birefringence that will probably be required for environmentally-stable MMFs. Naturally, this means that STML pulses could, in addition to having the four-dimensionally tailored intensity, wavelength, etc. depicted in Fig. 10(c), also have similarly tailored polarization and/or momentum. While this also adds significant complexity, these additional properties provide even richer opportunities for both controlling the pulse evolution within the cavity, and for creating coherent light with new capabilities in, for instance, nanoparticle manipulation, phase-matching nonlinear processes, or light-matter interactions in the most general sense.

Fig. 11. Modal dispersion management realized by a double-pass through a multimode fiber. By exchanging the pulse from mode A into mode B, and vice versa, the net modal dispersion can be eliminated. To achieve a controllable net modal dispersion, many more modes could be included, or the backward pass here could be replaced by propagation in a different-length fiber. An all-fiber design might be realized using fiber Bragg gratings.

4.4 Conclusions

As the title to this section boasts, multimode ultrafast lasers and amplifiers literally add new dimensions to ultrafast laser science. Higher dimensions add another layer of complexity to physical systems, and are often purposefully overlooked to simplify problems. Nevertheless, initial results provide promising indications for multimode and spatiotemporal nonlinear optics to lead to truly remarkable capabilities in ultrafast laser sources. However, it would be wrong to suggest that these promising indications are short-term prospects. Multimode nonlinear optics is at one scientific frontier of ultrafast laser science.

Most intuitively, lasers and amplifiers that can elegantly incorporate multimode fibers may have significantly higher power than devices based on single-mode, or even quasi-single mode, LMA fibers. This promise extends beyond ultrafast and across laser science, since dimensionality and spatial/spatiotemporal nonlinearities represent key limitations for high-power lasers of all kinds. Into the next decade, multimode laser science can leverage steady advances in understanding and controlling light in multimode waveguides for telecommunications and endoscopic imaging. However, while we see multi-gigawatt peak
powers as a plausible prospect for these sources, readers should leave this section with two questions in mind. First, what new concepts wait to be discovered in multimode, spatiotemporal laser systems? Second, what can a multimode laser do that fundamentally transcends traditional single-mode designs, and what would that mean for specific applications?

5. Conclusion

On one hand, ultrafast lasers have allowed humans to observe some of the fastest processes in nature. Beyond speed alone, ultrafast pulses can support peak powers and intensities that stretch beyond any reasonable human intuition. The scientific impact has, understandably, been remarkable. On the other hand, another role of ultrafast lasers is increasingly to bring tools that were once rare (e.g., high-brightness x-ray sources and particle accelerators) into more routine laboratory use. This is the mode of impact where ultrafast fiber lasers can shine the most. This translation of scientific innovations beyond their laboratories of origin is not always glamorous, but it is crucial, and it is difficult. Meeting the diverse range of real-world demands in a practical and commercially-viable manner will require exploiting the rich possibilities afforded by nonlinearity.

Our intention in this article has been to point to some likely future directions for this field, while at the same time illustrating some less-explored and remarkable aspects of the underlying science and engineering. Many scientists see applied fields focused on words like “cheaper,” “smaller,” or “more reliable” as unavoidably incremental. However, the journey to make ultrafast lasers mainstream is anything but. Scientists have had to learn to engineer nonlinearity, making the field one both of tangible near-term impact and of rich, nonlinear optical science. As we look to the future, we see this symbiosis of science and technology continuing, both in terms of real, widespread applications, and of the fiber laser sources with fundamentally new capabilities that will enable them.

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