Self-phase modulation enabled, wavelength-tunable ultrafast fiber laser sources: an energy scalable approach

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Abstract: We propose and demonstrate a new approach to implement a wavelength-tunable ultrafast fiber laser source suitable for multiphoton microscopy. We employ fiber-optic nonlinearities to broaden a narrowband optical spectrum generated by an Yb-fiber laser system and then use optical bandpass filters to select the leftmost or rightmost spectral lobes from the broadened spectrum. Detailed numerical modeling shows that self-phase modulation dominates the spectral broadening, self-steepening tends to blue shift the broadened spectrum, and stimulated Raman scattering is minimal. We also find that optical wave breaking caused by fiber dispersion slows down the shift of the leftmost/rightmost spectral lobes and therefore limits the wavelength tuning range of the filtered spectra. We show both numerically and experimentally that shortening the fiber used for spectral broadening while increasing the input pulse energy can overcome this dispersion-induced limitation; as a result, the filtered spectral lobes have higher power, constituting a powerful and practical approach for energy scaling the resulting femtosecond sources. We use two commercially available photonic crystal fibers to verify the simulation results. More specific, use of 20-mm fiber NL-1050-ZERO-2 enables us to implement an Yb-fiber laser based ultrafast source, delivering femtosecond (70-120 fs) pulses tunable from 825 nm to 1210 nm with >1 nJ pulse energy.

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References and links

1. Introduction

Multiphoton microscopy (MPM) has been widely used in biomedical imaging due to the unique features such as capability of optical sectioning, various imaging contrast mechanisms, and larger penetration depth in tissue imaging [1]. The success of MPM is largely driven by the rapid advance of femtosecond laser sources in the near infrared wavelength range. For example, femtosecond pulses in the typical wavelength range 800-1300 nm can excite most of the important fluorophores employed in two-photon excited fluorescence microscopy. Besides causing less potential photo-damage due to less photon energies, the 1200-1300 nm wavelength range enables deep tissue imaging with ~1 mm penetration depth thanks to an optimal combination of reduced light scattering and low water absorption [2]. To date, no single laser can provide >1 nJ femtosecond (50-150 fs) pulses tunable in the entire 800-1300 nm wavelength range. Conventional solution relies on multiple laser systems each covering a portion of 800-1300 nm and the stitched spectrum spans the whole wavelength range. A typical combination is a Ti:sapphire laser tunable from 700 to 1040 nm plus a solid-state optical parametric oscillator (OPO) that covers the wavelength tuning range of 1040-1300 nm. However, high complexity (e.g., water cooling required), high cost, and large size of such a solid-state laser solution have spurred intensive development of reliable, cost-effective, and compact ultrafast sources in fiber format [3,4].

Two types of femtosecond fiber lasers operate in the wavelength range of 800-1300 nm: Yb-fiber laser in 1020-1060 nm and Nd-fiber laser in 910-935 nm [5]. Such a narrowband wavelength coverage can be further expanded using various fiber-optic nonlinear mechanisms, such as dispersive wave generation [6,7], Raman self-frequency shift [8,9], supercontinuum generation (SCG) [10], and four-wave mixing [11], to name a few. Most of the spectral broadening processes favor certain fiber group-velocity dispersion (GVD), which can be engineered for photonic crystal fibers (PCFs) featuring much smaller mode area and
thus stronger nonlinearity compared with conventional single-mode fibers. Requiring negative GVD at the laser emission wavelength, dispersive wave generation normally generates femtosecond pulses at shorter wavelength whereas Raman self-frequency shift leads to a wavelength-tunable pulse towards longer wavelength. Limited by strong nonlinearity in PCFs, the resulting wavelength-converted pulses are limited to <1 nJ in pulse energy. SCG broadens the input optical spectrum into both shorter and longer wavelength range, spanning the entire range of 800-1300 nm; a subsequent bandpass (bandwidth of 10-30 nm) filter could select a spectral slice, which after proper phase compensation leads to femtosecond pulses. However, this method has two drawbacks: (1) SCG distributes input pulse energy in the broadened spectrum, and the selected spectral slice with 10-30 nm bandwidth includes little (<1 nJ) pulse energy. (2) SCG exerts strong nonlinear phase on the resulting spectrum, and therefore phase compensation of the filtered spectrum necessitates complex and lossy active devices (e.g., spatial light modulator). At the expense of complexity, four-wave-mixing-based fiber OPO can generate wavelength tunable pulses with much higher pulse energy. For example, Ref. 11 reports such a fiber OPO tunable in 867-918 nm for the signal and in 1200-1300 nm for the idler. Pumped by a µJ-level fiber laser system at 1040 nm, the fiber OPO produces 560-fs pulses after post compression with 30-nJ pulse energy, corresponding to 4.7% energy conversion efficiency from the pump to the idler [11].

In this paper, we propose and demonstrate a new type of fiber laser based femtosecond source, which employs self-phase modulation (SPM) in an optical fiber as the dominant spectral-broadening mechanism. Both the simulation and experiments demonstrate that this source is energy scalable and has a potential to cover the entire wavelength-tunable range of 800-1300 nm in an all-in-one unit. The resulting filtered spectra correspond to slightly chirped, femtosecond (70-120 fs) pulses, which might be easily compressed to the transform-limited duration by chirped mirrors.

2. Numerical simulation of fiber-optic spectral broadening

Nonlinear spectral broadening of ultrashort pulses in an optical fiber can be precisely modeled by the well-known generalized nonlinear Schrödinger (GNLS) equation [12]

\[
\frac{\partial A}{\partial z} + \left( \sum_{n=2}^{\infty} \beta_n \frac{i^{n-1}}{n!} \frac{\partial^n}{\partial T^n} \right) A = i\gamma \left( 1 + \frac{i}{\omega_c} \frac{\partial}{\partial T} \right) \left[ \int_{-\infty}^{\infty} R(t') |A(z,T-t')|^2 dt' \right], \quad (1)
\]

where \( A(z,t) \) denotes the pulse’s amplitude envelope. \( \beta_n \) accounts for the n-th order fiber group-velocity dispersion (GVD). Nonlinear parameter \( \gamma \) is defined as \( \gamma = \omega_c n_z / (c A_{\text{eff}}) \), where \( \omega_c \) is the pulse center frequency, \( n_z \) the nonlinear-index coefficient of fused silica with a typical value of \( 2.4 \times 10^{-20} \text{ m}^2/\text{W} \), \( c \) the light speed in vacuum, and \( A_{\text{eff}} \) the mode-field area. \( A_{\text{eff}} \) is connected to mode-field diameter \( d \) by \( A_{\text{eff}} = \pi (d/2)^2 \). \( R(t) \) describes both the instantaneous electronic and delayed molecular responses (i.e., stimulated Raman scattering) of fused silica, and is defined as

\[
R(t) = (1 - f_R) \delta(t) + f_R \left( \tau_i^2 + \tau_z^2 \right) / (\tau_i \tau_z^2) \exp(-t/\tau_z) \sin(t/\tau_i), \quad (2)
\]

where typical values of \( f_R, \tau_i, \) and \( \tau_z \) are 0.18, 12.2 fs, and 32 fs, respectively [12]. Taking into account dispersion, SPM, self-steepening (SS), and stimulated Raman scattering (SRS), Eq. (1) has been widely used to study nonlinear propagation of ultrashort optical pulses inside an optical fiber. Such a nonlinear propagation can significantly broaden the pulse spectrum and, under certain conditions, lead to supercontinuum generation.

To gain physical insight, we first neglect dispersion and investigate the role of each nonlinear effect—namely SPM, SS, and SRS—in section 2.1 and 2.2. In section 2.3, we
include dispersion in the simulation and show how dispersion affects the nonlinear spectral broadening.

2.1 Pure SPM

We first consider only SPM and neglect dispersion, self-steepening, and SRS. Consequently Eq. (1) is simplified as

$$\frac{\partial A}{\partial z} = i\gamma |A|^2 A. \quad (3)$$

Equation (3) has an analytical solution $A(z,t) = A(0,t) \exp(i\gamma |A|^2 z)$. Using this solution, we simulate a 200-fs hyperbolic secant-squared pulse (central wavelength at 1.03 µm with 50-nJ pulse energy) propagating inside an optical fiber with a mode-field diameter of 6 µm; the simulation results are summarized in Fig. 1. Figure 1(a) shows that the optical spectrum broadens dramatically along the fiber length and is composed of isolated spectral lobes; the number of these spectral lobes is linearly proportional to the fiber length—a unique feature of SPM-broadened spectrum. For example, after propagating 6-cm distance (Fig. 1(b)) the optical spectrum develops 24 spectral lobes and covers the spectral range between 800 nm and 1.4 µm—a spectral range highly desired for multi-photon microscopy. We numerically filter both the leftmost and the rightmost spectral lobes, and plot them as the insets of Figs. 1(c) and 1(d), respectively. The blue curves in these figures are the optical pulses corresponding to the filtered spectra; as a comparison, we also plot in these figures the transform-limited pulses (red curves) calculated from the filtered spectra. Clearly, both optical pulses are nearly transform-limited with the same pulse duration of 44 fs. Another intriguing feature of the SPM-broadened spectrum is that the leftmost and rightmost spectral lobes are the strongest; these two spectral lobes have a total energy of 21 nJ (10.5 nJ for each), accounting for >40% of the total energy. Note that other spectral lobes in Fig. 1(b) can also be filtered; however these intermediate spectra possess much less pulse energies compared with the leftmost/rightmost spectral lobes. In the rest of the paper, we restrict our discussion on these leftmost/rightmost spectral lobes.
Simulation results in Fig. 1 suggest a novel method to implement a multi-color ultrafast source. The filtered two spectral lobes plus the original laser wavelength enable the laser system producing ultrashort pulses at three different center-wavelengths. More important, the center wavelength of these filtered spectral lobes can be continuously tuned by adjusting the power coupled into the fiber for a fixed fiber length.

### 2.2 Effect of SS and SRS

The results in Fig. 1, though informative and impressive, are unpractical since only SPM is considered. Other nonlinear effects such as SS and SRS take place as well. To investigate their role in spectral broadening, we redo the simulation in section 2.1 by further including SS or both SS and SRS; the resulting spectra after propagating 6 cm are plotted in Fig. 2(a). The spectrum broadened due to SPM and SS (blue curve in Fig. 2(a)) is significantly blue shifted compared with the SPM-broadened spectrum (Fig. 1(b)). When SRS is also included, the resulting spectrum (red curve in Fig. 2(a)) becomes slightly narrower due to the small red shift of those spectral lobes on the left side; the corresponding pulse of this spectrum is shown as the inset. Nearly maintaining its initial pulse duration of 200 fs, the optical pulse exhibits a much steeper trailing edge because of SS. It is the SS-induced steep trailing edge that extends the overall spectrum more into the shorter wavelength range.
We filter the leftmost and rightmost spectral lobes in the spectrum broadened by SPM together with SS and SRS (red curve in Fig. 2(a)), and plot the corresponding optical pulses in Fig. 2(b). The filtered spectral lobes are shown as insets in Fig. 2(b). The filtered pulse centered at 0.7 µm has a duration of 19 fs with 5.6-nJ pulse energy; the other pulse centers at 1.23 µm with 67-fs duration and 13.2-nJ energy. Both pulses are nearly transform limited (off by <0.5 fs). We also calculate the peak wavelength and energy conversion efficiency as a function of propagation distance for the leftmost and right most spectral lobes, respectively; the simulation results are summarized in Fig. 2(c) for the leftmost lobe and Fig. 2(d) for the rightmost lobe. The peak wavelengths for both lobes shift linearly with respect to the fiber length. Meanwhile, the conversion efficiency continuously drops from 23% to 11% for the leftmost spectral lobe as the fiber length increases from 2.5 cm to 6 cm. As a contrast, the conversion efficiency for the rightmost spectral lobe exhibits a slight decrease, from 32% to 27%. The simulation results in this section reveal the following effects exerted by SS and SRS on spectral broadening and energy conversion to the leftmost/rightmost spectral lobes:

1. SS extends the broadened spectrum more towards the shorter wavelength.

2. For SPM-broadened spectrum, the leftmost and rightmost spectral lobes share the same energy. When SS and SRS are included, more energy is converted into the rightmost spectral lobe, though total conversion efficiency into these two spectral lobes is comparable for the two cases—40% for SPM-broadened spectrum and 38% if SS and SRS are considered as well.

3. The effect of SRS is minimal compared with SS.
2.3 Effect of dispersion

Fig. 3. Propagation of a 50-nJ, 200-fs pulse through 6-cm optical fiber with a mode-field diameter of 6 µm. (a) Optical spectra for simulations including SPM, SS, SRS, and GVD (5 fs²/mm). Inset: close-up of the spectral range from 600 to 800 nm. (b) Corresponding optical pulse. Inset: close-up of the pulse envelope in the temporal range of 250-300 fs. Leftmost and rightmost spectral lobes are filtered, respectively. The corresponding optical pulse (blue curve) and the calculated TL pulse (red curve) from the filtered spectrum are shown in (c) for the leftmost lobe and in (d) for the rightmost lobe. Insets: filtered optical spectra. TL: transform-limited.

The simulation in section 2.2 takes into account all the nonlinear effects and serves the purpose of understanding the physical mechanism underlying the spectral broadening; however, neglecting GVD makes the simulation inaccurate in predicting experimental results. GVD undoubtedly plays an important role in nonlinear fiber optics, and can be flexibly engineered in a broad range [13]. Various fascinating nonlinear phenomena arise from the nonlinear pulse propagation inside a fiber with negative GVD, such as modulation instability, soliton formation, soliton fission, dispersive wave generation, and Raman soliton, to name a few. Due to complicated nonlinear interaction taking place inside a negative-GVD fiber, the resulting broadened spectrum features fine structures with reduced phase coherence; generation of nearly transform-limited pulse from a filtered spectrum becomes challenging and suffers from poor conversion efficiency. In contrast, spectral broadening in a positive-GVD fiber avoids involving abovementioned nonlinear phenomena and generates much smoother optical spectrum. Therefore we restrict our discussion in the context of positive GVD.

We redo the simulation in section 2.2 by further including a GVD of 5 fs²/mm for the fiber with all other parameters unchanged. Figures 3(a) and 3(b) plot the optical spectrum and the pulse after 6-cm propagation distance. Due to the positive GVD, the initial 200-fs pulse increases its duration along the propagation, leading to a reduced nonlinearity and thus a narrower broadened-spectrum. As Fig. 3(b) shows, the pulse at 6-cm propagation distance has a duration of ~400 fs. Rapid oscillation (inset of Fig. 3(b)) appears at the pulse’s steep trailing edge, indicating onset of optical wave breaking [12], which in the spectral domain manifests as a pedestal extending to <650 nm (inset of Fig. 3(a)).

Comparison of Fig. 3(a) and Fig. 2(a) suggests that positive GVD tends to wash out the lobe structures in the optical spectrum; that is, the spectral valleys between two adjacent peaks are broadened out.
become shallower when positive GVD is included. We numerically use super-Gaussian shaped bandpass filters to select the leftmost and the rightmost spectral lobes, and plot them as the insets of Figs. 3(c) and 3(d), respectively. Similar to Figs. 1(c) and 1(d), the blue curves in these figures are the optical pulses corresponding to the filtered spectra, and red curves the transform-limited pulses calculated from the filtered spectra. The filtered spectral lobes peak at ~855 nm and ~1195 nm, corresponding to a 42-fs, 7.4-nJ pulse and a 71-fs, 10.3-nJ pulse, respectively. The transform-limited pulses calculated from the filtered spectra are 30 fs and 67 fs in duration, respectively, showing that the filtered pulses are slightly chirped.

To better understand the effect of GVD, we perform another simulation with the GVD increased from 5 fs²/mm to 15 fs²/mm with all other parameters unchanged. As the blue curve in Fig. 4(a) shows, the resulting optical spectrum becomes much narrower and its lobe structures tend to wash out. Due to larger GVD, optical wave breaking occurs at the leading edge of the pulse as well and becomes stronger at the trailing edge (blue curve in Fig. 4(b)), manifesting in the spectral domain as pedestals emerging at both the short- and long-wavelength edges (blue curve in Fig. 4(a)).

Fortunately, the detrimental effects caused by GVD can be prevented by increasing the input pulse energy and reducing the fiber length. Indeed, Eq. (1) remains unchanged if \( A(z,t), \beta_n, \) and \( z \) are replaced by \( \sqrt{N}A(z,t), N\beta_n, \) and \( z / N, \) where \( N \) is a positive number. Such a scaling property suggests that increasing the input pulse energy and shortening the propagation distance can cancel out the unfavorable effects of an increased GVD. To confirm this scaling property, we numerically propagate a 150-nJ pulse through 2-cm fiber with 15-fs²/mm GVD and plot the results as the red curves in Fig. 4. As expected, the resulting spectrum (red curve in Fig. 4(a)) and pulse (red curve in Fig. 4(b)) share exactly the same profile as their counterparts shown in Figs. 3(a) and 3(b) that are obtained from propagating 50-nJ pulse through 6-cm fiber with 5-fs²/mm GVD. The filtered spectra and pulses from the red curve in Fig. 4(a) are also the same in profile as those in Figs. 3(c) and 3(d), but possess 3 times more energy. More specific, the filtered pulses have 22.2 nJ (30.9 nJ) pulse energy for the filtered spectral lobe at ~855 nm (~1195 nm). These results suggest an energy scalable approach in implementing wavelength tunable ultrafast sources: increase input pulse energy and shorten fiber length to minimize the GVD effect such that fiber nonlinearities (mainly SPM) dominate the spectral broadening process.

3. Experimental results

To confirm the simulation results in the proceeding section, we carry out a detailed experimental study. We construct an Yb-fiber laser system that operates at 55-MHz repetition rate and produces 190-fs pulses centered at 1030 nm. The optical spectrum and the measured
autocorrelation trace of the pulse train are shown in Fig. 5(a). As the simulation predicts, use of low-dispersion fibers facilitates SPM-dominated spectral broadening, leading to further shift for the leftmost and rightmost spectral lobes. As a proof-of-principle demonstration, we choose two PCFs commercially available from NKT Photonics: NL-1050-ZERO-2 and NL-1050-NEG-1, both featuring low and flat dispersion in the wavelength range of 850-1250 nm. Their dispersion curves are plotted in Fig. 5(b); also plotted in the same figure for comparison is the dispersion curve of fiber HI1060—a popular single-mode fiber fabricated by Corning. Indeed, these two PCFs (NL-1050-ZERO-2 and NL-1050-NEG-1) have been widely used in nonlinear spectral broadening for supercontinuum generation [14–19] and generation of femtosecond pulses in the 1.3-µm spectral region [20–23].

Figure 6 records the rapid broadening of the output spectra generated from PCF NL-1050-ZERO-2 and NL-1050-NEG-1 for different input pulse energies of 1 nJ (Fig. 6(a)), 3 nJ (Fig. 6(b)), 5 nJ (Fig. 6(c)), and 7 nJ (Fig. 6(d)). Both fibers are 80 mm in length. Clearly, for a fixed fiber length, the spectrum broadens with increased pulse energy. Take PCF NL-1050-ZERO-2 (blue solid curves in Fig. 6) as the example: as we increase the coupled pulse energy from 1 nJ to 5 nJ, SPM dominates the spectral broadening and the rightmost spectral lobe red-shifts linearly with the increased energy. With 5-nJ pulse energy coupled into the fiber, optical wave breaking occurs at the pulse’s trailing edge and generates a noticeable spectral bump at the short-wavelength side peaking at 790 nm (blue solid curve in Fig. 6(c)). Further increasing pulse energy to 7 nJ leads to stronger optical wave breaking and thus a blue-shifted spectral pedestal reaching ~700 nm; meanwhile, a small spectral bump emerges at the long-wavelength side peaking at 1300 nm due to the optical wave breaking taking place at the pulse’s leading edge (blue solid curve in Fig. 6(d)). Onset of optical wave breaking slows down and eventually stops the red-shift (blue-shift) of the rightmost (leftmost) spectral lobe. Similar features can be found for the optical spectra (red dotted curves) generated by 80-mm PCF NL-1050-NEG-1.

It is noteworthy that these two PCFs have nearly identical mode-field diameter of 2.2 µm (corresponding to nonlinear coefficient of 37 W$^{-1}$km$^{-1}$ at 1064 nm). The huge difference between the two spectra generated from these two fibers at the same input pulse energy is thus caused by dispersion. The results in Fig. 6 clearly show that PCF NL-1050-ZERO-2 produces a broader spectrum than PCF NL-1050-NEG-1 at the same pulse energy because the former fiber exhibits less dispersion than the latter one (Fig. 5(b)). Furthermore, simulation results in section 2.3 suggest that positive GVD tends to wash out the lobe structures in the optical spectrum and the spectral valleys between two adjacent peaks become shallower. This is experimentally verified by comparing the five optical spectra obtained from 80-mm PCF NL-1050-ZERO-2. As we broaden the spectrum by increasing the input pulse energy form 1 nJ to
5 nJ, both the left and right spectral edges of the broadened spectrum experience more positive GVD due to the parabolic shape of the dispersion curve. Consequently, the spectral lobes become less pronounced. The optical spectra generated by 80-mm PCF NL-1050-NEG-1 share similar features with even shallower spectral valleys due to the larger dispersion than PCF NL-1050-ZERO-2.

![Output spectra from PCF NL-1050-ZERO-2 (blue solid curves) and NL-1050-NEG-1 (red dotted curves) with different input pulse energies of 1 nJ (Fig. 6(a)), 3 nJ (Fig. 6(b)), 5 nJ (Fig. 6(c)), and 7 nJ (Fig. 6(d)). Both fibers are 80 mm long.](image)

To investigate the energy scaling property offered by shortening the fiber length, we prepare another 40-mm long PCF NL-1050-ZERO-2 and adjust the coupled pulse energy such that the resulting rightmost spectral lobes peak at the same wavelength as those obtained from the 80-mm PCF. Figure 7 records the output spectra generated from both fibers at different input pulse energies. A comparison between the experimental results from 80-mm (blue solid curves) and 40-mm (red dotted curves) PCFs reveal the following interesting facts:

1. In order to generate the rightmost spectral lobe peaking at a certain wavelength, using shorter PCF requires more pulse energy.

2. Results in Figs. 7(a)-7(c) indicate that, before optical wave breaking becomes notable, reducing the fiber length by a factor of two (80 mm vs. 40 mm) demands nearly twice much energy (1 nJ vs. 2.1 nJ, 3 nJ vs. 6 nJ, and 5 nJ vs. 9.8 nJ) to overlap the rightmost spectral lobes. It can be expected that if we use proper optical bandpass filters to select the rightmost spectral lobes, the resulting filtered spectra from the 40-mm PCF have twice power/energy compared with those obtained from the 80-mm PCF. This proves the power/energy scalability of our proposed method.
Fig. 7. Output spectra from PCF NL-1050-ZERO-2 at different fiber lengths (80 mm versus 40 mm) and input pulse energies. Blue solid curves and red dotted curves represent optical spectral generated from 80-mm PCF and 40-mm PCF, respectively. We adjust the input pulse energies such that the spectra generated by both fibers have their rightmost spectral lobes peaking at 1.07 µm (Fig. (a)), 1.12 µm (Fig. (b)), 1.17 µm (Fig. (c)), 1.185 µm (Fig. (d)), and 1.20 µm (Fig. (e)). Coupled pulse energies for each fiber are presented in each figure as well.

(3) With 7-nJ pulse energy (Fig. 7(d)) coupled into the 80-mm PCF, onset of optical wave breaking at the pulse’s leading edge slows down the red shift of the rightmost spectral lobe. As the pulse energy is increased from 5 nJ to 7 nJ, the rightmost spectral lobe shifts only 15 nm from 1.17 µm to 1.185 µm. For the 40-mm PCF, optical wave breaking at the pulse’s leading edge is nearly absent due to less accumulated dispersion; as a result, only 11.1-nJ (rather than ~14 nJ) pulse energy is required to generate the rightmost spectral lobe peaking at 1.185 µm.

(4) Optical wave breaking arises from the interaction between SPM and positive GVD. Using a shorter PCF reduces the overall positive GVD and consequently mitigates the effect of optical wave breaking. This is evidenced by the results shown in Figs. 6(c)-6(d) the spectral bumps become less noteworthy for the spectra obtained using 40-mm PCF, whereas the leftmost lobes in these spectra experience a larger blue-shift. For example, the leftmost spectral lobe peaks at 0.83 µm when 11.1-nJ pulse energy is coupled into the 40-mm PCF. In contrast, this spectral lobe peaks at 0.86 µm for the 80-mm PCF with 7-nJ input pulse energy.

To demonstrate a wavelength-tunable ultrafast source with >1 nJ pulse energy, we further shorten PCF NL-1050-ZERO-2 to 20 mm. We vary the average power coupled into the fiber and use a series of optical bandpass filters to select the leftmost or the rightmost spectral lobes. The corresponding optical pulses are characterized by an autocorrelator. With average powers at 820 mW, 605 mW, 550 mW, 760 mW, and 900 mW, we obtain five representative filtered spectra (left column in Fig. 8) peaking at 825 nm, 875 nm, 1100 nm, 1150 nm, and 1210 nm with average powers of 60 mW, 56 mW, 154 mW, 167 mW, and 180 mW, respectively. At a repetition-rate of 55 MHz, all the filtered spectra exhibit >1 nJ pulse energies. The measured autocorrelation traces of the optical pulses corresponding to these filtered spectra are shown as red curves in the right column of Fig. 8. Also plotted in the right
column are the calculated autocorrelation traces of the transform-limited pulses allowed by the filtered spectra. Clearly these pulses are slightly chirped; the full-width-half-maximum duration of their autocorrelation traces is in the range of 96-164 fs. The corresponding pulse duration is estimated to be 70-120 fs, assuming a deconvolution factor of 1.4.

4. Conclusion

In summary, we propose and demonstrate a new method of producing widely tunable femtosecond pulses. The method employs fiber-optic nonlinearities to broaden an input optical spectrum, followed by optical bandpass filters to select the leftmost or rightmost spectral lobes. Both simulation and experimental results show that the filtered spectral lobes correspond to nearly transform-limited pulses with ~100 fs pulse duration. Fiber dispersion causes optical wave breaking, which slows down the shift of the leftmost/rightmost spectral lobes and ultimately limits the wavelength tuning range of the filtered spectra. A detailed numerical simulation verified by subsequent experimental results reveal that such a dispersion-induced limitation can be overcome by shortening the fiber length while increasing the input pulse energy. The benefits are twofold: (1) optical wave breaking is alleviated leading to larger spectral shift and (2) the filtered spectral lobes have higher power, indicating a practical approach of power scaling. Using two commercially available PCFs, we experimentally verify the simulation results. As a proof-of-principle, we use 20-mm PCF NL-1050-ZERO-2 to achieve spectral broadening and several optical bandpass filters to select the leftmost/rightmost spectral lobes. The experimental results show that we can implement a femtosecond (70-120 fs) source with the peak wavelength tunable from 825 nm to 1210 nm with >1 nJ pulse energy (repetition rate of our laser: 55 MHz). Both the wavelength tuning range and pulse energy can be improved by further shortening the fiber. We believe that our proposed source represents a cost-effective substitute of the conventional MPM driving source, i.e., a combination of Ti:sapphire laser plus a solid-state OPO. With the possibility of implementing our ultrafast source in an all-fiber format (Yb-fiber laser plus fiber-optic spectral broadening), this energy scalable approach paves an avenue to operate MPM in rugged environments outside research labs.
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