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Broadband spectral combining of three pulse-shaped fiber amplifiers with 42fs compressed pulse duration

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Abstract: We demonstrate ultra-broadband spectral combining of ultrashort pulses from Yb-doped fiber amplifiers, with coherently spectrally synthesized pulse shaping, to achieve tens-of-fs pulses. This method can fully compensate for gain narrowing and high order dispersion over broad bandwidth. We produce 42fs pulses by spectrally synthesizing three chirped-pulse fiber amplifiers and two programmable pulse shapers across an 80nm overall bandwidth. To the best of our knowledge, this is the shortest pulse duration achieved from a spectrally combined fiber system at one-micron wavelength. This work provides a path toward high-energy, tens-of-fs fiber chirped-pulse amplification systems.

1. Introduction

Yb-doped fiber laser systems are able to deliver high power, ultrashort pulses that can lead to a wide range of applications in science, industry, security, and medicine [1–3]. Many applications of high-energy, ultrashort optical pulses also require high repetition rate, resulting in high average power. For example, the next-generation laser-plasma accelerators require unprecedented laser performance, at up to multi-Joule pulse energy, tens-of-fs pulse duration, and up to 300 kW average power [4]. Fiber lasers are capable of very high average power and wall-plug efficiency, and with spatial beam combining and temporal pulse stacking can generate high energy for demanding applications [2].

As the most popular high power gain medium in fiber silica glass, Yb ions have a broad gain spectrum >80 nm, fundamentally compatible with pulses <40 fs. However, in high-energy fiber chirped-pulse amplification (FCPA) systems where total amplification gain can reach 100 dB [5–7], the non-flat emission cross section profile of Yb ions leads to gain narrowing that limits the amplified spectral bandwidth to <6 nm FWHM (>300 fs). The shortest pulse duration demonstrated with mJ-level pulse energy in a Yb-doped FCPA channel was around 120-130 fs [5,8], with spectral intensity and phase shaping to overcome gain narrowing and high order dispersion. Thus, additional laser methods are needed to enable 40 fs class pulse duration for broad applications.

Nonlinear pulse compression using spectral broadening in a nonlinear medium and subsequent compression has been rapidly developed as a post-laser short-pulse approach. However, the achievable peak power was limited to around a terawatt, due to ionization in gas-filled hollow-core fibers and multi-pass cavities, or self-focusing in solids (standalone, cascaded, or in-cavity) [9–12]. The highest demonstrated compressed, usable energies are limited to tens of mJ for tens of fs pulses [11,12], and a few mJ for few-cycle pulses [9,10]. Besides energy limitations, unwanted compressed pulse pedestals resulting from mismatched nonlinear chirp is a challenge for prepulse-sensitive applications including plasma acceleration.

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On the other hand, combining multiple spectra was demonstrated to generate ultrashort pulses [13–19], and spectral combining in FCPA systems to overcome gain narrowing was first demonstrated with three spectral channels in a Yb fiber system and a combined pulse duration of 403 fs [15]. Later on shorter pulses were demonstrated from spectrally combined FCPA systems [16–19], and 97 fs pulse duration at one-micron wavelength with 10 μJ pulse energy was achieved from a two-channel system [19]. Further advances toward shorter pulses from broadband, spectrally-combined FCPA systems are also hindered by high order dispersion mismatches besides broadband gain distortions. Multi-stage FCPA systems usually have a total fiber length of 50-100 m, resulting in significant higher order dispersion mismatches with the stretcher and compressor, which broaden and distort the final compressed pulse. In high energy systems, nonlinear spectral phases on chirped pulses also contribute to temporal pulse broadening, since they also result in higher order spectral phase mismatches.

In this paper, we show that ultra-broadband spectral combining in FCPA systems can achieve ~40fs pulse duration, while maintaining the ability to precisely control the spectral intensity and phase over the broad spectrum [20]. These results demonstrate principles that can be scaled to higher energy and average power laser systems. Future implementation of coherent spectral combining in spatiotemporal combination FCPA systems is a promising energy-scalable, short-pulse method for demanding applications including plasma acceleration (up to multi-J pulse energy with ~40 fs duration), as shown in Fig. 5.2.2 of the Brightest Light Initiative Workshop Report [2]. In such systems each spectral channel has a spatially combined fiber amplifier array, and spectral combining comes after spatial combining and before temporal pulse stacking.

To enable spectral combining in the tens-of-fs pulse duration regime, programmable, broadband pulse shaping that can provide precision, tunable spectral intensity and phase control is critical, since it's needed to compensate for gain narrowing, high order dispersion mismatches, and nonlinear phases. These effects become more severe with broader bandwidth. Digital programmable pulse shapers based on spatial light modulators are particularly attractive for such applications [5,8], and have been commercially developed as mature products that offer great advantages on programmability, stability, reliability, and compactness. While current commercial versions have limited passbands less than tens of nm (e.g. II-VI WaveShaper 1000 series), we show in this paper multiple pulse shapers can be coherently-spectrally synthesized in broadband spectral combining systems [20,21].

Here we demonstrate 42 fs pulses by spectrally synthesizing three chirped-pulse fiber amplifiers and two programmable pulse shapers operating at different but partially-overlapped spectra to cover all three spectral channels. After the spectral channels with pulse shaping and amplification are phase-synchronized, spectral intensity and phase control over the broad Yb:fiber gain spectrum can be achieved. To the best of our knowledge, 42 fs is the shortest pulse duration from a spectrally combined fiber system at one-micron wavelength. This work provides a path toward high-energy, tens-of-fs laser pulses, e.g. implementing broadband spectral combining in spatially-temporally combined FCPA systems [2,6,7], in which case more system optimizations (temporal and spectral) are needed to precisely and algorithmically compensate for different mismatches.

In the future development of high energy, tens-of-fs systems, there are a few important considerations. First, how to divide the broad Yb:fiber gain spectrum and assign pulse shapers, including the number of spectral channels and corresponding spectral ranges, should be determined by the amount of spectral intensity and phase compensation needed and optimized stretched pulse duration for energy extraction in each spectral channel. Indeed coherently synthesized pulse shapers distributed in multiple spectral-combining channels result in less bandwidth that each pulse shaper needs to cover, as well as reduced gain narrowing and high order dispersion compensation needed in each spectral channel. For example, it is shown that in high energy systems, >55 dB spectral intensity shaping might be needed even within 15 nm wavelength range (e.g. 1030-1045 nm) [5]. While the limited dynamic ranges for spectral attenuation in

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programmable pulse shapers (usually <30dB) can be mitigated by adding properly designed passive filters, more than three spectral channels over the broad Yb:fiber gain spectrum might be needed, with properly located wavelength ranges. Note that the pre-amplification spectral intensity shaping in system front end does not limit overall laser system efficiency. The wavelength ranges of spectral channels also need to be apportioned so that the stretched chirped pulses are about equal duration in each channel for optimal energy extraction. For example, in our recent design of a 200 mJ, 40 fs FCPA combination system, the three spectral channels are 1015–1052, 1052–1077, and 1077–1095 nm, for ~800 ps stretched pulse duration for each spectral channel. Second, while amplification of long-wavelength spectrum (e.g. 1077–1095 nm) becomes difficult due to low stimulated gain cross sections, near complete energy extraction in the final amplifiers is possible when operating in strong saturation regimes. For example, Fig. 1 shows a simulation of gain and output energy versus input energy at different wavelengths in an 85µm core-size Yb-doped chirally-coupled core (CCC) fiber amplifier [22]. This simulation is using a 1.9 m Yb-doped CCC fiber with 118W pump power at 976 nm, and an 81 ns pulse burst signal consisting of 81 chirped pulses (900 ps full pulse duration) [23], which can potentially be stacked to one high energy pulse [24]. At strong saturation, similar gain and output energy are achievable for long wavelength spectral channels, allowing for high extraction efficiency in final amplifier stages, although overall more amplification stages might be needed for long wavelength spectral channels.

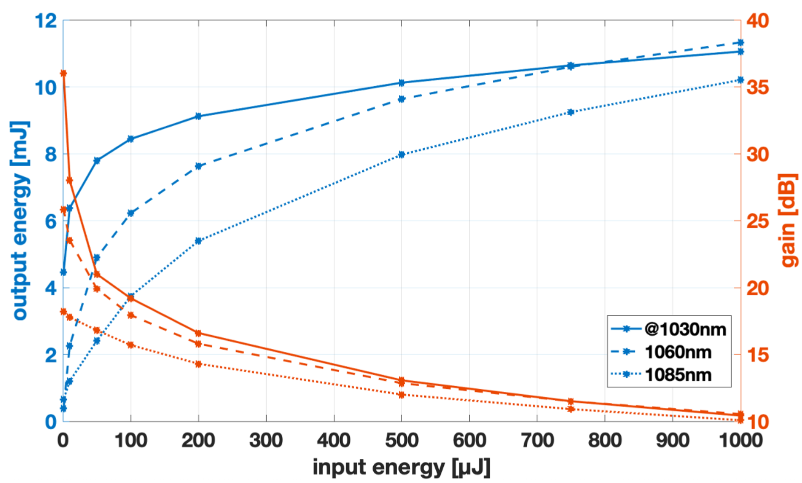

Fig. 1. Simulation of output energy and gain for different wavelengths in a 1.9m Yb-doped CCC fiber with 118W pump power at 976nm and an 81ns pulse burst signal.

2. Experimental setup

Figure 2 shows the experimental setup. In the front end, 120 fs laser pulses at 1040 nm center wavelength with 100 MHz repetition rate are generated from a mode-locked oscillator, amplified in a Yb-doped fiber amplifier (YDFA), and recompressed by a grating compressor before being sent to a photonic-crystal fiber (PCF) where the spectrum is broadened from 27 nm to 90 nm (edge-to-edge). The broadened pulses are spectrally split by a dichroic mirror with a cutoff wavelength at 1052 nm, shown in Fig. 2, and sent to two pulse shapers that shape the intensity and phase of the respective pulse spectra. The pulses reflected from this dichroic mirror are sent to the shaper in Channel 1, while the transmitted pulses are amplified by a YDFA, pulse-shaped by the other shaper, further split by another dichroic mirror with a 1072 nm cutoff wavelength (Fig. 2), and coupled to Channel 2 and 3. Each spectral channel (Ch1, 2, and 3) incorporates a fiber phase modulator and a YDFA. Dichroic mirrors (identical to the spectral splitters) then recombine three pulse-shaped and amplified spectra from the three fiber channels, and the combined pulse is compressed by a grating compressor and diagnosed by an autocorrelator. Durations of the chirped pulses from the three fiber channels are 23 ps, 19.5 ps, and 19 ps at the dichroic combiners.

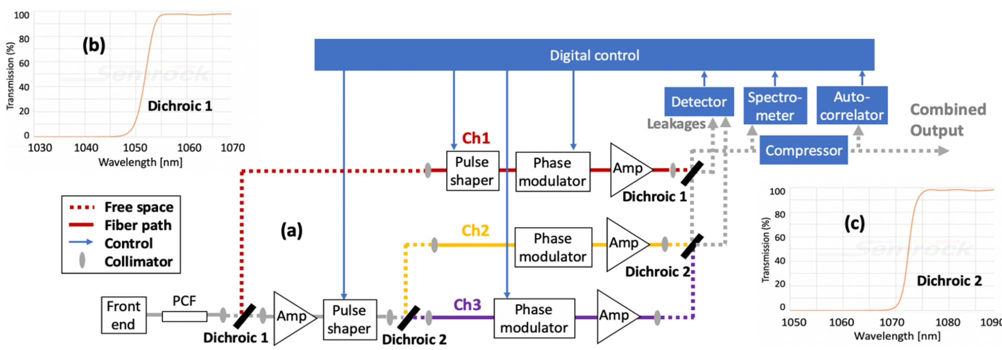

Fig. 2. (a) Experimental setup; (b) Dichroic 1 transmission spectrum; (c) Dichroic 2 transmission spectrum.

The dichroic mirrors are chosen to have a transition edge of a few nm, so that the overlapped spectra at the leakage ports of the dichroic combiners can be diagnosed for phase synchronization of the spectral channels, while maintaining low spectral combining loss. The fiber phase modulators in Channel 1 and 3 receive signals from the phase synchronization feedback loops, which diagnose the leakage signal power from the two dichroic combiners and phase-synchronize the three fiber channels at the overlapped spectral regions with a Stochastic Parallel Gradient Descent (SPGD) algorithm [25]. At the leakage port of each combiner, the overlapped spectra from two spectral channels are interferometric, and the SPGD algorithm minimizes the power there (destructive interference) so that the power at the combined output port is maximized and the combined spectra are in phase, which is needed to achieve the shortest combined and compressed pulse. We measured the free-running power spectrum (1-1000 Hz) of the leakage port of the dichroic mirror combining Channel 1 and 2, shown in Fig. 3, where the relative noise power density decreases to $<10^{-2}$ at 10 Hz and most noise peaks are below few hundred of Hz. The phase synchronization feedback loops are based on Field Programmable Gate Arrays (FPGA) and the overall feedback bandwidth is multiple kHz. The phase locking of Channel 1 and 2 has an RMS instability measured to be 0.89% (30 s data, 6.25 kHz sampling), primarily contributed by the combining process with imperfect phase locking. The combination of Channel 2 and 3 uses a separate, identical feedback loop. In both cases, channel 2 is the phase reference.

Another pulse-shaping feedback system diagnoses the combined spectrum and the autocorrelation signal of the combined and compressed pulse and sends control signals to the two pulse shapers accordingly. This is to compensate for spectral intensity distortions from broadening and amplification, and for various orders of residual spectral phase at the system output, thus yielding a distortion-free combined spectrum and near transform-limited compressed pulse width.

To achieve high resolution pulse shaping, it is critical to perform a wavelength calibration between the spectrometer and the two pulse shapers, using sharp-edge test functions of spectral attenuation, after which the three instruments can be operated based on the same wavelength reference. In this three-channel spectral combining experiment, we employ two pulse shapers that can cover the full bandwidth (1015-1095 nm), and another option is to use three shapers, one for each spectral channel. Considerations associated with high energy systems have been discussed in the Introduction section.

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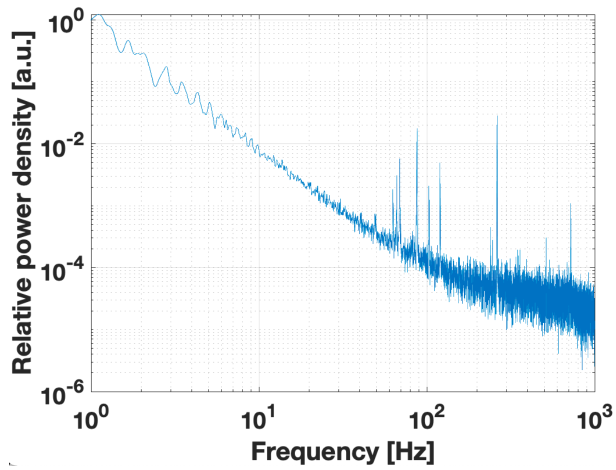

Fig. 3. Free-running power spectrum (1-1000 Hz) of the leakage port of the dichroic mirror combining Channel 1 and 2.

3. Results and Analysis

The shaped, amplified, and recombined spectrum measured after the combiners are shown in Fig. 4(a), which also shows the output spectrum from each spectral fiber channel. The programmable pulse shapers compensate for most of the spectral intensity distortions from broadening and amplification, except for some spectral gaps resulting from the initial nonlinear broadening process in the PCF, which is not optimized. The two overlapped spectral regions from the three fiber channels are in the range of 1047-1054 nm and 1069-1076 nm, as shown in Fig. 4(a). Our measure of average spectral combining efficiency, dividing the combined signal power (with all spectral channels phase synchronized) by the total power of the output signals from all three spectral channels before spectral combination, is measured to be 93.6%.

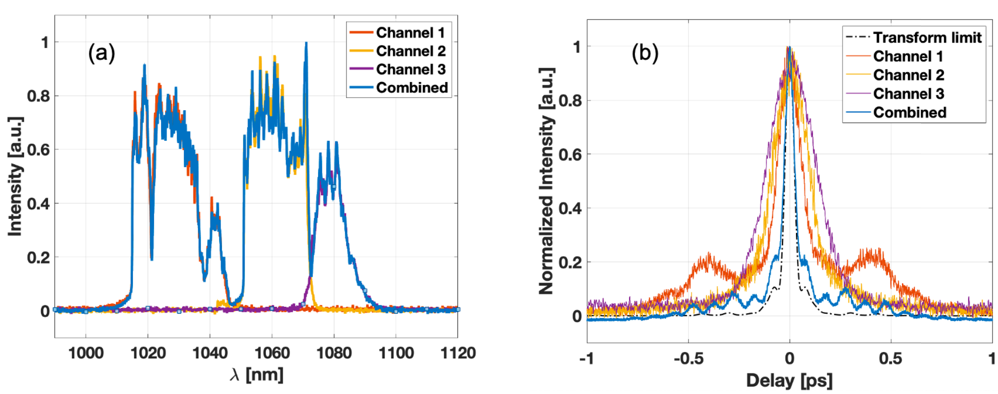

Fig. 4. (a) Measured spectra after dichroic combiners; (b) Measured autocorrelation traces after compression (combined pulse, and pulse from each channel), and calculated autocorrelation trace of the transform-limited pulse for the combined spectrum in (a).

An automatic algorithm is implemented to configure the spectral attenuation profiles needed by the pulse shapers. Figure 5(b) shows the attenuation profiles implemented in each channel by the two pulse shapers. Note that due to the lower power of Channel 3 and the spectral gap at about

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1035-1052 nm from the nonlinear broadening process (not optimized) in this experiment, the spectral attenuation is set to be constant values in these wavelength ranges. In future systems, with optimized front-end broadband seed source and efficient long-wavelength amplifiers operating in deep saturation regimes, the spectra at each dichroic combiner leakage port (overlapping spectral region) from the respective two spectral channels can be shaped to the same shape and intensity, so that the combiner leakage power is minimized to a negligible level via destructive interference, and the spectral combining efficiency can be maximized.

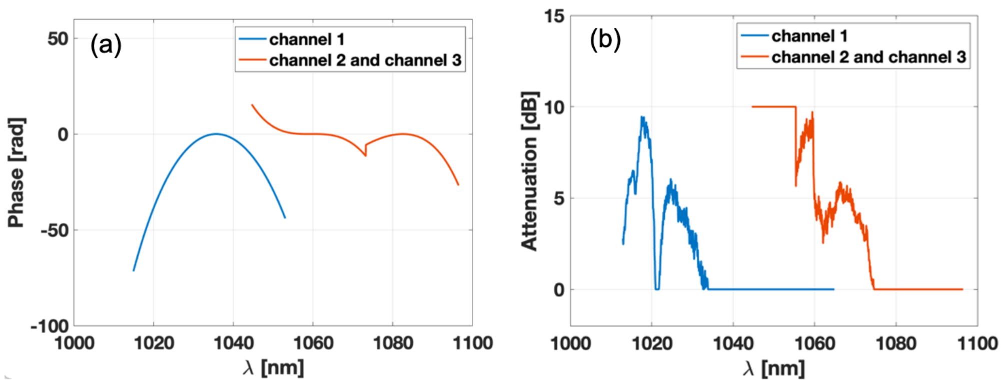

Fig. 5. (a) Spectral phase profiles of the pulse shapers; (b) Spectral attenuation profiles of the pulse shapers.

Programmable pulse shapers also need to apply spectral phases at various orders to the three spectral channels, essential for achieving a combined and compressed pulse duration that is close to the transform limit. To optimally compensate for spectral phase errors in the system, the spectral phase profiles of the pulse shapers are first tuned until the duration of the compressed pulse from each spectral channel is minimized individually, after which the spectral phase values are re-optimized to minimize the final combined and compressed pulse duration. Optimization of spectral phases is performed by programming the pulse shapers to change the coefficients of different orders of spectral phases (up to fifth-order dispersion) sequentially and in iterations while diagnosing the compressed individual and combined pulses with the autocorrelator. The optimized spectral phase profiles that are programmed to the pulse shapers for the shortest combined and compressed pulse are shown in Fig. 5(a).

After the spectral intensity and phase shaping are optimized as shown in Fig. 5, and the phases of the three spectral channels are synchronized, the combined and compressed pulse is diagnosed, with autocorrelation shown in Fig. 4(b). The combined pulse energy in this experiment is not high enough to yield an accurate and stable FROG measurement, but sufficient for autocorrelator diagnostics. In order to retrieve a meaningful pulse duration, we first calculate the transform-limited pulse based on the measured combined spectrum in Fig. 4(a) with the assumption of a flat spectral phase, whose FWHM pulse duration is 38 fs. We then calculate the autocorrelation trace of the transform-limited pulse, shown in Fig. 4(b) with an FWHM duration of 52 fs, corresponding to a deconvolution factor of 1.37. This factor is applied to the measured autocorrelation of the combined and compressed pulse (58 fs FWHM), to retrieve the combined and compressed pulse duration, calculated to be 42 fs FWHM. This calculation is only valid if the measured autocorrelation duration is close to its transform-limited counterpart, which is the case here (~10% deviation). Nevertheless, there is a clear mismatch between the wings of the autocorrelation traces for the measured and transform-limited pulses. We believe this is mainly due to the factors below. First, currently the spectral phase optimization only uses the autocorrelation FWHM duration as the figure of merit, while minimizing pulse pedestals has not yet been implemented. Second, the aforementioned shaper spectral phase optimization is performed manually, awaiting the development of an automated algorithm, resulting in residual spectral phase errors. Lastly, like any coherent-combined laser systems, spatial and temporal misalignments play detrimental roles but could be minimized with further system optimization.

Figure 4(b) also includes the autocorrelation traces of the pulses from Channels 1, 2, and 3 after pulse shaping and compression, measured at 146 fs, 185 fs and 280 fs (FWHM) respectively, corresponding to FWHM pulse durations of 106 fs, 135fs and 205 fs. Thus, the combined and compressed pulse (42 fs) is significantly shorter than the pulses from each spectral fiber channel after compression, and is close to the transform limit (38 fs) for the measured combined spectrum. The deconvolution factors for each spectral channel are calculated separately, based on each channel's spectrum.

4. Conclusion

In summary, we demonstrate ultra-broadband spectral combining of ultrashort pulses from Yb-doped fiber amplifiers, with coherently-spectrally synthesized pulse shaping, to achieve tens-of-fs pulses. We produce 42 fs pulses by spectrally synthesizing three chirped-pulse fiber amplifiers and two programmable pulse shapers across an 80nm overall bandwidth. The three fiber channels operate at different but partially overlapped wavelength ranges, and their spectral intensity and phase control are synthesized via phase synchronization in the overlapped spectral ranges. Coherently synthesized pulse shapers distributed in multiple spectral-combining channels result in less bandwidth that each pulse shaper needs to cover, as well as reduced gain narrowing and high order dispersion compensation needed in each spectral channel, thus can fully compensate for gain narrowing and high order dispersion over the broad Yb:fiber gain spectrum in high energy systems.

To the best of our knowledge, 42 fs is the shortest pulse duration achieved from a spectrally combined fiber system at one-micron wavelength. While this initial demonstration is performed at low power, it shows the key principles of ultra-broadband spectral combining in FCPA systems and coherently-spectrally synthesized pulse shaping, providing a path toward high-energy, tens-of-fs FCPA systems. For example, the future implementation of broadband spectral combining in spatially-temporally combined FCPA systems is a promising energy-scalable, short-pulse method for demanding applications.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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