Nonlinear chirped pulse amplification for 100-Watt-class GHz femtosecond all-fiber laser system at 1.5 μm

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Abstract In this work, we present a high-power, high-repetition-rate, all-fiber femtosecond laser system operating at 1.5 μm. This all-fiber laser system can...
deliver femtosecond pulses at a fundamental repetition rate of 10.6 GHz with an average output power of 106.4 W — the highest average power reported so far from all-fiber femtosecond laser at 1.5 μm, to the best of our knowledge. By utilizing soliton-effect-based pulse compression effect with optimized pre-chirping dispersion, the amplified pulses are compressed to 239 fs in an all-fiber configuration. Empowered by such a high-power ultrafast fiber laser system, we further explore the nonlinear interaction among transverse modes LP₀₁, LP₁₁, and LP₂₁ that are expected to potentially exist in fiber laser systems of using large-mode-area fibers. The intermodal modulational instability is theoretically investigated and subsequently identified in our experiments. Such a high-power all-fiber ultrafast laser without bulky free-space optics is anticipated to be a promising laser source for applications that specifically require compact and robust operation.

Key words: High-power femtosecond fiber laser, high repetition rate, nonlinear pulse compression, intermodal modulational instability

I. INTRODUCTION

In the past two decades, the study on high-power femtosecond (fs) fiber laser (HPFFL) has made significant progress thanks to the breakthrough in manufacturing large-mode-area (LMA) fibers, e.g., the chirally-coupled-core fiber[1] and large-pitch fiber (LPF)[2]. The use of LMA fibers is capable of generating hundreds-of-μJ pulse energy without compromising the beam quality[3]. Remarkably, a record pulse energy of 2.2 mJ was achieved using the LPF at 1.0 μm[4]. By further exploiting coherent beam combining technique[5],

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an average power of >10 kW\cite{6} and pulse energy of >20 mJ\cite{7} have been obtained. In contrast to the great success at 1.0 μm, the progress of studying HPFFLs at 1.5 μm is limited, and their performance metrics, particularly the average power and pulse energy, are largely unsatisfied. This can be mainly attributed to the large quantum defect for 980-nm pumping\cite{8} and technical challenge in fabricating high-gain Er-Yb-doped LMA fibers\cite{9,10}. The frontier applications, however, highly demand for HPFFLs at 1.5 μm, e.g., high-aspect-ratio through-silicon-vias fabrication\cite{11}, corneal surgery\cite{12,13}, etc. Moreover, HPFFLs at 1.5 μm are promising drive sources for frequency conversions through second-harmonic generation\cite{14,15}, Cherenkov radiation\cite{16}, soliton self-frequency shift (SSFS)\cite{17,18}, self-phase modulation\cite{19}, just to name a few. In general, the average-power (or pulse-energy) scaling of the 1.5-μm fs fiber laser is mainly based on the chirped pulse amplification (CPA)\cite{20}. A maximum average power of ~10 W has been reported for fs pulses at a repetition rate of 100 MHz\cite{21}, while mJ pulse energy has been obtained for fs pulses at kHz repetition rates\cite{22,23}. In most of prior schemes, either free-space components\cite{24} or specially-designed fibers (e.g., hollow-core photonic crystal fiber\cite{25}) were required for the final pulse compression, which however inherently increased their complexity. Inspired by the concept of ablation-cooled material removal technology using GHz-repetition-rate fs pulses\cite{26,27}, it is of great interest to explore high-power GHz fs fiber laser for emerging applications requiring fast high-repetition-rate ultrashort pulses. In 2021, a 10.9-W fs all-fiber laser system at 1.5 μm with a fundamental repetition rate of 4.9 GHz was reported\cite{28}, wherein the pulse amplification leveraged the soliton-effect-mediated self-compression process, named as nonlinear chirped pulse amplification (NCPA\cite{29}), which has been proven to be promising for high-power GHz-repetition-rate fs all-fiber laser with energy of several to tens of nJ\cite{30,31}.

To compare the parameter regimes of NCPA systems with those of conventional CPA systems, the typical average power and soliton order $N$ of 1.5-μm CPA- and NCPA-based HPFFLs are summarized in Fig. 1. In contrast
to the higher soliton order of CPA systems, i.e., typically higher than 100 for long enough dispersion length $L_D$, the soliton order of NCPA systems typically ranges between $N = 2$ and $N = 16$, and here it is worth noting that a soliton order of less than 16 is significantly important for preventing severe coherence degradation caused by parametrically amplified intensity noise of the high-power pulse\cite{32}. The definition of soliton order can be written as\cite{33}

$$N = \sqrt{\frac{\gamma P_{av} \tau}{3.526|\beta_2| f_R}},$$

where $\gamma$ is the nonlinear coefficient, $P_{av}$ is the average power, $\tau$ is the pulse duration, $f_R$ is the repetition rate and $\beta_2$ is the group velocity dispersion. By utilizing LMA fibers with lower nonlinear coefficient and increasing repetition rate, further power scaling of NCPA-HPFFLs at a relatively low soliton-order level could be realized, which is anticipated and depicted by the dashed line in Fig. 1. Meanwhile, we admit that pushing the power of 1.5-μm HPFFLs to 100-W level in all-fiber configurations approaches or even enters transverse mode instability (TMI) regime (shaded area in Fig. 1)\cite{34,35}, especially for a relatively large quantum defect for Er-Yb-doped fibers using 980-nm pumping scheme.

**Figure. 1.** The average power versus soliton order $N$ of the 1.5-μm high-power ultrafast fiber lasers. Squares and hexagrams respectively denote CPA- and NCPA-based fiber lasers. A more comprehensive survey of related references is provided in Appendix 1. The dashed-dotted line and dashed line correspond
to a 10-μm-core double-cladding fiber laser system ($f_R = 5 \text{ GHz}, \gamma = 1.6 \times 10^{-3}$) and a 25-μm-core large-mode-area fiber laser system ($f_R = 10 \text{ GHz}, \gamma = 4 \times 10^{-4}$), respectively (assuming $\tau = 5 \text{ ps}$). CPA: chirped pulse amplification; NCPA: nonlinear chirped pulse amplification; TMI: transverse mode instability.

In this work, we demonstrate a 100-W-class NCPA-based fs laser system at 1.5 μm in an all-fiber configuration by adopting LMA fiber. By leveraging the soliton-effect-based pulse compression effect as well as pre-chirping dispersion management, 239-fs pulses at a repetition rate of 10.6 GHz are generated with a maximum power of 106.4 W — a record value so far. The coherence performance of the high-power GHz fs pulses is evaluated by the spectral fringe visibility measurement, wherein optical spectra with the distinguishable 10.6-GHz longitudinal-mode spacing are recorded. Furthermore, the potential nonlinear interaction among transverse modes LP$_{01}$, LP$_{11}$, and LP$_{21}$ is carefully investigated for the high-power amplification using LMA fiber, and the intermodal (IM) modulational instability (MI) is theoretically investigated and experimentally identified.

II. Experimental setup: design and implementation

In this section, we firstly investigate the pulse characteristics in the NCPA system by numerically solving the generalized nonlinear Schrödinger equation (GNLSE). The numerical simulation aims to identify the appropriate range of pre-chirping group delay dispersion (GDD) for optimal pulse compression, based on which, the 1.5-μm 100-W-class GHz fs all-fiber laser system is designed.

2.1 Theoretical model of the 100-W-class GHz fs all-fiber laser system at 1.5 μm

To characterize the pulse propagation along the LMA fiber used in the main
fiber amplifier, the GNLSE is utilized\textsuperscript{[36]}

\[
\frac{\partial A}{\partial z} + \frac{i}{2} \frac{\beta_2}{\partial t^2} A - \frac{\beta_3}{6} \frac{\partial^3 A}{\partial t^3} = i \gamma \left(1 + \frac{i}{\omega_0} \frac{\partial}{\partial t}\right) \left(A(z,t) \int_{-\infty}^{\infty} R(t') |A(z,t - t')|^2 dt'\right),
\]

\[
R(t) = (1 - f_R) \delta(t) + f_R (\tau_1^{-2} + \tau_2^{-2}) \tau_1 e^{-t/\tau_2} \sin\left(\frac{t}{\tau_1}\right) H(t),
\]

\[
A(0,t) = \mathcal{F}^{-1}\left(\mathcal{F}\left[\sqrt{P_{p0}} \text{sech}\left(\frac{1}{1.763} \frac{t}{\tau_0}\right)\right] e^{i \beta_{PC} \omega^2/2}\right),
\]

where $A(z, t)$ is the slowly-varying field envelope at a carrier angular frequency $\omega_0$. $R(t)$ accounts for the Raman response, wherein $\delta(t)$ and $H(t)$ are Dirac function and Heaviside step function, respectively. The key parameters used in Eq. (2) are provided in Table 1. Considering the power variation in the main fiber amplifier, an effective fiber length $L_{\text{eff}}$ in the numerical calculation is defined

\[
L_{\text{eff}} = \frac{e^{\theta_{LMA}} - 1}{g e^{\theta_{LMA}}} + L_{PF} \sim 3 \text{ m},
\]

where $L_{LMA}$ and $L_{PF}$ are the length of LMA fiber and the matching passive fiber, respectively. To study the coherence degradation, an intensity noise with a fraction of $\sim 2\%$ is applied to the input signal $|A(0, t)|^2$.

By varying the pre-chirping GDD $\beta_{PC}$, the optical spectrum, as well as the compressed pulsewidth of the pulse at $z = L_{\text{eff}}$, is visualized and shown in Fig. 2. According to the spectral-temporal characteristics, three distinctive regimes are identified. In regime I for $|\beta_{PC}| \leq 0.25 \text{ ps}^2$, the asymmetrically red-shift component clearly identifies the Raman-effect-driven SSFS\textsuperscript{[37,38]}, as manifested by the spectral evolution. In this case, appreciable energy transfer to Raman solitons can occur when the length of LMA fiber exceeds the fission distance $L_{fiss}$\textsuperscript{[32]} that is defined by $L_{fiss} \sim L_D/N \propto \tau/\sqrt{P_p}$, where $L_D$ is the dispersion length, $\tau$ and $P_p$ are the pulsewidth and peak power with respect to the pre-chirped signal $A(0, t)$. From this perspective, smaller $\beta_{PC}$ that results in shorter
pulsewidth and higher peak power corresponds to a smaller fission distance \( L_{fiss} \), indicating a higher possibility of SSFS. In regime III for \(|\beta_{PC}| > 1 \text{ ps}^2\), the duration of the compressed pulse is broadened to the ps level as a relatively weak nonlinear effect. Specifically, the pulse stretch with larger pre-chirping GDD renders an optimal distance for self-compression \( L_{SC} \sim 0.16\pi L_{fiss} \) that is considerably longer than the length of LMA fiber.

Table 1. Key parameters used in the numerical simulation

<table>
<thead>
<tr>
<th>Parameters of the fiber amplifier</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-chirping GDD ( (\beta_{PC}, \text{ps}^2) )</td>
<td>-1.5~1.5</td>
</tr>
<tr>
<td>Length of LMA gain fiber ( (L_{LMA}, \text{m}) )</td>
<td>4.5</td>
</tr>
<tr>
<td>Length of LMA matching passive fiber ( (L_{PF}, \text{m}) )</td>
<td>1.5</td>
</tr>
<tr>
<td>Gain coefficient ( (g, \text{m}^{-1}) )</td>
<td>0.67</td>
</tr>
<tr>
<td>Nonlinear coefficient ( (\gamma, \text{W}^{-1} \text{m}^{-1}) )</td>
<td>4×10^{-4}</td>
</tr>
<tr>
<td>Second-order dispersion ( (\beta_2, \text{ps}^2/\text{km}) )</td>
<td>-20</td>
</tr>
<tr>
<td>Third-order dispersion ( (\beta_3, \text{ps}^3/\text{km}) )</td>
<td>0.3</td>
</tr>
<tr>
<td>Fractional contribution of the delayed Raman response ( f_R )</td>
<td>0.18</td>
</tr>
<tr>
<td>Phonon frequency ( (\tau_1^{-1}, \text{fs}^{-1}) )</td>
<td>12.2^{-1}</td>
</tr>
<tr>
<td>Bandwidth of the Lorentzian line ( (\tau_2^{-1}, \text{fs}^{-1}) )</td>
<td>32^{-1}</td>
</tr>
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<table>
<thead>
<tr>
<th>Parameters of the pulse</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Peak power ( (P_{\text{p0}}, \text{W}) )</td>
<td>1×10^4</td>
</tr>
<tr>
<td>Initial pulsewidth ( (\tau_0, \text{ps}) )</td>
<td>1.2</td>
</tr>
<tr>
<td>Carrier angular frequency ( (\omega_0, \text{THz}) )</td>
<td>1210</td>
</tr>
</tbody>
</table>

In Regime II, it exhibits higher-order soliton dynamics without the onset of soliton fission (i.e., generation of Raman solitons). In this regime, the pre-chirping GDD imposed upon the pulse leads to a self-compression distance \( L_{SC} \) that fits the length of LMA fiber, such that the nonlinear spectral broadening occurs before the generation of Stokes wave resulted from the Raman effect. The design of the NCPA system here must rely on the control of soliton dynamics: on one hand, the pre-chirping GDD should not be too small, otherwise the soliton fission occurs and thus generates redshifted Raman solitons with limited spectral coherence; on the other hand, much too large pre-chirping GDD will weaken the nonlinear spectral broadening, and thereby hinders the pulse self-compression. According to the numerical simulation, an appropriate pre-chirping GDD can vary in a range of \( 0.25 \text{ ps}^2 < |\beta_{PC}| \leq 1 \text{ ps}^2 \), which corresponds to an adjustable length of 6.2 m when using the dispersion-
compensation fiber (DCF, ~120 ps²/km dispersion).

**Figure.** 2. The numerical simulations of the amplified signals with different pre-chirping group delay dispersions (GDDs). (a) The contour plot of optical spectra with varying pre-chirping dispersion. SSFS: soliton self-frequency shift. (b) The corresponding pulsewidth variation. The regimes I, II and III are designated according to the spectral-temporal characteristics, and the pulse amplification governed by Raman effect, soliton effect, and weak nonlinearity, respectively, are identified.

### 2.2 Experimental setup and implementation details

The experimental setup of the 100-W-class GHz fs all-fiber laser system at 1.5 μm is illustrated in Fig. 3. The laser system mainly consists of a Fabry-Pérot fiber oscillator serving as the seed, four stages of fiber pre-amplifiers, and a main fiber amplifier using polarization-maintaining LMA (PLMA) fiber.

Ultrashort fiber resonator of the seed laser consists of a 1-cm-long homemade Er-Yb-doped fiber (EYDF), a semiconductor saturable-absorber mirror (SESAM, Batop), and a fiber-type dielectric film (DF). The homemade EYDF has a core/cladding diameter of 5.4/127 μm, a numerical aperture of 0.206 at 1.5 μm, and a gain coefficient of 9.13 dB/cm at 1535 nm[39]. The EYDF is pumped by a 974-nm single-mode laser diode (SM-LD, 460 mW maximum power). The EYDF was inserted into a size-matched ceramic ferrule, both end
facets of which were perpendicularly polished. The SESAM used for passive mode-locking has an absorbance of 4%, a modulation depth of 3%, and a relaxation time of 10 ps. The DF has a high reflectivity of 99.5% at 974 nm and a reflection of 99.2% at 1550-1580 nm, which was directly coated onto a fiber ferrule using a plasma sputter deposition system. The average power of the seed under fundamental mode-locking is about 1.2 mW and the pulsewidth of the seed is estimated to be 2.2 ps. A polarization controller (PC1) is used to adjust the state of polarization and an isolator (ISO) is applied to protect the seed from back reflection. The output of the seed is then fed into the 1st pre-amplifier, wherein a 2.5-m-long Er-doped fiber (EDF, Coractive Er35-7) is used, pumped by a 974-nm SM-LD (460 mW maximum power). The pre-chirping dispersion, crucial for performing the NCPA system, is implemented by employing different lengths of DCF (YOFC DM1012-D; highlighted by dashed box in Fig. 3), i.e., 26 m, 32 m, and 38 m in the experiment. An ISO is placed at the output to prevent back reflection. The loss of fusion splicing between DCF and standard single-mode fiber (Corning SMF-28e) is ~2 dB. The average power after the 1st pre-amplifier is 15.1 mW. The configuration of the 2nd pre-amplifier is similar to that of the 1st pre-amplifier, and the average power after the 2nd pre-amplifier is boosted to 160.8 mW. Another PC (PC2) is placed at the output to optimize the state of polarization before entering the polarization-maintaining (PM) parts of the fiber laser system (mainly the 4th pre-amplifier and main fiber amplifier).

Further power scaling is realized by using cladding-pump scheme. In the 3rd pre-amplifier, a 3.5-m-long double-cladding EYDF (DC-EYDF, Coractive DCF-EY-10/128H) is utilized as the gain medium, which is forward-pumped by a 974-nm multimode laser diode (MM-LD, BWT, 9 W maximum power) through a (2+1)×1 signal-pump combiner (SPC). The average power measured after the EYDF is 1.6 W. The 4th pre-amplifier has a similar configuration as that of the 3rd pre-amplifier, except for the PM gain fiber and pigtails, i.e., 4.5-m-long PM-DC-EYDF (Coractive DCF-EY-10/128-PM) and matched PM-DC
fiber. The maximum power of the 974-nm MM-LD in this stage is 27 W. The average power after the 4\textsuperscript{th} pre-amplifier is boosted to 5.8 W at a pump power of 21 W. In the main fiber amplifier, a 4.5-m-long PLMA-DC-EYDF (Nufern PLMA-EYDF-25P/300-HE) is forward-pumped by six 940-nm MM-LDs (Lamda Photonics, 70 W maximum power for each) through a (6+1)×1 PM-SPC. At the end of the PLMA-DC-EYDF, a quartz block head (QBH) is connected for the final output.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{The schematic diagram of the experimental setup. Dispersion-compensation fiber (DCF) is employed to perform pre-chirping dispersion management. SESAM: semiconductor saturable absorber mirror; DF: dielectric film; EYDF: Er-Yb-doped fiber; PC: polarization controller; WDM: wavelength-division multiplexer; SM-LD: single-mode laser diode; ISO: isolator; EDF: Er-doped fiber; MM-LD: multimode laser diode; SPC, signal-pump combiner; DC-EYDF, double-cladding EYDF; OC: optical coupler; PM-DC-EYDF: polarization maintaining DC-EYDF; PLMA-DC-EYDF: polarization maintaining large-mode-area DC-EYDF; QBH: quartz block head; PM: polarization-maintaining.}
\end{figure}

The output power of the main fiber amplifier is monitored by a thermal power sensor (Ophir FL1100A-BB-65). The optical spectrum is analyzed by an optical spectrum analyzer (Yokogawa AQ6370D), and the pulsewidth is measured by an autocorrelator (APE pulseCheck USB50). The performance of the seed is quantified using a 12.5-GHz high-speed photodetector (Newport 818-BB-51F), a 20-GHz real-time oscilloscope (Teledyne SDA 820Zi-B), and a 26.5-GHz radio-frequency (RF) signal analyzer (Agilent N9020A).
Figure 4. The characterization of the seed. (a) The optical spectrum. (b) The radio-frequency (RF) spectrum measured at a resolution bandwidth (RBW) of 10 Hz. (c) The RF spectrum measured at a 25-GHz span at a RBW of 30 kHz. (d) The oscilloscopic trace. Here, the pulse train at a 10.6-GHz repetition rate is viewed as a sinusoidal waveform due to the limitation of the electrical bandwidth. The inset shows the pulse trace in a wider span of 10 μs.

III. Experimental results and discussion

3.1 Characteristics of the seed

The mode-locking with a fundamental repetition rate of 10.6 GHz has a pump threshold of ~90 mW, and the average output power of the signal is about 1.2 mW at a pump power of ~110 mW. The optical spectrum centered at 1565 nm has a 3-dB bandwidth of 1.6 nm, as illustrated in Fig. 4(a), corresponding to a transform-limited pulsewidth of ~1.6 ps (assuming a sech²-pulse shape). The RF spectrum is acquired at a resolution bandwidth (RBW) of 10 Hz, as shown in Fig. 4(b), wherein a 10.6-GHz fundamental frequency and an 89-dB signal-to-noise ratio (SNR) are indicated, implying a good short-term mode-locking stability. Over a wider frequency span (i.e., 25 GHz), no sidelobe or satellite
peak in the RF domain is observed, as shown in Fig. 4(c), confirming a stable operation without polarization rotation\textsuperscript{[40]}. Such a stationary state of polarization is particularly important for PM-fiber amplifier\textsuperscript{[41]}. Fig. 4(d) presents the oscilloscopic trace of the seed that exhibits good intensity uniformity, wherein a temporal period of 94 ps is indicated, in accordance with the repetition rate of \(\sim 10.6\) GHz. It is worth noting that, limited by the electrical bandwidth (i.e., only 12.5 GHz for the photodiode in this case), the pulse trace exhibits to have a nearly sinusoidal waveform.

3.2 Operation regimes of the 100-W-class GHz fs all-fiber laser system

![Figure 5](https://doi.org/10.1017/hpl.2023.36)

*Figure. 5.* (a) The output power of the main fiber amplifier as a function of the pump power. (b) The autocorrelation trace measured at the maximum output power of 106.4 W when using a 32-m-long DCF.

Through monitoring the pulsewidth at the port 2 of the 4\textsuperscript{th} pre-amplifier while changing the length of the DCF, a 26-m-long DCF that corresponds to the zero pre-chirping GDD in this system is identified. Inspired by the result of the numerical simulation, we further prolong the length of the DCF to 32 m (within an adjusting range of \(\sim 6.2\) m) for self-compressing the pulsewidth to the fs regime. Fig. 5(a) presents the output power of the amplified signal as a function of the launched pump power, and a maximum signal power of 106.4 W is obtained at a pump power of 285 W, which is, to the best of our knowledge, the highest power of fs fiber laser at 1.5 \(\mu\)m. Please note that, the average power of the amplified signal was measured after passing through two dichroic mirrors with high reflection at 940 nm and high transmission at 1565 nm. The slope
efficiency of the main fiber amplifier is about 36.28%, while 23.21% and 25.38% for the 3rd and 4th pre-amplifiers, respectively. It should be pointed out that, although the EYDF has a lower pump absorption at 940 nm (typically, four times lower than that of 974 nm) that may lead to a longer length of gain fiber, the use of 940-nm pumping strategy can effectively reduce the thermal effect and suppress the amplified spontaneous emission (ASE). The autocorrelation trace, as shown in Fig. 5(b), exhibits a pulsewidth of 293 fs, assuming a sech²-pulse shape. There exists a visible pedestal in the autocorrelation trace, a typical feature of the soliton-effect-mediated self-compression process. The energy ratio of central pulse is calculated to be 26.6%.

To gain a deeper insight into the self-compression characteristics, we have adopted different lengths of DCF to study the distinctive operation regime predicted in the numerical simulation. For a 26-m-long DCF, the laser system operates in the regime I that approaches the zero pre-chirping GDD. Both the numerical and experimental results confirm the generation of broadband Stokes wave, as shown in Figs. 6(a) and 6(b), respectively. Note that, the optical spectrum of Fig. 6(b) is recorded at a lower signal power of 80 W to prevent the potential Raman scattering in the fiber link. The coherence loss, i.e., the orange curve of Fig. 6(a), can be identified by the fringe visibility of the spectral modulation imprinted by a longitudinal mode spacing of 10.6 GHz. As shown in the closeup of Fig. 6(b), a ~4-dB spectral fringe contrast suggests a degraded coherence (~0.43) at the central spectral region of the signal; while the spectral fringes become almost invisible for redshifted Stokes components, implying the prominent decoherence occurred.
Figure 6. The operation regimes of the high-power fiber laser system by employing different lengths of DCFs. (a) 30 simulated optical spectra operated in the Raman-effect-dominated regime (Regime I) with different random Raman noise (grey curves), the average simulated optical spectrum (black curve) and the degree of coherence (orange curve). (b) Experimental optical spectrum operated in Regime I. The inset shows a ~4-dB spectral fringe contrast suggesting a degraded coherence (~0.43) at the central spectral region of the signal. (c) The degree of coherence in the soliton-effect-dominated regime (Regime II), wherein the central spectral region of the signal shows a good quality of coherence. (d) Experimental optical spectrum operated in Regime II. (e) Experimental optical spectrum and autocorrelation trace operated in the weakly-nonlinear regime (Regime III). (f) The autocorrelation trace operated in Regime III. The less-broaden optical spectrum and ps-level pulsewidth indicate weak nonlinearity that is not sufficient for soliton-effect compression.

By prolonging the DCF to 32 m, the fiber laser system enters the regime II, wherein the SSFS is well inhibited, as manifested by the measured optical spectrum shown in Fig. 6(d). The spectral broadening governed by the soliton dynamics results in effective pulse compression that the compressed pulses have a pulsewidth in the sub-300 fs level, as shown in Fig. 5(b). The calculated
spectral fringe visibility is provided in Fig. 6(c), which verifies a relatively good coherence over the spectral range: with regard to the main part of short-wavelength components, a coherence of \( \sim 1 \) is calculated for the center wavelength components, i.e., the left panel of Fig. 6(c), while a reduced coherence of \( \sim 0.5 \) for the long-wavelength components, i.e., the right panel of Fig. 6(c), which is mainly resulted from the Raman-effect-assisted MI. More details about the MI influence will be discussed in the next section. Further increasing the DCF length to 38 m results in a pre-chirping GDD of \( |\beta_{PC}| > 1 \) ps\(^2\), for which the spectral-temporal characteristics are shown in Figs. 6(e) and 6(f), and a less-broadened optical spectrum and a ps-level pulsewidth are obtained.

### 3.3 Instability mechanism in the 100-W-class GHz fs all-fiber laser system

The MI is a typical phenomenon in optical fiber, especially in the anomalous dispersion regime\(^{[47,48]} \), and it can act as a predominant mechanism of spontaneously amplifying the relative intensity noise of the signal through the parametric process, leading to the coherence deterioration. In general, the frequency-dependent gain \( g_{MI}(\Omega) \) of the MI in the optical fiber can be described as\(^{[49]} \),

\[
g_{MI}(\Omega) = |\beta_2\Omega|\sqrt{(4\gamma p_p/\beta_2)^2 - \Omega^2},
\]

where \( \Omega \) is the offset frequency relative to the carrier frequency \( \omega_0 \). The LMA gain fiber used in the main fiber amplifier has a core diameter of 25 \( \mu \)m and a NA of 0.1, which is larger than the minimum NA of 0.05 for single-mode guiding, such that it supports high-order modes (HOMs), i.e., LP\(_{01}\), LP\(_{11}\), and LP\(_{21}\) modes as shown in Fig. 7(a). As a result, it can associate with IM-MI through cross-phase modulation (XPM)\(^{[50,51]} \). To study the potential IM-MI between the transverse modes, we utilize a couple nonlinear Schrödinger equation in the formalism of
\[
\frac{\partial A_1}{\partial z} = \frac{\delta_{12}}{2} \frac{\partial A_1}{\partial t} - i \frac{\beta_{21}}{2} \frac{\partial^2 A_1}{\partial t^2} + i(\gamma_{11}|A_1|^2 + 2\gamma_{12}|A_2|^2)A_1, \tag{5a}
\]
\[
\frac{\partial A_2}{\partial z} = -\frac{\delta_{12}}{2} \frac{\partial A_2}{\partial t} - i \frac{\beta_{22}}{2} \frac{\partial^2 A_2}{\partial t^2} + i(2\gamma_{21}|A_1|^2 + \gamma_{22}|A_2|^2)A_2, \tag{5b}
\]

with \( \gamma_{pq} = \frac{n_2 \omega_0}{c} \left( \int_{-\infty}^{\infty} |F_p(x,y)|^2 |F_q(x,y)|^2 \, dx \, dy \right)^{-1} \left( \int_{-\infty}^{\infty} |F_p(x,y)|^2 \, dx \, dy \right)^{-1} \left( \int_{-\infty}^{\infty} |F_q(x,y)|^2 \, dx \, dy \right)^{-1}, \)

where \( A_1 \) and \( A_2 \) are slowly-varying field envelope with respect to two distinct transverse modes. \( F_p(x,y) \) describes the transverse field distribution of transverse mode \( p \). \( \gamma_{pq} (p,q = 1,2) \) are the nonlinear coefficients responsible for nonlinear interaction between transverse modes \( p \) and \( q \). \( c \) is the speed of light, and \( n_2 \) is the nonlinear refractive index. Other key parameters are provided in Table 2. Fig. 7(b) illustrates the calculated first- and second-order dispersion curves of different linear-polarized modes.

**Figure. 7.** The intermodal modulation instability (IM-MI) potentially existed in the LMA fiber based main fiber amplifier. (a) The transverse modes supported by the 25-μm-core LMA gain fiber, i.e., LP\(_{01}\), LP\(_{11}\), and LP\(_{21}\) in this case. In the calculation, the refractive index difference between the core and cladding is set to 0.0035. (b) The calculated first- and second-order dispersion curves for different linear-polarized modes. (c) The optical spectra at the average powers of 80 and 100 W. (d) The calculated gain spectra of MI and IM-MIs resulted from the nonlinear interactions between LP\(_{01}\)-LP\(_{11}\) and LP\(_{01}\)-LP\(_{21}\) mode pairs.
By applying linear stability analysis on the perturbations adding to the fields of $A_1$ and $A_2^{[52]}$, the gain spectrum of the IM-MI can be written as

$$
g = \max[\text{Im}(K)],$$

$$
\left[\left(K + \frac{\delta_{12}}{2} \Omega\right)^2 - \beta_{21} \Omega^2 \left(\gamma_{11} P_1 + \frac{\beta_{21} \Omega^2}{2}\right)\right]
\times \left[\left(K - \frac{\delta_{12}}{2} \Omega\right)^2 - \beta_{22} \Omega^2 \left(\gamma_{22} P_2 + \frac{\beta_{22} \Omega^2}{2}\right)\right]
= 4\gamma_{12}^2 P_1 P_2 \beta_{21} \beta_{22} \Omega^4.
$$

(6)

Subsequently, we compare the optical spectra of the amplified signal with gain spectra of the MI and IM-MIs, as shown in Figs. 7(c) and 7(d). There exists a short-wavelength sidelobe for an output power of 100 W, as shown in Fig. 7(c), which can be attributed to the IM-MI excited by the LP$_{01}$-LP$_{11}$ interaction. According to the experiment, the short-wavelength sidelobe presented when the average power exceeded 85 W, and its intensity consistently enhanced with the average power. In the meanwhile, the spectral hump can have been produced by the interplay between the MI and IM-MI. Notably, the evidence of the IM-MI elucidates a distinctive mechanism for understanding how the presence of HOMs influences the performance of a high-power GHz fs fiber laser. The stability of most CPA fiber laser systems is sensitive to the onset of the TMI when operating with high average power[35]. The present NCPA-mediated scheme, on the other hand, operates with much lower soliton order $N$, such that it may only suffer from the mode instability dominated by these classic nonlinear effects that mainly relate to the peak power instead of the average power, e.g., the IM-MI and intermodal four-wave mixing (IM-FWM)$^{[53]}$. In contrast to the IM-MI that mainly experiences the nonlinear phase modulation (i.e., the XPM), the IM-FWM can facilitate the energy transfer from fundamental mode LP$_{01}$ to HOMs in the phase-matching condition$^{[54]}$. Hence, when the LMA gain fiber is not well coiled to suppress the HOMs$^{[55–57]}$, the
LP$_{21}$ component can be parametrically amplified through the IM-FWM, which thus gives rise to the mode instability, as schematically illustrated in Fig. 8(a). Due to the existence of modal dispersion and mode coupling effect, pulses with different group velocities can form a pulse doublet with a temporal separation of $\Delta t = \delta_{12}(L_{LMA} + L_{PF}) \sim 17.8$ ps at the output of the main fiber amplifier. For a better understanding, the corresponding autocorrelation trace is also provided at the right-hand side of Fig. 8(a). In the experiment, if the LMA gain fiber is handled with inappropriate manners, like coiling with a relatively large bend radius, we can observe two kinds of spectral modulation pattern as shown in Figs. 8(b) and 8(c). The dominated spectral modulation pattern corresponds to the longitudinal mode spacing of $\sim 10.6$ GHz, as shown in the left panel of Fig. 8(c). The second kind of spectral modulation pattern, particularly in the longer wavelength region, is mainly resulted from the spectral signature of the pulse doublet, i.e., the right panel of Fig. 8(c), wherein a modulation period of 0.46 nm coincides well with the temporal separation $\Delta t$ of 17.8 ps. Based on the above analysis, the MI/IM-MI and IM-FWM can be the key mechanisms of the instability potentially existed in the present 100-W-class GHz fs all-fiber laser system.
Figure 8. The influence of the intermodal four-wave mixing (IM-FWM) on the output performance of the high-power fiber laser system. (a) The IM-FWM-mediated energy transfer from transverse mode LP_{01} to LP_{21}. With the presence of the modal dispersion, the pulses of transverse modes LP_{01} and LP_{21} walk off from each other, and form a pulse doublet separated by Δt through the mode coupling. The relevant autocorrelation trace is provided as the inset on the right-hand side. (b) The optical spectrum measured with the maximum output power if an inappropriate coiling scheme is used in experiment. (c) The closeup of the intrinsic longitudinal mode (left) and spectral structure resulted from the pulse doublet pattern (right).

Table 2. Key parameters used for calculating intermodal modulation instability

<table>
<thead>
<tr>
<th>Transverse mode (Mode number q)</th>
<th>LP_{01}  (q = 1)</th>
<th>LP_{11} (q = 2)</th>
<th>LP_{21} (q = 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group velocity mismatch with LP_{01} (δ_{12}, fs/mm)</td>
<td>0</td>
<td>1.75</td>
<td>2.97</td>
</tr>
<tr>
<td>Second-order dispersion (β_{2q}, fs^2/mm)</td>
<td>-30.29</td>
<td>-30.86</td>
<td>-27.56</td>
</tr>
<tr>
<td>Nonlinear overlap</td>
<td>f_{1q}</td>
<td>3.174×10^9</td>
<td>3.416×10^9</td>
</tr>
<tr>
<td></td>
<td>f_{2q}</td>
<td>3.416×10^9</td>
<td>3.292×10^9</td>
</tr>
<tr>
<td></td>
<td>f_{3q}</td>
<td>1.41×10^9</td>
<td>f'</td>
</tr>
</tbody>
</table>

*Cross-phase modulation between transverse modes LP_{11} and LP_{21} is not considered here
IV. Conclusion

In conclusion, we have demonstrated a high-power all-fiber fs laser system at 1.5 μm that can deliver ultrashort pulses at a fundamental repetition rate of 10.63 GHz with an average output power of up to 106.4 W — a record for the all-fiber fs laser operating at 1.5 μm. By optimizing the pre-chirping GDD and leveraging the soliton-effect-based pulse compression effect, the amplified pulses are compressed to 239 fs. Furthermore, we have discussed the IM-MI that potentially exists in the few-mode LMA gain fiber. This high-power all-fiber fs laser system exhibits to be compact, robust and stable, and thus it is anticipated to be a promising tool for scientific, industrial and medical applications.
Appendix 1 – Summary of the high-power ultrafast fiber laser at 1.5 μm

Table 3. Comparison of high-power ultrafast fiber lasers at 1.5 μm

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Repetition rate (MHz)</th>
<th>Pulsewidth (ps)</th>
<th>Fiber type in main fiber amplifier</th>
<th>Amplifying technique</th>
<th>Year</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>156</td>
<td>0.45</td>
<td>10-μm core DCF</td>
<td>CPA</td>
<td>2012</td>
<td>[8]</td>
</tr>
<tr>
<td>1</td>
<td>55</td>
<td>0.81</td>
<td>DCF-EY-7/128</td>
<td>CPA</td>
<td>2013</td>
<td>[58]</td>
</tr>
<tr>
<td>2.5</td>
<td>200</td>
<td>0.39</td>
<td>DCF-EY-7/128</td>
<td>CPA</td>
<td>2013</td>
<td>[59]</td>
</tr>
<tr>
<td>3.4</td>
<td>75</td>
<td>0.765</td>
<td>DCF-EY-7/128</td>
<td>CPA</td>
<td>2014</td>
<td>[60]</td>
</tr>
<tr>
<td>8.65</td>
<td>50</td>
<td>0.835</td>
<td>EYDF-25P/300-HE</td>
<td>CPA</td>
<td>2014</td>
<td>[61]</td>
</tr>
<tr>
<td>8</td>
<td>35</td>
<td>0.85</td>
<td>35/250 LMA fiber</td>
<td>CPA</td>
<td>2014</td>
<td>[62]</td>
</tr>
<tr>
<td>10</td>
<td>10000</td>
<td>0.1</td>
<td>High-power EDFA</td>
<td>CPA</td>
<td>2015</td>
<td>[63]</td>
</tr>
<tr>
<td>2</td>
<td>&lt;1</td>
<td>~0.9</td>
<td>EYDF-25P/300-HE</td>
<td>CPA</td>
<td>2015</td>
<td>[22]</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>2.44</td>
<td>PM-EYDF-6/125-HE</td>
<td>CPA</td>
<td>2016</td>
<td>[64]</td>
</tr>
<tr>
<td>3.5</td>
<td>43</td>
<td>0.175</td>
<td>EY-DC-10/125</td>
<td>CPA</td>
<td>2017</td>
<td>[24]</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>0.44</td>
<td>DCF-EY-10/128</td>
<td>CPA</td>
<td>2017</td>
<td>[21]</td>
</tr>
<tr>
<td>1</td>
<td>&lt;1</td>
<td>0.4</td>
<td>PLMA-EYDF-25P/300-HE</td>
<td>CPA</td>
<td>2018</td>
<td>[23]</td>
</tr>
<tr>
<td>1</td>
<td>40.6</td>
<td>0.344</td>
<td>DCF-EY-10/128-PM</td>
<td>CPA</td>
<td>2020</td>
<td>[25]</td>
</tr>
<tr>
<td>10.9</td>
<td>4900</td>
<td>0.063</td>
<td>MM-EYDF-10/125-XPH</td>
<td>NCPA</td>
<td>2021</td>
<td>[28]</td>
</tr>
<tr>
<td>106.4</td>
<td>10600</td>
<td>0.239</td>
<td>PLMA-EYDF-25P/300-HE</td>
<td>NCPA</td>
<td>2022</td>
<td>This work</td>
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</table>

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