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Communication

High-Power GHz Burst-Mode All-Fiber Laser System with Sub 300 fs Pulse Duration

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Abstract: An all-fiber low-repetition-rate SESAM mode-locked fiber oscillator combined with a dispersion-managed active fiber loop produces a flexible GHz burst-mode laser source. The high-power output is then produced by amplifying the GHz burst-mode laser source using an all-fiber chirped-pulse amplification system. Then, the laser is compressed using a grating pair compressor; a maximum amplified power of 97 W is obtained. This results in a compressed high power of 82.07 W with a power stability RMS of 0.09% and beam quality better than 1.2. Accurate dispersion control allows for the production of a high-quality pulse duration of 265 fs.

Keywords: GHz femtosecond laser; all-fiber laser; burst mode; dispersion control

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Citation: Li, F.; Zhao, W.; Fu, Y.; Xing, J.; Wen, W.; Wang, L.; Li, Q.; Cao, X.; Zhao, H.; Wang, Y. High-Power GHz Burst-Mode All-Fiber Laser System with Sub 300 fs Pulse Duration. *Photonics* **2024**, *11*, 570. https://doi.org/10.3390/photonics11060570

Received: 29 May 2024
Revised: 14 June 2024
Accepted: 17 June 2024
Published: 18 June 2024

1. Introduction

High-power and high-energy femtosecond lasers have gained extensive use in scientific and industrial fields for various applications, such as attosecond laser generation [1], ultrafast pump-probe spectroscopy [2], THz generation [3], and material precision micro-machining [4–7]. Especially in ultrafast micro-machining, these lasers are favored because they can remove material without causing heat damage. Typically, the repetition rate of femtosecond lasers ranges from hundreds of kilohertz to megahertz to attain high-peak-power density. However, traditional micro-machining techniques exhibit low material removal speeds. Recent studies [8–12] have suggested that incorporating the innovative ablation-cooling concept with high-repetition-rate femtosecond pulses can significantly enhance the material removal process's throughput.

The GHz femtosecond laser source has garnered significant interest among scientists [13,14]. Generating the GHz repetition-rate mode-locked laser poses a challenge in mode-locked laser development due to the limited cavity length of the oscillator, which must be kept at approximately 10 cm. Although some GHz results have been reported for solid-state lasers and Yb-fiber lasers, the long-term stability of this kind of GHz laser still remains a challenge. Researchers have successfully developed a 1.2 GHz repetition rate, self-starting, 168 fs mode-locked laser with an average power of 47 mW using a carbon nanotube saturable absorber mirror and a Yb:KYW crystal [15]. The Kerr-lens mode-locked Yb:KGW laser also produced a 2 GHz femtosecond laser with an average output of 1.7 watts and a pulse duration of 145 fs [16]. To meet the rigorous cavity length requirement, and using a 1 cm heavily Yb-doped phosphate glass fiber as the gain medium and a high-dispersion output coupler to regulate cavity dispersion, a 3 GHz repetition rate femtosecond laser with an average power of 53 mW was created [17]. A 1 GHz femtosecond laser with an average power of 600 mW was created using a nonlinear polarization rotation mode-locked approach and a gain fiber with high absorption (~1600 dB/m) for pump power [18]. In these studies, the spatial arrangement posed a barrier to the long-term stability of the GHz femtosecond laser; hence, researchers battled to develop the all-fiber setup of high-repetition-rate femtosecond lasers. The researchers used a 100 MHz all-fiber mode-locked laser and a repetition multiplier to increase the repetition rate to 1.6 GHz and amplified the laser to 72 W at a 200 kHz burst repetition rate [19]. A 1 cm-long Er-Yb-doped fiber with a high gain of 9.13 dB/cm, a semiconductor saturable absorber mirror, and a fiber-type dielectric film consisting of a 1.5 µm GHz mode-locked laser, through three-stage single-mode fiber amplifier and three-stage double-cladding fiber amplifier, achieved a maximum amplified output power of 106.4 W and was compressed to 293 fs, but a visual pedestal was present [20]. The 2.2 GHz burst-mode femtosecond laser is created by combining a low-repetition-rate mode-locked laser with an active fiber loop. After amplification and compression, the average power at a 233 kHz burst repetition rate is ~32.6 W. The active fiber loop's non-perfect dispersion control causes pulse elongation in the GHz burst regime, with pulse widths longer than 1 ps a 100 ns burst duration [21].

This work uses a dispersion-managed active fiber loop with a self-made, low-repetition-rate, environmentally stable, semiconductor saturable absorber mirror (SESAM) mode-locked all-fiber oscillator to generate a flexible GHz burst-mode laser source. The active fiber loop's characteristics are optimized to create an all-fiber laser source that bursts at 1.08 GHz. In order to attain a high power output, this GHz burst-mode laser source is then amplified using an all-fiber chirped-pulse amplification system. The main amplifier is a high-gain silicate glass fiber, which produces an amplified power of up to 97 W. After that, a 1600 line/mm grating pair compressor is used to compress the laser. At a 100 kHz burst repetition rate, a high compressed power of 82.07 W is obtained with an excellent power stability RMS of 0.09%, corresponding to a burst energy of 820 µJ. Moreover, with the high power output, a good beam quality (M2) better than 1.2 is achieved. Even at a 100 ns burst duration, a high-quality short pulse duration of 265 fs is achieved because of the design of the high-order dispersion compensation and the accurate dispersion control of the fiber loop. To the best of our knowledge, this GHz femtosecond laser system with an active fiber loop has the shortest pulse duration and highest average power. The high-power all-fiber burst-mode femtosecond laser has high stability, super compactness, and reliability, and it can provide an effective light source to increase the efficiency of femtosecond micro-machining.

2. Experimental Setup

The experimental setup of the high-power GHz burst-mode femtosecond laser system is schematically shown in Figure 1. The system consists of a GHz burst-mode seeder, one-stage single-mode fiber amplifier, a pulse stretcher based on chirped fiber Bragg grating (CFBG), one-stage 10/125 double-cladding fiber amplifier, one-stage high-gain silicate glass fiber (SGF) amplifier as the main amplifier, as well as a grating pair compressor.

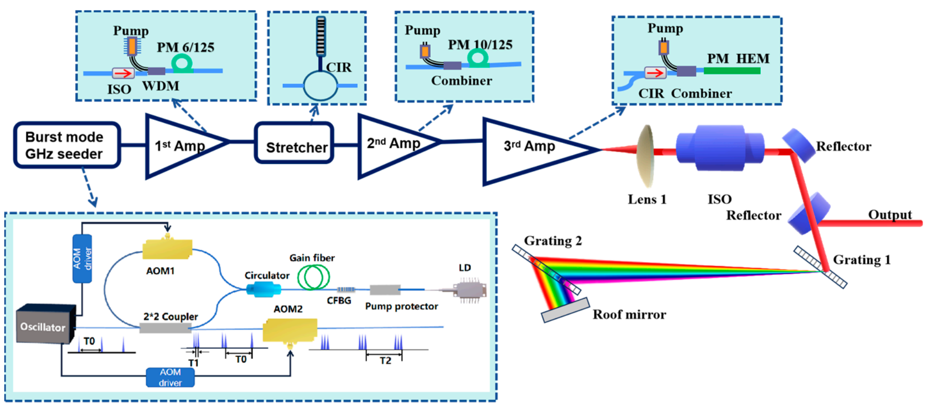

Figure 1. Schematic of the GHz burst-mode femtosecond laser system.

The burst-mode GHz seeder comprises a home-made SESAM mode-locked all-fiber oscillator, a dispersion-controlled active fiber loop, and an AOM outside the active fiber loop. The oscillator's fundamental configuration is the same as our previous study [22], which delivers pulses with 34.8 MHz repetition rates and power around 5 mW. The central wavelength is about 1030 nm with a spectral width of 12 nm. The active fiber loop consists of a 2 × 2 fiber coupler with a 50:50 splitting ratio, a circulator, a 0.6 m-long Yb-doped gain fiber (Nufern, PM-YSF-HI-HP), and a CFBG with a dispersion of 0.254 ps/nm for the dispersion compensation of the fiber loop. AOM1 is used as a shutter to control the pulse train transmission. To drive the two AOMs, the oscillator can generate two synchronous Transistor–Transistor Logic (TTL) signals with adjustable signal widths, repetitions, and delays. Through the 2 × 2 fiber coupler, the mode-locked laser's output is coupled into the active fiber loop. All pulses have a 50% output power after coupling, with the remaining 50% being delivered into the fiber ring for transmission, amplification, and dispersion compensation. The precise meaning is as follows: the pump power is injected through chirped fiber Bragg grating (CFBG) to offer pump power to the gain fiber to amplify the pulses in the fiber loop, the length of the fiber loop is set to approximately 575 cm, and the pulses transmitted through the fiber ring are compensated using CFBG with a dispersion of 0.254 ps/nm. The control board within the seed source sends a programmed synchronous trigger signal to the acousto-optic modulator 1 (AOM1), which in turn controls participant pulse stacking. AOM1 closes when the necessary maximum number of pulse stacks is reached. Acousto-optic modulator 2 (AOM2) synchronously extracts the pulse train following the fiber loop's output to create a pulse burst with a predetermined number of pulses and repetition rate. This scheme's GHz pulse-sequence generation method is based entirely on an all-fiber structure, which offers great stability and reliability. This makes it a technically sound approach to creating GHz pulse sequences. The length difference between the fiber loop and the oscillator cavity determines the pulse interval. $T0$ is the pulse interval of the mode-locked seed source, and according to the repetition rate of 34.8 MHz, the corresponding pulse interval, $T0$, is 28.6 ns, with a cavity length of ~2.97 m, and $T1$ is the generated GHz pulse interval.

$$T1 = \Delta L \times n/c = \left(2\, L_{Oscillator} - L_{Fiber\ loop}\right) \times n/c\,; \tag{1}$$

where ΔL is the length difference between twice the length of the laser cavity and the length of the fiber loop, n is the refractive index of quartz fiber (~1.45), and c is the speed of light in vacuum. When the controlled ΔL is shorter than 20.689 cm, the pulse interval is less than 1 ns, and the corresponding repetition frequency is greater than 1 GHz. Much higher repetition rates can be achieved by carefully adjusting the fiber loop's length; when ΔL reaches below 0.26 mm, the repetition rate can reach the THz regime. Following the GHz pulse train's passage through the programmable fiber-coupled acousto-optic modulator 2 (AOM2) with synchronization signal delay, a pulse train sequence with a repetition rate of 100 kHz is selected; T2 is the interval of the pulse train. When the laser burst repetition rate is set at 100 kHz, the corresponding value of $T2$ is 10 μs; by adjusting the signal width adding on the driver of AOM2, we can control the number of pulses in the burst. In the experiment, a burst of ~100 pulses operated with a burst repetition of 100 kHz is selected as the burst-mode GHz seeder.

Then a 0.6 m-long Yb-doped gain fiber amplified the power to roughly 13 mW. The three-port fiber circulator and temperature-tuning chirped fiber Bragg grating make up the stretcher, which can offer a dispersion of ~50 ps/nm. Additionally, because the CFBG's bandwidth has a 17 nm reflection band, the stretcher cannot provide spectrum filtration for the seeder spectrum. After the stretcher, the pulse is stretched to ~400 ps (spectrum width of ~8 nm). The next stage involves a power amplifier using double-cladding (DC) fiber with a core diameter of 10 μm and cladding diameter of 125 μm (Nufern, Connecticut, United States, PLMA-YDF-10/125-M), pumped by a fiber-coupled multimode semiconductor laser with a maximum power of 9 W, which amplifies the power to approximately 1 W. The main amplifier is a Yb heavily doped silicate glass fiber amplifier with a mode field diameter of 40 μm and length of merely 20 cm, which is used to boost the power to 97 W. This high-efficiency medium was pumped by two 100 W LDs with a locked wavelength of 976 nm through the high-power (2 + 1) × 1 combiner. After amplification, the laser is collimated by a lens with a focal length of 50.8 mm. A high-power spatial isolator (ISO) is used to avoid backward reflection to protect the main amplifier. The compressor is a grating pair with a groove density of 1600 lines/mm with a diffraction angle of 55.5°. Two gratings with sizes of 30 mm × 20 mm × 6.35 mm and 135 mm × 20 mm × 6.35 mm were employed, and the linear distance of the two gratings was ~95 cm.

3. Results and Discussion

As demonstrated in Figure 2, an oscilloscope (LECROY, New York, United States) with a 36 GHz bandwidth and an 80 GS/s sampling frequency is used to measure the produced GHz burst-mode laser. AOM2 controls the number of pulses that make up a burst; this is depicted in Figure 2a. At a burst repetition rate of 100 kHz, ~30, 60, 80, and 100 pulses are generated; this burst repetition rate is measured in Figure 2b. The intra-pulse interval, which is 925 ps, is shown in Figure 2c, indicating an intra-pulse repetition rate of 1.08 GHz. The intra-burst pulse amplitude is not the same, which can be optimized through the fiber amplifier in the fiber loop and AOM2, when adding a signal generated by an arbitrary wave generator. By adjusting the diffraction efficiency of each pulse, the pulses' amplitude can be controlled better. However, in GHz burst-mode femtosecond laser micromachining, the different amplitudes of the pulses have little effect on the processing. The ablation-cooled regime's physics can be understood as follows: each pulse causes an instantaneous temperature rise, and when the pulse interval is substantially shorter than the material's thermal relaxation time, the target temperature has a small net increase, and ablation occurs when the temperature exceeds a critical value [8]. In the generation of the GHz burst mode through the active fiber loop, the CFBG inside the fiber loop with a dispersion value of 0.254 ps/nm is employed to produce the dispersion compensation of the pulses transmitted in the fiber loop. However, the reflection band of the CFBG is not flat (the reflective spectrum is Gaussian); the more pulses contained in a burst controlled by AOM1, the more pulses are reflected by the CFBG, so the spectrum is narrowed. As shown in Figure 3, when the burst contains many more pulses, the spectrum narrows form ~12 nm to ~6 nm (FWHM) when the pulses increases from 15 pulses to 780 pulses. To reduce spectra narrowing, the CFBG utilized in the fiber loop can be optimized with a flat reflection spectrum. In the subsequent amplification, the number of pulses is set as 100 pulses, which still has a wide spectrum to support a short pulse duration.

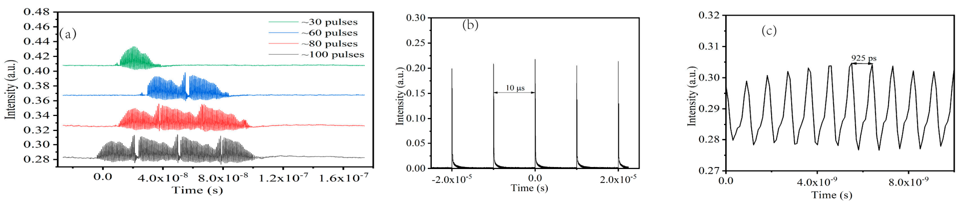

Figure 2. Experimentally measured 1.08 GHz burst-mode laser. (**a**) Different numbers of pulses in a burst; (**b**) burst repetition rate of 100 kHz; (**c**) pulse interval measurement.

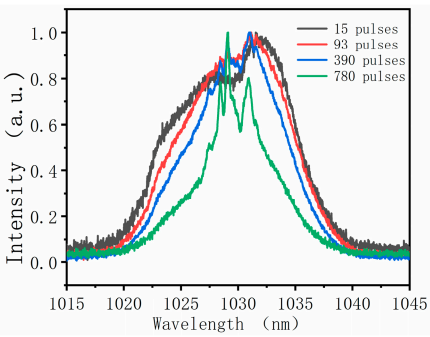

Figure 3. Spectra with different pulses in a burst.

The main amplifier is a high-gain silicate glass fiber amplifier. The fiber is mounted on an aluminum block, and the block is water-cooled. The amplification performance is shown in Figure 4, and has a high slope efficiency of 66%. At the maximum pump power of 156.7 W, a 97 W amplified output power is obtained at a 100 kHz burst repetition rate. The limitation of the output power is the heat dissipation capacity of the high-gain silicate glass fiber amplifier; on the other hand, it is also vulnerable to laser reflection from optical components that follow the amplifier, which can damage the amplifier module. The system has some potential to obtain a higher power, to avoid damage, and keep the system's long-term stability. The output power is set to 97 W. Then, the pulses are compressed by the high-efficiency grating pair; an average power of 82.07 W is obtained, corresponding to a compression efficiency of 84.6% and a burst energy of 820 μJ. To assess the system's stability, we measured the compressed output power at its high power level in one hour; it showed that the system has an excellent power stability RMS of 0.09% at 82.07 W.

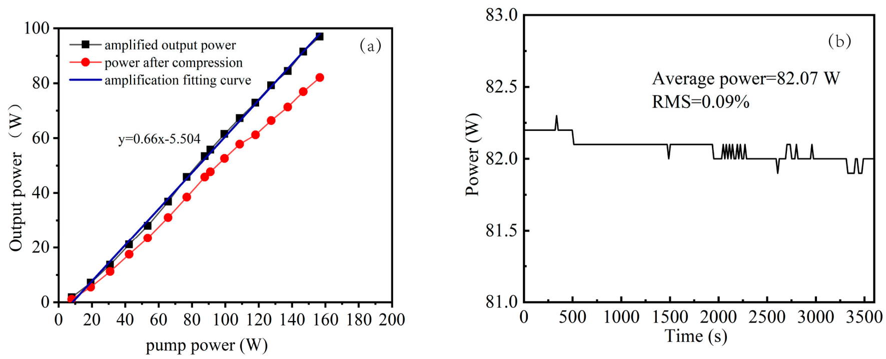

Figure 4. The laser output performance; (**a**) the amplified output power and compressed output power versus the pump power; (**b**) the compressed output power stability measurement.

The compressed spectrum and autocorrelation trace are shown in Figure 5. The compressed spectrum is shown in Figure 5a; it still has a spectrum width of ~4 nm (FWHM), which can support a sub-300 fs pulse duration. In order to obtain the transform-limited short-pulse-duration output, we need very precise dispersion control. Creating a zero dispersion of the fiber loop is the first step, and creating a perfect dispersion of the stretcher, fiber in the CPA system, and compressor is the second. Table 1 displays the comprehensive dispersion control and illustrates that the fiber loop's second-order dispersion is well compensated to a nearly zero dispersion. The single-mode fiber's second-order dispersion and third-order dispersion are approximately 0.024764 ps^2/m and 46 $\times$ 10^3 fs^3/m, respectively, and its length is approximately 5.75 m. The CFBG's dispersion within the fiber loop is 0.254 ps/nm ($\beta_2 = -\frac{\lambda^2 D}{2\pi c} = -0.143\ ps^2$). The stretcher is a temperature-tuning CFBG device that Teraxion Inc. (Quebec City, QC, Canada) sells commercially. It provides second-order and third-order dispersions, as well as the ability to tune dispersions when adding varying temperature gradients to the CFBG. The table displays the precise dispersion and tuning capabilities. The fiber's length in our CPA system is ~6 m; the estimated dispersion is also calculated and shown in the table. The compressor is a 1600 line/mm grating pair, the second-order dispersion is matched through carefully adjusting the distance of the grating pair, and finally, the optimized linear distance is 95 cm, which introduces a second-order dispersion and third-order dispersion of $-28.1\ ps^2$ and 0.241 ps^3, respectively. The second-order dispersion of 28.148 ps^2 and third-order dispersion of $-0.241\ ps^3$ are engraved in the stretcher of the CFBG, and the stretcher also has second-order dispersion and third-order dispersion tuning capabilities via the temperature gradient. This allows for the precise adjustment and perfect matching of the dispersion with the compressor and fiber dispersion in the CPA system. Additionally, the active fiber-loop dispersion is precisely controlled through the length of the fiber loop and the application of CFBG within the fiber loop to achieve zero dispersion transmission for every pulse. As a result, a short pulse with a pulse duration of 265 fs with a small pedestal is achieved by Lorentz fitting.

Lorentz fitting is used because the Lorentz fitting curve is well matched to the data curve. The beam quality is also measured, and, as shown in Figure 6, at the 82 W compressed output level, the beam quality can still be better than 1.2. The high beam quality at this high power level is due to the all-fiber structure and the fiber amplifier's excellent thermal cooling capability.

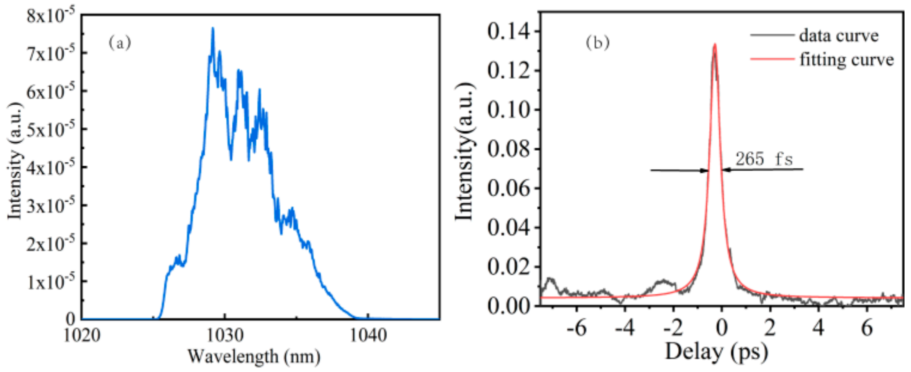

Figure 5. The spectrum and pulse width measurement of the compressed output laser; (**a**) the spectrum; (**b**) the pulse width.

Table 1. Dispersion control of the GHz system to achieve perfect dispersion compensation.

Dispersion Control	Type of Dispersion	Values
Zero dispersion control of active fiber loop	Second-order dispersion of single-mode fiber in the fiber loop Third-order dispersion of single-mode fiber in the fiber loop CFBG used in the fiber loop	0.1424 ps^2 2.645×10^{-4} ps^3 -0.143 ps^2
Stretcher	Second-order dispersion of the CFBG stretcher Third-order dispersion of the CFBG stretcher Second-order dispersion tuning range of the CFBG stretcher Third-order dispersion tuning range of the CFBG stretcher	28.148 ps^2 -0.241 ps^3 $\geq$0.823 ps^2 $\geq$0.0576 ps^3
Fiber dispersion in the CPA system	Second-order dispersion of the fibers Third-order dispersion of the fibers	~0.149 ps^2 2.76×10^{-4} ps^3
Compressor	Linear distance of the grating pair Second-order dispersion of the grating pair Third-order dispersion of the grating pair	95 cm -28.1 ps^2 0.241 ps^3

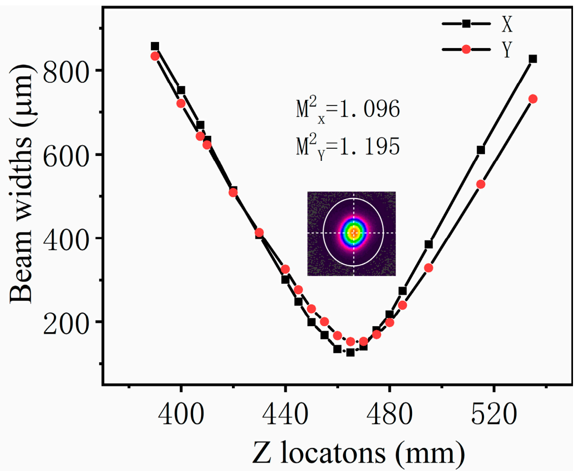

Figure 6. The beam–quality measurement.

4. Conclusions

An all-fiber GHz burst-mode femtosecond laser source based on an active fiber loop is constructed and amplified at a GHz burst repetition rate of 100 kHz with ~100 pulses in a burst; the maximum output power of 97 W is obtained from the all-fiber chirped pulse amplification (CPA) system. After compression, a compressed power of 82.07 W with an excellent power stability RMS of 0.09% is obtained, corresponding to a burst energy of 820 μJ. A measured beam quality better than 1.2 is obtained at this high power level. The satisfactory dispersion control of the CPA system and the active fiber loop results in a high-quality pulse duration of 265 fs. The light source with excellent comprehensive parameters will certainly result in new breakthroughs for the improvement of ultrafast laser processing efficiency.

Author Contributions: Conceptualization, writing, and funding acquisition, F.L.; Conceptualization and supervision, W.Z.; Conceptualization, supervision, and writing—review and editing, Y.F.; Data curation and experimental setup, J.X. and W.W.; Circuit control, W.W. and L.W.; Experimental setup, Q.L. and X.C.; project administration and supervision, H.Z. and Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Chinese Academy of Science "Light of West China" Program under Grant XAB2021YN12, in part by Shaanxi Young Science and Technology Star under Grant 2022KJXX-98, in part by the Key Project of "Double Chain" Integration of Shaanxi Province, in part by the National Natural Science Foundation of China under Grant 61690222, and in part by The Youth Innovation Promotion Association XIOPM-CAS under Grant XIOPMQCH2021007.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data can be provided upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

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