Amplification of 1.08 GHz repetition rate femtosecond laser pulses to 97 W average power by a fiber amplifier

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Abstract: We demonstrate a femtosecond Yb:fiber laser amplification system which delivers 97 W average output power at a repetition rate of 1.08 GHz using a rod-type photonic crystal fiber. The re-compressed output pulse is 233 fs. Numerical simulation was also conducted in agreement with our experimental results.

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1. Introduction

High-repetition-rate femtosecond fiber lasers have attracted lots of interests due to its large longitude-mode spacing and high longitude-mode power, which is very important for multiple applications, such as optical frequency combs [1–3], coherent optical communication [4], photonics-based radar system [5], and nonlinear bio-imaging [6]. Amplified GHz-level repetition rate femtosecond pulses can be applied for multiple state-of-the-art scientific applications, such as GHz intra-burst repetition rate micromachining [7–9], coherent optical pulse stacking [10,11], and cavity-enhanced high harmonic generation [12,13]. In coherent pulse stacking, GHz repetition rate is preferred because it reduces significantly the cavity or delay line length and therefore can minimize the dimension and improve the mechanical stability. In cavity-enhanced high harmonic generation, high power GHz repetition rate laser pulses are also required in achieving high signal to noise ratio (SNR) and small foot print.

A recent work on high power amplification to more than 100 W in an intra-burst 1 GHz repetition rate has been reported [14]. However, the laser source used in that work is a SESAM mode-locked fiber laser which delivers quite low average power and broad pulses (picosecond). Therefore, a set of five-stage amplifier is employed which introduces high complexity of the optical system. In order to achieve femtosecond pulses, they have to take nonlinear amplification process to compress the pulse. Although they claim the compressed pulse is 473 fs, a large-scale pedestal is presented under the femtosecond peak.

In this paper, we demonstrate a 100 W level amplification of a 1.08 GHz repetition rate femtosecond fiber laser in a standard three-stage chirped pulse amplification system. The schematic design of this high power 1.08 GHz repetition rate fiber laser is introduced in section 2. In section 3, the experimental results are introduced. The amplified average power is 97 W and the compressed pulse duration is 233 fs, 1.25 times the transform limited pulse duration. Further numerical simulations and analyses are investigated and illustrated in section 4. Conclusions and outlooks are described in section 5.
2. Experiment arrangement

The schematic layout of the high power 1.08 GHz repetition rate fiber laser system is shown in Fig. 1. The system consists of a home-made fiber oscillator, an all-fiber stretcher, three stages of fiber amplifiers and a transmission grating pair compressor.

The femtosecond seed pulses are delivered from the 1.08 GHz Yb-doped fiber laser applying the nonlinear polarization evolution (NPE) mode-locking mechanism [15]. The output power of the seed laser is 400 mW. The fiber stretcher consists of 15 m PM980 fiber ($\beta_2 = 0.023 \text{ ps}^2/\text{m}$, $\beta_3 = 0.000046 \text{ ps}^3/\text{m}$) and 1.5 m non-PM dispersion compensation fiber (DCF, OFS stretcher fiber FemtoComp, $\beta_2 = 0.12 \text{ ps}^2/\text{m}$, $\beta_3 = -0.00096 \text{ ps}^3/\text{m}$). The pulses are stretched to $\sim 8 \text{ ps}$. Unfortunately, the OFS DCF introduces 24 dB insertion loss into this all-fiber stretcher. The coupled average power 400 mW was decreased to 1.5 mW. Therefore, an additional stage of pre-amplifier must be applied to compensate the corresponding insertion loss.

The two pre-power amplifiers are a single-mode polarization maintaining (PM) fiber amplifier with 0.5 m Yb-401 PM fiber (CorActive, 5 $\mu$m core-diameter, cladding absorption @976 nm 420 ± 25 dB/m) plus a large-mode-area PM fiber amplifier with 1.3 m Yb-doped double-cladding PM fiber (Liekki, 11.9 $\mu$m core-diameter, cladding absorption @976 nm 11.1 dB/m). 0.8 m rod-type large mode PCF fiber (NKT aeroGain ROD, 85 $\mu$m core diameter, cladding absorption @ 976 nm 15 dB/m) is used as the gain fiber for the main amplifier. A transmission type grating pair (Lightsmyth, 1000 lines/mm) is used as the optical pulse compressor for compressing the amplified 1.08 GHz pulses.

3. Experiment results

The average power of the seeding pulses after the all-fiber stretcher was amplified by the pre-power-amplifiers scaling up to 5 W. Further power amplification is applied with the rod-type fiber amplifier. Figure 2 illustrates the amplified output power from the rod-type fiber amplifier as a function of the injected pump power. The corresponding slope efficiency is 64.5%. The inset shows the near-field beam profile of the final output beam. The total B-integral of the system is estimated to be about 0.142 rad. Therefore, the 1.08 GHz seed pulses are amplified based on the typical chirped pulse amplification [16].
The amplified output power is linearly increased by increasing the pump power implying the amplifier is not working in the saturation region. The average output power was final boosted to 97 W when the pump power was set to 150 W. The corresponding output pulse energy is calculated to be $\sim 90$ nJ. Further power amplification can be achieved until reaching the power threshold of the transverse mode instability [17] by injecting more pump power.

Figure 3(a) plots the optical spectra of the seed pulse from the oscillator (black curve) and the output pulse amplified by the rod-type fiber amplifier (red curve). Figure 3(b) plots the intensity autocorrelation traces of the compressed pulses from the compressor (black curve) and the transform limited pulses (red curve). The decreasing in spectral bandwidth is caused by the gain narrowing effect in the amplifier and gain bandwidth mismatch between different type of gain fibers. The transmission grating pair with 112 mm separation distance is employed to compress the amplified pulses from $\sim 8$ ps to 233 fs with 80% compression efficiency. The output pulse duration of the IAC trace is $233 \times 1.414$ fs based on the Gaussian assumption, 1.25 times the corresponding transform limited pulse duration. The small pedestals in the IAC are attributed to the residual high-order dispersion and residual high order mode of the rod-type fiber amplifier.

**Fig. 3.** (a) Measured optical spectra of the output pulse from the oscillator and rod-type fiber. (b) IAC trace of the compressed pulses (black trace), IAC trace of the transform limited pulses (red trace).

4. **Discussion and perspective**

Based on the aforementioned discussions, the rod-type fiber amplifier is not saturated with a slope efficiency of 64.5%. Therefore, higher amplified output power can be achieved if more
pump power is injected. Unfortunately, only 160 W pump power was available at the time of the experiment. The slope efficiency of the rod-type fiber amplifier is limited by the 35.7 degree working temperature of the 976 nm multimode pump diode [18], which makes the central wavelength of the pump laser was away from the perfect matching the peak wavelength of the cladding absorption. The ideal pumping temperature of this 976 nm pump diode is calculated to be \(\sim 39\) degree, which cannot be maintained by our external cooling system when further lifting the pump current.

In order to further optimize the amplification system, a numerical model was built in simulating the dynamics of the signal pulses with GHz-level repetition rate and calculating optical parameters in improving the optical amplification performance. We modeled the process of pulses in an Yb-doped fiber amplifier (YDFA) by the combination of two sets of equations, which are the rate equations and the generalized Schrödinger equation (GNLSE) utilizing the split-step Fourier method [19–22]. We assume the nonlinear coefficient \(n_2\) of the fiber component as \(2.6 \times 10^{-20}\) m\(^2\)/W and the gain bandwidth of the gain fiber as 37 nm. Other main parameters used in the numerical model are shown in Table 1. Figure 4 illustrates the simulated spectra and the corresponding experimentally achieved optical spectra during the whole amplification process. The simulation results match perfectly with the experimental results. The optical spectrum of the signal pulse is firstly broadened due to the self-phase modulation effect inside the OFS stretcher fiber with rather small core-diameter shown in Table 1. The 1.08 GHz repetition rate of the signal pulses significantly inhibits the potential nonlinear effects, making the gain narrowing effect play a dominant role during the pulse amplification process. The spectral bandwidth of the pulse is deceased from 27 nm to 13 nm, while the pulse energy is amplified from 0.0014 nJ to 91.4 nJ. Further higher power scaling can lead to narrower spectral bandwidth with a longer pulse duration. Therefore, for applications requiring sub-100 fs pulse duration, either shaping the spectral profile of the seed pulse or introducing designed nonlinear phase into the amplification process can be applied against the gain narrowing effect [23].

| Table 1. Parameters of the amplification system for the simulation |
|---------------------------------------------------------------|
| MFD (µm) | \(\beta_2\) (fs\(^2\)/mm) | \(\beta_3\) (fs\(^3\)/mm) |
| PM980 | 6.7 | 23 | 46 |
| OFS DCF | 2.9 | 120 | -960 |
| Gain fiber of amplifier 1 | 6.0 | 23 | 46 |
| Gain fiber of amplifier 2 | 11.9 | 23 | 46 |
| Gain fiber of amplifier 3 | 85.0 | 23 | 46 |

Further calculation was conducted for a better pulse compression of the amplified seed pulses. By optimizing the dispersion conjugate condition between the all-fiber stretcher and the transmission grating pair compressor, a perfectly compressed pulse with 106 fs pulse duration (1.03 times transform limited pulse duration) can be achieved as shown in Fig. 5. The potential uncompensated spectral phase introduced by the gain bandwidth mismatch is neglected in order to calculating the influence of the high order dispersion management in compressing the amplified pulses. The green area in Fig. 5 is the autocorrelation trace of the calculated transform limited pulse and the black curve is the autocorrelation trace of the calculated compressed pulse. The residual TOD of the all-fiber system is calculated to be \(\sim 471369\) fs\(^3\). In order to achieve the perfectly compressed results, the stretcher fiber PM980 needs to be cut form 15 m to 2.7 m. Furthermore, the angle of the transmission grating pair needs to be 31.3 degree with a separation distance of 55 mm to satisfy the dispersion conjugation condition. Therefore, based on above discussion, more perfect compression of the amplified pulses should be possible.
5. Conclusions

We have demonstrated the chirped pulse amplification of a femtosecond laser at a 1.08 GHz repetition rate. About 97 W output power was achieved before the pulse compression. Further amplification can be achieved by increasing the pump diode working temperature or injecting more pump power. The compressed output pulse duration was measured to be 233 fs assuming a Gaussian pulse profile. The final output power from the compressor is 78 W. A numerical model was built to investigate the dynamics of the signal pulse during the amplification process. Numerical calculations were conducted in order to optimize the amplification process and the optical pulse compression. The experimental results agree well with the simulation.

This high power, high repetition rate, all-fiber laser can be used to such applications as cavity enhanced HHG, pulse stacking and frequency comb applications to achieve higher SNR, better
systematic stability and smaller footprint. It can also be applied to high efficiency micromachining by turning the amplifier to burst mode.

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**Data availability.** No data were generated or analyzed in the presented research.

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