

Generation of 110 W infrared and 65 W green power from a 1.3-GHz sub-picosecond fiber amplifier

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Abstract: A fiber amplifier that generates nearly transform-limited sub-picosecond pulses and greater than 100 W average power at 1.3-GHz repetition rate is described. Modest stretching of the seed pulses allows the amplifier to be operated in the linear regime. The amplified and dechirped pulses exhibit excellent beam quality, and can be frequency-doubled to produce green pulses at 65 W average power. Detailed characterization of the performance is presented.

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References and links

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1. Introduction

Scaling of the average and peak powers of fiber laser sources has been significant over the last decade [1–3]. By taking advantage of large-diameter fiber cores, cladding-pumped architectures, and chirped-pulsed amplification (CPA) techniques, average powers of up to a few hundred watts have been demonstrated [4–8]. At the same time, these high-power fiber systems offer excellent beam quality, overall efficiency, stability and reliability. The repetition rate of pulsed fiber amplifiers is typically less than 200 MHz. There are a few recent reports of high-power fiber laser systems with higher repetition rates [9–13]. These systems are seeded by pulses in the range of 5-20 ps. The pulses accumulate substantial nonlinear phase shifts in the amplifiers, with the consequent spectral broadening. In Ref [13], the spectral broadening was exploited to generate 430-fs pulses through a self-phase modulation process, or 110-fs pulses through parabolic pulse amplification, both at ~1 GHz repetition rate. Amplification of femtosecond fiber and solid state oscillators at GHz repetition rate in fiber amplifiers has been limited to 5 W [14] and 20 W [15], respectively, to date.

High-power fiber lasers with gigahertz repetition rates are in demand for a number of applications, such as the production of frequency combs for metrology and optical frequency synthesis [16], high-repetition-rate optical parametric oscillators, and the next generation of electron accelerators such as the energy-recovery linac (ERL) [17]. In some of these applications, a pulse duration around 1 ps and nearly transform-limited bandwidth is desired. To our knowledge, a fiber amplifier with these parameters has not been reported.

Here we describe a gigahertz-repetition-rate and high-average-power Yb fiber amplifier. Chirped 8-ps pulses with sufficient bandwidth to support 800-fs pulses are amplified to 150 W infrared (IR) average power, and then dechirped to 110 W power with pulse duration of 890 fs. The modest pulse chirp is adequate to avoid significant nonlinear phase accumulation in the amplifier and keep pulse amplification operated in the linear regime. The amplified and dechirped pulses exhibit excellent beam quality, and efficient frequency-doubling yields 65 W of green power. Detailed characterization of the IR and green pulses will be presented.

2. Experimental setup

The experimental schematic of our fiber amplifier is shown in Fig. 1. The seed source is a commercial harmonically-mode-locked Yb-doped fiber oscillator from PriTel. The fundamental frequency of the oscillator is 16.05 MHz, which is actively mode-locked on its 81st harmonic. After its repetition rate is synchronized to an external radio-frequency (RF) master clock at 1.3 GHz, the timing jitter is estimated to be less than 1 ps with a digital communication analyzer, and any sideband frequencies are suppressed to at least 60 dB below the clock frequency (Fig. 2(a)). The average power of the oscillator is 20 mW, and the spectral bandwidth is about 2 nm, centered at 1040 nm (Fig. 2(b)). The oscillator spectrum can support 800-fs pulses, but output pulses with 8-ps duration and roughly linear chirp are obtained. We exploit the ~10-times stretching of the seed pulses to reduce the peak power,

which allows amplification to the 100-nJ level without distortion from nonlinear phase accumulation.

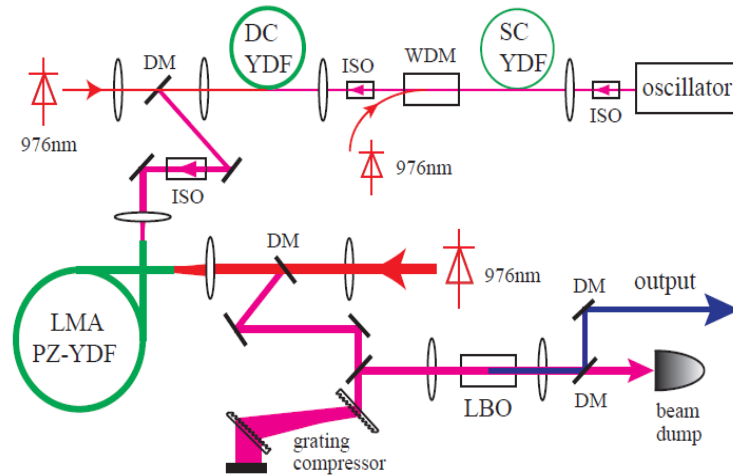


Fig. 1. Schematic of the experimental setup: LMA, large mode area; PZ-YDF, single-polarization Yb-doped fiber; WDM, wavelength division multiplexer; SC, single-clad; DC, double-clad; ISO, optical isolator; DM, dichroic mirror.

The optical pulse train from the oscillator is first amplified in a 3-m single-mode Yb-doped fiber with absorption of 30 dB/m at 976 nm from CorActive, and then in 2.2 m of single mode polarization-maintaining (PM) double clad (DC) ytterbium-doped fiber with a 15-micron core and absorption of 8 dB/m at 976 nm (DC-135/15-PM-Yb) from NKT photonics. Both preamplifiers are counter-pumped by 976 nm diodes with 600 mW and 10 W pump power, respectively. Their output powers are 250 mW and 3.5 W, respectively. The optical spectrum after the second preamp is almost identical to the one from the oscillator, and amplified spontaneous emission (ASE) is 40 dB below the main output spectrum. The polarization extinction ratio (PER) of the amplified pulses is more than 15 dB, which is further improved to more than 30 dB through an optical isolator.

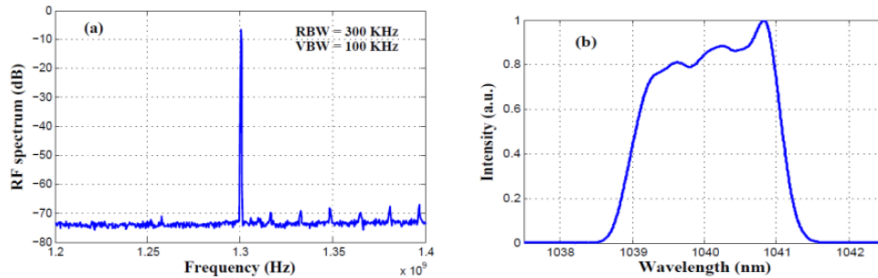


Fig. 2. RF spectrum (a) and optical spectrum (b) from the oscillator.

The main amplifier is 2.5 meter of single-mode, polarizing DC Ytterbium-fiber with $650 \mu\text{m}^2$ large mode area and absorption of 10 dB/m at 976 nm (DC-200/40-PZ-Yb-03) from NKT photonics. The fiber is placed on a water-cooled metal plate, and counter-pumped by a fiber-coupled 976 nm laser diode. The amplifier fiber is coiled with a diameter of 30 cm, and the two fiber ends are arranged to have their slow/fast optical axes placed in the same orientation. With this arrangement, very high PER and efficiency can be achieved.

3. Characterization of amplified pulses

The amplifier characteristic is shown in Fig. 3(a). The maximum average power is 150 W when 230 W pump power is incident on the gain fiber. The optical-to-optical efficiency from pump to infrared output power from the amplifier is 67%. At the maximum output power, the nonlinear phase shift accumulated by the pulse is calculated to be about 2. As shown in Fig. 3(b), there is minimal distortion of the amplified spectrum, and ASE is suppressed more than 30 dB below the amplified signal. The M^2 values in both directions are less than 1.05 for any output power. The PER of the amplified pulses is above 12 dB, and there is no degradation with increasing output power. The RF spectrum measured at 150 W output (Fig. 3(c)) shows that any sideband frequencies are 60 dB below the locked clock frequency.

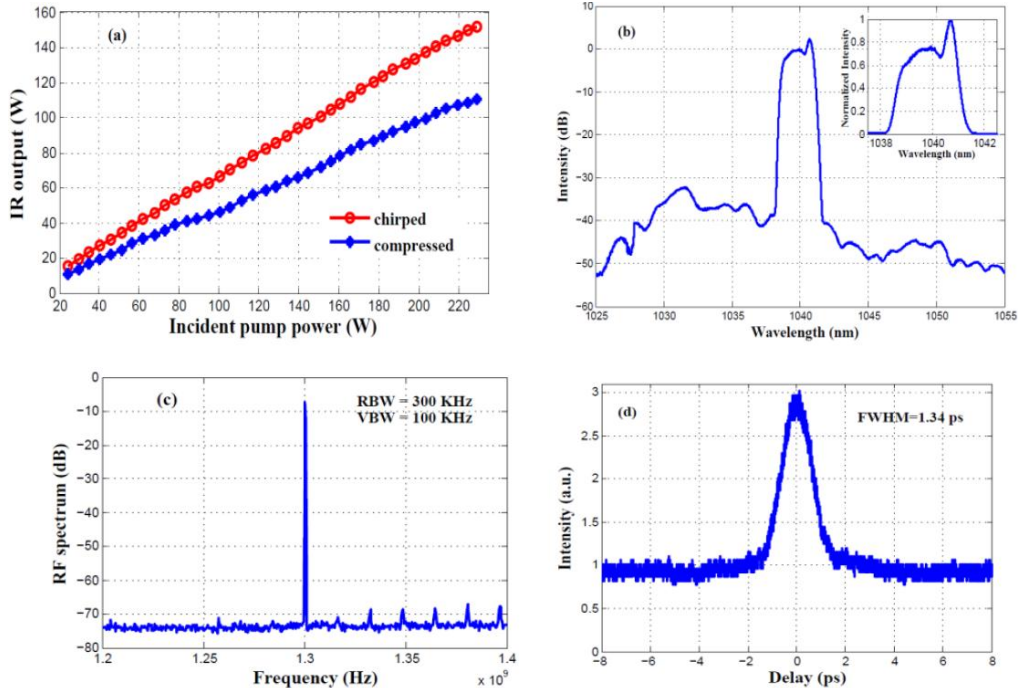


Fig. 3. Chirped and compressed output versus pump power (a); optical spectrum in log and linear scale (insert) (b) and RF spectrum (c) at 150 W IR output; (d) autocorrelation signal of the compressed IR pulses.

The amplified pulses are chirped, with pulse duration of 8 ps. The pulses are compressed by a pair of fused silica transmission gratings with 1250 lines per mm from Ibsen. The gratings are s-polarization dependent and operated at Littrow angle. The diffraction efficiency of the compression grating pair is about 74%. Including the loss of the unpolarized amplified component, the overall efficiency of the compression stage is 70%. With 150 W from the amplifier, 110 W output with pulse duration of 890 fs is produced (Fig. 3(d)). The time bandwidth product is 0.49. The M^2 values of the compressed pulses at any output power are less than 1.1 in both directions, so the beam is close to diffraction-limited.

The power of the amplifier is currently limited by available pump power. The pulse energy could be increased by a factor of 2-3 before nonlinear phase shifts would begin to distort the spectrum. Unfortunately, it is not possible to increase the seed-pulse duration significantly with the present oscillator. A modified oscillator or a pulse stretcher will be needed to increase the pulse energy above 200-300 nJ, which correspond to 250-350 W average power.

This system has been constructed for long-term stable operation. Rigid opto-mechanical components are used throughout the system. The amplifier has been operated for a few hours per day over a two-month period without any adjustments. The output power fluctuates by about 1%, which we attribute to small drift of the pump laser wavelength.

Fiber-integrated components for the two preamp stages, fiber-integrated high-power pump diodes and photonic band-gap fiber for pulse compression are all available. If a high-power fiber isolator could also be obtained, it would be possible to build a fully fiber-integrated version of the amplifier presented here. Such an all-fiber system should be even more stable and reliable, and would be very attractive for applications.

4. Green power generation through second harmonic generation

High average power sources of pulsed green light are important for laser machining, optical parametric oscillators, and ERLs, e.g. To get high power pulsed green light, we carried out frequency-doubling by focusing the compressed output onto a $5 \times 5 \times 15\text{-mm}^3$ lithium triborate (LBO) crystal. An achromatic doublet (AC254-075-B, $f = 7.5\text{ cm}$) from Thorlabs is used to focus the amplifier beam to a 50-micron diameter. The crystal is cut for the commonly-used type-I temperature-tuned interaction [11, 17]. With increasing input, it is necessary to adjust the oven temperature to compensate for the internal heating of the LBO crystal [18]. After the SHG crystal, a lens is used to collimate the second-harmonic beam, and two dichroic mirrors are employed to remove the unconverted fundamental-frequency light.

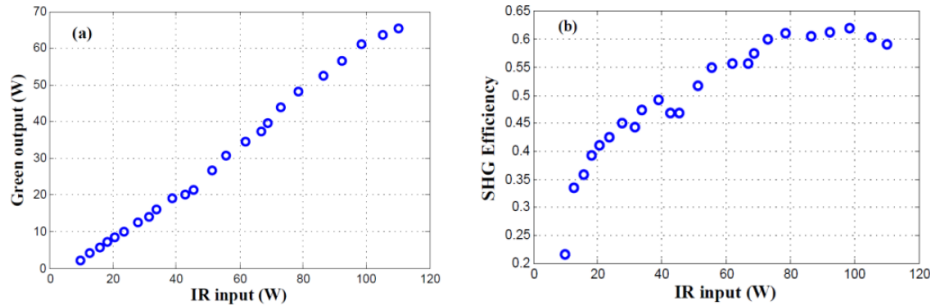


Fig. 4. Green power generation (a) and conversion efficiency (b) versus IR input.

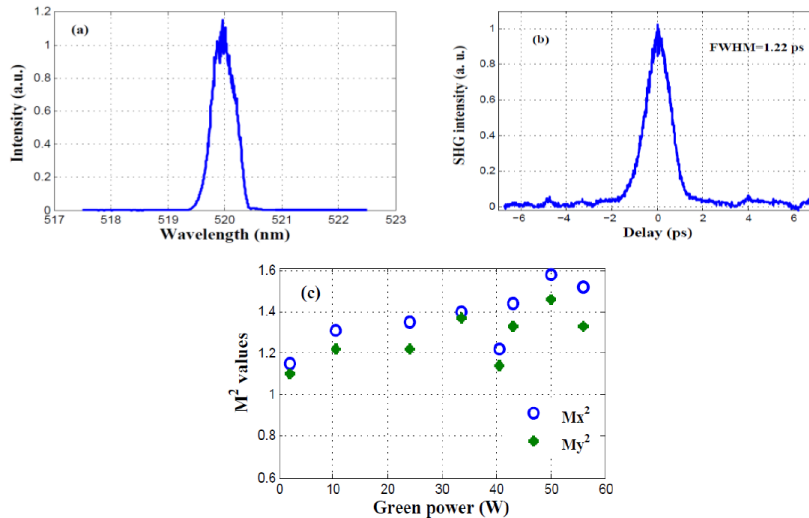


Fig. 5. Optical spectrum (a) and autocorrelation signal (b) at 58 W green output power. M^2 values versus various green output power is shown in (c).

The second-harmonic power and the conversion efficiency are shown in Fig. 4(a) and 4(b), respectively. The green power is approximately proportional to the input power. The approximately-linear dependence has been observed in prior work on high-power harmonic generation [11, 18]. A maximum green power of 65 W at 520 nm is obtained with 110 W input power. The conversion efficiency is thus 60%, and this corresponds to a 29% optical-to-optical efficiency from pump to green power. The efficiency could be improved by the use of a custom high-efficiency grating pair [19].

The optical spectrum and intensity autocorrelation at 58 W green power are shown in Fig. 5(a) and 5(b), respectively. The full-width at half-maximum (FWHM) is 1.2 ps, which corresponds to about 800 fs pulse duration if a Gaussian pulse shape is assumed. The spectral bandwidth of the second-harmonic pulses is 0.5 nm. The spatial beam quality of the second-harmonic pulses was characterized by measuring M^2 values at various green powers. The beam profile degrades slightly with increasing output power, as shown in Fig. 5(c). Considering the nearly diffraction-limited profile of the infrared beam, it is believed that the thermally-induced distortion [18] in the LBO crystal is responsible for the undesired change in the spatial mode of the green pulses.

5. Conclusion

In summary, we have presented a fiber amplifier that generates 8-ps chirped pulses at 150 W average power at 1.3 GHz repetition rate. Excellent spatial mode quality and high optical-to-optical efficiency have been achieved in the amplifier. After de-chirping the output pulses, we obtain 110 W power with pulse duration of 890 fs. Frequency doubling yields more than 65 W green power. Such a high-power and high-repetition-rate system should be suitable for a wide array of applications.

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