High-power and pulse energy picosecond narrow linewidth laser system based on tapered fiber amplifier for second harmonic generation

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Abstract

We present the results of compact and cost-efficient high-power and energy laser system based on a picosecond gain-switched DFB laser diode operating at a wavelength of 1064 nm with spectral linewidth less than 0.1 nm and pulse duration of 50 ps and tapered double clad fiber (T-DCF) amplifier. The unique properties of T-DCF as efficient amplification of low power seed signal and suppressed threshold of nonlinearities allow achievement of both high peak power of 170 kW and pulse energy of 9 μJ at pulse repetition rate of 10 MHz while maintaining spectrum linewidth as narrow as 0.1 nm. High average output power of 150 W was obtained with slightly broader laser linewidth. We also demonstrate second harmonic generation with over 30 W at 532 nm wavelength with conversion efficiency of 38%. These results make MOPA system based on gain-switched DFB laser diode and T-DCF amplifier an attractive source for material processing and sensing application including time resolved Raman spectroscopy.

1. Introduction

Ultrafast fiber lasers with picosecond pulse durations in 1 μm wavelength range are widely used in microprocessing [1], Raman spectroscopy [2] and harmonic generation in nonlinear media [3] due to a number of attractive properties. Such laser systems are compact, have high peak power and pulse energy and provide near diffraction-limited beam quality.

Most of these high-power fiber lasers are based on the master oscillator power amplifier (MOPA) configuration [4]. The master oscillator sets the basic parameters of the radiation such as wavelength, pulse repetition rate and duration. The optical amplifiers provide amplification of this signal to the required high values. Usually, a mode-locked fiber laser is used as a seed source in such laser systems [5]. However, gain-switched (GS) semiconductor distributed feedback (DFB) and Fabry-Perot (FP) laser diodes have drawn attention as a robust master oscillator [6]. These laser diodes are cheaper, simpler and more reliable than mode-locked fiber lasers. However, the main drawback of gain-switched laser diodes is the extremely low pulse energy, in the range of several tens of picojoules. To employ GS laser diodes for high-power laser systems, it is necessary to use several pre-amplifiers to achieve power comparable to mode-locked fiber lasers and sufficient to seed a high-power amplifier incorporated large-mode area (LMA) fibers.

In this work, we will utilize an alternative approach based on an ytterbium-doped tapered double-clad fiber (T-DCF) as a gain module for a power amplifier. The narrow part of the T-DCF supports only single-mode propagation. The light entering the single-mode narrow part of the T-DCF propagates to the wide part, which is heavily multimode, without any change in the number of modes [7]. As a result, only fundamental mode with a beam quality close to the diffraction limit propagates at the wide side of the T-DCF fiber. The pump light, propagating through the multimode cladding, gradually enters into the highly doped core, where it is absorbed. Previously, we have shown that amplifiers based on a T-DCF can efficiently amplify a weak input signal (several milliwatts) [7]. As a consequence, the number of required pre-amplifiers is decreased, which simplifies the overall system. The detailed properties of active tapered fibers were described in several publications earlier [8-9].

In this paper, we fully exploit unique properties of the T-DCF to efficiently amplify a low power seed signal generated by a gain-switched seed source with only one pre-amplifying stage. The average output power up to 150 W has been reached at 10 MHz pulse repetition rate with a moderate line broadening. An amplified 1064 nm radiation was further used for second harmonic generation resulting in over 30 W optical power at 532 nm wavelength and 10 MHz repetition rate with the conversion efficiency of 37%. The obtained results make a MOPA system based on a gain-switched DFB laser diode seed source and a T-DCF amplifier an attractive cost-efficient and powerful laser source for material processing and sensing applications including time-resolved Raman spectroscopy.

2. Experimental setup

The experimental setup is shown in Figure 1 (a, b). The infrared (IR) fiber-based laser system includes a seed laser, a pre-amplifier and a high-power T-DCF amplifier. We used an in-house compact short-pulsed driver to generate picosecond seed pulses from a gain-switched DFB laser diode. The center wavelength of the laser diode was ~1064 nm; the pulse duration was 50 ps (Fig. 1c, d). The seed spectrum width was 52 pm. The average output power of the seed source was 300 µW at a frequency of 10 MHz. In order to amplify seed pulses, a single-stage single-mode ytterbium-doped fiber amplifier (YDFA) pumped at 976 nm was used. After the fiber pre-amplifier, the radiation power increased up to ~100 mW.

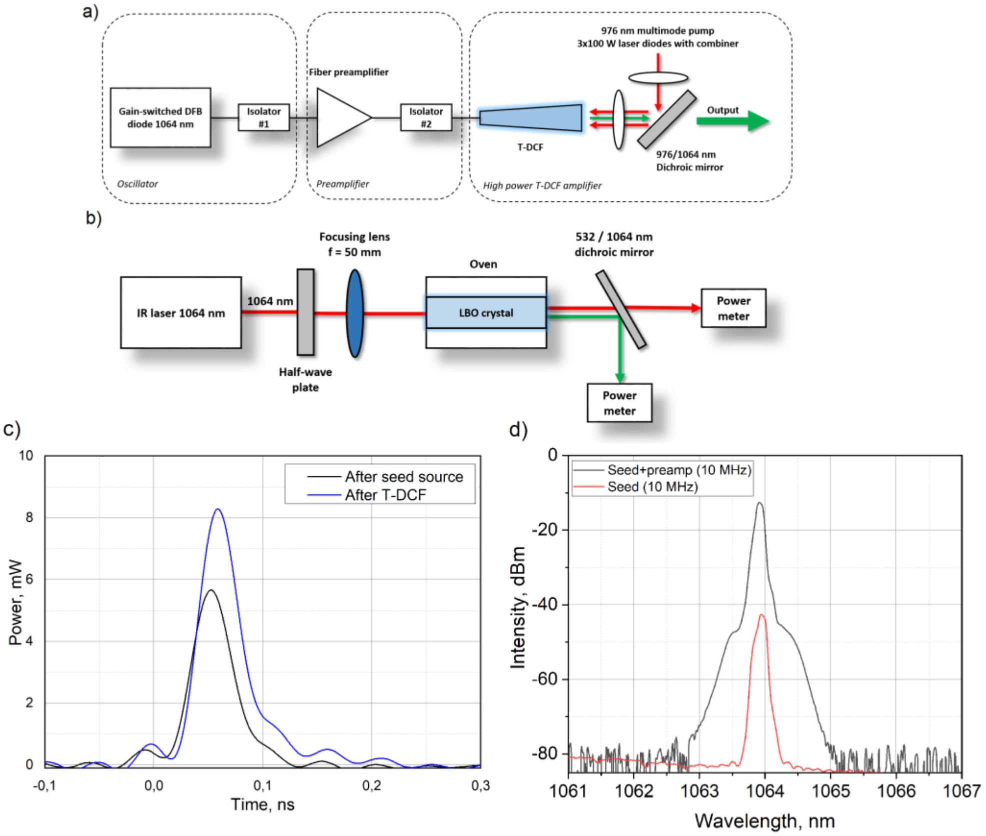

Fig. 1. Schematic diagram of MOPA laser setup (a) and experimental setup for the second harmonic generation (SHG) (b). The temporal (c) and spectral profile of the pulses at 10 MHz (d).

The main high-power amplifier was consisted of a polarization-maintaining Yb-doped double-clad tapered fiber (T-DCF). The active T-DCF fiber was supplied by Ampliconyx Ltd. The in-core and cladding absorptions were 900 dB/m and ~25 dB/m at 976 nm, correspondingly. An ytterbium double-clad tapered fiber had cladding-to-core diameter ratio (CCDR) of 10 with an output core diameter of 50 µm. The input core diameter was 10 µm. The total length of the T-DCF was about 3 m. The T-DCF amplifier was designed to operate in a counter-propagating pumping scheme shown in Fig. 1(a). The beam from 976 nm multimode pump source was collimated and directed via the dichroic filter, and then focused by the second lens at the T-DCF end face. The end face of the tapered fiber was polished at an 8 degree angle to avoid parasitic lasing. The filter was transparent for the outgoing amplified signal at 1064 nm. The pump source included three 100 W wavelength-stabilized laser diodes with 105/125 µm output fiber. The pump laser diodes were spliced to 3x1 combiner with 220/240 µm output fiber. More detailed information about this amplifier can be found in our previous works [7-12].

The setup for frequency doubling is presented in Figure 1 (b). We employed a critically phase-matched 10-mm long AR-coated LiB3O5 crystal (LBO) type 1 operated at 480C [13] to implement second harmonic generation process (from 1064 to 532 nm). The phase-matching condition was maintained by precise temperature control in a specially designed temperature-stabilized crystal oven. A half-wave plate was used to ensure the desired direction of polarization. The beam was focused into LBO crystal by an aspheric lens with a focal distance of 50 mm (Thorlabs AL2550M-B). To separate a residual 1064 nm and a generated 532 nm light, we used a dichroic mirror with reflectance 99.16% and 0.88% at 532 and 1064 nm, respectively.

3. 1064 nm laser system

First, we investigated the output laser system characteristics at 10 MHz repetition rate. The dependence of the output power on the pump power is shown in Fig. 2 (a). The maximum achieved average power at 10 MHz was 150 W. The corresponding slope efficiency was approximately 70%. The laser spectrum measured at the maximum average power is presented in Fig. 2b. As it can be seen the fraction of the amplified spontaneous emission (ASE) at the short wavelength range of the spectrum (near 1040 nm) is very small. The signal-to-noise ratio (SNR) in this case is almost 40 dB. It should be noted that the threshold for the stimulated Raman scattering has not been reached even at the maximum power. Therefore, the spectrum did not contain the corresponding Raman peak, and all power was distributed between the signal and ASE at 1 µm.

We measured the M^2-parameter at the maximum power by using Thorlabs M^2 Measurement system with BC106N-VIS beam profiler. The results are shown in Fig. 2(c). The system demonstrated high beam quality with a pure single-mode operation (M^2<1.2) within the whole power range. No sign of modulation instability has been obtained.

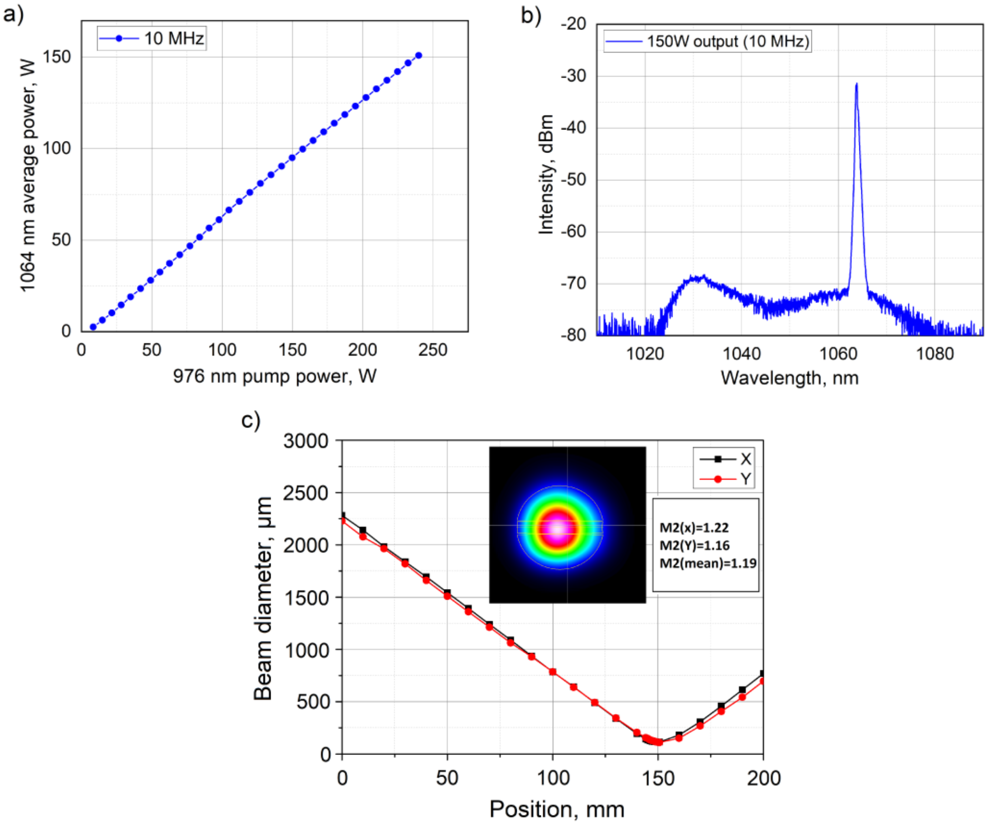

Fig. 2. a) Dependence of output power on pump power, b) Spectrum of the output signal at a frequency of 10 MHz with a maximum output power of 150 W, c) The measured M2-parameter at 150W output power and the far-field beam profile (insert).

The spectrum broadening is a typical limiting factor for power scaling of such laser systems. We investigated this phenomenon (Fig. 3). The spectra were measured by Ando AQ6317B optical spectrum analyser with 0.01 nm spectral resolution. At a repetition rate of 10 MHz, the signal spectrum is relatively smooth with a pronounced peak at the central wavelength of 1063.82 nm. The broadening of the spectrum from 52 to 124 pm was associated with an increase in the intensity of the side peaks following an increase in the average power from 25 to 90 W. However, it always remained below 100 pm when the power did not exceed 80 W level. The series of spectra indicated the linewidth broadening with output power are presented in Fig. 3. At the maximum achieved power level of 150 W the spectrum width was equalled to 142 pm (Fig. 2b). The spectrum broadening at 10 MHz is a result of noisy pulse amplification: the GS pulses exhibit phase, temporal and amplitude fluctuations. The seed power level at the input of the tapered amplifier at 10 MHz is quite high resulted in efficient amplification of the noisy pulses and corresponding spectral broadening due to SPM, XPM and FWM [14-16].

To define the pulse energy and peak power, we integrated the spectral part of the optical power corresponding to the signal peak. The ASE at 1 μm was excluded. The pulse energy at 10 MHz was 9 μJ and the peak power was 170 kW. Our experimental results confirm the ability of tapered amplifiers to generate pulses with high peak power and narrow linewidth.

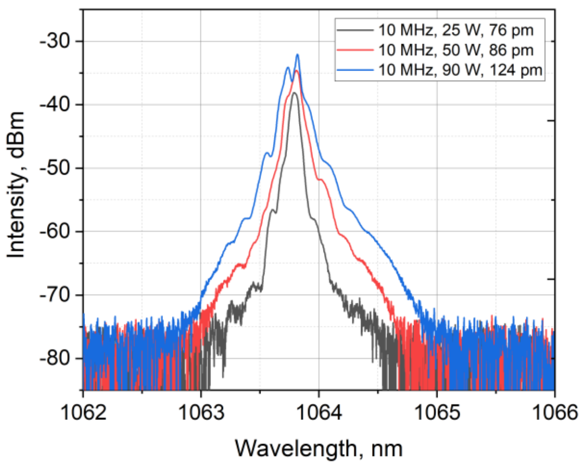

Fig. 3. The spectra of 1064 nm signal at 10 MHz repetition rates at the different output average powers.

4. Second harmonic generation

The results of experiments on the second harmonic generation are shown in Fig. 4. Fig. 4a shows the dependence of the average power of green-band radiation on the average pumping power of a high-power fiber operated at 1064 nm. As can be seen, the maximum output power of the green radiation of 32 W was achieved at the pulse repetition frequency of 10 MHz and the average IR pumping power of 83 W, thus resulting in the SHG efficiency of 38 % (Fig. 4b). The further increaser of output power over 83 W resulted in spectral line broadening over 100 pm. Therefore, despite the system capability to deliver output power up to 150 W at 10 MHz, we limited the system performance in terms of SHG at the IR linewidth value below 100 pm.

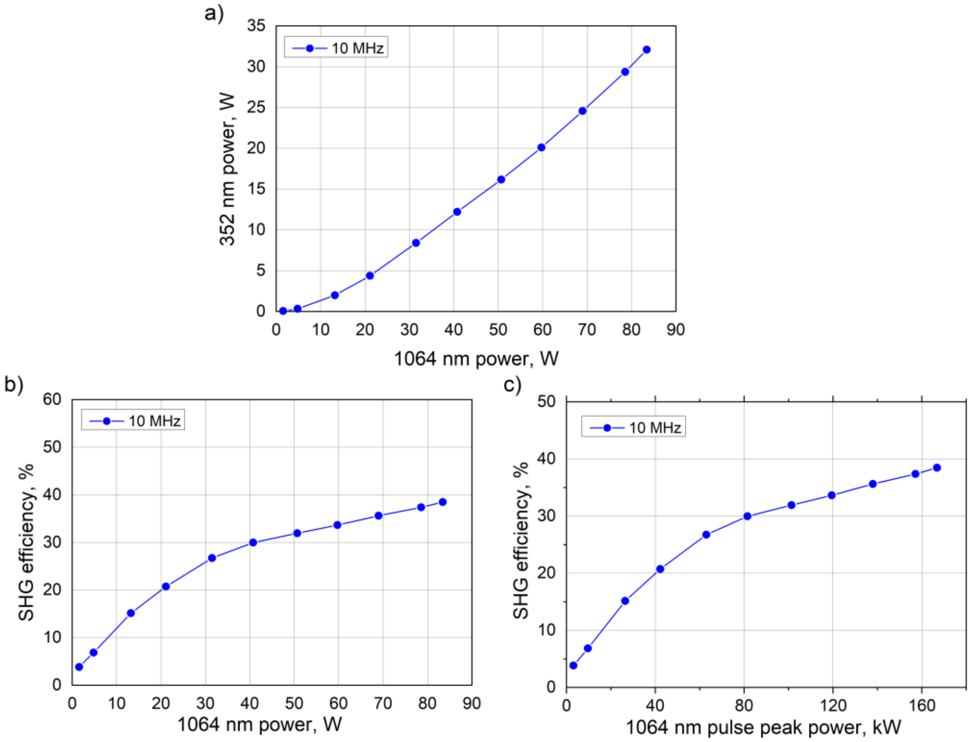

Fig. 4. The dependence of the output power at 532 nm (a) and efficiency of SHG (b) on the power of 1064 nm signal at 10 MHz repetition rates, (c) on the pulse peak power of 1064 nm signal at 10 MHz repetition rates.

Figure 5 shows the spectrum of SHG at 532 nm. The spectrum was measured using a Bristol 771 series spectrum analyzer with spectral resolution of 4 GHz in the visible range. Due to coarse resolution of the spectrum analyzer, we could not estimate the spectrum linewidth in the green spectral range. We believe that in our particular case it should not be more than 100 pm (the bandwidth of the IR signal).

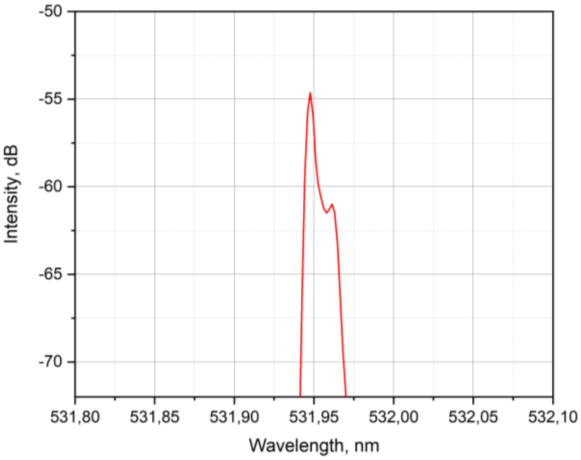

Fig. 5. The spectrum of SHG at 532 nm.

5. Conclusion

In this paper, we have demonstrated a compact, powerful narrow linewidth laser system based on a gain-switched DFB laser diode and innovative tapered fiber amplifier. The embedded mechanism of the effective self-phase modulation suppression in a tapered fiber allowed to maintain ultra-narrow linewidth up to megawatt level of the peak power. The system is capable of delivering up to 150 W average power at 10 MHz repetition rate with moderate linewidth broadening from 76 pm to 142 pm. We also demonstrated the possibility of using a 50-ps pulsed laser source to generate the second harmonic with the high conversion efficiency of up to 38%. We obtained up to 32 W of the green radiation at a wavelength of 532 nm. The MOPA system based on a gain-switched DFB laser diode seed source and a T-DCF amplifier demonstrated superior performance in simplified scheme with reduced number of pre-amplifiers stages becoming an attractive cost-efficient solution for material processing, second harmonic generation and sensing application including time-resolved Raman spectroscopy. The further peak power and pulse energy scaling is possible by decreasing the repetition rate of the gain-switched DFB laser seed.

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