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Widely Tunable Pulse Duration 100 mJ Single-Mode MOPA System Based on Yb-Doped Tapered Double-Clad Fiber and Nd:YAG Solid-State Amplifiers

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Abstract: We report on a 1064 nm master oscillator power amplifier (MOPA) system based on pulse-modulated laser diode seed sources combined with fiber preamplifiers and a Yb-doped tapered double-clad fiber (T-DCF) amplifier used as an all-fiber master oscillator and a two-stage side-pumped solid-state power amplifier. The combination of two master oscillators and a single power amplifier allowed us to obtain pulses with a duration ranging from 10 ns to 10 µs with energy up to 137 mJ at 100 Hz. For the first time, we demonstrate a widely tunable pulse duration and a solid-state MOPA system with over 100 mJ energy based on a T-DCF fiber seed laser.

Keywords: MOPA; tapered double-clad fiber; Nd:YAG; variable pulse width

1. Introduction

Tunable pulse duration lasers based on master oscillator power amplifier (MOPA) configuration with fiber seed sources are emerging as alternatives to traditional Q-switched lasers for developing advanced laser processes in various application fields. The ability to precisely control pulse characteristics (such as rise time, width, shape, and repetition rate) over a wide range enables the expansion of applications using a single laser source with a broader spectrum of process parameters for material processing, characterization, and testing.

Several laser designs with variable pulse widths have been developed for a range of applications in physics, including studies on flow and combustion, laser ignition, laser machining, medical procedures, and the conservation of historical artifacts. In [1], a variable-pulse oscillator is formulated and combined with a burst-mode amplifier to produce high-energy laser pulses with durations spanning from 100 ps to 1 ms, featuring near-Gaussian temporal pulse shapes. The study demonstrates pulse energy reaching up to 600 mJ at 1064 nm, exhibiting a Gaussian spatial profile and excellent beam quality within this pulse duration range, utilizing various amplification configurations.

The range of pulse durations can be extended by using multiple pulse generation technologies in one system. In [2], the generation of pulses is contingent upon the targeted laser performance, with options including the direct modulation of the drive current of a seed laser diode or the modulation of the output from a seed laser diode functioning in continuous wave (CW) mode through electro-optic modulators. Subsequently, these modulated pulses undergo amplification in a chain of amplifiers within a MOPA configuration.

In their work [3], Maximilian Beyer and colleagues successfully demonstrated the efficient amplification of the output from a narrow-bandwidth seed laser through a two-stage diode-pumped Nd:YAG amplification configuration. The system achieved notable results, producing an output of 2.6 kW and 520 mJ at 1064 nm, as well as 1.3 kW and 262 mJ

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at 532 nm, all with a pulse duration of 200 μs. This setup holds promise as a potential pump source for Ti:sapphire, dye, or optical parametric amplifiers, enabling the generation of tunable high-power single-frequency radiation suitable for precision measurements and laser slowing, as discussed in [4].

Zhou Yiping et al. successfully demonstrated a sub-nanosecond master oscillator power amplifier (MOPA) laser system operating at 1.06 μm with high pulse energy, as detailed in [5]. The master oscillator employed an electro-optical Q-switched laser with a pulse duration of ~730 ps. Through the utilization of an end-pumped preamplifier and two-stage side-pumped amplifiers, laser pulses were generated with a pulse energy reaching 47.1 mJ at a repetition rate of 500 Hz, resulting in a peak power of around 64.5 MW.

In the work by Wu Wentao et al. [6], a sub-nanosecond burst-mode MOPA Nd:YAG laser system operating at 1.06 μm was presented. This system comprises a cavity-dumped Q-switched master oscillator and a double-pass side-pumped amplification setup. During the 1 kHz burst-mode operation, the output exhibited a single pulse energy of 29.8 mJ within a burst duration of 100 ms. The pulse width was measured at 900 ps, resulting in a peak power of 33.1 MW. Furthermore, under 10 Hz operation, the single pulse energy reached 81 mJ with a pulse width of 900 ps, corresponding to a peak power of 90 MW.

In [7], Liu Lei et al. demonstrated a sub-nanosecond MOPA system with a pulse repetition frequency of 1 kHz at 1.06 μm. The system is based on an integrated seed source with a pulse energy of 6.2 mJ and two conductively cooled, end-pumped Nd:YAG slab gain modules. After a four-pass amplification stage and a double-pass amplification stage, a maximum pulse energy of 434 mJ with a pulse duration of 691 ps was obtained, corresponding to a peak power of 628 MW.

In [8], N. Coppendale et al. detail a high-energy laser system with frequency-chirped characteristics specifically designed for the optical Stark deceleration of cold molecules [9]. This system generates two pulse-amplified beams, each capable of reaching up to 700 mJ, featuring flat-top temporal profiles with controlled frequency and intensity across durations spanning from 20 ns to 10 μs. The dual beams originate from the amplification of a single, rapidly tunable Nd:YVO4 microchip-type laser operating at 1064 nm, with the ability to achieve frequency chirping of up to 1 GHz throughout the pulse duration.

Such laser systems have been proposed for precise cleaning in a variety of restoration problems and materials [10]. The system's capability to adjust the pulse duration within a range from tens to hundreds of nanoseconds up to several microseconds proves advantageous. This tunability in pulse duration helps mitigate the risk of strong mechanical forces and excessive substrate heating, a common issue observed with conventional Nd:YAG laser systems.

Our MOPA system was developed as a laser source for testing semiconductor devices. For such systems, it is crucial to have a widely tunable duration of laser pulses, along with sufficiently high pulse energy that can be tuned across a wide range, and beam quality close to the diffraction limit. To achieve these goals, a laser source with a variable pulse repetition rate, pulse duration range from 10 ns to 10 μs, a pulse energy of over 100 mJ, and a beam quality with an M2 factor below 1.3 was required.

In this work, we achieved the three-orders-of-magnitude tuning range of pulse duration, along with over 100 mJ pulse energy by using high-pulse-energy all-fiber seed source featuring Yb-doped double-clad tapered fibers to deliver the highest possible seed energy and just a two-stage solid-state amplifier while maintaining beam quality close to the diffraction limit. The simplicity of the solid-state amplifier is achieved thanks to the design of the fiber seed based on the double-clad tapered fiber which allows to push the threshold of stimulated Brillouin scattering and extract the energy in the range of 100 to 450 μJ from the all-fiber seed for the above-mentioned pulse duration range while maintaining beam quality close to the diffraction limit with an M2 parameter below 1.3.

2. Experimental Setup

The experimental setup is shown in Figure 1. The fiber-based master oscillators consist of distributed feedback (DFB) laser diodes, fiber preamplifiers, and a fiber amplifier based on an ytterbium-doped tapered double-clad fiber (T-DCF). Optical pulses with a duration of 10–100 ns were generated through the modulation of a DFB laser diode, while pulses with a duration of 1–10 microseconds were formed by modulation of a CW mode a DFB laser diode output using an acousto-optic modulator (AOM). This approach was chosen for generating longer pulses to facilitate exponential pre-shaping, which helps prevent mainly the amplification of the pulse's leading edge. Pre-shaping minimizes pulse distortion caused by gain depletion effects during the amplification of longer pulses, thus effectively reducing pulse narrowing. Furthermore, utilizing laser diodes as seed sources enables fine-tuning of the emission wavelength to match the amplification peak of the Nd:YAG amplifiers.

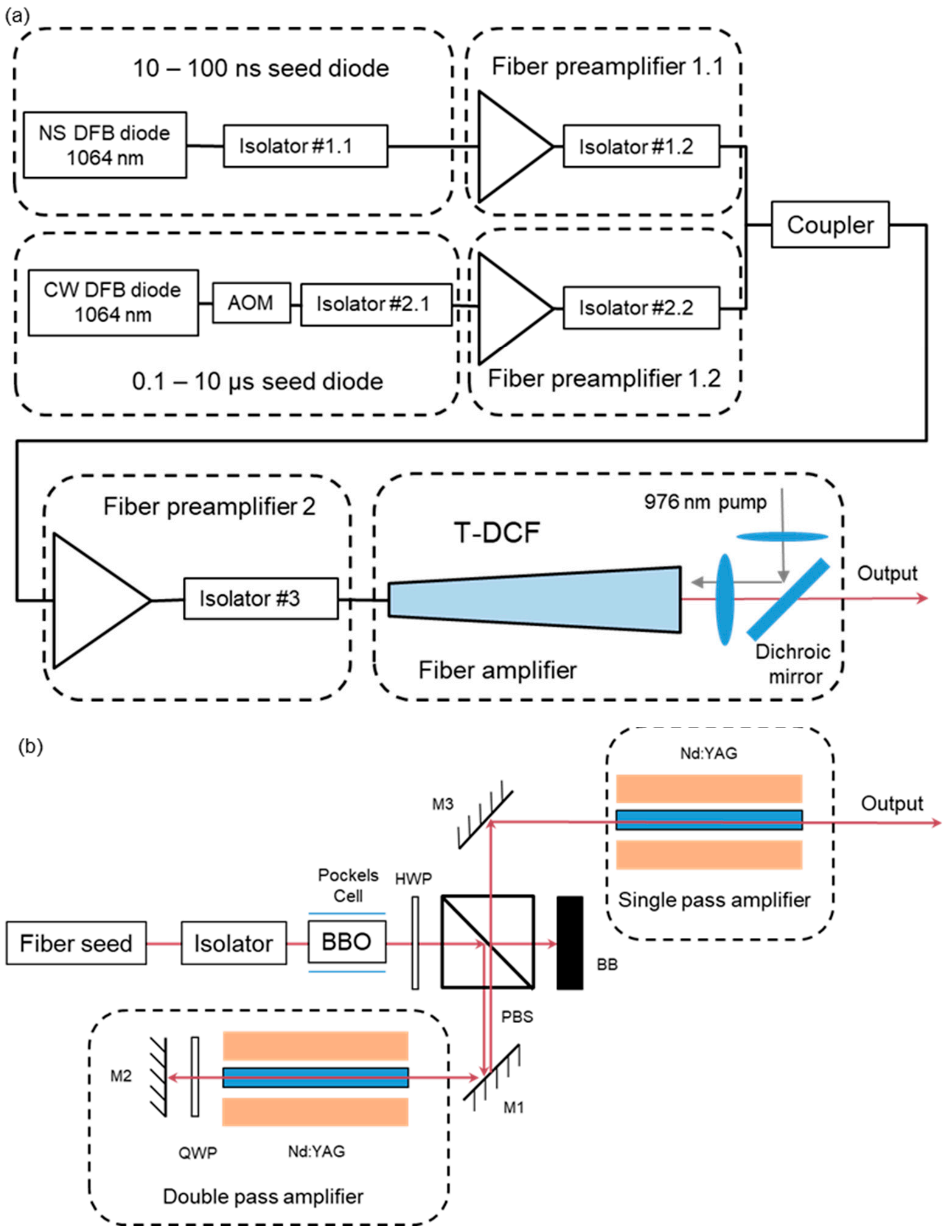

Figure 1. Experimental setup for hybrid laser system. (**a**) Fiber seed laser; (**b**) Nd:YAG rods amplifier. AOM: acousto-optic modulator; T-DCF: tapered double-clad fiber; HWP: λ/2 wave plate; QWP: λ/4 wave plate; PBS: polarization beam splitter; BB: beam blocker.

The pulse repetition rate for both seed sources was set at 10 kHz. The outputs from each seed source were amplified by single-stage single-mode ytterbium-doped fiber amplifiers (YDFA) 1.1 and 1.2 (Figure 1a) pumped at 976 nm. The dual-seed diode configuration allowed optimization of the first fiber amplification stages for their respective pulse duration ranges. At the input of the second preamplifier, the pulse energy was approximately 1 μJ for the entire pulse duration range.

The optical outputs from preamplifiers 1.1 and 1.2 were combined using a 50/50 coupler. An additional single-mode Yb-doped fiber preamplifier, pumped at 976 nm, was used to amplify the signal after the combined output to a level sufficient for efficient amplification in the tapered double-clad amplifier, typically in the range of 10–20 mW but below the threshold of nonlinear effects. When optimizing fiber amplifiers, particular attention was given to the spectral width, which had to remain less than 100 pm for effective amplification in solid-state amplifiers. After each preamplifier stage, we implemented a Cladding Mode Stripper (CMS) and utilized a 2 nm bandpass filter to effectively filter the amplified spontaneous emission (ASE).

The amplified signal from fiber preamplifier 2 was launched to the T-DCF amplifier. Calculations demonstrated that to achieve the target pulse output energy of over 100 mJ, optical pulses at the input of the solid-state amplifier needed to have an energy exceeding 0.1 mJ. This level of energy is challenging to obtain in ordinary single-mode fiber amplifiers for pulses with a spectrum width below the bandwidth of stimulated Brillouin scattering (SBS). SBS imposes significant limitations on peak power and corresponding pulse energy when amplifying narrowband signals. Due to DFB LDs with a spectrum width below 2 MHz being used as seed sources in our setup, the spectrum width at the target pulse duration range of 10 ns to 10 us is close to the CW value of 2 MHz. To overcome the limitations imposed by SBS, we employed tapered double-clad fibers as the high-power fiber amplifier. It was demonstrated in [11] that using T-DCF amplifiers allows us to push the SBS threshold to a high peak power level while maintaining beam quality close to the diffraction limit. The T-DCF amplifier employed in this work was specifically configured to function in a counter-propagating pumping scheme, as illustrated in Figure 1a. The beam from the 976 nm multimode pump source was collimated, passed through the dichroic filter, and then focused onto the T-DCF end face by the second lens. The dichroic filter allowed transparency for the amplified signal at 1064 nm. Further in-depth information about this amplifier can be found in our previous publication [12].

The output of the fiber seed laser was followed by a Faraday optical isolator to prevent parasitic oscillation and back reflection from the amplifier, ensuring a polarization extinction ratio (PER) of the transmitted radiation at the level of 30 dB. A Pockels cell, based on a BBO crystal, a half-wave plate (HWP), and a polarization beam splitter (PBS) were used as a pulse picker to reduce pulse frequency to 100 Hz, which conforms to the maximum operating frequency of the pump LD bar stack. The idler pulses passing through the PBS were absorbed by the beam blocker (BB), while the selected pulses, due to the polarization rotation in the Pockels cell, were reflected from the PBS and sent to the amplification stages.

In both amplification stages, two identical side-pumped amplifiers were employed, each consisting of a 1.1 at% Nd:YAG rod with a 3 mm diameter and a length of 60 mm. To further suppress parasitic oscillation and ASE, both facets of the laser rods were wedged by 3°. A highly reflecting mirror at 1064 nm (M2) implemented the double-pass amplification in the first active element, while the quarter-wave plate (QWP) provided the transmittance of radiation through the PBS to the second active element. Highly reflecting mirrors (M1 and M3) at 1064 nm were used for the precise alignment of radiation into the active elements.

The laser rods were water-cooled to the central wavelength of 808 nm for the LD, and they operated in the pulse-pumped mode. The peak power of each pump LD bar stack was 1200 W with a pulse width of 250 μs. The total peak pump power of each amplifier was 3600 W. To achieve high pump efficiency and uniform gain distribution, the LD bars were positioned around the Nd:YAG rod in a three-fold symmetric configuration.

The pump pulses of the laser rods were synchronized with the opening of the Pockels cell with adjustable delay between the leading edge of the pump pulse and the position of the signal pulse.

3. Results and Discussion

The pulse energy values for each pulse duration after each amplification stage are presented in Table 1.

Table 1. Pulse energies (PE) and peak power (PP) at different amplifier stages.

Stage		10 ns	100 ns	1 μs	10 μs
Seed PE, nJ		1.2	40	324	521
Fiber preamplifier 1 PE, μJ		0.32	0.33	1.14	2.18
Fiber preamplifier 2 PE, μJ		6.4	3.5	10.3	15.3
Fiber amplifier	PE, mJ	0.19	0.1	0.3	0.45
	PP, kW	19	1	0.3	0.045
Main amplifier	PE, mJ	114	104	132	137
	PP, kW	11,400	1040	132	13.7

The maximum pulse energy from the high-power fiber amplifier was determined based on the onset of stimulated Brillouin scattering, which is characterized by pulse instability and rapid increase in the back-reflected signal. The pulse energy from preamplifier 2 was chosen to be both low enough to avoid SBS in the narrow part of the T-DCF and sufficiently large to ensure efficient amplification in the T-DCF amplifier. It can be observed that the T-DCF amplifier allows for a significant increase in pulse energy, from a few microjoules to at least 100 μJ for 100 ns pulses. These results are consistent with the data published in [11]. The somewhat lower pulse energy achieved in our experiments compared to [11] is because the T-DCF used in the current work had smaller core diameters in the narrow (9 μm) and wide (40 μm) sides of T-DCF. The decrease in the threshold pulse peak power with an increase in pulse duration is because the spectrum width for very long pulses approaches that of continuous wave (CW) radiation, and the SBS threshold becomes close to that of the 2 MHz bandwidth signal in a single-mode fiber. Nevertheless, the pulse energy obtained at the output of the T-DCF amplifier is sufficient to reach the desired value in excess of 100 mJ from the solid-state amplifier described above for the entire range of pulse durations.

The maximum energy of pulses with a duration of 1 and 10 μs is almost the same, while for pulses with a duration of 10 and 100 ns, it differs. We attribute this to the fact that different shapes of the driving pulse were used to compensate the gain drop at the trailing edge of the pulse. Figure 2 shows the pulse shape from the seed source before the preamplifiers and the pulse shapes of the outgoing pulses.

Since the laser source is designed for testing semiconductor devices, the equivalent pulse duration was calculated from the output pulse based on its approximation by a rectangular pulse, the peak power and energy of which are equal to the peak power and energy of the real pulse. This procedure allows the use of relatively simple models for calculating radiation effects on semiconductor devices. To achieve a nearly Gaussian bell-like pulse shape and the required equivalent pulse duration, substantial pre-shaping of the seed laser pulses was necessary, especially for long pulses. Thus, exponential growth pulses were used for pulse durations of 1 and 10 microseconds, while linear and rectangular pulse shapes were used for pulse durations of 100 ns and 10 ns, respectively. The dual LD seed source allows us to control pulse shapes and achieve nearly identical pulse shapes for the entire range of the pulse durations, and the presence of the chip is taken into account in the model for calculating radiation effects on semiconductor devices.

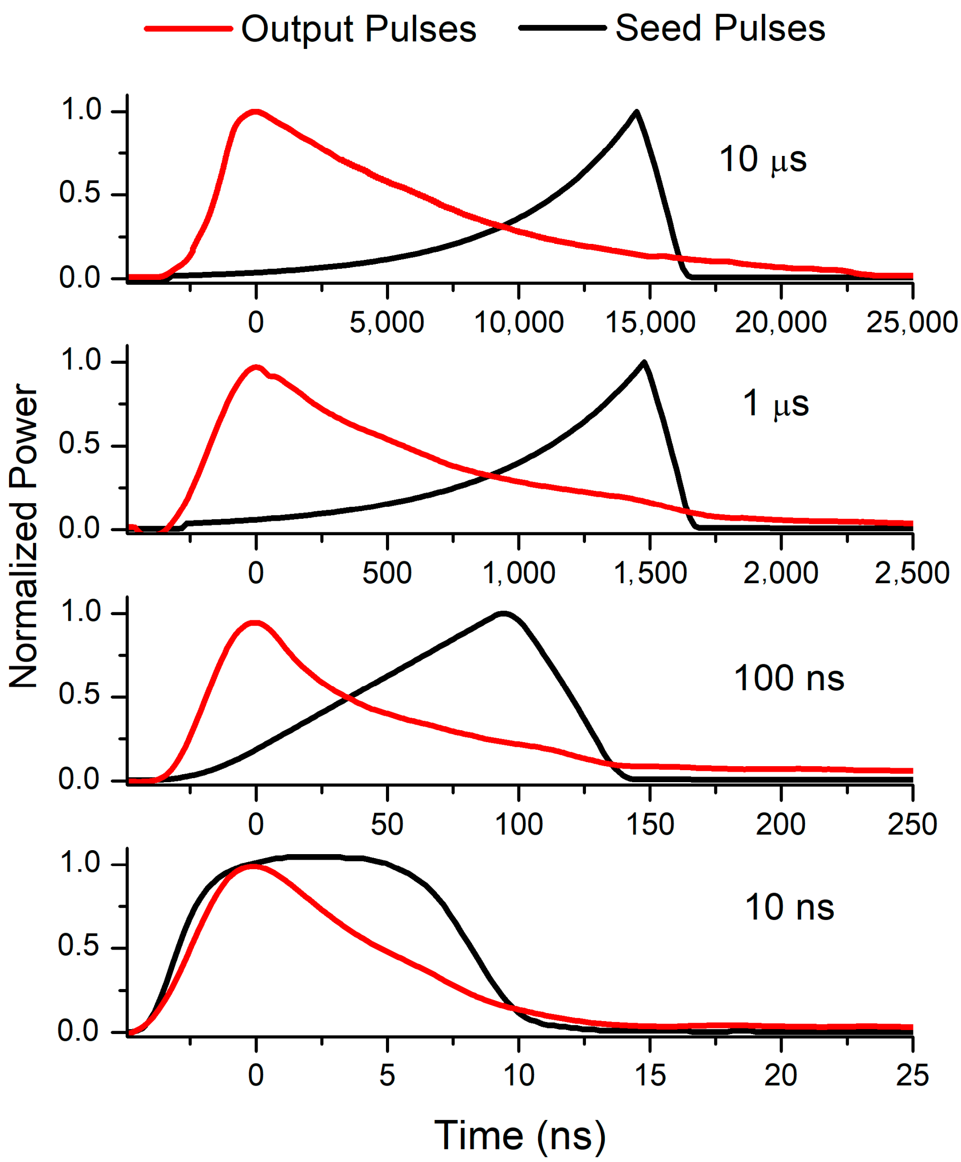

Figure 2. Seed pulses versus output pulses.

The laser source stability was tested at various frequencies from a single pulse to 100 Hz. In the entire frequency range and at all pulses durations, the deviations in pulse energy did not exceed 5%. This result was achieved due to the fact that the fiber seed always operated at a frequency of 10 kHz, which ensured the formation of stable pulses. The synchronization control board provided the fast and time-accurate opening of the Pockels cell and ensured the input of the signal pulse into the main amplifier at exactly the specified time from the start of pumping with a deviation of no more than 5 ns over the entire frequency range. This, together with the choice of the pulse shape, made it possible to achieve the required pulse stability.

Beam quality measurements were conducted using a Thorlabs M2 Measurement System [13]; the measurement results are presented in Table 2. The calculation of the M2 parameter was carried out by the built-in device software; the output beam has an M^2 value of 1.2 with a diameter of 3 mm at the $1/e^2$ intensity level, a Gaussian profile, and a residual divergence of 1 mrad. The profile of the resulting beam is shown in Figure 3.

Table 2. M^2 measurement results.

Parameter	Unit	Result
M^2 X′		1.20
M^2 Y′		1.19
M^2 mean		1.20
Beam Waist Position X′	mm	131.30
Beam Waist Position Y′	mm	131.22
Beam Waist Diameter X′	µm	95.40
Beam Waist Diameter Y′	µm	89.20
Rayleigh Length X′	mm	5.58
Rayleigh Length Y′	mm	4.98
Divergence Angle X′	deg	0.98
Divergence Angle Y′	deg	1.04
Divergence asymmetry	%	1.06

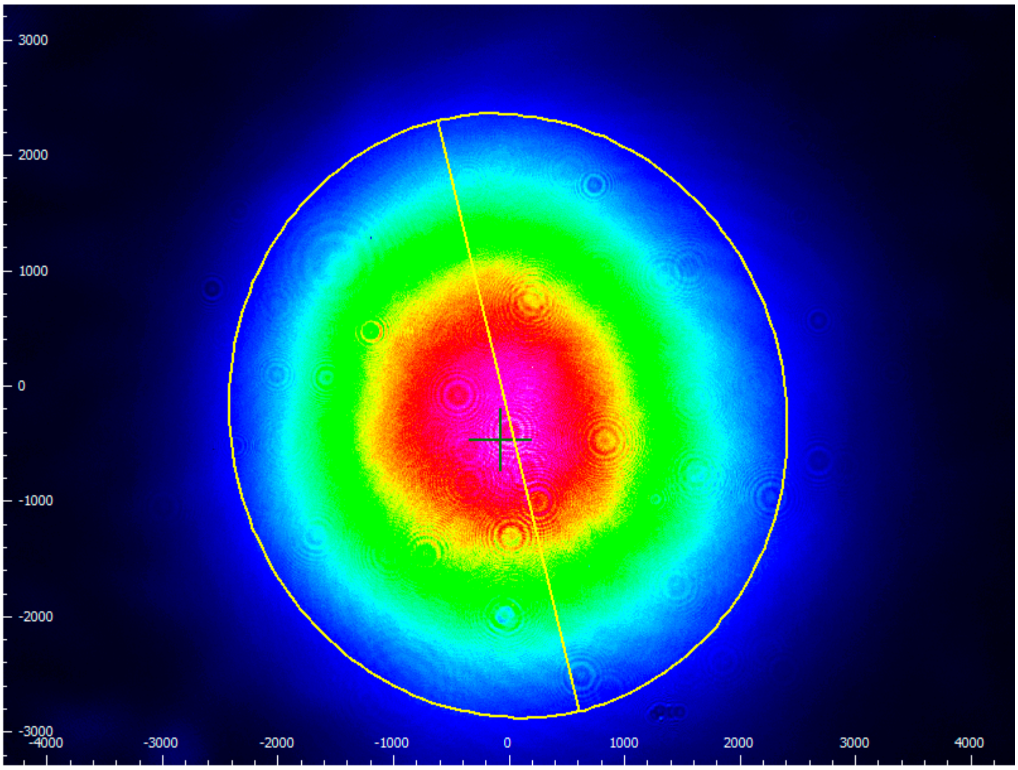

Figure 3. Resulting beam: near-field intensity profile.

The MOPA system was designed as a laser source intended for the testing of semiconductor devices. Within this testing framework, the emitted radiation from the source was configured to form a beam characterized by a uniform distribution of intensity across a 20 mm diameter area. To control the output power, a series of fixed reflective filters were employed, incrementally reducing the power in 10 dB steps. Following this power adjustment, the precise value of the pulse energy was fine-tuned using a polarization filter. Subsequently, the laser pulses were directed towards the sample situated within the receiving chamber, accompanied by the necessary recording equipment for analysis.

4. Conclusions

In summary, we have demonstrated a widely tunable pulse duration of 0.01–10 µs, with high pulse energy of 137 mJ, and a 1064 nm MOPA laser system for a pulse repetition rate of 0–100 Hz with excellent beam quality (M2 = 1.2). The system utilizes both continuous wave (CW) and nanosecond (NS) laser diodes as seed sources, which are followed by fiber amplifiers and two side-pumped laser rods. Pulse pre-shaping is achieved through direct modulation of the NS laser diode and AOM modulation of the CW laser diode. The key feature of the developed laser system is the high-energy T-DCF-based fiber amplifier, which allows us to boost the pulse energy up to the level sufficient to reach 100 mJ by the two-stage Nd:YAG solid-state amplifier across the entire pulse duration range. The MOPA system was developed as a laser source for testing semiconductor devices.

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