# Polarisation maintaining 100W Yb-fiber MOPA producing μJ pulses tunable in duration from 1 to 21 ps


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**Abstract:** This paper demonstrates a single polarisation, 1.06 µm Yb-doped fiber MOPA, delivering 21 ps pulses in a diffraction limited beam at repetition rates of up to 908 MHz and average output power of 100 W. The maximum pulse energy was 1.7 µJ at a repetition rate of 56 MHz, with corresponding peak power of 85 kW. The 100 W power was limited by available diode pump power and scaling to higher power levels is discussed. We also report self-phase-modulation based pulse compression which produced pulse durations as short as 1.1 ps from an external grating compressor. Using 4.2 ps pulses at a repetition rate of 227 MHz enabled 26 W of visible laser power (50% SHG efficiency) to be demonstrated.





**OCIS codes:** (060.2320) Fiber optics amplifiers and oscillators; (060.4370) Nonlinear optics, fibers; (140.2020) Diode lasers; (250.4480) Optical amplifiers.


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## 1. Introduction

High average power laser sources operating in the picosecond regime are useful for a wide range of applications including industrial materials processing, frequency-doubling and broadband wavelength tuning using OPOs. Over recent years, fiber amplifiers have become a key enabling technology in many of these areas. In particular, Ytterbium-doped fiber amplifiers (YDFA) have high single-pass gain, low quantum defect and optical-to-optical efficiencies above 80%. The resulting low thermal load and inherently favorable geometry minimize thermal effects to enable continuous-wave powers of 6 kW in a diffraction-limited beam [1].

However, in picosecond- pulsed fiber master-oscillator-power-amplifier (MOPA) systems operated at repetition rates below ~100 MHz, nonlinear effects such as self-phase-modulation (SPM) and stimulated Raman scattering (SRS) arising in the core of the fiber have restricted the average powers obtained. Since the high peak power is the key factor, nonlinearity management techniques such as chirping the input pulses and using microstructured fiber to achieve extremely large mode areas are commonly applied in femtosecond systems [2,3]. The disadvantages of such techniques are that the dispersion management components increase the complexity of the system, and that the novel fiber architectures have not yet been thoroughly field tested [4,5].

A consideration for industrial applications such as micromachining is that many materials have larger absorbance in the green compared to the near IR. Using green laser sources also enables a smaller spot size to be used than is achievable using near-IR wavelengths. Hence it is advantageous if the Yb-laser output at ~1.06 μm can be frequency doubled which requires that the output has good polarization purity and narrow linewidth (without excessive nonlinear spectral broadening).

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An attractive route to achieving high average powers with short pulse sources without problematic nonlinear effects is to reduce the energy per pulse by dramatically increasing the repetition rate. There has been progress with fiber oscillators, VECSEL sources [6–8] and gain-switched laser diodes for generating high repetition rate picosecond pulses. Output powers in excess of 300 W have previously been demonstrated from a YDFA system using a 1060 nm gain-switched Fabry–Pérot (FP) laser diode delivering 20 ps pulses at GHz repetition rates as a seed laser [9–11]. However, the sub-microJoule pulse energies from those systems were far from ideal for materials processing and free space pump and signal coupling greatly compromised the practicality of the systems. Moreover, the output was not robustly single-transverse-mode and the amplifiers were not all polarization-maintaining (PM), thus limiting the environmental stability and the utility of the system for many frequency conversion applications.

Here we report the use of a gain-switched (GS) diode seed in a fiberised, PM-YDFA MOPA system generating linearly polarized, diffraction-limited, 21 ps pulses at user selected repetition rates ranging from 56 MHz to 908 MHz and at an average output power of 100 W. At the lowest repetition rate of 56 MHz the 21 ps pulses from our system have a maximum energy of 1.7 µJ, and peak power of 85 kW which meets the requirements of a variety of materials processing applications. This system represents a considerable improvement in practicality and performance relative to previous high power, fiber-based picosecond pulse sources [12]. The GS diode used self-seeding with a 1060 nm fiber-Bragg-grating instead of seeding with an external laser in order to ensure stable operation. The polarization stability is maintained with PM fiber amplifiers and a tapered splice to the final stage large-mode-area fiber ensures the stability of the mode quality. Using a large core final stage fiber and 975 nm pumping to minimize the absorption length enabled these high-energy pulses to be generated without excessive nonlinear broadening due to Self Phase Modulation (SPM). The system has proven to be very reliable in our laboratory and we have recently used the system to pump an OPO [13] and for frequency doubling of the output with a Lithium Triborate (LBO) crystal which provided >56% SHG efficiency to create a 56 W visible source of 20 ps pulses [14].

The slight spectral broadening at the highest pulse energies has enabled the pulses to be compressed to as short as 1.1 ps using a grating pair. The flexibility of having a tunable pulse duration is also compatible with SHG and we used 4.2 ps pulses at a repetition rate of 227 MHz and average (compressed) output power of 52 W to demonstrate 26 W of visible laser power (50% SHG efficiency).

This paper is structured as follows. In section 2, the experimental setup of the seed diode and fiber-amplifier chain is described. Section 3 reports the results obtained and suggestions for power scaling. Section 4 describes compression of the pulses using a grating pair and the use of the compressed pulses for SHG conversion. The conclusion is in Section 5.

## 2. Experimental setup

The experimental setup is shown in Fig. 1. The seed was a 1060 nm Fabry-Perot (FP) laser diode in a fiber-pigtailed package that was gain-switched using a pulsed drive current with an associated DC bias. We combined the two techniques of first stabilizing the pulse-to-pulse operation by self seeding with the reflection from a fiber-Bragg-grating (FBG) that we previously reported in refs [15,16]. and using a chirped fiber Bragg grating (CFBG) to remove the inherent chirp of the GS diode output pulses (see [17]) as we reported previously in ref [18]. The gratings were fabricated in house and were matched in wavelength by strain-tuning by compression of the grating [19,20]. The resulting GS diode amplitude jitter was ~2% and the timing jitter was ~3 ps (dominated by jitter from the drive electronics) [16].

A fiber pigtailed EOM was used as a pulse picker to reduce the repetition rate and it was driven by a slave pulse generator triggered from the driver operating the seed diode. This allowed us to optimize the seed in terms of side-mode-suppression-ratio and chirp, while maintaining repetition rate flexibility, and we have found this easier to operate in terms of maintaining optimum pulse quality compared with changing the diode modulation frequency directly as we had reported earlier [21].

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The amplifiers were configured in a three-stage YDFA MOPA chain. Fiberised optical isolators were used to prevent ASE leakage between the amplifier stages. The first stage was a 3 m long core pumped YDFA using single mode (5 µm core, 130 µm cladding, NA = 0.13) PM Yb-fiber and was bi-directionally pumped using 160 mW, 975 nm telecommunications-grade diodes. The second stage YDFA was a 7 m long cladding pumped single mode (5 µm core, NA = 0.13; 130 µm inner cladding, NA = 0.46) PM Yb-fiber with 10 W, 975 nm pumps coupled into the inner cladding using a fiberised combiner in a backward pumping configuration. The 1060 nm wavelength was chosen in order to optimise the performance of the cladding-pumped power amplifier, but this required careful choice of the preamplifier fiber lengths in order to balance the conflicting requirements of nonlinearity management and short-wavelength ASE suppression. The pigtail fiber of the final isolator was kept as short as possible to minimize SPM.

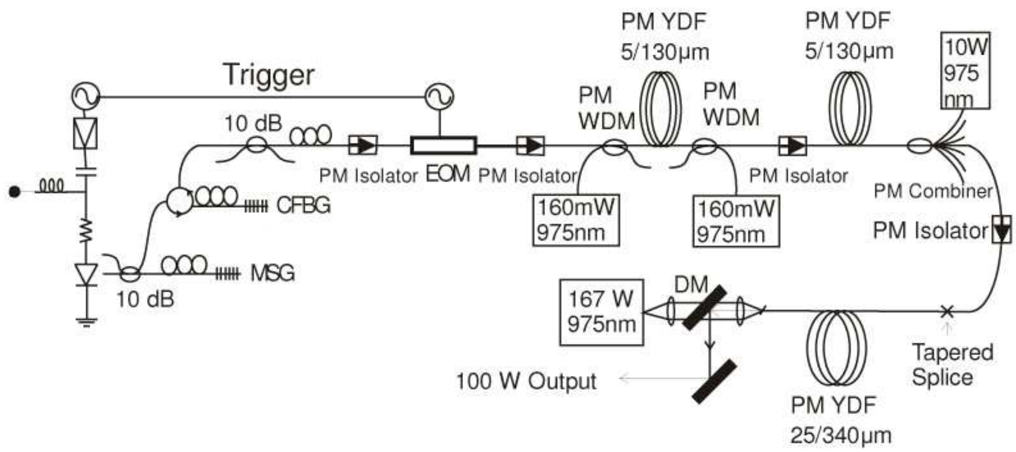


Fig. 1. Schematic diagram of the Yb-doped fiber MOPA. MSG – mode selective grating; CFBG – chirped fiber-Bragg-grating.

The power amplifier was a 5.7 m long, polarization maintaining (PM) fiber with an inner-cladding diameter of 340 µm with an NA of 0.45 and a core diameter of 25 µm with an NA of 0.055 (Nufern). The V-number of the core was 4.07 meaning that in theory it supported approximately 7 modes. The fiber was tapered down to have a 125 µm outer diameter and a corresponding core diameter of 9.2 µm. The associated V-number was therefore reduced to 1.5 so that only the fundamental mode would be supported. The tapered fiber was spliced to a 15 cm length of passive PM 980 fiber (Corning) then the uncoated tapered region and the splice were protected with a high-index UV-cured coating that was also used to glue the taper to an aluminium plate which served to dissipate heat generated from unabsorbed pump light from the amplifier. The splice loss from the taper to the PM980 fiber was measured to be less than 1 dB. The length of the tapered region was optimised by repeated testing of the output mode quality with different taper lengths. We finally selected a taper length of 80 mm, which was found to be the minimum length that led to robust single-mode output from the amplifier fiber. The $M^2$ was measured to be ~1.02 when the amplifier fiber operated at the maximum 100 W output power. This fiberised approach greatly improves the mode stability compared to a free space launch where coupling variations lead to variation in the output beam quality. To prevent damage to the output, a 2 mm long pure silica mode-expanding end-cap was spliced to the fiber and it was angle polished to avoid backward-reflected power from coupling into the fiber core. The amplifier was end-pumped using a commercially available 975 nm diode stack with a maximum pump power of 167 W. The diodes were water-cooled to ensure wavelength stability. A simple lens combination was used to achieve ~83% coupling efficiency into the fiber. The signal and pump paths were split by dichroic mirrors. Since the fiber had an absorption at 975 nm of ~2.7 dB/m, there was only a low level (~5 W maximum) of unabsorbed pump at the tapered splice.

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## 3. Results

The seed-diode pulses were characterised after the CFBG and circulator using a linear FROG technique. (The FROG setup is described in ref [18].) The gate width of the EOM-based FROG was ~200 ps, and complete pulse information can be retrieved for pulses which are more than an order of magnitude shorter than this gating time. The pulses measured after the CFBG compressor and circulator had a duration of ~21 ps with an average power of 1.3 mW at a repetition rate of 908 MHz. The pulse temporal profile and chirp are shown in Fig. 2(a) and the spectrum is shown in Fig. 2(b). The spectral bandwidth of the pulses is 0.15 nm and the corresponding time bandwidth product is 0.8.

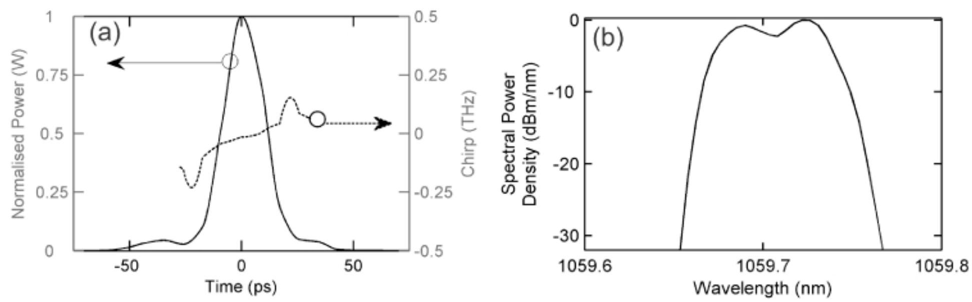


Fig. 2. (a) Seed pulse temporal profile and chirp; and (b) Spectrum of the seed pulse. The temporal and spectral data have been normalized with respect to the peak power or peak spectral density respectively.

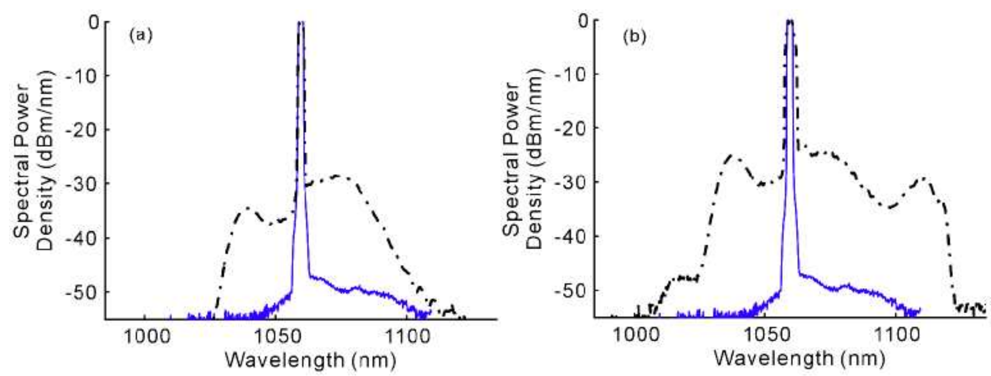


Fig. 3. Spectra of seed-diode (blue solid line) and final 100 W output (black dash line). (a) Pulse repetition rate 227 MHz; and (b) Pulse repetition rate 56 MHz. The spectra were measured with an ANDO (AQ6317B) spectrum analyser using 2.0 nm resolution.

When characterizing the system, the average power was fixed at 200 mW at the output of the pre-amplifiers, and at 100 W at the output of the final amplifier. Due to the pulse energy and peak-power requirements of our intended applications, we operated the system at repetition rates of 227 MHz and 56 MHz. As shown in Fig. 3, a reasonable output OSNR was maintained as the repetition rate was reduced – the signal was 30 dB (227 MHz) or 25 dB (56 MHz) above the ASE level. Numerical integration indicated that the corresponding signal was 98% or 96% of the total power at 227 MHz and 56 MHz respectively. Therefore the maximum extracted pulse energy was 1.71 μJ at a repetition rate of 56 MHz with a corresponding peak power of 85 kW at an average output power of 100 W. Figure 3 shows the onset of SRS approximately 30 dB below the signal for the 56 MHz results at a wavelength of ~1115 nm. The SRS peak power threshold of the final amplifier, calculated assuming 27 dB gain and constant gain per unit length, was ~89 kW, which is similar to the experimentally measured power [22,23].

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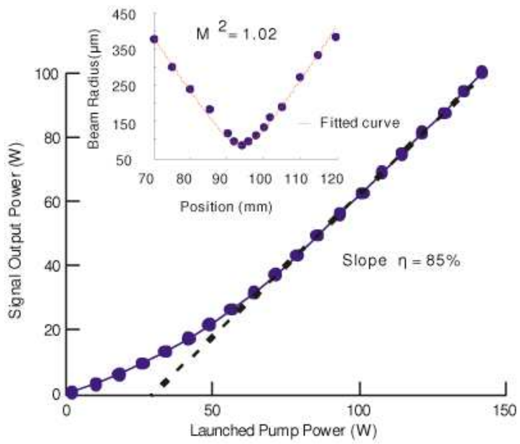


Fig. 4. Output power from the final stage amplifier vs. launched pump power. Inset: Mode quality measurement data. (Beam radius vs. distance from a f = 100 mm focal length lens.)

Figure 4 shows the performance of the final amplifier. The slope efficiency was 85% with respect to launched pump power and the amplifier shows no power roll-off at the 100 W level. The beam quality of the amplified signal output was measured to be $M^2 = 1.02$ at a power of 100 W as shown in the inset. The measured polarization extinction ratio (PER) was 19 dB under full power operation.

The spectra in Fig. 5(a) are shown at the sub-harmonics of the diode repetition rate. There was minimal nonlinear evolution at a repetition rate of 908 MHz but as the repetition rate was reduced the pulse peak power increased and the spectra were broadened due to SPM. The degree of spectral broadening observed is relatively modest in absolute terms – just a few nm at the lowest repetition rates (highest peak powers) investigated, although this corresponds to relative broadening by factors of up to 20. The spectral broadening at a given repetition rate can obviously be eliminated by reducing the average output power (and corresponding peak power), however for many applications the spectral properties are not of great importance and it is the peak power and pulse duration that matter. In this regard the spectral broadening can in fact be beneficial as we shall see in Section 4 where it has been exploited to allow pulse compression and peak power enhancement, thus greatly extending the operational parameter space of the source. In the time domain the pulse shape was measured using a 32 GHz photodiode and sampling oscilloscope providing ~30 ps overall time resolution. The traces in Fig. 5(b) show that the seed and final output pulses were both within the resolution limit and thus that there is minimal temporal broadening.

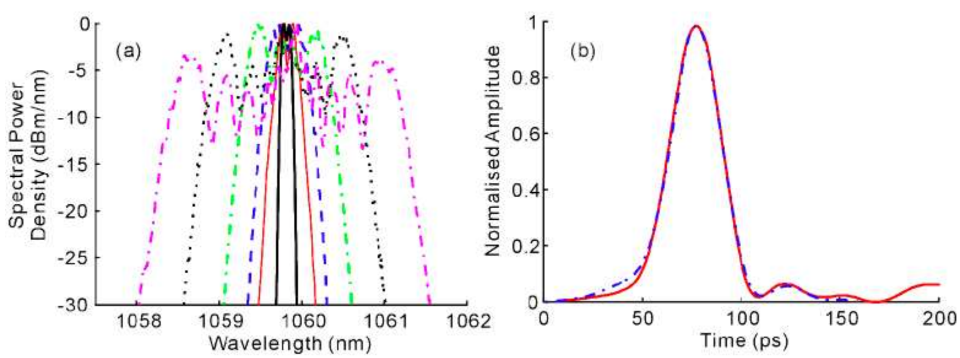


Fig. 5. (a) Spectra of seed (black solid line) and final output at a power of 100 W at repetition rates of 908 MHz (red solid line), 454 MHz (blue dashed line), 227 MHz (green dash dotted line), 113 MHz (black dotted line) and 56 MHz (black dash dotted line); and (b) photo diode trace of seed pulse (red solid line) and final output (blue dash dotted line) measured at an average power of 100 W and repetition rate of 56 MHz.

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The maximum average power at the system output was limited by the available pump power. The saturation energy, $E_{sat}$, was calculated to be 50 μJ and hence it is not a constraint to pulse energy in our system [24] and since neither SRS nor SPM were constraints at the 100 W power level, we suggest that significant further average power scaling should be possible by using a pump source having higher output power than currently available in our laboratory. Suitable pump sources capable of delivering output powers of ~800 W that can be focused into the 330 µm spot size required for the final amplifier fiber are commercially available [25]. Neither SRS nor SPM are critically limiting the performance of the system even at the lowest 56 MHz repetition rate so the main considerations would be maintaining a good OSNR and managing the thermal load. We consider that it is quite reasonable to expect output powers in the region of 500 W would be achievable at repetition rates of 227 MHz and above. To avoid OSNR degradation of the amplified signal the output power of the 2nd pre-amplifier could be increased from 0.2 W to 1.0 W (increasing the gain from ~9 dB to 16 dB) so as to maintain the same maximum gain required from the final stage amplifier.

## 4 Pulse compression

In this section we demonstrate pulse compression that enables our system to address applications that require increased peak power and improved time resolution. The use of SPM in a nonlinear element to obtain pulse compression is a well established technique [26,27] and either an external length of fiber can be used for spectral generation, or the spectral broadening can occur in the amplifier chain (as in parabolic pulse generation [28]). In our system pulses emerge from the GS diode with a negative chirp but after the CFBG they are close to transform limited. SPM in the amplifier chain then broadens the bandwidth without changing the pulse duration. Hence, at the output of the system the pulses are chirped due to the SPM. Adding a diffraction grating compressor at the output of the system eliminates that chirp [27]. To complement the experimental work, we performed numerical modeling using a standard split-step code to numerically solve the nonlinear Schrödinger equation (NLSE) with gain [27]. The amplifier fiber lengths, core diameters and gain in the simulations were set to match the experimentally measured values for each amplifier stage. We implemented a numerically optimized compressor to maximize the peak power by applying second and third order dispersion. We used the numerical model to calculate the B-integral and we assessed the quality of the recompressed simulation pulses by numerically integrating the power in the main peak (without pre- or post-pulses). We assumed a compressor transmission efficiency of 65% in order to match the experimentally observed efficiency for the dielectric grating compressor described below.

The highest levels of SPM and hence the maximum degree of pulse compression were obtained at the lowest repetition rate of 56 MHz. Modelling showed that with the compressor in place, an acceptable fraction of the energy remained in the main peak (excluding pre or post-pulses) at average powers of up to 70 W and this was confirmed experimentally by observing the increase in the pedestal level on the autocorrelation measurements.

For the experimental results we initially used a 1500 gr/mm gold coated grating, and passed only a fraction of the output power through the compressor to avoid thermal distortions arising from the heat load on the grating surface. Figure. 6(a) shows the uncompressed-pulse autocorrelations and demonstrates that the pulses were very similar in duration at both 35 W and 70 W output powers. The red dotted line is the autocorrelation of the seed pulse before the amplifiers, which confirms that there is no significant temporal broadening due to the pulse evolution through the system. (The clipping seen at the left edge of the trace is due to the limited span of the instrument.) The compressed pulse autocorrelation data is shown in Fig. 6(b). at the same power levels and with the grating separation at each power level adjusted to minimize the autocorrelation width observed on an oscilloscope. The autocorrelation FWHM was 2.7 ps at the 35 W output power level and 1.8 ps at the 70 W output power level. The quality of the compressed pulses is high. The spectra shown in Fig. 6(c) have the characteristic modulation associated with SPM and the 3 dB

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bandwidth (measured at the widest edges of the spectrum) was 1.1 nm at 35 W power, and 2.3 nm at 70 W power. When compared with the seed pulse bandwidth of 0.15 nm, the data clearly shows substantial nonlinear broadening.

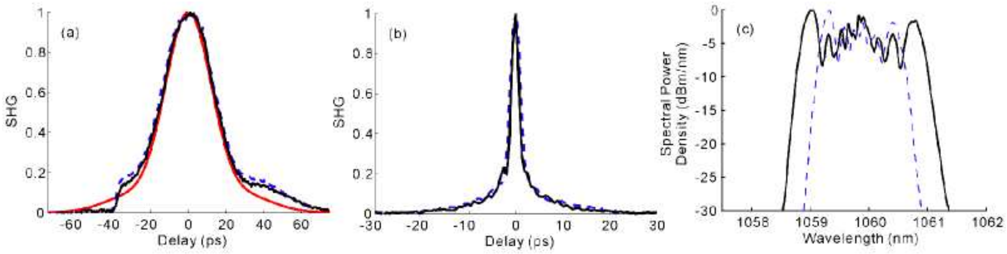


Fig. 6. (a) Autocorrelations of uncompressed pulses; (b) Autocorrelations compressed pulses; and (c) Spectra of the final output pulses at 56 MHz. Data shown at a power of 35 W (blue dashed lines) and at 70 W (black solid line). The autocorrelation of the seed pulse before the amplifier chain is shown in red on (a). The spectra in (c) were measured with 0.01 nm resolution, and have been normalized with respect to the peak.

The modelled autocorrelation predictions were in good agreement with the experimental results (data not shown in the interests of brevity). For the 70 W simulations at 56 MHz the estimated B-integral was ~27 radians, the estimated pulse duration was ~1.1 ps and the compressed peak power was ~431 kW. Numerical integration indicated that the main peak (without pre- or post-pulses) contained 57% of the total energy. Recently, compressor efficiencies in excess of 90% have been demonstrated using suitably designed dielectric gratings which would enable an increase in output power of 38% compared to the results here [5] giving a maximum possible peak power of ~595 kW.

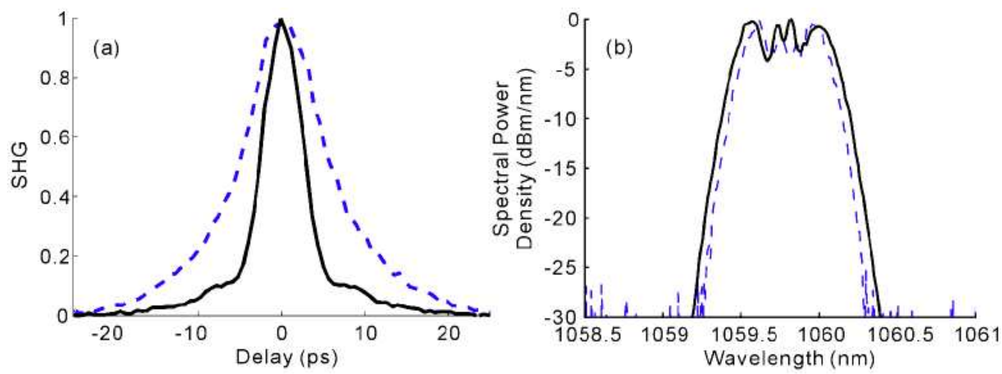


Fig. 7. (a) Compressed pulse autocorrelations at 227 MHz with final amplifier powers of 30 W (blue dash line) and 83 W compressed (black solid line); (b) Spectra of 83W average power level at the compressor input (black solid line) and compressor output (blue dash line).

In order for the output bandwidth to be suitable for SHG with a LBO crystal having an acceptance bandwidth of 0.7 nm we then selected a repetition-rate of 227 MHz and we found that a maximum power of 83 W was possible while keeping the spectral broadening within the crystal acceptance bandwidth. Using a dielectric grating with 1740 lines per mm in the compressor we passed the full power from the system through the compressor and the measured throughput efficiency was 65%. Figure 7 shows the results with the grating separation fixed at the optimum position for pulse compression at the 83 W power level. The compressed pulse autocorrelation widths decreased from 8.2 ps to 6.0 ps as the MOPA system power increased from 30 W to 83 W. Figure 7(b) shows the spectra at full power at the input and output of the compressor which confirms the full bandwidth was transmitted by the compressor. The 3 dB bandwidth measured at the widest edges of the spectrum was 0.6 nm at 83 W power. For the 83 W simulations at 227 MHz the estimated B-integral was ~6 radians,

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the pulse duration was ~4.2 ps and the peak power was ~46 kW. Numerical integration indicated that the main peak (without pre- or post-pulses) contained 77% of the total energy. An increase in the maximum peak power to ~63 kW would be possible using state-of-the-art gratings in the compressor.

The experimental setup for SHG using the compressed pulses is shown in Fig. 8(a). The 15 mm long LBO crystal was cut for noncritical phase matching at an operating wavelength of 1060 nm. The LBO crystal was chosen because of its high damage threshold relative to other potential crystal choices such as PPLN or KTP. The beam size at the waist position was 43 µm ($1/e^2$ intensity diameter) with a corresponding Rayleigh range of 1.4 mm. (The beam waist was measured in air prior to inserting the crystal and the Rayleigh range also corresponds to the value in air.) A half-wave plate placed immediately before the focusing lens was used to rotate the polarization of the fundamental light to maximize the second harmonic signal. Figure 8(b) shows the average output power of the compressed pulses and of the second harmonic signal as a function of the power from the laser. The LBO crystal was kept at a constant temperature of 152 °C for maximum conversion efficiency. We produced a maximum of 52 W of power from the compressor which produced 26 W of power at 530 nm corresponding to an optical conversion efficiency of 50%. The insets to Fig. 8(b) show that the spectrum of the 530 nm pulses had a FWHM of 0.2 nm and that the SHG beam M-squared measurement gave a value of 1.08, which was very close to that of the MOPA pump beam.

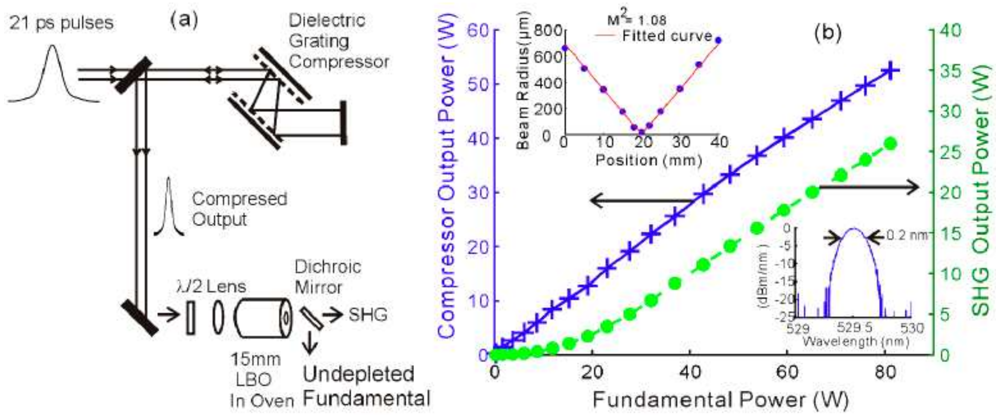


Fig. 8. (a) Schematic setup of SHG using compressed pulses at 227 MHz; (b) Compressor output power and SHG Output Power vs. Fundamental power from fiber MOPA; Top left insert shows beam quality of SHG; Bottom right insert shows the spectrum of SHG at 26 W.

## 5. Conclusion and future work

We have demonstrated a fiberised, diode-seeded, YDFA MOPA system generating linearly polarized, diffraction-limited, 21 ps pulses at repetition rates ranging from 56 MHz to 908 MHz and at an average output power of 100 W. The polarization stability is ensured by using PM amplifier fibers and the stability of the mode quality is ensured by using a tapered splice to the final amplifier. Compared to our previous work, the incorporation of a robustly single mode, PM amplifiers directly spliced together has considerably improved the modal and polarization stability. At the lowest repetition rate of 56 MHz the 21 ps pulses from our system have a maximum energy of 1.7 µJ, and peak power of 85 kW. The system demonstrates an attractive combination of controllable repetition-rate gain-switched diode seed and high-power single-mode PM-fiber amplifiers can create a source suitable for a wide variety of applications.

In addition, we report compression of the pulses to as short as 1.1 ps by exploiting the SPM induced spectral broadening that was observed at the highest pulse energies and adding a grating-based compressor at the output. A maximum compression factor of 17 was achieved

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and a corresponding enhancement in peak power to ~590 kW would be possible with the use of optimized compressor gratings. We used 4.2 ps pulses at a repetition rate of 227 MHz and average (compressed) output power of 52 W to demonstrate 26 W of visible laser power (50% SHG efficiency).


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