56W Frequency Doubled Source at 530 nm Pumped by a Single-Mode, Single-Polarization, Picosecond, Yb^{3+}-Doped Fiber MOPA

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Abstract— **We report a frequency doubled green source at 530nm pumped based on an all-fiber, picosecond, single polarization Yb^{3+}-doped fiber MOPA delivering 20ps pulses at user selectable repetition rates of up to 910MHz and an average output power in excess of 100W at 1.06µm. The output of the MOPA was frequency doubled using a LBO crystal. Up to 56 W of green light was generated at a corresponding repetition rate of 227 MHz at an overall conversion efficiency of 56%. The diode-to-green optical power conversion efficiency was 37%.**

Keywords: Ytterbium, Optical fiber amplifiers, Ultrafast optics and Oscillators

I. Introduction

High average power laser sources at 530 nm with good beam quality are in demand for a number of applications including material processing [1], medical treatments [2], pumping OPOs [3], and laser displays [4] to name but a few. In material processing green laser sources perform better than their counterpart IR sources in many applications including marking, precision microfabrication, trimming etc. due to the smaller spot sizes achievable and the larger absorbance for most materials. Although femtosecond lasers have been used extensively for high precision material processing applications these lasers are often complex in nature, expensive and high maintenance making them unattractive for industrial use. Recently it has been realized that picosecond lasers offer most of the advantages of fs systems e.g. high precision, low thermal damage etc but are typically far more robust and practical. Moreover, since ps lasers are typically capable of high repetition rates and higher average powers than fs systems they allow for higher material removal rates.

Mode-locking is by far the most popular means for generating ultrashort (ps/fs) pulses with relatively high pulse energies [5, 6]. However the nature of mode-locking means that the pulse repetition rate is often defined by the cavity round trip time for stable long term operation. It is possible to reduce the repetition rate by using a pulse picker but this comes at the cost of added complexity. Gain switching (GS) of laser diodes provides a practical and low cost method to generate ps pulses at user defined repetition rates and milliwatt average power levels. Such devices represent excellent seeds for high power fiber MOPAs allowing power scaling to the 100W regime with µJ pulse energies. We recently reported average powers in excess of 300W from a 1060nm gain-switched Fabry–Pérot (FP) laser seeded ytterbium doped fiber amplifier (YDFA) MOPA [7]. Whilst this represents an impressive achievement it is to be appreciated that this system incorporated free space pump and signal coupling - greatly compromising the practicality of the system. Moreover, the output polarization was ill-defined limiting the utility of the system for many frequency conversion applications.

Herein we present a fiberised, diode-seeded, YDFA MOPA system generating linearly polarized, diffraction-limited, 20ps pulses at repetition rates ranging from 113.8 MHz to 910 MHz and at average output powers in excess of 100W. This system represents a considerable improvement in practicality and performance relative to previous high power, fiber-based picosecond pulse sources [7, 8]. The single-mode, single polarization output of the MOPA was focused into a 15 mm long Lithium Triborate (LBO) crystal. Stable second harmonic power of 56 W was obtained at 530 nm with considerable scope for further power scaling.

II. Experiment and Results

Fig. 1 shows the experimental setup. A 1060 nm FP laser diode in a high-speed polarisation maintaining (PM) fiber-pigtailed package was gain-switched using a pulsed drive current with an associated DC bias. The FP diode was wavelength stabilized with a fiber Bragg grating centered at 1060 nm to ensure single longitudinal mode operation. The polarization extinction ratio (PER) of the seed laser is over 25 dB. A chirped fiber Bragg grating (CFBG) was used to compensate the inherent chirp of the GS pulses prior to amplification. The compression process resulted in ~20 ps pulses with a corresponding average power of 1.3 mW at a repetition rate of 910 MHz. The time bandwidth product of

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the compressed pulses is ~0.69. An inline electro optic modulator (EOM) with a PER over 30 dB was used as a pulse picker to vary the pulse repetition rate. This allows 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 [9]. The excess loss of the EOM meant that we required to use a three-stage YDFA MOPA chain. The first stage was a 4.5 m long core pumped YDFA using single-mode (4.5 µm core and 125 µm cladding diameter, NA=0.15) Yb-doped fiber fabricated in-house and was bi-directionally pumped using two 160 mW, 975 nm telecommunications-grade diodes. An average power of 50 mW and 35 mW were achieved after the 1st stage core pumped amplifier at the repetition rates of 908 MHz and 227 MHz respectively (with corresponding pulse energies of 55 pJ and 154 pJ). The corresponding signal gain at 227 MHz was 25 dB. The second stage YDFA comprised a 3.5 m long cladding-pumped single-mode (6 µm core, NA=0.12; 125 µm inner-cladding of NA=0.45) YDFA pumped with two 7 W, 915 nm pump diodes coupled into the inner-cladding using a fiberised combiner. Up to 4 W of average power could be generated after the 2nd stage cladding pumped amplifier although we only used 1W (14.5 dB gain at 227 MHz) in practice to reduce nonlinearities in the final amplifier. Although the pre-amplifiers are not PM, the output had a well-defined polarization state and a fast-axis blocking PM isolator was used to ensure single- polarization input to the power amplifier. After the isolator the power is about 500 mW. The preamplifier output polarization state was also stable and power fluctuations after the polarizing isolator were typically ~2% over a period of several hours. Recently the two non-PM pre-amplifiers have been replaced with the equivalent PM fibers to make the system fully PM.

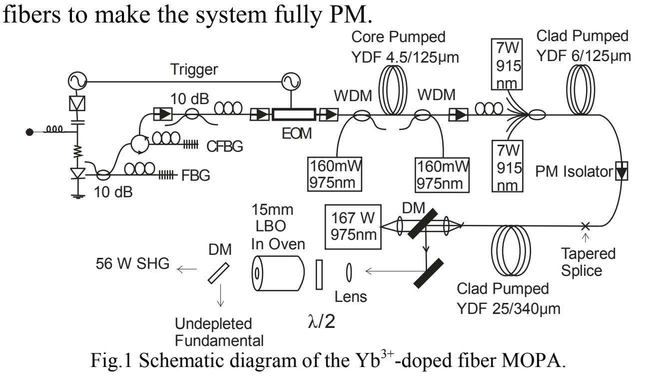

Fig.1 Schematic diagram of the Yb^{3+}-doped fiber MOPA.

The power amplifier was a 5.7 m long, PM fiber with an inner-cladding diameter of 340 µm, an NA of 0.45 and a core diameter of 25 µm with an NA of 0.055 (Nufern). This fiber has an absorption of 2.7 dB/m at 976nm. Although the core supports several transverse modes, robust single-mode operation was obtained by tapering the input end of the fiber to a diameter of 125 µm. The estimated mode field diameter of the fundamental mode is estimated to be 23 µm. Tapering also reduced the splice loss to the smaller core single-mode fiber from the isolator. To prevent damage to the output end, a 2 mm long pure silica mode-expanding end-cap was spliced to the fiber which was angle-polished to avoid power being retro-reflected back into the fiber core. The amplifier was end-pumped using a 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.

Figure 2 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. The spectrum measured with an ANDO (AQ6315B) spectrum analyzer at a repetition rate of 908 MHz has a signal level about 37 dB above the ASE after the second stage amplifier, and 37 dB above the ASE at the system output at the 100 W power level shown in Fig. 3. The pulse energy and peak-power requirements of our intended applications dictated that we operated the system at a repetition rate of 227 MHz to get the best conversion performance. As shown in Fig. 3, a good OSNR was maintained as the repetition rate was reduced with an OSNR of 23 dB at the output at 227MHz and with 97 % of the total power in the signal band. Therefore the maximum extracted pulse energy was 0.43 µJ corresponding to a peak power of 21 kW at an average output power of 100 W. The spectral bandwidth of the amplified pulses increased from 0.3 nm to 0.9 nm due to SPM assisted spectral broadening inside the final stage amplifier at this repetition rate. The measured PER was 19 dB under full power operation.

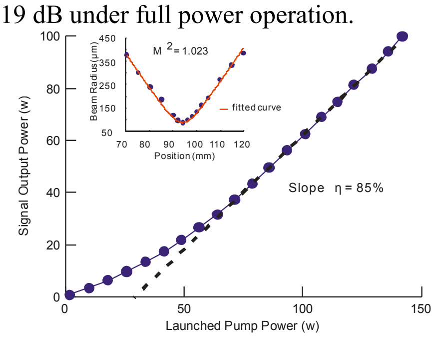

Fig. 2 Output power of final stage amplifier vs. launched pump power.

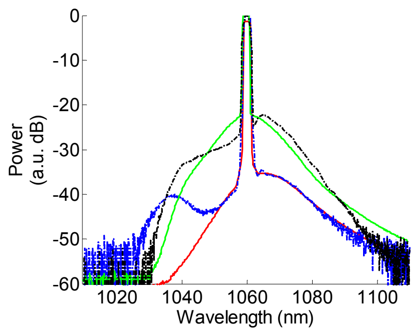

Fig. 3 Spectral plot of the 2nd stage amplifier output (solid red line), and final output (dashdot blue line) for pulses at repetition rate of 908 MHz and a spectral plots of th e 2nd stage amplifier output (solid green line), and final output (dashdot black line) for pulses at repetition rate of 227 MHz. The spectra were measured with an ANDO (AQ6317B) spectrum analyser using 2.0 nm resolution.

The pulse width of the seed source was measured using FROG technique and was found to be ~21 ps as shown in Fig. 4(a).

An intensity autocorrelator was used to measure pulse widths at different average output power levels and are illustrated in Fig. 4(b). The plots show that no significant temporal distortion occurs during amplification.

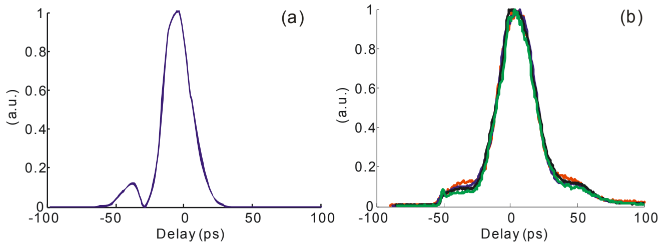

Fig. 4 (a) FROG trace of seed pulse (b) Autocorrelation traces at 12W (red), 36W (blue), 70W (black) and 100W (green).

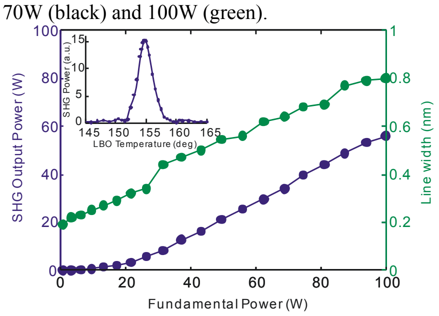

Fig. 5 Dependence of the second harmonic power at 530nm on the fundamental signal (circle) and the corresponding spectral bandwidth of the fundamental light (square). The inset shows the temperature tuning curve of the LBO crystal.

The single polarization output of the MOPA was launched into a 15 mm long LBO crystal. The LBO crystal was chosen because of its high damage threshold relative to other potential crystal choices such as PPLN or KTP. The diameter of the focused beam at the waist position was 70µm corresponding to a Rayleigh range of 12mm. The crystal was cut for noncritical phase matching at an operating wavelength of 1060 nm. 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. The temperature tuning curve of the crystal is shown in the inset of Fig. 5 and has a FWHM of 3^0C. The crystal was kept at a constant temperature of 155^0C for maximum frequency conversion. Fig. 5 shows the average output power of the second harmonic signal as a function of the fundamental power. It also shows that the spectral bandwidth of the fundamental signal increases linearly with output power due to SPM inside the power amplifier. A maximum second harmonic power of 56W was obtained at a fundamental power of 100W corresponding to an overall optical conversion efficiency of 56%. The observed roll-over in SHG power was believed to be due to the SPM in the final amplifier which broadened the spectrum of the fundamental light beyond the acceptance bandwidth of the SHG crystal for MOPA powers above 80W. A repetition rate of 227 MHz was found to provide the best combination of induced SPM and conversion efficiency although the MOPA itself can provide far higher pulse peak powers at lower repetition rates. It should be possible to improve the SHG conversion efficiency by carefully designing the final stage amplifier to better maintain the spectral integrity of the seed laser. Nevertheless, we have still managed to achieve an overall diode-to-green optical conversion efficiency of 37%. The 3dB spectral bandwidth of the frequency doubled signal at full power was measured to be 0.4nm as shown in Fig. 6. The M^2 of the frequency doubled light was also measured to be <1.05.

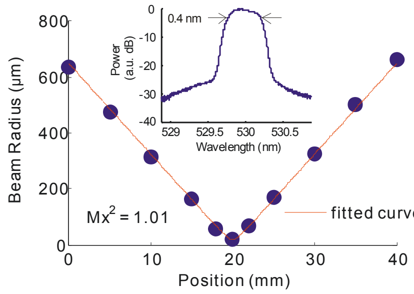

Fig. 6 M^2 measurement at power of 30 W and in insert: spectrum of the SHG light at a MOPA power of 56 W.

III. Conclusions

We have successfully demonstrated a robust, all-fiber 100 W, linearly polarized, near diffraction-limited, 20 ps pulse source at 1.06 µm based on a YDFA MOPA seeded by a gain-switched laser diode.

We have also managed to generate 56W of green light at 530nm at an overall conversion efficiency of 56% by using a 15 mm long LBO crystal. The corresponding diode-to-green optical conversion efficiency was 37%. Further power scaling is primarily limited by the spectral integrity of the fundamental light. It is possible to improve the conversion efficiency by optimizing the final stage amplifier.

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