

An all-fiber PM MOPA pumped high-power OPO at 3.82 μ m based on large aperture PPMgLN

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ABSTRACT

We report a large aperture PPMgLN based OPO generating 21W of average output power at a slope efficiency of 45%, pumped by the output from a polarization maintaining Ytterbium doped fiber MOPA operating at 1060nm producing 58W of average output power and 20ns pulses at a repetition rate of 100kHz. A maximum of 5.5W of optical power was recorded at the idler wavelength of 3.82 μ m without thermal roll-off. We have experimentally verified that the pulse rise/fall time plays a significant role in the OPO conversion efficiency and that further enhancement in the OPO conversion efficiency will be possible using sub-nanosecond rise and fall times.

Keywords: Optical fiber lasers, optical parametric oscillators, PPMgLN, pulse shaping

1. INTRODUCTION

High power optical parametric oscillators (OPO) operating in the mid-infrared (IR) wavelength range (3–5 μ m) are desirable for a wide range of applications including spectroscopy, environmental monitoring, LIDAR and missile counter-measures [1-2]. Quasi-phase-matched (QPM) OPOs based on periodically poled magnesium-oxide doped lithium niobate (PPMgLN) have moved into the mainstream of OPO research due to the large effective nonlinear coefficient, excellent power handling characteristics and wide transparency range of PPMgLN crystals [3-5].

High efficiency and high power PPMgLN based OPOs pumped by bulk solid state pump sources have been extensively investigated [2-5]. Fiber laser pumped OPOs represent a new generation of compact, high power parametric devices due to the excellent beam quality, simple thermal management schemes and ultrahigh electrical-optical conversion efficiencies of such pump sources [6-9]. The highest reported mid-IR power so far from a fiber pumped OPO is 10 W operating at 2.94 μ m pumped by a 50 W continuous wave Yb doped fiber laser operating with a tightly focused beam waist of 70 μ m [9]. However, when the mid-IR is generated at longer wavelengths, especially at wavelengths exceeding 3.5 μ m, a much larger beam size is required in order to overcome the stronger thermal-lensing effects due to the higher idler absorption. In order to keep high pump intensities and to retain high OPO conversion efficiencies at these wavelengths pulsed fiber lasers with high peak powers become the favored form of pump source.

We have previously reported a pulsed fiber master oscillator power amplifier (MOPA) pumped OPO based on a 50 mm \times 1 mm \times 1 mm PPMgLN crystal [10]. An overall OPO output power of 11 W (with 2.7 W of idler power at 3.5 μ m) was achieved pumped by a 28 W MOPA. Herein we significantly improved the MOPA performance in terms of higher output peak power by adopting a shorter amplifier fiber (using a fiber with a stronger cladding pump absorption) and greater stability by using a fully polarization maintaining (PM) fiberized system. Moreover, we designed and fabricated a larger aperture PPMgLN wafer which allows for a relatively large focused beam waist which helps to reduce thermal-lens effects. Using adaptive pulse shaping of the seed diode [11-12] we demonstrate a reduction in the impact of dynamic gain saturation and optical Kerr/Raman nonlinearities within the fiber MOPA, obtaining shaped signal and idler pulses at the OPO output. A total OPO power output of 21 W with an idler power of 5.5 W were obtained at a pump power of 58 W, with no sign of thermal roll-off indicating considerable scope for further power scaling.

2. SYSTEM SETUP

A schematic diagram of the all-fiber PM MOPA and the OPO system is illustrated in Fig. 1. The MOPA was seeded by a fiber pigtailed Fabry-Perot laser diode (Bookham CPE425) wavelength stabilized at 1060 nm with an external fiber Bragg grating. The diode was modulated by a Stanford pulse generator to deliver rectangular pulsed output with adjustable repetition rate and a selectable pulse duration ranging from a few ns to hundreds of ns. The seed laser output passed through an in-line electro-optic modulator (EOM), which was driven by an arbitrary waveform generator (AWG) with 4ns feature definition triggered by the Stanford pulse generator. The AWG waveform applied to the EOM was designed to produce rectangular shaped pulses at the amplifier output in the presence of dynamic gain saturation within the fiber MOPA and to minimize the impact of optical Kerr/Raman nonlinearities. We chose to use an EOM for pulse shaping rather than direct modulation of the diode drive current itself as this provided a faster shaping capability. The seed signal from the EOM was amplified by an all-fiber, three-stage PM amplifier chain to deliver single mode, single polarization output.

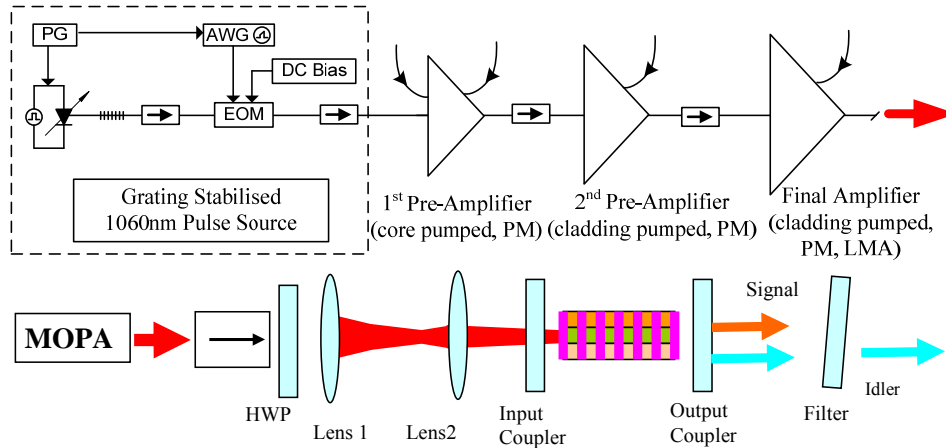


Fig. 1 Fig. 1 Schematic of the Yb-doped all-fiber PM MOPA and PPMgLN based OPO system

The first and second pre-amplifiers were identical to those described in Ref. [12], whereas the fiber of the final stage amplifier in this case was a large mode area (LMA), PM, double-clad active fiber (Nufern PLMA-YDF-25/250). The fiber has a core diameter of 25 μm and a core NA of 0.06. The cladding diameter of the polymer coated fiber was 250 μm with a cladding NA of 0.45. The measured cladding absorption of the fiber at the pump wavelength (975 nm) was 5.1 dB/m. A 3.8 m length of this fiber was chosen such that the amplifier not only provides optimum signal gain but also absorbs most of the launched pump power. To minimize the splice loss between the passive single-mode PM fiber and the LMA active fiber the outer diameter of the LMA fiber was tapered down to 90 μm and a core diameter of 9 μm during splicing. This helps to reduce the mode field diameter mismatch between the two dissimilar fibers ensuring a lower splice loss. Moreover tapering allowed us to obtain robust single mode operation even though the active fiber core can support several transverse modes. A 2 mm long pure silica mode-expanding end-cap was spliced to the end of the fiber to reduce the intensity at the fiber facet. The end cap was angle polished to avoid retro-reflection back into the fiber core. The amplifier was end-pumped using a 975 nm diode stack. A simple lens combination was used to achieve $\sim 80\%$ coupling efficiency into the fiber. A dichroic mirror was used to split the pump and signal output.

The collimated output beam from the MOPA was passed through a pair of telescopic lenses and focused into the PPMgLN crystal for OPO generation. Two back-to-back bulk isolators were used to safeguard the fiber amplifier chain from any unwanted reflections. The total pump loss through this back-to-back isolator combination was 0.63 dB. The polarization of the MOPA output was rotated by a half wave plate (HWP) to align to the principal axis of the PPMgLN crystal for maximum OPO conversion efficiency. By choosing different combinations of focal length lenses we could get the required focused beam waist within the crystal. In our experiment we chose a beam waist of ~ 1.2 mm corresponding to a long Rayleigh length of ~ 1 m. This allowed us to use plane cavity mirrors which are much more convenient in terms of alignment compared to the use of curved mirrors. The input mirror was anti-reflection coated across the 1.06 μm band and had a high reflectivity from 1.4 μm to 1.6 μm as well as from 3.5 μm to 4.0 μm . The

output coupler had a high reflectivity coating across the 1.06 μm band and exhibited high transmission between 3.5 μm to 4.0 μm . The reflectivity of the output coupler at 1.47 μm was 55%. The PPMgLN crystal used was a home made wafer [13] with a uniform homogeneous domain reverse period of 29.4 μm and a channel size of 50 mm \times 2 mm \times 2 mm. Both ends of the crystal were finely polished and were anti-reflection coated at wavelengths of 1.06 μm , 1.4 μm to 1.6 μm and 3.5 μm to 4.0 μm . A filter with high reflectivity at the signal wavelengths was used to block the OPO signal so that the idler power could be measured separately.

3. EXPERIMENTAL RESULTS

The impact of the peak power of the pump pulses and the focused beam size in the PPLN crystal on the OPO conversion efficiency were first investigated. To do this we fixed the pump pulse repetition rate at 100 kHz and investigated the OPO performance as we varied the pump pulse duration at fixed pump spot size (1.2mm diameter). Changing the pulse duration at a fixed average output power ensures the peak power scales with the pulse duty cycle. We chose pulse durations of 100 ns, 48 ns, 24 ns and 20 ns respectively (corresponding to the duty cycles of 100, \sim 200, \sim 400 and 500). The results are summarized in Fig. 2.

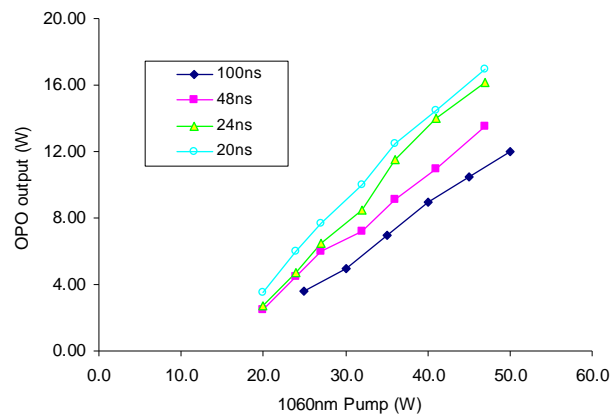


Fig. 2. OPO Output power as a function of 1060 pump power at various average pump power levels. The pulse peak power is obtained by multiplying the average power by the corresponding duty cycle.

It is observed that the higher the pump peak power the better the OPO conversion efficiency. Reducing the repetition rate whilst maintaining the pulsewidth could also in principle be used to increase the peak power, however the build up of strong amplified spontaneous emission (ASE) in the 1030-1040 nm region at high MOPA output powers limited our ability to this option.

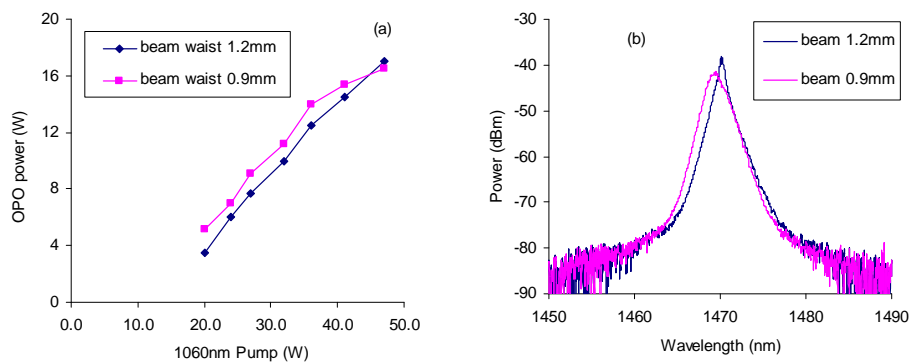


Fig. 3. (a) Output power and (b) signal spectra of OPO with regard to varied beam sizes.

In Fig. 3 we show the OPO performance for different focused beam sizes (1.2 mm vs. 0.9 mm) for the same pump pulse conditions. When the average pump power was relatively low, the OPO conversion efficiency for smaller beam waist (higher intensity) was higher than that with larger beam waist. However, when the average pump power exceeded 40 W a clear roll-off in OPO power (pink curve in Fig. 3(a)) can be observed which we believe to be due to the temperature increases/thermal gradients within the PPMgLN crystal driven by idler absorption that affects the phase matching conditions – evidence in support of this postulate is provided by the shifting and broadening of the OPO signal spectrum observed in (Fig. 3(b)). Therefore for a given pump peak power one has to optimize the beam waist on the crystal to maximize the OPO output.

Based on these initial trials, a beam waist of 1.2 mm was chosen for the MOPA operating at a repetition rate of 100 kHz and a pulse duration of 20 ns. These settings allowed us to achieve relatively high peak power pulses without a strong accompanying ASE component. A maximum average (peak) output power of 76 W (38 kW) with a polarization extinction ratio of 13 dB and good beam quality ($M2 < 1.1$) was obtained from the fiber MOPA. Fig. 4(a) plots the spectra at the output of the final stage amplifier for three different output powers with square shaped optical output pulses. The 3 dB spectral bandwidth of the laser output broadened slightly from 0.2 nm to 0.4 nm at the highest pulse energies used in our OPO experiments. The ASE at 1040 nm and the stimulated Raman scattering (SRS) at 1115 nm were 25 dB and 40 dB lower than the signal peak respectively at the highest operating peak power.

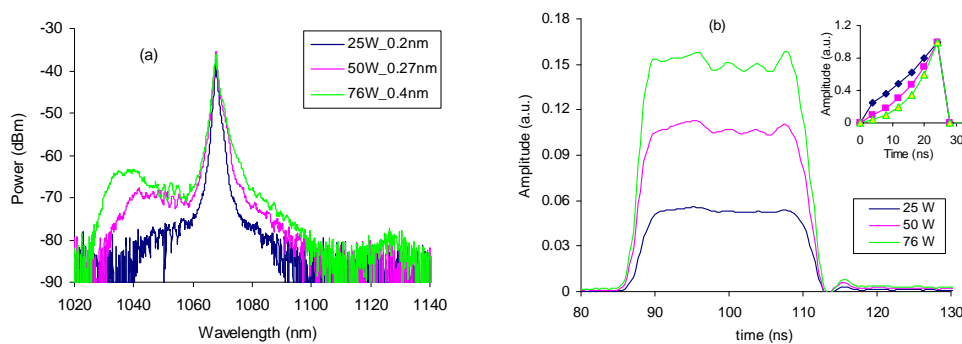


Fig. 4. (a) Spectra and (b) pulse shapes of the MOPA output for various output powers.

Although in principle it is helpful to use a shaped pulse with a relatively strong peak power close to the leading edge in order to reduce the OPO threshold [14], we found when trying this experimentally that the OPO conversion efficiency was not improved when the overall pump power (and peak power) was high. Accordingly to preserve the spectral integrity and minimize SRS without compromising the pulse energy, the initial pulses were pre-shaped to obtain square output pulses from our MOPA system. The pulse shapes at different power levels are shown in Fig. 4(b) (the inset shows the corresponding pre-shaped pulses from the seed diode).

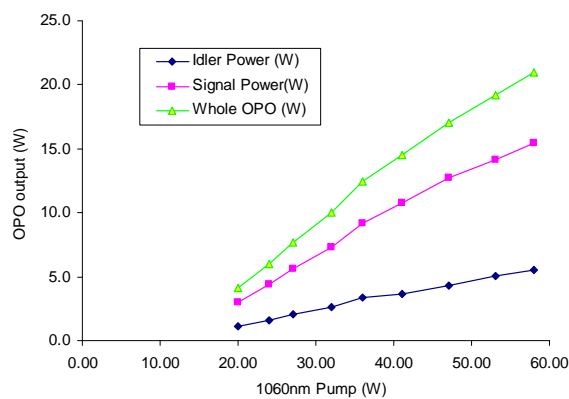


Fig. 5. Output power dependence of the OPO on 1060nm pump coupled into the PPMgLN.

Although a maximum average output power of 76 W was available at the output of the MOPA the output power was reduced to 58 W (single polarization) after passing through the isolators. Fig. 5 plots the signal, idler and the total OPO output powers as a function of the pump power. The threshold average power for the OPO is estimated to be ~ 15 W corresponding to a peak power of ~ 7.5 kW. Altogether 21 W of OPO output power was obtained at a slope efficiency of 45% of which 5.5W power was measured at the idler wavelength of $3.82 \mu\text{m}$. No thermal roll-off was observed indicating that further power scaling is possible with the availability of higher pump power. This signifies the importance of using a large-aperture PPLN crystal to scale up the OPO output power.

As is shown in Fig. 6(a), the OPO signal wavelength was increasingly red-shifted with increasing pump power. This can be attributed to internal heating within the PPMgLN crystal due to the relatively high absorption of PPMgLN within the idler wavelength band. The shift in wavelength is observed to be peak power dependent – implying that the internal heating of the crystal may be associated with the higher idler intensity and corresponding idler loss. It is possible to estimate the rise in internal temperature of the PPMgLN crystal from the observed wavelength shift. Our calculations indicate that the internal temperatures rose by about 10°C as the average pump power increased from 20 W to 58 W. The 3 dB bandwidth was measured to be less than 0.5 nm at the highest operating power. Fig. 6(b) illustrates the OPO signal pulse shapes at different power levels. The OPO takes a long time to build-up at relatively low pump pulse peak power resulting in low conversion efficiency. At high pump pulse peak power the OPO build-up time was reduced to about 4 ns: similar to the rise time of the pump pulse.

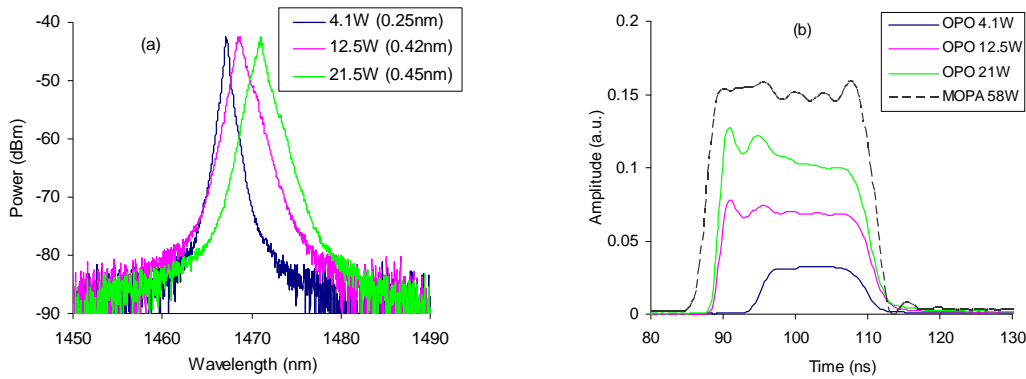


Fig. 6. (a) Spectra and (b) pulse shapes of the OPO signal for various pump powers.

4. CONCLUSIONS

In summary, we report a large aperture PPMgLN based OPO generating 21 W of average output power at a slope efficiency of 45%, pumped by the diffraction limited output from a polarization maintaining Ytterbium doped fiber MOPA operating at 1060 nm producing 78 W of average output power and 20 ns pulses at a repetition rate of 100 kHz. Up to 5.5 W of average power was obtained at the idler wavelength of $3.82 \mu\text{m}$ without thermal roll-off. Further enhancement in the OPO conversion efficiency should be possible using pulses with sub-nanosecond rise and fall times and operating the MOPA at 1030-1040 nm to mitigate short wavelength ASE build-up.

5. ACKNOWLEDGEMENTS

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