High average power parametric wavelength conversion at 3.31–3.48 µm in MgO:PPLN

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Abstract: We present results of high average power mid-infrared (mid-IR) generation employing synchronized nanosecond pulsed ytterbium and erbium fiber amplifier systems using periodically poled lithium niobate. We generate greater than 6 W of mid-IR radiation tunable in wavelength between 3.31–3.48 µm, at power conversion efficiencies exceeding 75%, with near diffraction limited beam quality (M² = 1.4). Numerical modeling is used to verify the experimental results in differing pump depletion regimes.

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1. **Introduction**

The mid-infrared (mid-IR) spectral region is rich in applications, including absorption spectroscopy, remote sensing and defensive countermeasures. Optical parametric oscillators (OPOs) are an established technology for generating coherent radiation in this area, capable of multi-Watt output power levels in the 3–5 µm range. In particular, ytterbium (Yb):fiber laser pumped OPOs based on periodically poled lithium niobate (PPLN) have received much attention, due to both the high power scalability and temporal flexibility of Yb:fiber systems, and the excellent optical properties of PPLN [1–3]. However, the resonant cavity of an OPO is potentially disadvantageous, for example: OPOs are fixed repetition rate devices; high output beam quality at high average powers can be difficult to achieve; they can also require careful cavity alignment/active synchronization to ensure efficient operation. Devices based instead on optical parametric amplification (OPA), difference-frequency generation (DFG) or optical parametric generation (OPG) offer non-resonant single-pass operation, which can potentially be less complex and more robust than their OPO counterparts.

Typically however, single-pass parametric conversion based architectures (OPG/OPA/DFG) offer lower conversion efficiencies than resonant cavity based sources (OPOs). Recent results of Yb:fiber laser PPLN pumped single-pass OPA/DFG systems in the 3–4 µm region reached total pump conversion efficiencies on the order of 40–50% at Watt-level average powers [4,5]. In comparison, the pump conversion in optimized OPOs can exceed 90% [6]. However, we recently demonstrated improved pump conversion efficiencies of up to 79% in a single-pass architecture [7], approaching the performance obtainable in optimized OPOs. This was achieved, in part, by employing synchronized fiber laser pump and signal sources, in contrast to the continuous-wave (CW) signal seeds employed in Refs. [4,5]. However, in previous work [7], we did observe back-conversion of the signal and idler wavelengths to the pump wavelength at the highest available pump powers. More recently, we eliminated the issues with back-conversion, through the use of different pump and signal lasers, and scaled the generated mid-IR power [8]. In this manuscript, we expand upon the work in [8], presenting beam quality measurements of the generated mid-IR light and more detailed numerical modeling of the source. We demonstrate a high average power (6.2 W) mid-IR source based on parametric wavelength conversion in PPLN, tunable over the range 3.31–3.48 µm at power conversion efficiencies exceeding 75%. This is, to the best of our knowledge, the highest average power generated in the mid-IR using fiber pump sources employing a single-pass (i.e. non-resonant) approach in PPLN. The use of fiber-based pump sources results in the generation of mid-IR radiation with near diffraction limited beam quality (M² = 1.4). We also present numerical simulations of the system, making use of focused Gaussian beam theory together with numerical solutions of the three coupled wave equations [9,10].

Note from hereon in, we use the term parametric conversion to refer to the nonlinear wavelength conversion. There is conflicting use of the terms DFG/OPA in the literature, so for the sake of clarity we use neither. We do, however, employ the pump, signal and idler nomenclature throughout, where \( \omega_{pump} = \omega_{signal} + \omega_{idler} \), to denote the three interacting waves in the parametric conversion.

2. **Experimental setup**

The experimental setup of the Yb: fiber erbiuim(Er): fiber master oscillator power amplifier (Yb/Er: fiber MOPA) systems used in this work are shown in Fig. 1. The Yb: fiber MOPA was seeded by an intensity modulated distributed feedback laser diode (DFB-LD) at 1.065 µm. The continuous wave (CW) output of the DFB-LD was modulated by a fiber coupled electro-optic modulator (EOM), producing pulses with selectable durations from 0.2–3 ns, at repetition rates between 1–50 MHz with a spectral linewidth of ~ 40 pm [Figs. 1(b) and 1(c)]. The Er:fiber
MOPA arm employed the same seed oscillator architecture, with the DFB-LD replaced by an external-cavity laser diode (ECLD) tunable from 1.50–1.58 \( \mu \text{m} \). Similar pulse duration and repetition rate parameters were accessible with the Er:fiber MOPA [Figs. 1(d) and 1(e)]. In both MOPAs, two fiber amplifier stages consisting of Yb or Er doped fiber amplifiers (YDFA/EDFA) were then used to amplify the seed oscillators to average powers of 27/2 W, from the Yb/Er:fiber MOPA respectively. In both systems the modulators were driven using synchronized electrical pulse generators. Adjustable electrical delay lines between the pulse generators enabled easy temporal overlap of the pulses. The setup was similar to that used in [7], with the exception that in this work both MOPAs used duration tunable seed oscillators, resulting in greater flexibility when optimizing the nonlinear conversion. Optimized optics were also employed, enabling \( \sim 30\% \) more pump power incident on the crystal than was previously available [7].

The fiber amplifiers used in both arms were non-polarization maintaining, therefore, the output polarization state of the MOPAs tended to evolve during initial turn-on of the system. This evolution was due to temperature induced birefringence changes in the fiber. Quarter/half waveplate sets were used at the output of the MOPAs to linearize the polarization state for optimal nonlinear conversion [Fig. 1(f)]. After approximately half an hour of operation, the polarization state of the MOPAs stabilized, and subsequent adjustment of the waveplates was minimal. The second half waveplate and polarizing-plate beamsplitter (PPBS) were used in the Yb:fiber MOPA arm to provide control of the average power incident on the crystal. A dichroic mirror, highly
reflective for the pump and highly transmissive for the signal, was used to direct the beams towards the crystal focusing lens. An f = 75 mm lens was used to focus the incident pump and signal beams into the crystal, resulting in beam waist diameters (D4 widths) for the pump and signal of 85 µm and 95 µm respectively. Figure 1(g) shows the beam caustics of the pump and signal measured in air, at the focal position of the crystal. There is a ~ 6 mm difference in focal positions for the pump and signal, attributed to chromatic aberration of the focusing lens used, and non-ideal wavefront curvature of the pump and signal beams. With the pump pulse presented in Fig. 1(c) [1 ns at 25 MHz], this pump spot size corresponds to a peak intensity in the crystal of ~ 30 MW/cm², well below the typical damage threshold quoted for PPLN in this pump power and pulse duration range of 0.1–1 GW/cm² [4, 5].

The PPLN used throughout this work was a 40x10x1 mm crystal doped with 5 mol.% MgO (MgO-PPLN - Covesion UK). A grating period of Λ=29.98 µm was employed for all the results presented herein. The entrance and exit faces of the crystal were anti-reflection coated for the pump, signal and idler wavelengths. The crystal was held in a copper oven enclosed in an insulated PTFE housing, and the oven temperature could be adjusted from 20–230 °C with ±0.1 °C accuracy. An uncoated CaF₂ plano-convex lens was then used to collimate the pump, signal and idler from the crystal, before a CaF₂ prism spectrally dispersed the three beams for analysis.

3. Mid-IR generation

Once spatially and temporally overlapped within the PPLN crystal, efficient parametric wavelength conversion was observed between the pump and signal. Using a pump wavelength of 1.065 µm with a signal wavelength of 1.56 µm produced idler radiation at 3.35 µm [Fig. 2(b)]. The GHz linewidth MOPAs used as the pump and signal [Figs. 1(b) and 1(d)] transfer their narrow spectral linewidths to the mid-IR, resulting in the generation of idler radiation with linewidths on the order of Δf ~ 5 GHz [Fig. 2(b)]. By tuning the temperature of the oven (133–210°C) and the corresponding signal wavelength of the Er:fiber MOPA (1.535–1.570 µm), it was possible to tune the idler over the range 3.31–3.48 µm. Example spectra from a truncated section of this tuning range are presented in Fig. 2(a). Spectra beyond 3.4 µm were not measured in this work, due to limitations of the measurement range of the optical spectrum analyzer used (Yokogawa AQ6376). However, the existence of the longer wavelength idler radiation (> 3.4 µm) was confirmed through the measurement of the amplified signal wavelength and the signal and idler powers, and was also demonstrated in our earlier work [7].
were also very stable, with the idler power exhibiting a root-mean-square (RMS) power deviation was used throughout, corresponding to a maximum signal gain of 9.5 dB. The generated powers for the parametric conversion. A large footprint Nd:YAG slab MOPA pump source was also used, between the three waves when operating in the high pump depletion regime. Possible beam profiles of the pump/signal/idler. These effects are also coupled with back-conversion of power quality in the conversion process can be attributed to the Gaussian beam profiles of the pump and mid-IR radiation at full power was also excellent (M² < 0.3) over a 3 hour test period. The presented average powers account for losses from the crystalface, we produced 12.7 W of amplified signal and 6.2 W of generated idler, corresponding to a maximum total pump conversion of 75%. An input signal power of 1.6 W (in the crystal) was used throughout, corresponding to a maximum signal gain of 9.5 dB. The generated powers were also very stable, with the idler power exhibiting a root-mean-square (RMS) power deviation of < 0.3% over a 3 hour test period. The presented average powers account for losses from the uncoated CaF₂ optics after the crystal, and therefore, represent powers at the exit face of the crystal directly. The combination of high average powers, tunable from 3.31–3.48 µm with GHz spectral linewidths, mean that this source could be suitable for mid-IR spectroscopic applications requiring high spectral power densities.

The results presented in Fig. 3 are typical of the source performance across its spectral tuning range, with greater than 6.0 W of mid-IR light produced from 3.31–3.48 µm. Further wavelength tuning was not possible due to restrictions on the Er:fiber MOPA gain bandwidth. These results represent, to the best of our knowledge, the highest average powers generated through single-pass parametric wavelength conversion in PPLN utilizing fiber pump systems. Higher average powers have been demonstrated in [11], but a more complex dual stage OPO/OPA scheme was employed for the parametric conversion. A large footprint Nd:YAG slab MOPA pump source was also used, resulting in relatively low brightness idler radiation with M² values of ~ 4.

In contrast to their bulk laser counterparts, fiber lasers are compact, efficient and robust, and have the additional benefit of possessing inherent excellent beam quality. The pump and signal fiber MOPAs used in this work both had M² < 1.1, and Fig. 4 reveals that the beam quality of the mid-IR radiation at full power was also excellent (M² = 1.4). The slight degradation in beam quality in the conversion process can be attributed to the Gaussian beam profiles of the pump and signal MOPAs, and the corresponding non-uniform conversion efficiency across the transverse profiles of the pump/signal/idler. These effects are also coupled with back-conversion of power between the three waves when operating in the high pump depletion regime. Possible beam

Fig. 3. (a) Example amplified signal (green), generated idler (red) and combined (blue) powers produced during parametric conversion. (b) Typical pump conversion to the signal, idler and combined wavelengths.

An example optimized power curve for the source is shown in Fig. 3(a), with the corresponding pump conversion shown in Fig. 3(b). We define the pump conversion as being the proportion of pump photons converted to the amplified signal, generated idler or both. In contrast to our previous work where we observed strong back-conversion of the signal/idler to the pump [7], the pump conversion only begins to roll off at the highest available pump power. This was readily achieved by adjusting the peak pump intensity in the crystal using two methods: coarse adjustment using different crystal focusing lenses, and finer adjustment through pump/signal duration and/or repetition rate tuning. At the maximum available pump power of 25.5 W at the crystal face, we produced 12.7 W of amplified signal and 6.2 W of generated idler, corresponding to a maximum total pump conversion of 75%. An input signal power of 1.6 W (in the crystal) was used throughout, corresponding to a maximum signal gain of 9.5 dB. The generated powers were also very stable, with the idler power exhibiting a root-mean-square (RMS) power deviation of < 0.3% over a 3 hour test period. The presented average powers account for losses from the uncoated CaF₂ optics after the crystal, and therefore, represent powers at the exit face of the crystal directly. The combination of high average powers, tunable from 3.31–3.48 µm with GHz spectral linewidths, mean that this source could be suitable for mid-IR spectroscopic applications requiring high spectral power densities.
quality improvement may be possible; it has been shown that gain-guiding and back-conversion effects can be counter-balanced by adjusting the focusing conditions in the crystal [12].

![Graph showing beam diameter vs. longitudinal position](image)

**Fig. 4.** Measured beam diameter (D4σ widths) of the idler in the horizontal and vertical beam axis through the focus of a lens, with a Gaussian fit to the beam caustic. Taken at full power and measured using a pyroelectric scanning slit beam profiler.

![Graph showing conversion vs. time](image)

**Fig. 5.** Sampling optical oscilloscope traces of signal and pump for increasing levels of pump conversion, from 0% to 75%, after undergoing parametric conversion in PPLN. Signal pulses shown on top row in green, with corresponding pump pulses on the bottom row in blue. All pulse amplitudes are normalized.

quality degradation could also be alleviated through the use of flat-top beam profiles rather than Gaussian, leading to more uniform conversion efficiency across the transverse axes of the beams.

Figure 5 shows the measured traces of the pump and signal pulses as a function of increasing pump conversion. The pulse amplitudes are normalized for easier comparison. The idler pulses could not be measured directly due to a lack of diagnostics in the mid-IR, but can be inferred from the amplified signal traces. The pump pulses underwent increasing depletion with increasing conversion, with the center of the pulse being almost completely depleted at the highest conversion level (75%). The corresponding signal pulse duration decreased slightly with
increasing conversion, from 850 ps initially to 730 ps at 75% pump conversion. A slight shortening was expected due to the finite rise and fall time of the pump/signal pulses. The electrical pulsers used to drive the respective EOMs in each MOPA arm were also slightly different, thus, the shape of the pump and signal pulses did not match exactly. Improved conversion efficiency could be expected with better pump and signal pulse overlap, in particular, the use of more rectangular pulses with faster rising and falling edges. There was also no obvious sign of back-conversion in the temporal domain, in contrast to our previous work [7]. The use of duration tunable pump and signal MOPAs allowed easy optimization of the nonlinear conversion at any average power level, avoiding unwanted excessive back-conversion. This feature is essential for further power scaling of mid-IR average power levels using this configuration.

4. Numerical simulations

Software programs such as SNLO [13] can be used to obtain exact numerical solutions of the three wave mixing equations for parametric processes, including the effects of linear and nonlinear absorption coefficients ($\alpha$ and $\beta$), nonlinear refraction coefficient ($\gamma$), beam focusing parameter ($\xi$), phase mismatch parameter ($\sigma$), beam walk-off parameter ($\rho$) and pump depletion parameter ($\kappa$). However, the analysis pioneered by Boyd and Kleinman [14] is also often convenient, especially for incident beams with Gaussian transverse distribution, to determine the maximum expected value for the output beam power as a function of various sample or beam parameters. Using that analysis, an expression for idler beam power for the case of small pump conversion was previously obtained as a double integral (denoted by $h_1$) containing the various parameters above [10]. For the case of high pump conversion, the generated power values cannot be analytically expressed in terms of integrals, but the relevant $h_1$ parameter can still be obtained from numerical solution of the coupled wave equations. In addition to the beam and sample parameters, $h_1$ in this case becomes also a function of the incident beam powers.

If $P_2(0)$ and $P_3(0)$ denote the incident signal and pump beam powers, the generated idler power at the exit of the sample with length $\ell$ is given by [9]

$$P_1(\ell) = \frac{P_2(0)P_3(0)}{P_{DF}} h_1$$

with

$$P_{DF} \equiv \frac{c\epsilon_0 n_2^2 A_1 A_2^2}{32\pi^2 d_{\text{eff}}^2 \sigma}$$

and

$$h_1 = \frac{n_1}{n_3} \frac{P_{DF}}{\pi P_2(0)} \int_{-\infty}^{+\infty} |u_1(x_1, y_1, 1)|^2 dx_1 dy_1$$

The various parameters used in Eqs. (1)–(3) and the equations below are defined in [9], with the idler, signal and pump beam parameters described respectively by the suffixes 1, 2 and 3. $u_1$, $u_2$ and $u_3$ denote the complex amplitudes of the idler, signal and pump beams, normalized with the incident pump beam amplitude and $x_1$, $y_1$ and $z_1$ denote the normalized coordinates, with $z_1 = 1$ at the sample exit. Using the same notation, the signal output power can be expressed as

$$P_2(\ell) = P_2(0) h_2$$

with

$$h_2 = \frac{n_2 P_3(0)}{n_3 P_2(0)} \frac{1}{\pi} \int_{-\infty}^{+\infty} |u_2(x_1, y_1, 1)|^2 dx_1 dy_1$$
and the pump output power is

\[ P_3(\ell) = P_3(0) h_3 \]  

with

\[ h_3 = \frac{1}{\pi} \int_{-\infty}^{\infty} |u_3(x_1, y_1, 1)|^2 \, dx_1 \, dy_1 \]

For quasi-phase matched nonlinear interactions, the parameter \( \sigma \) in the coupled wave equations is replaced by

\[ \sigma = 2\pi \left( \frac{n_3}{\lambda_3} - \frac{n_2}{\lambda_2} - \frac{n_1}{\lambda_1} - \frac{1}{\Lambda} \right) \]

where \( \Lambda \) denotes the grating period of the nonlinear material with alternate layers having opposite sign of the nonlinear optical coefficient.

Using Eqs. (3) and (5), the pump power dependence of the generated signal and idler power was calculated theoretically at the peak phase matching temperature. Wavelength and temperature dependent values of the refractive indices \( n_1, n_2 \) and \( n_3 \) were obtained from the Sellmeier equations given by Gayer et al. [15], and other parameters used were \( \ell = 4 \, \text{cm}, \, n_{02} = 33.60 \, \mu\text{m}, \) \( n_{03} = 30.05 \, \mu\text{m}, \) \( \Lambda = 29.98 \, \mu\text{m}, \) and \( d = d_{\text{eff}} = 11 \, \text{pm/V}. \) The distance between the waist positions of the pump and signal, as measured in air [Fig. 1(g)], was 6 mm. The results are shown in Fig. 6 along with the experimentally measured values. Different values of \( d_{\text{eff}} \) were trialed in the simulations, and \( d_{\text{eff}} = 11 \, \text{pm/V} \) was found to give the best agreement between the numerical analysis and the experiment. In this case, \( d_{\text{eff}} \) was used as the free parameter to match the numerical results to the experimental data. However, there were other factors in the experiment which could also affect \( d_{\text{eff}} \), other than the quality of the crystal and the poling. For example, pulsed pump and signal MOPAs were employed. When calculating the peak intensity of the pulses any low-level CW light between the pulses was neglected. The pump/signal pulse shapes also had finite rise-times, which again could lead to a slight overestimation of the peak power of either. There were also experimental uncertainties in the focusing conditions and powers in the crystals, and thermal and absorption effects were neglected in the modeling; these could also cause deviations of theory from experiment. Thus, the \( d_{\text{eff}} \) used in the simulations contains

![Graph showing amplified signal and idler powers](image-url)
Fig. 7. Measured temperature bandwidth curves for different pump power levels of 5 W, (a), and 25.5 W, (b). Plotted on both is the simulated data as well. (c) Normalized temperature bandwidth curves of the generated idler power, for the high and low conversion regime.

all of these uncertainties, and should not be taken as an absolute value of \( d_{\text{eff}} \) for the PPLN employed in the experiment.

The generated idler power \( P_3(\ell) \) was also determined as a function of sample temperature for two values of the incident pump peak power, \( P_3(0) = 5 \text{ W} \) (200 W peak) and \( P_3(0) = 25.5 \text{ W} \) (1020 W peak), with incident signal power \( P_2(0) = 1.6 \text{ W} \) (75 W peak). Theoretically predicted temperature dependence at the low and high values of pump power matched the experimental values well, as shown in Figs. 7(a) and 7(b). A small offset of 0.7 °C was used between the high and low conversion regimes, in order to correctly match the peaks of the numerical and experimental data. This shift was necessary due to an increased thermal load in the crystal in the high conversion regime. The normalized plots are shown in Fig. 7(c), with an increase in temperature acceptance bandwidth observed for operation in the high conversion regime. This is expected, as the parametric gain bandwidth will increase with increasing signal gain and pump conversion.

5. Conclusions

In this manuscript, we have presented a high average power, fiber MOPA pumped, single-pass parametric conversion source emitting over 6.0 W in the spectral range 3.31–3.48 \( \mu \text{m} \). The mid-IR radiation possessed excellent beam quality (\( M^2 \approx 1.4 \)) and high spectral power densities as a result of the GHz spectral linewidths of the pump and signal MOPAs employed. This is, to the best of our knowledge, the highest average power achieved with a single-pass configuration in PPLN employing fiber MOPA pump sources. The fiber sources were key to achieving high output beam quality in the mid-IR. The use of synchronized pump and signal lasers also supports very high pump conversion efficiencies of 75%, approaching those achieved in resonator based
systems. We also presented numerical studies of the source, using focused Gaussian beam theory and coupled wave equations for the interacting beams. Good agreement was found between the numerical simulations and the experimental system, demonstrating the validity of this numerical approach in the heavily depleted pump regime.

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