Mid-Infrared Difference Frequency-Generation with Synchronized Fiber Lasers


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Abstract: We present results on high-average power difference frequency generation of pulsed Yb/Er fiber systems to the mid-IR (6.2 W at 3.35 μm), and use focused Gaussian beam theory to validate our experimental results.

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1. Introduction

Optical parametric oscillators (OPOs) are a proven route to generating multi-Watt level average powers in the 2–5 μm mid-infrared (mid-IR) range, a spectral region of great interest for gas spectroscopy, defensive countermeasures and remote sensing applications [1]. Optical parametric generation (OPG), optical parametric amplification (OPA) or difference frequency generation (DFG) offer single-pass alternatives to OPOs, and can be simpler, more robust and cost-effective.

In recent work, we demonstrated very high pump conversion levels using DFG of two picosecond pulsed Yb and Er fiber lasers, but observed strong pump back-conversion at the highest pump power levels, leading to reduced conversion to the mid-IR [2]. In this paper, we review recent experimental progress on improving pump conversion at higher average power levels, resulting in the generation of 6.2 W at 3.35 μm. This is, to the best of our knowledge, the highest average power generated in the mid-IR through single pass DFG/OPA using fiber based pump sources. In particular, we use pulse duration tunable pump and signal master-oscillators. This enables easy adjustment of the pump and signal peak intensities in the crystal to optimize the pump conversion, whilst keeping the focusing conditions of the interacting beams constant. We also investigate the effect of pump conversion levels on the temperature bandwidth curves, and find operation in the high conversion regime results in a wider temperature bandwidth. We compare the experimental results with theoretical focused Gaussian beam calculations, including the effects of heavy pump depletion [3]. Ongoing work is aimed at continued power scaling of the mid-IR light.

2. Setup and Results

The experimental setup is shown in Fig. 1 (a), and is similar to that described in Ref. [2]. Two pulse duration tunable master-oscillator power fiber amplifier (MOPFA) systems are used to pump a 40x1x1 mm MgO-doped periodically-poled lithium niobate (PPLN) crystal (5% MgO doped – Covesion UK). The pump and signal MOPFAs are centered at 1.064 μm and 1.56 μm respectively, resulting in an idler wavelength of 3.35 μm. Both MOPFAs can be tuned from 0.1–2.5 ns, enabling adjustment of the peak beam intensities in the crystal to optimize the pump conversion. The beams are focused in the crystal using an f = 75 mm plano-convex lens, resulting in a focused spot size (1/e² diameter) in the crystal of 85 μm for the pump (measured) and signal (calculated). This corresponds to a peak pump intensity of 31 MW/cm² at the focus of the crystal.

Figure. 1 (b) shows the measured pulse durations of the input pump (1 ns) and signal (850 ps) pulses, corresponding to the optimized powers obtained shown in Fig. 1 (c) and (d). Due to a small mismatch between the shape of the pump and signal pulses, optimal DFG occurs for a full width half maximum (FWHM) pump pulse duration that is fractionally larger than the signal pulse. The amplified signal, idler, and combined powers are shown in Fig. 1 (c), with maximum values of 12.7 W, 6.2 W and 18.9 W, respectively. The corresponding pump conversion values are shown in Fig. 1 (d), with a maximum total pump conversion of 75% (we define pump conversion as being the amplified signal plus idler powers as a fraction of the incident pump power). The conversion efficiencies show a roll-off at the highest
Fig. 1. (a) Setup diagram. (b) Pump and signal pulse duration streak camera traces. (c) Powers generated in DFG process, where the signal represents the amplified signal only. (d) Pump conversion to DFG power, defined as amplified signal plus idler power as a fraction of the incident pump power.

focused Gaussian beam theory is used to verify the experimentally measured powers. Figure 2 shows the generated mid-IR power (normalized) as a function of crystal oven temperature, for low (5 W) and high (25.5 W) incident pump power levels. The shape of the curves show a good agreement with the numerical results, obtained by solving the coupled wave equations for the three interacting beams, assuming the incident beams to be Gaussian in transverse spatial distribution and focused at the crystal center. The temporal shapes of the incident beams are assumed to be rectangular [Fig. 1 (b)]. The value of $d_{eff}$ is assumed to be 13 pm/V and the temperature dependent refractive indices at the three wavelengths are obtained from the Sellmeier equations given in Ref. [5]. A temperature offset of 11.5 °C (low) and 12.5 °C (high) is required to match the peaks. These offsets are attributed to a mismatch in the measured oven and actual crystal temperatures, small differences in crystal composition altering the refractive index to that used in the model, and possible mis-calibration of the optical spectrum analyzers used to measure the wavelengths of the pump and signal. The difference in the offset required to correctly match the central phase-matched temperature in each pump regime is due to the increased thermal load in the crystal at low and high pump powers.

The numerically predicted powers are higher than the experimentally obtained values in the low pump power regime [inset Fig. 2 (a)], and slightly lower for the high pump power regime [inset Fig. 2 (b)]. These differences are attributed to non-ideal focusing conditions in the low-power case (the focusing was optimized for the high pump regime level and kept constant throughout), and uncertainties in the pump/signal beam diameters and peak intensities in the high-power case. However, the shape of the predicted normalized curves agree well with the experimental data in both the low and high pump power regimes, in particular predicting the increase in crystal temperature bandwidth with increasing
Fig. 2. Normalized temperature acceptance bandwidth curves of the generated idler, both experimental and numerical, taken at different pump power levels: green indicates 5 W of pump power, and blue 25.5 W of pump power. Black lines indicate simulation results obtained using parameters from the experiment. Inset (a) and (b) show the raw idler powers in both low (green) and high (blue) pump power cases, with the simulations in black. Axes of insets are idler power (W), and temperature (deg C) [vertical and horizontal respectively].

4. Conclusion and outlook

We have demonstrated a high-average power DFG based mid-IR source, generating 6.2 W at 3.35 µm. This is, to the best of our knowledge, the highest mid-IR power generated in a fiber-pumped single-pass DFG/OPA source. We also use focused Gaussian beam theory to verify our experimental results and find good agreement between theory and experiment. Beam quality measurements of the generated mid-IR light at high conversion levels will be presented, as well as ongoing work to further increase the mid-IR light through pump-MOPFA scaling.

References