Fibre laser based parametric amplification and difference frequency generation for tunable mid infrared sources

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Mid infra-red generation in compact configurations providing diverse pulsewidth and linewidth formats with average powers at the watts level offers a wide range of applications opportunities ranging from remote sensing and polymer machining to medical diagnostics and imaging. Although very significant progress has been made with fluoride-based fibre lasers, large gaps exist in the achieved spectral coverage, while although successful supercontinuum has been reported throughout the near and mid infra-red, operational power levels at any given wavelength and pulse formats are somewhat restricted. There are a vast number of laser-based solutions for achieving mid infra-red generation [1], improved versatility can, however, be achieved using conventional master oscillator power fibre amplifier configurations in the infra-red to pump both parametric amplification and difference frequency generation in crystals to extend operation throughout the mid infra-red with wavelength tunability. Here we report the performance of three exemplar configurations with an objective of achieving integrated, turn-key operation of these sources and power scalability.

For tunable generation in the region of 3 microns, where water and tissue exhibit high absorption, the simplest solution for pulse width and pulse repetition rate versatility is frequency difference generation of Yb and Er fibre MOPFAs in poled oxide crystals [2]. In an initial demonstration, the Yb pump was fed from an actively mode locked external fibre cavity semiconductor laser, generating pulses of ~150 ps that were amplified to average powers of ~ 23 W in two stages, with a linewidth of 0.13 nm. The Er-MOPFA based signal was seeded from a tunable external cavity laser diode (1500nm-1580nm) that was modulated by a Mach Zehnder modulator driven by an electrical pulse generator at the common clock signal around 39.945 MHz. This produced pulses of ~400 ps and a linewidth of 0.03 nm at an average power of ~ 2 W. An optical delay line allowed temporal overlap of the pump and signal at the 40 mm long, MgO:PPLN poled crystal with a poling period of 29.98 μm, which was mounted in a temperature controlled oven. The maximum focussed pump intensity was 28 $MWcm^{-2}$, well below the damage threshold of the crystal. Average idler powers of ~3.5W were recorded, tunable from 3.28 μm - 3.5 μm, limited only by the tuning range of the Er signal, and with long term idler stability better than 0.4%. Shorter idler output pulse durations can be achieved by varying the time delay, hence temporal overlap between the pump and signal, however with an accompanying reduction in conversion efficiency. By optimising overlap and increasing pulse durations average idler powers in excess of 6W with linewidths of ~0.2 nm were achieved.

Above 4 microns, oxide crystals exhibit increased absorption losses and the chalcopyrite crystals, such as $ZnGeP_2$ (ZGP) are the preferred hosts for optical parametric generation in the range 4-7 μm. One problem with ZGP is that pump wavelengths greater than 1.9 μm are required to avoid absorption associated with the small bandgap energy of the material. On the other hand, $CdSiP_2$ (CSP) with a bandgap energy of 2.45 eV permits pumping down to 1 μm (where phase matching supports idler generation 6-7 mm), although at this pump wavelength, two photon absorption can become problematic. High idler conversion efficiencies can be achieved, particularly when pumped at long wavelengths 1.5-1.9 μm, however, only with critical phase matching. Pumping around 1-1.3 μm allows non-critical phase matching and for pumps around 1.24 μm tunability in the range of 4 μm can be achieved via phase matched temperature tuning. Experimentally, this was demonstrated using a 1.24 μm Raman fibre amplifier as the pump source. A Yb-MOPFA generating 0.05-2 ns pulses at 1-20 MHz repetition rate and average powers up to 20W was used to pump a 5 m length of phosphosilicate amplifier fibre seeded by a 1 mw signal from a laser diode at 1.24 μm. Up to 8W at 1.24 μm was generated for a pump power of 12W at 1.064 μm. As the seed signal source for optical parametric generation in the 13 mm long CSP crystal, a spectrally filtered, cw-pumped fibre supercontinuum source was used. Centred around 1.7 μm with a bandwidth of ~ 30 nm, up to 200 mW was available in the filtered seed signal. Through using a cw signal source, the problem of temporal synchronism of the pump and signal was removed, while reducing the pump intensity threshold. A double pass geometry of the crystal was also utilised to further reduce the required pump threshold. For an average pump power of 2.6W, more than 0.25W of idler at 4.2 μm was generated. On temperature tuning the crystal from 25 ^{o}C to 175 ^{o}C, spectral tunability 4.2 μm to 4.6 μm was observed.

With DFG or OPA the requirement to provide temporally synchronised pump and signal sources complicates the experiment configuration, increases cost for commercial development, makes fibre integration more difficult and detracts from “turn key” operation. Using a cw signal, simplifies the configuration but generally results in lower conversion efficiency, consequently a pulsed pump and signal are preferable, hence requiring temporal synchronisation of the sources. Mechanisms to overcome this have been investigated in a 3 μm source using a $\chi^{(3)}/\chi^{(2)}$ cascaded nonlinear conversion configuration, deploying picosecond pulses, which has the potential to be fibre integrated and pumped by a single source. A Yb MOPFA providing 35 ps pulses at ~8 MHz and an average power of 5W was used to pump a 0.35m length of photonic crystal fibre. At a pump power of 3W, four wave mixing generated a Stokes signal ~1.64 μm. By integrating a PCF with different pitch and hole diameters, the dispersion zero, hence the phase matching conditions can be adjusted and alternative Stokes wavelengths generated. With the short fibre lengths deployed and for the power levels and pulse lengths used the undepleted pump and the generated Stokes signal were temporally synchronised at the output of the PCF. These were directed into a 10 mm long MgO:PPLN crystal with a 31.3 μm poling period generating an idler around 3.05 μm. On temperature tuning the crystal from 40^{o}C to 100^{o}C, the idler tuned from ~ 3.05 μm to 2.88 μm with a maximum average power of 115 mW in the idler at 60^{o}C. This source has been applied to ambient mass spectrometry imaging of porcine tissue as a preliminary proof of principle of source application. Work continues to extend the wavelength capabilities of the source and to enable full fibre integration.

References

[1] K.L.Vodopyanov, Laser-Based Mid-Infrared Sources and Applications, ISBN:9781118301814, Wiley, (2020)

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