MIRSURG

Mid-Infrared Solid-State Laser Systems for Minimally Invasive Surgery

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Specific Targeted Research
Theme 3: **Information and Communication Technologies (ICT)**

D3.3: High-power mid-IR SPOPO at 6.45 μm

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	Dissemination Level	
PU	Public	PU
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

1. Background

The goal of this deliverable was the development of a high-power SPOPO near the target wavelength 6.45 μm to provide the mid-IR radiation suitable for surgical applicaitons. One of the approaches envisioned in the original proposal was the use of cascaded two-step pumping using a near-degenerate 1st-stage SPOPO near 2 μm to provide the pumping radiation for the 2nd-stage SPOPO for the generation of 6.45 μm. However, as outlined in the 1st annual report and description of this deliverable in the first year, an equally effective approach was identified as the non-degeneate output of the 1st-stage SPOPO to provide idler radiation in the 3-4 μm spectral range. This would provide the pumping radiation for the 2nd-stage SPOPO based on ZGP in noncritical phase-mathcing (NCPM) configuration to ultimately delvier the output wavelength at 6.45 μm. To this end, during the second year of the project, we developed a high-power non-degenerate 1st-stage picosecond SPOPO based on MgO:PPLN pumped by an Yb fiber laser providing ~5 W of mid-IR output power in the 3-4 μm spectral range for use as pump for 2nd-stage SPOPO to provide the required mid-IR output radiation near 6.45 μm, as reported in the 2nd annual report.

In the meantime, during the 3rd year of the project, the availability of high-quality samples of the the new nonlinear optical crystal, cadmium silicon phosphide CdSiP$_2$ (CSP) [1], with unique nonlinear optical properties, provided an exceptional opportunuity for the realization of the envisioned source of mid-IR radiation near near 6.45 μm using alternative direct pumping scheme using a single-stage SPOPO appraoch. Among the important optical properties of CSP are a large band-gap which permit direct pumping at 1064 nm by deploying the most commonly available Nd-based solid-stae lasers, high effective nonlinear coefficient (d_{eff}~84.5 pm/V), and noncritical phase-matching (NCPM), which make it a uniquely attractive nonlinear material candidate for generating mid-IR wavelengths in the 6-6.5 µm range [2].

Using a high-quality sample of this new nonlinear material, we successfully developed a compact, high-repetition-rate SPOPO, synchronously pumped by a master oscillator power amplifier (MOPA) system at 1064.1 nm, generating an idler energy as high as 1.5 mJ at 6246 nm with a photon conversion efficiency of 29.5%. The SPOPO could be tuned over 486 nm, with more than 1.2 mJ over >68% of the tuning range in good spatial beam quality.

2. Experimental design

The schematic of the experimental setup is shown in Fig. 1. The pump laser is a high-energy master oscillator-power amplifier (MOPA) pump laser system supplied by the Partner Bright. The power amplifier is seeded by a 450 MHz passively mode-locked oscillator providing 5.4 ps micro-pulses. An acousto-optic modulator selects a train of micro-pulses with 1 µs duration (macro-pulse) at a repetition rate of 20 Hz and the successive amplifier stages increase the macro-pulse energy up to 50 mJ, corresponding to an average power of 1 W. This represents a single micro-pulse energy of 0.1 mJ with a measured pulse width of 8.6 ps. The pump laser operates at a central wavelength of 1064.1 nm and has an FWHM spectral bandwidth of 0.16 nm. This is shown in the inset of Fig. 1, relative to the parametric gain bandwidth of 0.33 nm for 12.1-mm-long CSP crystal, estimated using the relevant Sellmeier equations [1]. The output beam from pump laser has a diameter of 2 mm and a beam quality factor of M^2~1.1. The CSP crystal is a 12.1-mm-long, 4-mm-wide (along the c-axis), 5-mm-thick sample grown from stoichiometric melt by the horizontal gradient freeze technique [1]. It is cut at $\theta=90^\circ$, $\phi=45^\circ$ for type-I ($e \rightarrow oo$) interaction under NCPM and housed in an oven with temperature stability of ±0.1°C. Both crystal faces are antireflection coated with a single layer sapphire coating, providing high transmission (T>98.7%) for the pump and signal over 1064-1300 nm and T>76% for the idler over 6000-6500 nm. The SPOPO is configured as a singly-resonant oscillator in a compact linear standing wave cavity comprising two curved mirrors, M$_1$ and M$_2$, with radius of curvature r=3 m (ZnSe substrate). Both mirrors are highly reflecting (R>99%) for signal over 1200-1400 nm, and highly transmitting at 1064 nm (T>97%) and for the idler over 5500-7500 nm (T>98%). The pump beam has a waist radius of w_0~1.5 mm after the input mirror (M$_1$) to avoid any damage, while using the maximum aperture of the crystal. A dichroic mirror, M$_3$, highly reflecting (R>99%) at 1064 nm and highly transmitting (T>95%) for idler, separates the generated idler from the undepleted pump. In the measurements of energy and efficiency, all the data were corrected for transmission and reflection coating losses. The total round-trip optical length of the cavity, including the CSP crystal, is 666 mm, corresponding to a 450 MHz repetition rate, ensuring the synchronization with the pump laser.

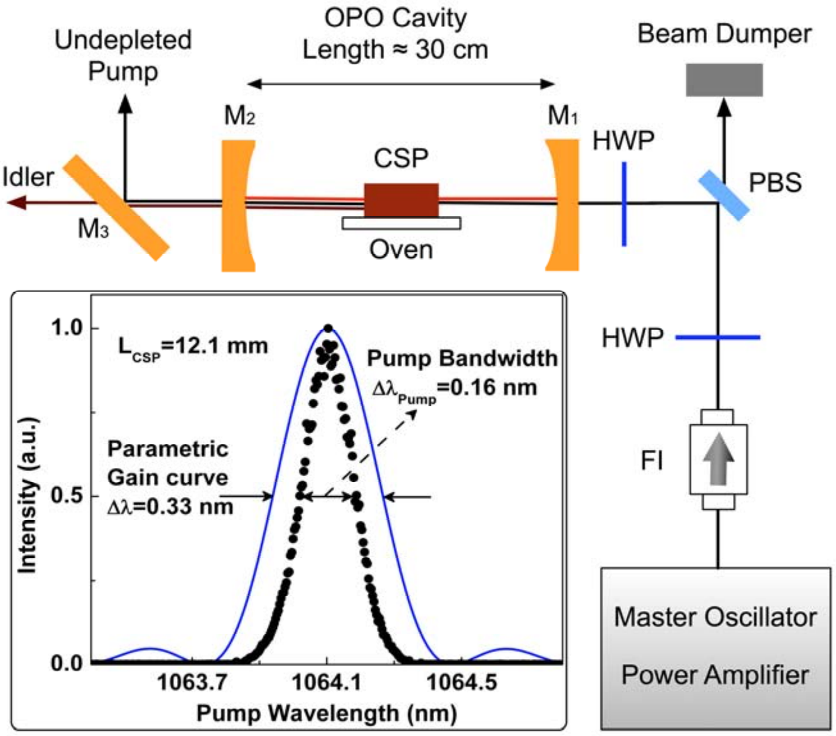

Fig. 1. Experimental setup of synchronously pumped high energy picosecond SPOPO. FI, Faraday isolator; HWP, Half-wave-plate; PBS, Polarization beam splitter; M, Mirrors. Inset: Pump laser spectrum relative to parametric gain bandwidth for 12.1-mm-long CSP crystal.

3. Results

We first determined the residual loss of the CSP crystal at the pump from the measured transmission data at 1064.1 nm. As depicted in Fig. 2, we observed a drop in the transmission of CSP crystal with increasing pump intensity, showing a nonlinear behavior. Using a simple two photon absorption model, we fitted the measured data for linear (α) and two photon (β) absorption coefficients, resulting in a value of α=0.075 cm^{-1}, β=2.4 cm/GW for *extraordinary* (e) and α=0.15 cm^{-1}, β=2.6 cm/GW for *ordinary* (o) polarizations. These values indicate the improved quality of this crystal as compared to the earlier samples [3-6]. Further, using this data, we have estimated the energy band gap (E_g) resulting in the values of 2.08 eV (e) and 2.06 eV (o), confirming the large band gap of CSP.

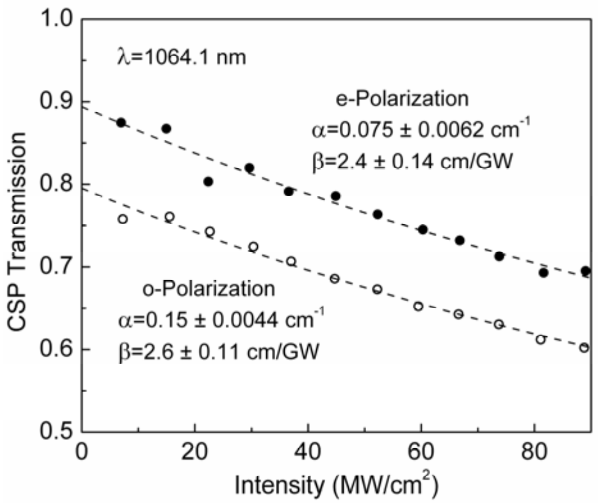

Fig. 2. CSP transmission as a function of pump intensity for o- and e-polarization at 1064.1 nm.

We characterized the SPOPO with regard to output pulse energy and tunability by varying the crystal temperature at constant pump energy of 30 mJ. Figure 3 shows the extracted idler energy as well as the transmission of CSP crystal across the tuning range. Using a 500 μm fused silica etalon, we extracted part of the intracavity signal to monitor the wavelength. The signal wavelength was recorded by using a low-resolution (~10 nm) InGaAs spectrometer (Ocean Optics, NIR Quest), and was further confirmed by single-pass second harmonic generation into the red in a 5 mm type-I (oo→e) BBO crystal. The idler wavelength was inferred from the second harmonic of the signal, which was measured using a high resolution (~1 nm) CCD array spectrometer (Ocean optics, USB 4000).

By changing the CSP crystal temperature from 30ºC to 180ºC, we could tune the idler wavelength from 6091 to 6577 nm, corresponding to a total tuning range of 486 nm. The generated idler energy varies from 1.3 mJ at 6091 nm to 1 mJ at 6577 nm, reaching a maximum of 1.5 mJ at 6275 nm, with >1.2 mJ over >68% of the tuning range. This represents a maximum idler energy conversion efficiency of 5% and a photon conversion efficiency of 29.5%. The drop in the idler energy towards the longer wavelengths is attributed to the water absorption peak near 6.4 μm and residual multi-phonon absorption in the CSP crystal, resulting in reduced transmission, as evident from Fig. 3. The corresponding pump depletion is recorded to be >42% over more than 64% of the tuning range with a maximum pump depletion of 51% at 6483 nm. Also shown in the inset of Fig. 3 is the macro-pulse envelope of the input and the depleted pump, measured using a fast photodiode, at 30ºC, corresponding to an idler wavelength of 6091 nm, clearly showing >50% depletion.

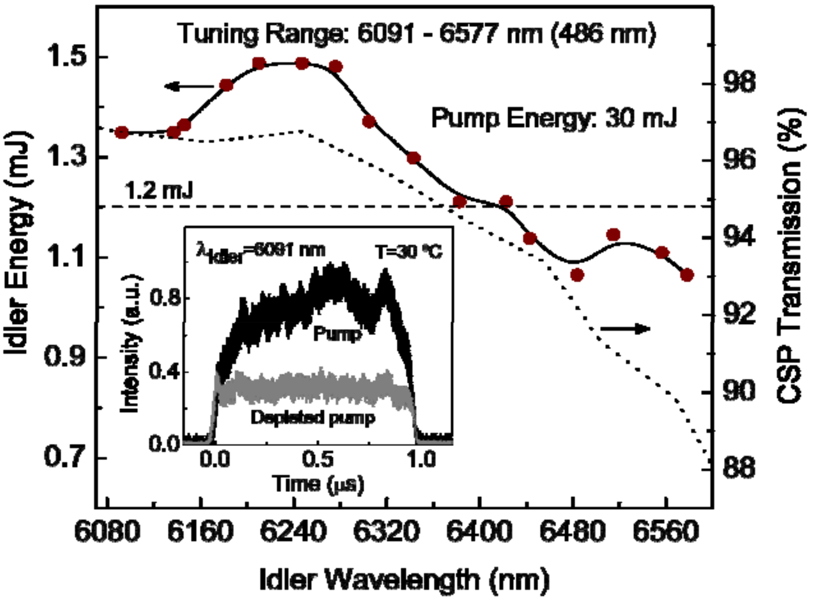

Fig. 3. Idler energy and CSP transmission across the tuning range. Inset: Macro-pulse envelope of the input pump and the depleted pump.

We also performed idler energy scaling measurements at different wavelengths across the SPOPO tuning range. The variation of the idler energy and pump depletion as a function of the pump energy obtained at a temperature of 30ºC corresponding to an idler wavelength of 6091 nm is shown in Fig. 4. As evident from the plot, 1.35 mJ of idler is obtained for a pump energy of 30 mJ at a slope efficiency, η=4.6%, implying a peak idler energy efficiency of 4.5%, representing a photon conversion efficiency of 25.7%. The threshold pump energy is measured to be 0.7 mJ, corresponding to single micro-pulse energy of 1.5 μJ and strong pump depletion reaching >50% is achieved above input pump energy of 5 mJ. The peak efficiency in this experiment was limited by the low optical damage threshold of the single layer sapphire coating on the CSP crystal, observed beyond 30 mJ of pump energy. Increasing the pump energy to 31.5 mJ, representing a peak intensity of 100 MW/cm^2, resulted in surface damage on the input face of the crystal, while no damage was observed on the exit face, indicating that the damage is due to the pump beam. Although the damage did not prevent SPOPO operation, a substantial drop of 37% in the idler energy was noticed. We also characterized the SPOPO near 6400 nm, a technologically important wavelength for surgical applications [7], as shown in the inset of Fig. 4. At a 130ºC, corresponding to an idler wavelength of 6422 nm, an idler energy up to 1.1 mJ is generated for a pump energy of 30 mJ at a slope efficiency of η=3.8%, with an increased threshold pump energy of 1.6 mJ due to water absorption and reduced crystal transmission.

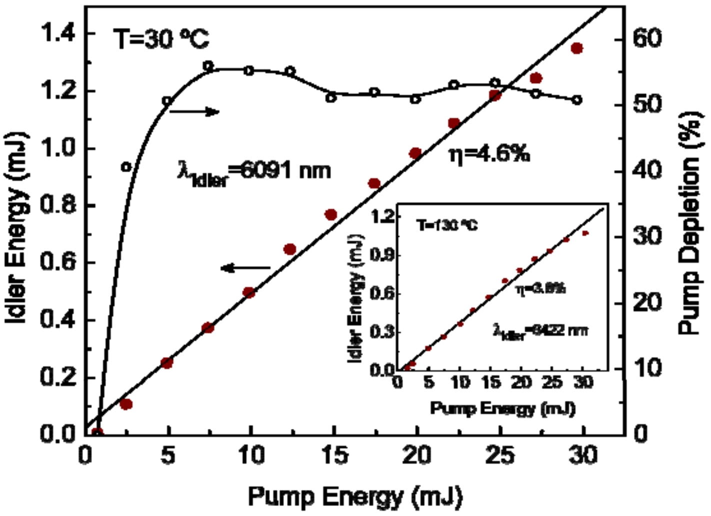

Fig. 4. Idler energy scaling and pump depletion as a function of input pump energy at λ_{Idler}=6091 nm. Inset: Idler energy scaling at 6422 nm.

Further, we have measured the duration of the signal pulses extracted from the SPOPO using a home-made autocorrelation setup. Figure 5 shows the measured autocorrelation profile at 1289 nm, where the amount of signal energy extracted from the cavity was >1.3 mJ for an incident pump energy of 30 mJ. The FWHM of the trace is 16.3 ps, resulting in the signal pulse duration of 10.6 ps, assuming a sech^2 pulse shape. This value of pulse duration was confirmed by repeating the measurement several times, and similar pulse duration is expected across the tuning range. Also shown in the inset of Fig. 5 is the signal beam profile at 1289 nm, measured using a pyroelectric camera (Spiricon, Pyrocam-III).

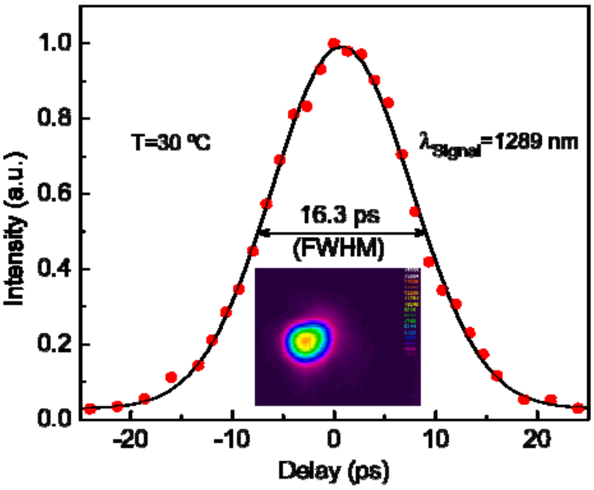

Fig. 5. Typical autocorrelation of the SPOPO signal pulse at 1289 nm, with a duration of 10.6 ps (x1.54, assuming sech^2 pulse shape). Inset: Signal beam profile at 1289 nm.

The corresponding idler beam profile at 6091 nm, recorded at the full output energy, is shown in Fig. 6. Both signal and idler beam profiles confirm good beam quality in TEM_{00} spatial mode, which is important for surgical applications.

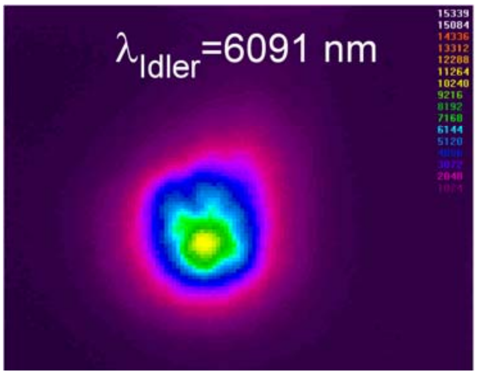

Fig. 6. Spatial beam profile of the idler pulse at 6091 nm, showing TEM_{00} mode.

4. Summary

We have thus successfully developed a highly compact, efficient and high-energy picosecond SPOPO at 450 MHz repetition rate which can provide generating high-energy mid-IR pulses near 6.45 μm using direct pumping at 1064 nm [8]. The SPOPO exploits the new nonlinear material CSP and is synchronously pumped by a MOPA laser system developed by Partner Bright. The SPOPO can be tuned over 486 nm across 6091-6577 nm, covering the technologically important target wavelength of 6.45 μm for surgical applications. Using a compact (~30 cm) cavity and improved, high quality nonlinear crystal, an idler macro-pulse energy as much as 1.5 mJ has been obtained at 6275 nm at a photon conversion efficiency of 29.5%, and >1.2 mJ over more than 68% of the tuning range, for an input macro-pulse energy of 30 mJ. Both the signal and idler beams are recorded to have good beam quality with TEM_{00} spatial profile, and the extracted signal pulses are measured to have durations of 10.6 ps. The compact design, high energy, suitable pulse structure, and the potential for energy scaling using larger aperture crystals, make the SPOPO a promising source for practical surgical applications in the mid-IR, as envisioned in the MIRSURG project.

References

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