MIRSURG

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

Grant agreement no.: 224042

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

D3.2: High-power 1st stage quasi-CW SPOPO

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Actual submission date: month 12

Start date of project:	01/06/2008
Duration:	3 years
Organisation name of lead contractor for this deliverable:	ICFO The Institute of Photonic Sciences

Project co-funded by the European Commission within the Seventh Framework Programme (2008-2011)		
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 activities of the ICFO partner during the first 12 months of the MIRSURG project have been focused on the realization of the 1st-stage quasi-cw picosecond SPOPO for high output power generation and wavelength tuning near 2 μm, to be then deployed as the pump for a secondary SPOPO providing output at 6.45 μm. A schematic of the proposed experimental setup for the cascaded SOPO is shown in Fig. 1. The primary fist-stage SPOPO is designated at OPO 1, while the second-stage SPOPO is designated as OPO 2. The main research efforts during the first 12 months of the MIRSURG project concern the development of OPO 1.

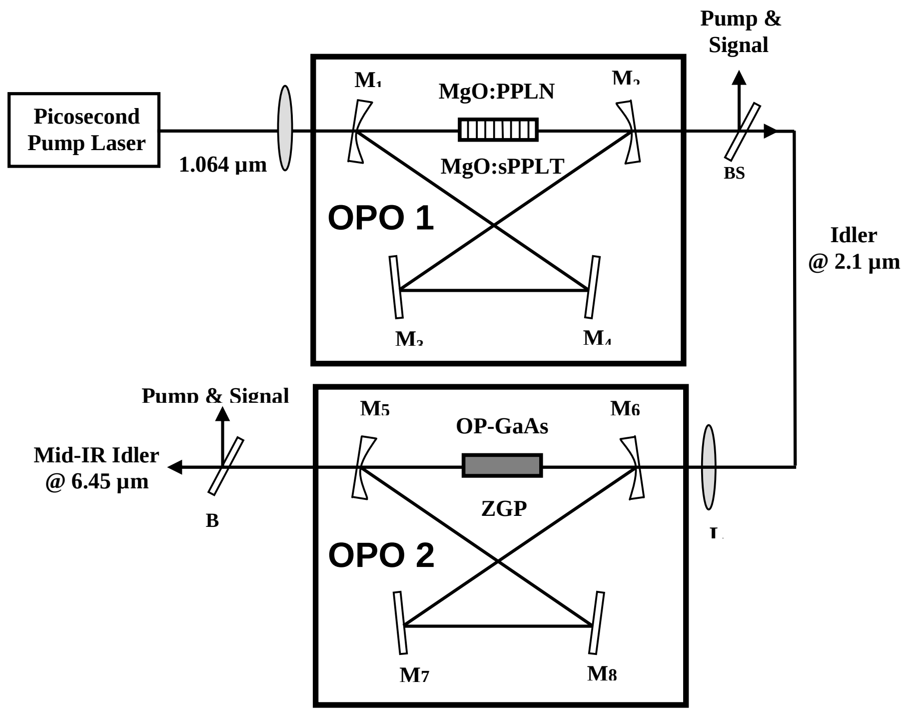

Fig. 1. Schematic of the proposed experimental configuration for the cascaded OPO.

2. Laser pump source

The choice of laser pump source was governed by the need for an ultimately practical, compact, and portable system for surgical procedures. With the rapid advances in high-power ultrafast fiber laser technology, coinciding with the start of the MIRSURG project, a unique and timely opportunity was presented for the procurement of a high-power picosecond Yb fiber laser as the primary pump for the proposed SPOPOs. A photograph of the fibber laser system is shown in Fig. 2 and the performance parameters of the laser are listed in Table 1. Although this laser will not be the system to be ultimately deployed for the proposed surgical applications in the MIRSURG project, its choice was envisioned to help establish many of the critical design and performance parameters that would be attainable for an SPOPO system at 6.45 μm that could be ultimately realized in an all-fiber format in the future.

Fig. 2.
Picosecond Yb fiber laser
(Fianium, FP1060-20)

Parameter	FP1060-20
Maximum Average Power	20 W
Central Wavelength	1064nm +/- 1nm
Spectral Bandwidth	<1nm
Repetition Rate	80 MHz
Pulse-Pulse Stability	<1% rms
Pulsewidth	20 ps
Beam Diameter	2 mm
Circularity	>95%
M^2	<1.3
Divergence	TBD
Optical Isolation to Back Reflections	>35dB
Power Consumption	<200W
Cooling	Air Cooled

Table 1. Performance parameters of the picosecond Yb fiber laser.

This laser system was delivered to the ICFO partner laboratory in December 2008. Following its delivery, the laser was carefully characterized with regard to all important operating parameters, with the results shown in Figs. 3-6.

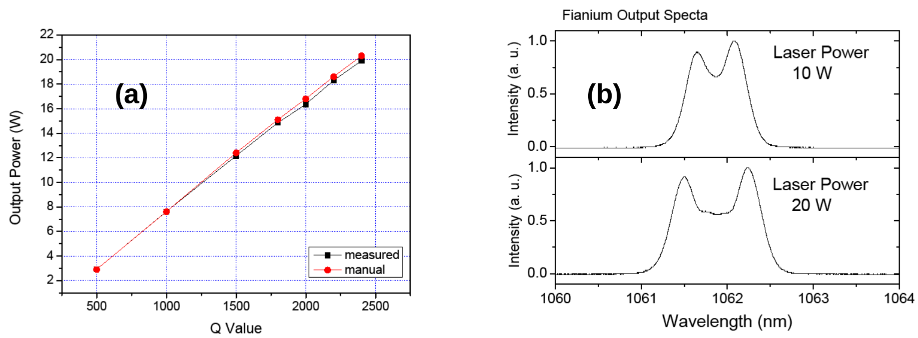

Fig. 3. Measurement of (a) average optical output power as function of input drive power to the picosecond Yb fiber laser, and (b) spectral characteristics at 10 W and 20 W of average output power.

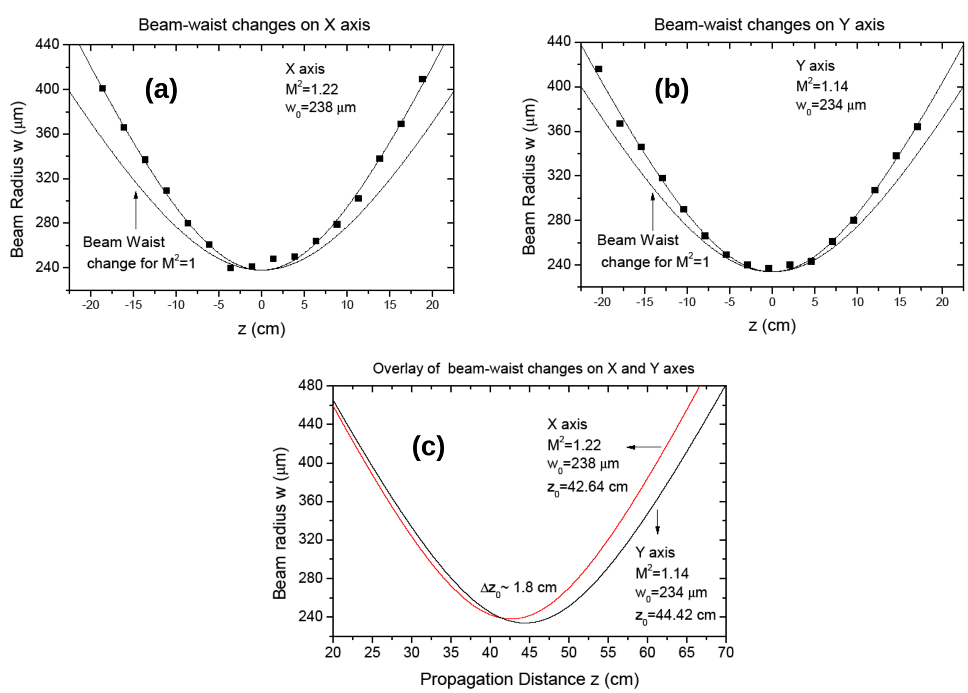

Fig. 4 (a)-(c) Measurements of beam quality factor M^2 along the orthogonal X and Y axes of output beam from the picosecond Yb fiber laser, and (c) the overlay of the beam waists along the propagation axis, Z.

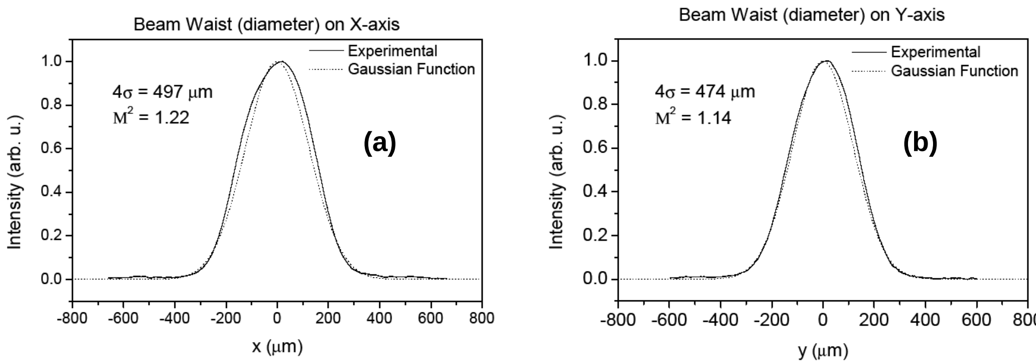

Fig. 5 (a), (b) Intensity profiles of the output beam from the picosecond fiber laser along the orthogonal X and Y axes and the corresponding Gaussian fits, confirming near TEM_{00} spatial profiles.

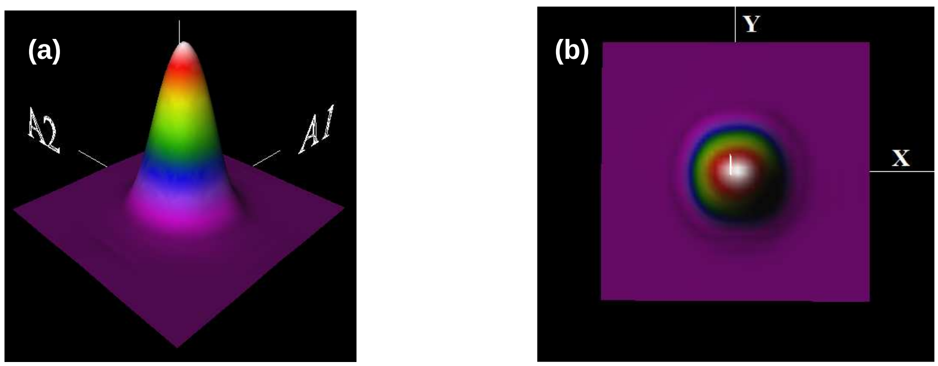

Fig. 6 (a), (b) Recorded intensity profiles of output beam from the picosecond Yb fiber laser, confirming Gaussian and TEM_{00} spatial beam profiles.

3. Nonlinear Crystal

The choice of the nonlinear material for the 1st-stage SPOPO (OPO 1 in Fig. 1) was determined by the need to provide output radiation in a suitable wavelength range near- to mid-IR (2 to 4 µm), and at sufficient power, to pump the 2nd-stage SPOPO (OPO 2 in Fig. 1) in order to generate 6.45 µm output in the most efficient and effective phase-matching geometry. While it was originally envisaged that the optimum configuration to achieve this outcome would be a 1st-stage SPOPO operated near degeneracy close 2.1 µm, subsequent studies revealed a more effective geometry based on noncritical phase-matching (NCPM) in MgO:PPLN. In this scheme, the 1st-stage SPOPO would provide idler output at high power and with wide wavelength tuning in 2.3-3.6 µm range under temperature-tuned NCPM, thus providing most suitable pump wavelength for the 2nd-stage SPOPO based on ZGP, also under NCPM, to deliver mid-IR output at 6.45 µm. The expected temperature tuning curves for the 1st-stage SPOPO based on MgO:PPLN under NCPM, calculated from the temperature dependent Sellmeier equation for the material for different grating periods, are shown in Fig. 7 (a). In Fig 7 (b), the predicted tuning range of the 2nd-stage SPOPO based on ZGP, under NCPM, and pumped by the idler output from 1st-stage SPOPO is shown, clearly confirming the feasibility of output generation at the target wavelength of 6.45 µm using a grating period of Λ=31 µm near room temperature.

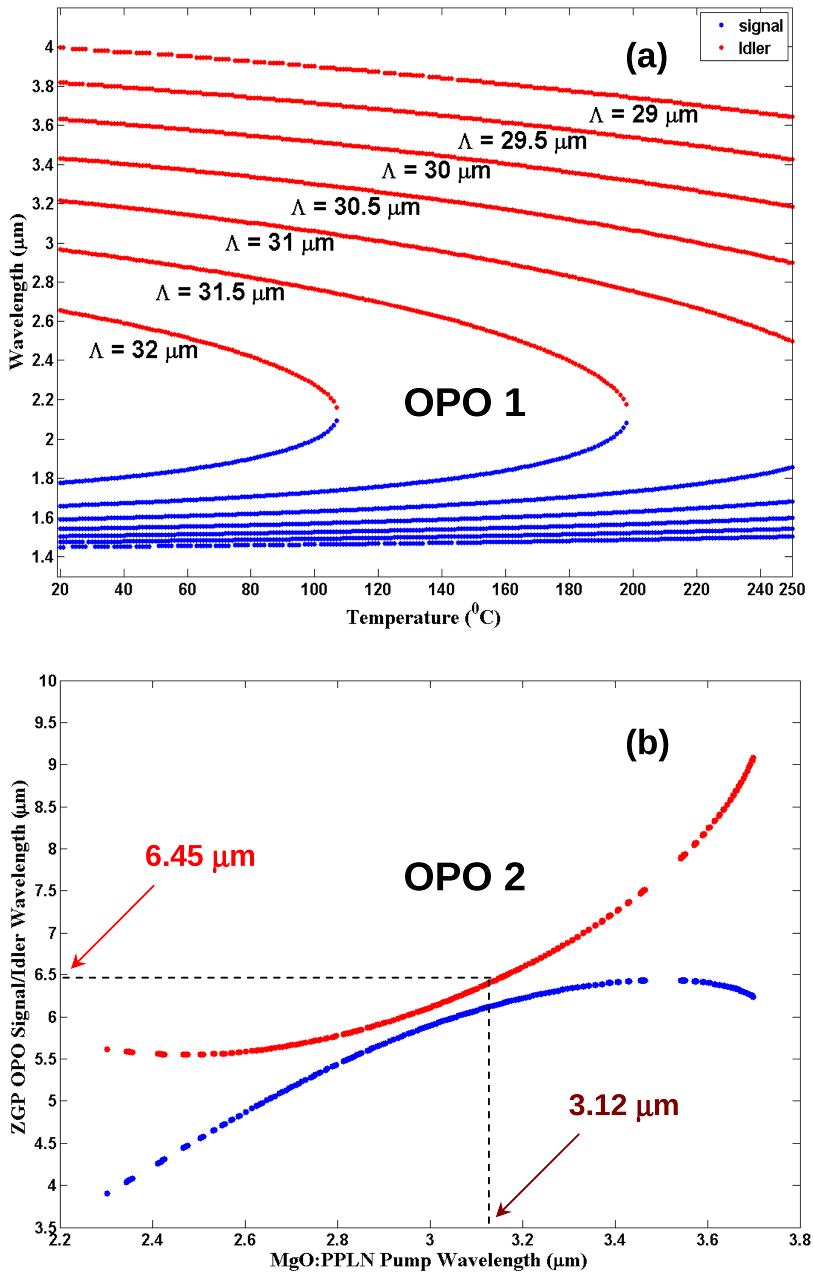

Fig. 7. (a) Temperature tuning curves for the 1st-stage SPOPO based on MgO:PPLN under NCPM with different grating periods. (b) Pump tuning curves for 2nd-stage SPOPO based on ZGP under NCP using the idler output of the temperature-tuned MgO:PPLN-based SPOPO in (a).

4. Experimental Results

Having determined the optimum design parameters for the 1st-stage SPOPO, we procured the necessary components for the implementation of the device, including the MgO:PPLN gain crystal, cavity mirrors with suitable coatings, focusing optics for the pump, and suitable transmission optics for the extraction of the signal and idler output from the oscillator. We deployed a 50-mm-long, 5%-doped MgO:PPLN crystal, with five different grating periods ranging from 29.5 μm to 31.5 μm, in steps of 0.5 μm. The crystal was housed in an oven that can be temperature tuned from room temperature to 200 °C. MgO:PPLN crystal, with multiple gratings, which was antireflection coated at pump and signal wavelengths.

During the period coinciding with the implementation of the 1ststage SPOPO, however, we encountered some technical difficulties with the operation of the picosecond Yb fiber laser with regard to output power and pulse-to-pulse stability, necessitating the return of the laser to the manufacturer for inspection, repair, and upgrade. This resulted in the absence of the laser from the ICFO partner laboratory until early May 2009. In the meantime, in the interest of timely progress of the project and to avoid any delays in the implementation of the 1st-step SPOPO, we deployed a high-power, continuous-wave (cw) Yb fiber laser at 1064 nm available in the ICFO partner laboratory as an alternative pump source to achieve operation of the 1st-step SPOPO, but in cw operation. In addition to avoiding lengthy delays, the implementation of the 1st-step OPO in cw operation, using the same pump wavelength at 1064 nm and similarly high power, would also provide valuable data on many important operating parameters and design benchmarks for the 1st-stge picosecond SPOPO, including the expected signal and idler wavelength tuning range, attainable output power and efficiency, and potential influence of thermal effects in the nonlinear material at high pump powers on the OPO performance.

A schematic of the experimental setup is shown in Fig. 8. The fundamental pump source used was a cw Yb fiber laser (IPG Photonics, YLR-30-1064-LP-SF), delivering linearly polarized, single- frequency radiation at 1064 nm with maximum output power up to 30 W. An isolator at the output end of the fiber protects the laser from any back reflections. The pump source has an M^2<1.01 and a nominal linewidth of 89 kHz.

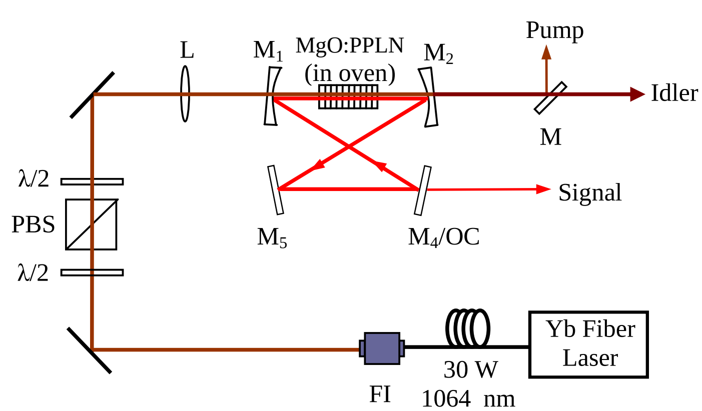

Fig. 8. Experimental setup of the cw OPO based on MgO:PPLN crystal pumped by a 30-W cw Yb fiber laser at 1064 nm. FI: Faraday isolator, λ/2: Half-wave plate, PBS: Polarizing beam splitter, L: Lens, M_1 , M_2: Plano-concave mirrors, M_3 , M_4:Plane mirrors, OC: Output coupler, M : Dichroic mirror.

In order to maintain stable output characteristics, the pump laser was operated at the maximum power and the fundamental power to the crystal was varied by using a combination of half-wave plate and polarizing beam splitter. A second half-wave plate was used to control the polarization for phase-matching in the MgO:PPLN crystal. The pump beam was focused to a beam waist radius of 67 μm at the centre of the crystal. The OPO was configured in a symmetric ring resonator comprising two plano-concave mirrors, M_1 and M_2, and two plane mirrors, M_3 and M_4. All mirrors had R>99%@ 1.3-1.9 μm and T>90%@2.2-4 μm, thus ensuring singly-resonant oscillator (SRO) configuration at the signal, with non-resonant idler extracted in a single pass through the OPO cavity. Output coupling of the SRO could be achieved by replacing one of the mirror (M_4), which was high reflecting at the signal wavelength, by an output coupler with T~5% across 1.3-1.9 μm. Optimized focusing for the pump and careful cavity design ensured good overlap of the pump and generated signal beam waists at the center of the MgO:PPLN crystal. A dichroic mirror, M, was used to separate the generated idler from the transmitted pump.

The OPO was tuned by changing the temperature of the nonlinear crystal. Varying the crystal temperature from 55 to 120 °C resulted in the generation of idler wavelength over 133 nm, from 3015 to 3148 nm, with a single grating period grating period of 31 µm. Using all highly reflecting mirrors for M_1-M_4, and in the absence of any signal output coupling, we were able to generate >7.1 W of cw output power across the entire tuning range of the idler in the mid-IR for an input pump power of 25 W at the input to the OPO crystal, as shown in Fig. 9(a). At this level of input pump power, we also recorded pump depletions >81% across the entire OPO tuning range, as shown in Fig. 9(b).

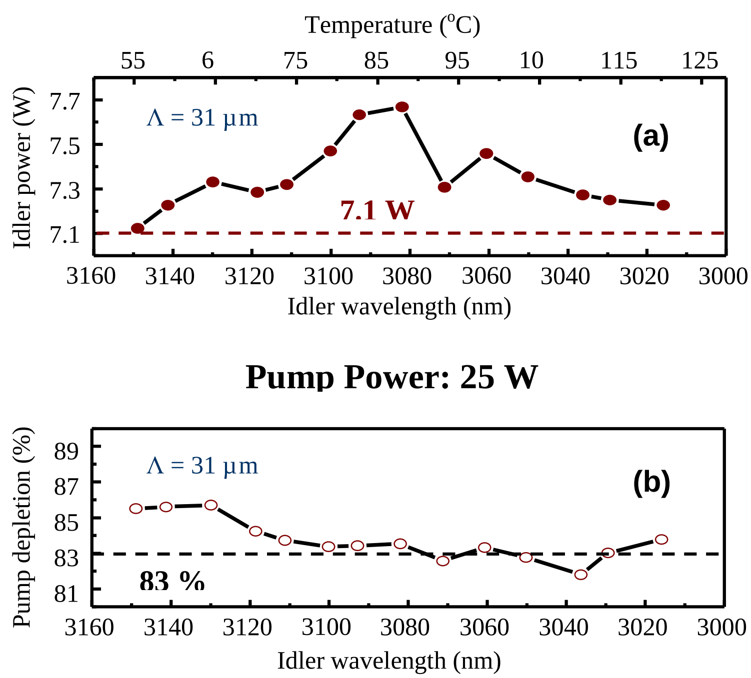

Fig. 9. (a) Extracted mid-IR idler power, and (b) pump depletion, across the idler tuning range for 1st-stage cw OPO, in the absence of signal output coupling.

We also performed power scaling measurements of the idler at a fixed temperature of 100 °C. A maximum output idler power of 7.6 W was generated at 3060 nm at a pump depletion >85%, using the 31 µm grating period (Fig. 10). As can be seen, a saturation effect is observed in the idler power at higher pump powers, which we attribute to increasing thermal loading of the

MgO:PPLN crystal due to higher pumping powers and larger intracavity signal intensities in the absence of signal output coupling.

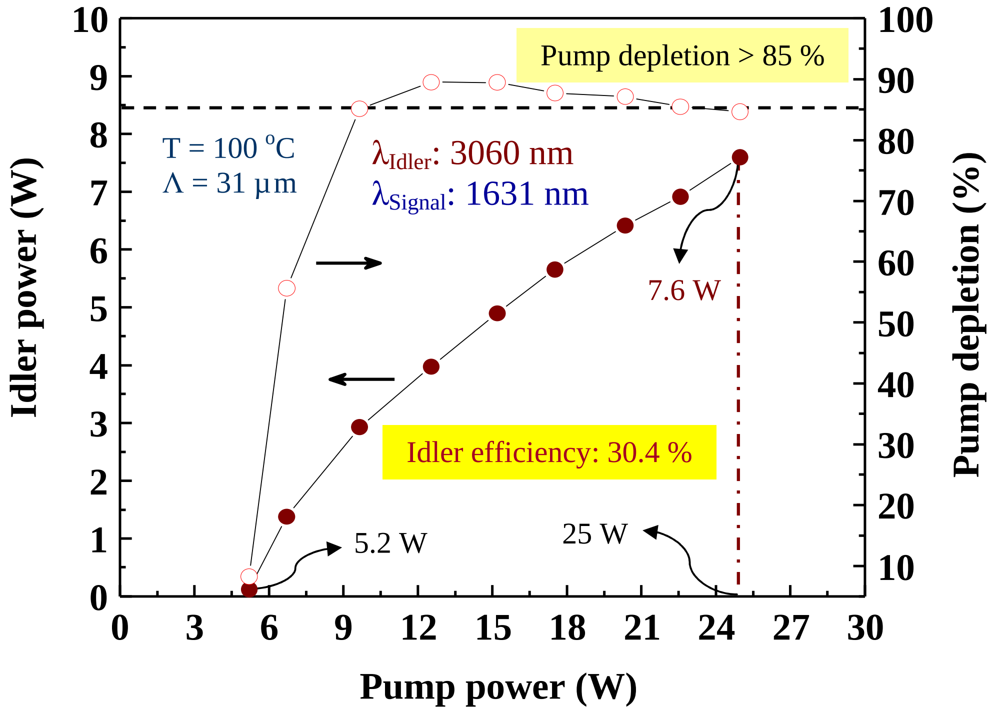

Fig. 10. Extracted idler power and pump depletion as functions of input pump power to the 1st-stage cw OPO in the absence of signal output coupling.

Given the saturation in idler output power at higher pump powers due the large circulating signal powers internal to the OPO cavity, evident in Fig. 10, it was determined that thermal loading of the crystal could be more efficiently addressed by partial output coupling the signal power from the OPO cavity. In addition to alleviating excessive thermal heating of the crystal, this strategy would also provide useful signal output as well as idler power, would significantly extend the useful tuning range of the OPO, and also increase the extraction efficiency of the device. To this end, we deployed an output-coupled (OC) SRO configuration, where one of the plane mirror in the SRO cavity (M_4 in Fig. 8) was replaced by a 5% output coupler. The performance comparison of the two OPO configurations with regard to power scaling is shown in Fig. 11. The measurements were performed for a grating period of 31 µm at a temperature of 100 ^{o}C. While the OC-SRO configuration was characterized by a higher threshold than the SRO, we were able to extract up to 8.3 W of signal output power at 1629 nm simultaneously with an idler power of 8.3 W at 3067 nm, resulting in a total output power of 16.6 W for 26.8 W of input pump power (Fig. 12). This corresponds to an overall power extraction efficiency (signal plus idler) as high as 62%.

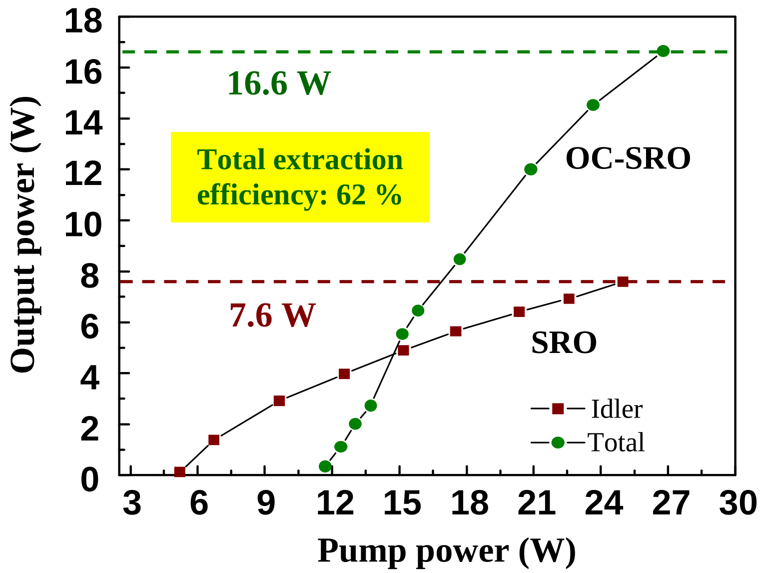

Fig. 11. Comparison of threshold and total extracted output power from the 1st-stage cw OPO in SRO and OC-SRO configurations as a function of pump power, for a grating period of 31 µm at a phase-matching temperature of 100 °C.

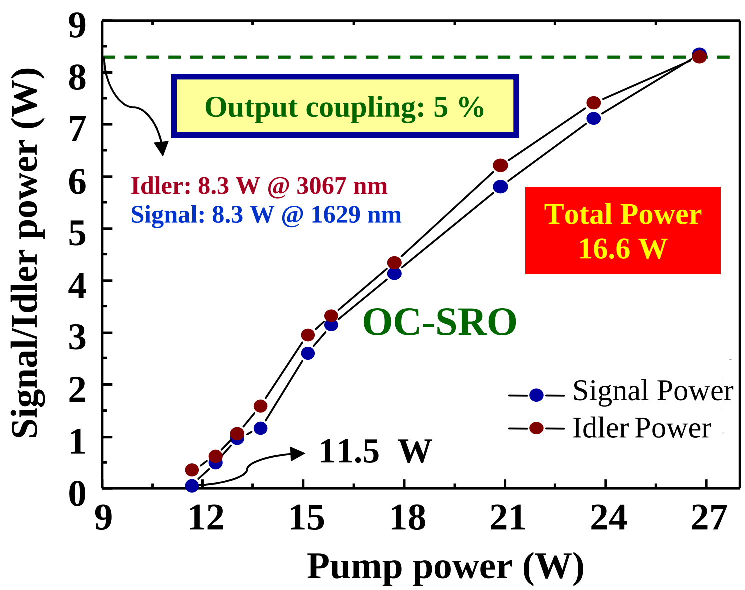

Fig. 12. Total extracted signal and idler output power from the 1st-stage cw OPO in OC-SRO configuration as a function of pump power, for grating period of 31 µm at a phase-matching temperature of 100 °C.

Operation of the 1st-stage cw OPO in the OC-SRO enabled continuous wavelength tuning of the crystal from room temperature to 125 °C, resulting in the generation of the signal wavelengths from 1593 to 1645 nm and idler wavelengths ranging from 3012 to 3204 nm using the 31 µm grating period, as shown in Fig. 13. The OC-SRO can maintain signal and idler powers of >7 W almost throughout the entire tuning range. It is also evident that the OC-SRO configuration, in addition to providing substantial signal power and usable signal tuning range, has also extended the available idler tuning range from 3015-3148 nm in the SRO to 3012-3204 nm in the OC-SRO. This can be attributed the reduction in intracavity signal power due to output coupling, thus reducing thermal loading of the crystal, and hence permitting OC-SRO operation at lower crystal temperatures down to room temperature. On the other hand, in SRO operation, crystal heating effects due to absorption of high circulating signal intensities prevented room-temperature operation of the OPO.

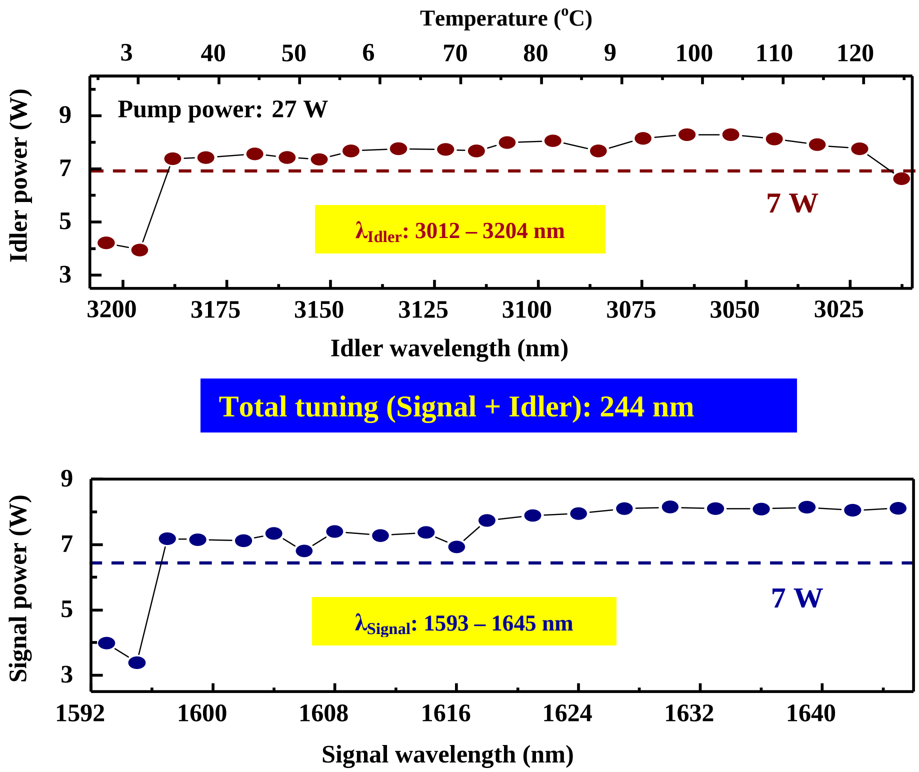

Fig. 13. The extracted idler and signal power from the 1st-stage cw OPO in OC-SRO configuration across the tuning range for grating period of 31 µm by varying the phase-matching temperature from room temperature to 125 °C.

5. Conclusions and Outlook

In the first 12 months of the MIRSURG program, the ICFO partner has thus achieved an important first objective by successfully demonstrating a 1st-stage OPO for the near- and mid-IR capable of providing unprecedented output power of 16.6 W at 62% extraction efficiency. In addition to >8 W of near-IR signal power, the demonstrated OPO provides up to 8.1 W of idler output power over a tunable range of 3012-3204 nm the in the mid-IR. The generated idler power and tuning range are ideally suited for the development of the 2nd-stage OPO based on ZGP under NCPM for the generation of mid-IR output at the target wavelength of 6.45 µm. Although the described 1st-stage OPO has exploited a high-power cw Yb fiber laser instead of a picosecond Yb fiber laser as the pump source, the experimental results have provided extremely valuable insight and important benchmarks for the realization of the picosecond SPOPO. In particular, we have established that extremely high output powers in excess of 8 W with extended tuning in the mid-IR can be achieved with high pump depletion and at high extraction efficiencies using fiber laser pumping. Moreover, we have studied the effects of thermal loading on the OPO performance and have established that thermal heating of the crystal can be minimized by using signal output coupling in an OC-SRO configuration. Given the near-identical design for the 1st-stage picosecond SPOPO to the cw OPO already developed during the first 12 months of the project, and with the availability of the picosecond Yb fiber laser in the ICFO partner laboratory, direct application of the described techniques will readily lead to the successful realization of the 1st-stage SPOPO, and this is currently being implemented. We expect to have the corresponding results on the performance of the 1st-stage picosecond SPOPO within the coming months. In addition, the design studies of the 2nd-stage cw OPO and picosecond SPOPO based on ZGP are also already underway, and the necessary components including the nonlinear material, focusing optics, OPO mirrors, and mid-IR detection and measurement diagnostics are currently being acquired. We, therefore, believe that during the neat 12 months of the MIRSURG project, substantial further progress will be achieved in the realization of the 2nd-stage OPO for the generation of output radiation at 6.45 μm.

Publications

1. S. C. Kumar, R. Das, G. K. Samanta, and M. Ebrahim-Zadeh, “Generation of 16.6 W of tunable mid-infrared radiation with an Yb-fiber-laser-pumped, continuous-wave optical parametric oscillator”, *4th International Conference on Mid-Infrared Coherent Sources*, *MICS´2009*, Trouville, France, paper Mo10 (June 2009)

2. S. C. Kumar, R. Das, G. K. Samanta, and M. Ebrahim-Zadeh, “16.6 W, continuous-wave, Yb-fiber-laser-pumped, singly-resonant optical parametric oscillator based on MgO:PPLN”, *CLEO/Europe-EQEC*, Munich, Germany, paper CD7.2 THU (June 2009).