1. Publishable summary

The MIRSURG project, comprising researchers from 9 European institutes and companies, is focused on the development of a laser source that will enable minimally invasive neurosurgery. The laser should emit at a wavelength near 6.45 µm and provide high single pulse energy and average power. The penetration depth at this wavelength will be comparable to the cell size (several micrometers), which will make it possible to avoid collateral damage when ablating the tissue. Conventional lasers for tissue ablation operate at wavelengths either near 2 µm or at 10.6 µm, evaporating the tissue as a result of the strong water absorption. The idea to perform neurosurgery with lasers emitting in the mid-infrared (mid-IR) spectral range near 6.45 µm, where non-aqueous resonant tissue absorption also comes into play, has been known for at least 15 years. However, suitable lasers operating at this wavelength could not be developed in the past.

Previous experiments in USA have verified that the use of mid-IR free-electron-lasers (FELs) at wavelengths near 6.45 µm, with a penetration depth of the focused beam comparable to the cell size and coupled both into the spectral wing of the water bending mode and the amide-II vibrational mode, results in tissue ablation with minimal collateral damage and very effective ablation rate. This finding is extremely important as a useful tool for minimally invasive human surgery. However, the clinical use of FELs is ultimately not viable due to large size, high cost, operational complexity and restricted access at a few multi-million-dollar accelerator-based facilities worldwide. Therefore, it is important to develop new technologies to replace the FELs for practical clinical applications in human surgery. If the promising results so far obtained with the mid-IR FELs could be reproduced or even improved using lasers based on more practical alternative technologies, then the engineering effort to develop compact, inexpensive, table-top laser systems suitable for clinical use will be well justified.

Thus, the main objective of MIRSURG is to develop advanced table-top solid-state photonic sources for a specific wavelength in the mid-IR spectral range, as a practical, reliable and cost-effective alternative to large-scale FELs, for an important application in biomedicine (health): minimally invasive surgery (MIS).

Several attempts to develop non-FEL alternatives have largely failed to meet the necessary requirements in terms of pulse energy and repetition rate. In fact, no suitable lasers exist that emit in this wavelength region. Frequency conversion in nonlinear optical crystals, however, makes it possible to transform the wavelength of powerful near-IR lasers into the mid-IR to reach the target wavelength of 6.45 µm. The main strategy in the project MIRSURG is to exploit nonlinear optical techniques (optical parametric oscillators, OPO) in combination with novel near-IR laser pump sources (near 1 and 2 µm) and new materials (e.g. orientation patterned GaAs), to obtain an unprecedented energy level near 6.45 µm at a repetition rate of 100 Hz. Two basic approaches, differing in the time structure, will provide less than few µs (macro) pulse duration. The project encompasses four distinct elements: (1) Material research; (2) Pump laser development; (3) OPO development; and (4) Validation in tissue ablation experiments.

The MIRSURG project is focused on the design and realization of solid-state laser systems operating near 6.45 µm with temporal structure suitable for MIS. The requirements, as derived from the unique experience with FELs and some very preliminary and mostly unsuccessful experiments with three alternative sources can be summarized as follows:

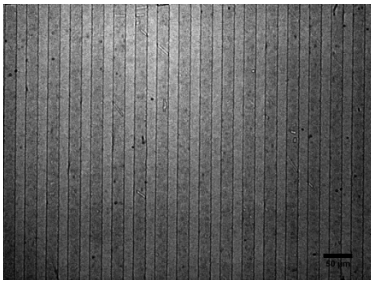
- the pulse duration may vary from a few nanoseconds (single pulse version) to a few microseconds (macro-pulse version).
- there is minimum pulse energy for efficient tissue ablation and ~10 mJ at 6.45 µm are desirable.
- effective MIS will require a sufficiently high pulse repetition rate. Thus, the goal is to have a

repetition rate of ~100 Hz which, at a pulse energy of ~10 mJ, translates into an average power of ~1 W. Variable repetition rate on the other hand would allow one to study its influence (at least above 30 Hz, the maximum for FEL) on the soft tissue ablation process.

The proposed approaches for generating 6.45-µm radiation for MIS rely on OPOs, as no laser media exist currently which allow a direct emission at this wavelength.

The material research within MIRSURG focuses on nonlinear optical crystals suited to meet the requirements of MIS with unprecedented advantages, including easier availability. Indeed, ZGP, as one of the most promising candidates for the proposed MIS application, is available only from non-European suppliers or institutions.

The route followed in this project is built on former demonstrations of Orientation-Patterned Gallium Arsenide (OP-GaAs), relying on a special epitaxial growth step (based on Hydride Vapour Phase Epitaxy or HVPE), fast enough to obtain hundreds of microns-thick layers on substrates pre-patterned with the suitable Quasi-Phase Matching (QPM) period. OP-GaAs provides a unique opportunity to achieve new mid-IR OPO based on a material developed in Europe. In phase with the gradual increase in thickness planned over the project duration, the second year has enabled to fabricate the first OP-GaAs samples with thickness ~0.75 mm.



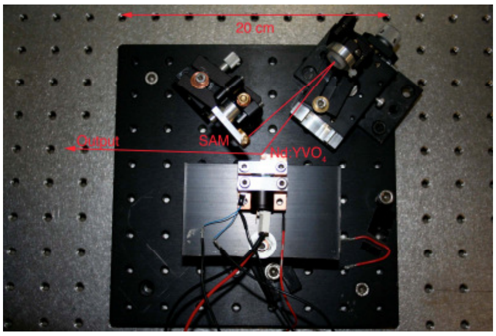
Selectively etched surface of a large aperture PPKTP crystal.

The 3-mm thick crystal (5-mm wide and 10-mm long) containing ferroelectric domain structure with periodicity of 38.88 µm was used in the first stage OPO to generate >3 W average power near 2.1 µm. The large aperture crystals showed good homogeneity that allows one to utilize all available pump power at 1.064 µm in the cascaded down-conversion scheme.

On the other hand, periodically poled oxide materials of the KTP family, with specially designed properties, are interesting for the first stage of cascaded OPO schemes. The fabrication and characterization of this family of crystals is also part of the material studies in the project, benefiting from the experience in that kind of QPM devices. In the second year, periodic structuring technology was developed for KTA and thick samples of KTP and Rb:KTP solid solutions, from which active elements were fabricated for first stage OPO experiments. Moreover, from OPO studies, the nonlinearity and Sellmeier dispersion relations of KTA were confirmed.

Finally, these efforts are complemented with characterization and evaluation of several more rarely used wide band-gap semiconductors (obtained from external collaborators) applicable in OPO schemes for direct conversion from 1 µm to 6.45 µm by birefringent phase-matching. Important properties, besides the transparency, dispersion and second order nonlinear coefficients, are the damage threshold and the two-photon absorption (TPA). In the second year, these parameters were studied for GaS_xSe_{1-x}, and $CdSiP_2$ (CSP). Damage characterisation of a new Li-compound suitable for pumping at 1064 nm, $LiGaS_2$ (LGS), was also performed, revealing superior (above 3 J/cm^2 and ~5 times larger than for $LiInSe_2$) optical damage resistivity.

Some of the proposed approaches based on direct or cascaded synchronous OPO pumping (SPOPO) with picosecond pulses, require powerful pump sources at the desired repetition rate of 100 Hz. The novel concept developed is the amplification of a macro-pulse of several hundreds picosecond pulses, obtained with fast acousto-optic modulation from a low-power cw diode-pumped mode-locked oscillator at 1064 nm: a high-frequency 450-MHz, 6-ps laser, specifically developed and engineered to allow easy and reliable operation during the experiments. A second 1-GHz oscillator has also been developed and tested in the second year as a possible more compact option.



Layout of the 1-GHz laser.

A 100-mW, ~7-ps $Nd:YVO_4$ oscillator operating at 1 GHz and pumped by a high-brightness laser diode, has been developed and tested to increase the overall system compactness. In the amplifier part, an all-diode-pumped solid-state amplifier system has been designed for a much more modern implementation of the architecture originally based on lamp-pumping: this will be more compact, efficient and suitable for clinical use.

Both the low-energy, high-gain module and the high-energy preamplifier have been built and tested successfully. Starting from a 1 µs long pulse train with 30-nJ energy, the two-slab $Nd:YVO_4$ amplifier side-pumped by two 200-W qcw arrays has shown single-pass amplification up to 1.3 mJ. A semiconductor saturable absorber has been used to suppress effectively background noise. The high-energy preamplifier uses a $Nd:YVO_4$ slab and a 6-bars 1.3-kW stacked array for pumping: as much as 13 mJ on the macro-pulse train at 100 Hz has been achieved. Two additional Nd:YAG amplifiers pumped by 2-kW diode stacks, currently under preparation, will boost the output energy to the 10-W average power minimum goal for this picosecond pump system.

Another concept followed in the pump laser development relies on the fact that the efficiency of an OPO in general increases for pump wavelengths which are already close to the wavelength that has to be generated. Therefore, as an alternative to lasers emitting at ~1 µm, Tm-lasers emitting at around 2 µm have been chosen as the OPO pump sources, as they are very efficient due to direct diode pumping at around ~800 nm, using a cross-relaxation process which doubles the quantum efficiency. Taking into account the high pulse energies that have to be generated, of the order of 10-100 mJ, Tm:YAG was chosen as the laser medium for the 2-µm pump laser. It shows a much better mechanical strength than, e.g. Tm:YLF, and a less severe thermal lensing than, e.g., Tm:YALO.

Novel cavity geometries for the Tm:YAG laser have been developed and tested. In particular, a dual end-pumping scheme based on total internal reflections and minimized heat deposition has proved to be promising. In the second year, maximum pulse energies of the Q-switched Tm:YAG laser up to 13.6 mJ were achieved at a pulse duration of 400 ns or 13.2 mJ at a pulse duration of 300 ns. The dual end-pumping scheme shows no problems to create a diffraction limited beam quality at any operation point. Future work will be devoted to further energy scaling towards 100 mJ and new cavity design to shorten the pulse length which is advantageous for the subsequent OPO pumping.

Ho-lasers, due to their longer wavelength and shorter pulse durations, are more efficient in pumping ZGP based OPOs near 2 µm, but diode pumping with conventional laser diodes is impossible. The concept followed in this project is based on in-band pumping of Ho:YAG for simple and effective laser design, without the use of an intermediate Tm-laser. Ho:YAG is a particularly attractive laser material for achieving high energy (10-100 mJ) levels at 2 µm in Q-switched operation, owing to its long storage time in the upper laser level. Key components for the proposed new technology development are 1.9-µm (AlGaIn)(AsSb) laser diode arrays. Such devices have been developed only recently and their performance had to be addressed in relation to the specific application. During the second year of the project, the dependence of the spectral properties of such high power multi-bar stacks emitting at around 1.9 µm on the power was investigated.

In cw free-running operation of the direct-diode-pumped Ho:YAG laser oscillator 55 W of output power at 2.122 µm were achieved in the second year. The corresponding slope efficiency was 45% with respect to the incident pump power. Another important achievement, in view of OPO pumping, is the first demonstration of Ho:YAG laser wavelength stabilization by a Volume Bragg Grating (VBG) at 2.096 µm. In Q-switched operation, maximum pulse energies of 7 mJ at a repetition rate of 500 Hz with 33% output coupling were achieved limited by damage of the coatings of the resonator elements. Further energy increase through improvement of the resonator design, as well as spectrum narrowing with VBG in Q-switched operation, are under investigation.

In parallel with the ongoing work on material research and pump laser development, during the second year of the project substantial progress has been made in the development of OPO sources for the generation of mid-IR radiation to reach the target wavelength of 6.45 µm using direct single-step or cascaded two-step conversion schemes.

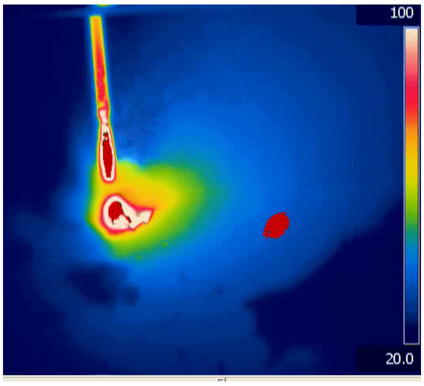
In the first approach, involving single-step conversion of a pulsed picosecond SPOPO, for the first time CSP was employed with 1064-nm pumping. Under 90°-phase-matching, the SPOPO produced quasi-steady-state idler micropulses near 6.4 µm with an energy as high as 2.8 µJ at 100 MHz. The train of 2 µs long macro-pulses, each consisting of 200 micropulses, follows at a repetition rate of 25 Hz which corresponds to an average power of 14 mW. The pump depletion (conversion efficiency) exceeds 40%. The 12.6 ps long mid-IR micropulses have a spectral width of 240 GHz. With regard to cascaded two-step picosecond SPOPO, a 1^{st}-stage cw OPO has already been successfully demonstrated using an Yb-fiber laser at 1064 nm. With a 50-mm MgO:PPLN crystal and 30 W of pump power, record idler powers of >8 W have been extracted in TEM_{00} spatial profile and tuning over 2.8-3.2 µm demonstrated. Direct translation of this experiment to a 20-W picosecond Yb-fiber laser at 81 MHz has also been implemented, where a total output of >12 W, with nearly 5 W of idler power over the wavelength range of 3.06-4.16 µm has been generated. This will provide the pump source for the 2^{nd}-stage SPOPO based on ZGP under non-critical phase-matching to reach the target wavelength of 6.45 µm with up to 1 W of average power.

In the second approach, using direct single-step pumping of a pulsed nanosecond OPO, the main focus during the second year was the first demonstration of a nanosecond, 90°-phase-matched singly resonant OPO based on CSP and pumped at 1064 nm, to produce idler pulses near 6.45 µm with an energy as high as 470 µJ (highest in this wavelength range for any non-oxide material pumped at ~1 µm) at 10 Hz and average power as high as 9.1 mW at 20 Hz. The present power limit is set by AR-coating damage and substantial improvement is expected with the next available samples. Progress according to the plan has been achieved in the second year also in realizing nanosecond cascaded down-conversion scheme which also employs a commercial high-energy Q-switched Nd:YAG laser as a pump source. Large aperture periodically poled crystals developed within the project have been employed for building the first down-conversion stage. Here the 2.1 µm radiation at an average power of 3.2 W and at a repetition rate of 100 Hz has been generated.

Manufactured RISTRA cavity with mounted cavity mirrors.

This OPO cavity was developed for high-pulse-energy operation to ensure good beam quality using 2-µm laser pump sources. It has been realized on a high-precision machine and tested for its mechanical tolerances. The special OPO cavity design called RISTRA makes an intra-cavity image rotation, the pumped region is thus better used by the oscillating signal and a much more uniform phase is obtained across the beam, leading to a more symmetric beam shape. Optical tests in OPO setups will be soon realized.

Finally, a non-planar cavity OPO has been designed and manufactured, for the use with 2-µm Q-switched Tm- and Ho-lasers to convert this radiation to powerful 6.45 mm light in a single step.



Thermal image of biological tissue during exposure with 2 µm laser light.

Simulating an endoscopic procedure in water using a new method to visualize temperatures underneath the surface. The tissue is sandwiched between infrared transparent windows and irradiated by a fiber from above. The thermo-camera can visualize the dynamics of (absolute) temperature distribution from the side through the window underneath the tissue surface. This method is an unique approach for temperature imaging in biological tissue developed within the project.

Parallel to the OPO development, further progress has been made in the design of the coupling system, IR fiber transmission and visualization setups. The coupling system was made open for flexibility and easier alignment with experimental laser/OPO systems. The transmission results of IR fibers will be further improved before the testing with the 6.45 µm laser systems available through the consortium.

A unique innovative thermal imaging setup has been designed to image absolute temperatures underneath the surface of tissue. The setups were made transportable for experiments on-site of the consortium partners. The first on-site experiment has been realized, however, the SPOPO did not reach the minimal energy levels necessary for effective tissue ablation. Scientific studies comparing tissue ablation effects of IR laser in relation to pulse length and fluence have been conducted for future comparison with the 6.45 µm laser sources.

The MIRSURG website www.mirsurg.eu informs about the project MIRSURG, both the partners and the interested (expert) public. The website describes aims and content of the project in general, and lists the partners (with links) that are involved. The work packages are described in detail. It is the main and unique instrument for dissemination of knowledge in the sense that it contains complete information on the results produced within MIRSURG. The pages related to the results obtained are regularly updated. In addition to the Recent Highlights, at present the website contains full texts of all Press Releases, Publications in Journals, Presentations at Conferences, as well as a list of seminars/lectures/courses and unpublished reports with links to the corresponding media/events.

In the second year, 25 scientific papers were published in peer-reviewed journals with 6 of them being Invited/Review papers or book chapters. Results from the research were reported at 23 International Scientific Conferences, in 11 different countries. The total number of conference presentations was 54 and 16 of them were Invited/Plenary or Post-deadline Talks. A total of 10 seminars/lectures/talks or short courses (unpublished) were given at different events in 6 countries. Finally, a total of 8 Ph. Theses are being carried out fully or partially supported by the MIRSURG project.

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