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:

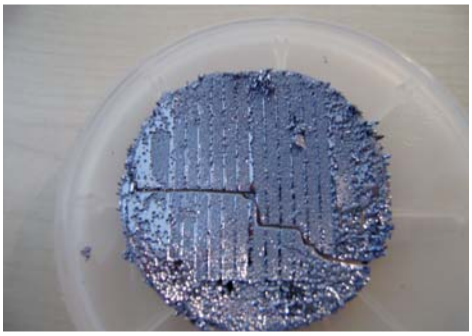
- the pulse duration may vary from a few nanoseconds (single pulse version) to a few microseconds (macro-pulse version).
- the pulse energy is a very critical parameter and should exceed 10 mJ at 6.45 μm.

- efficient tissue ablation will require a pulse repetition rate of at least 10 Hz. While at present it is unknown if a pulse repetition rate of the order of 1 kHz is still not feasible, considerations related to the average power and thermal load point to a preferable upper limit of 100 Hz, with the aim of achieving highest possible pulse energy. Thus, the goal will be to have an average power of 1 W (pulse energy ranging from 10 to 50 mJ at repetition rates from 100 to 20 Hz, respectively).
- It is highly desirable for pulse repetition rate of the developed sources to be variable, which would allow the study of the influence of pulse repetition rate (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 US suppliers or some representatives of Russian 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.



Top view of the OP-GaAs wafer after growth.

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 first year has enabled to fabricate the first dedicated 400 µm thick crystals and even to recently obtain thicker layers. Progress in sample preparation has also enabled to ease the characterization.

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.

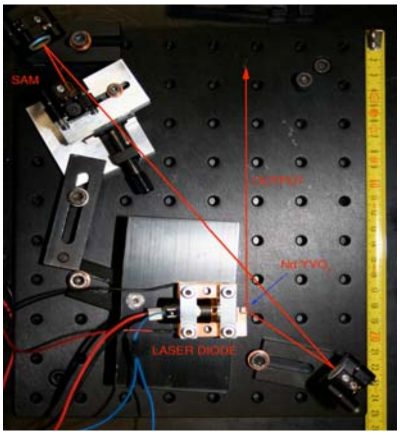
Three promising ferroelectric materials have been selected, investigated and successfully periodically poled: Rb:KTP, KTA, and Mg:near-stoichiometric $LiTaO_3$ (Mg:sLT). At the moment the poled structures are being evaluated in mid-IR OPOs.

Finally, these efforts are complemented with the characterization and evaluation of several more rarely used wide band-gap semiconductors (obtained from external cooperation) to be used in OPO schemes for direct conversion from the 1 µm band to 6.45 µm by birefringent phase-matching. Important properties, besides the transparency, dispersion and second order nonlinear coefficients, are the damage threshold in the nanosecond regime and the two-photon absorption (TPA).

The following nonlinear crystals have been selected and investigated: $LiInSe_2$ (LISe), $HgGa_2S_4$ (HGS), GaS_xSe_{1-x}, and $CdSiP_2$ (CSP). CSP turned out to possess extraordinarily suitable properties for the envisaged application and OPO experiments with it are planned for the second year.

Some of the proposed approaches, based on direct or cascaded synchronous pumping 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 (~10^3) of picosecond pulses, obtained with fast acousto-optic modulation from a low-power cw diode-pumped oscillator at 1064 nm. An ultrafast high-energy picosecond laser system poses additional challenges in comparison to Q-switched nanosecond lasers for pumping alternative OPOs. In particular, reliability and robustness of the mode-locked oscillator is required, as well as efficient high-gain amplification.

Hence, it was decided to develop oscillators at relatively high repetition rates, 0.5-1 GHz, in order to make them more compact and robust. Furthermore, the pre-amplifier will be designed as an ultra-high-gain diode-pumped bounce amplifier, relaxing the requirements of the high-energy lamp-pumped post-amplifier. The amplified macro-pulse, with 200 mJ energy at 100 Hz, will be used for synchronous pumping of OPOs at 1-µm for direct or indirect generation at 6.45 µm.



Layout of the 450-MHz laser.

In the first year a 100-mW, ~6-ps Nd:YVO_4 compact diode-pumped oscillator at 450 MHz has been developed and tested. Furthermore, a 1-GHz picosecond laser has been designed as an alternative plug-in oscillator. A novel cost-effective output coupling technique has been proved successful for mode-locking stabilization against self Q-switching. The computer-programmable electronic control of the acousto-optic pulse-picker has been developed to enable selection of arbitrarily shaped macro-pulse trains with length >100 ns, with typical energy of 100 nJ at 1 µs duration, as required by the application.

Another concept followed 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 around 1 µm, thulium-doped lasers emitting at around 2 µm have been chosen as the OPO pump sources, as they are in itself 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, which are on 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 internal total reflections and minimized heat deposition has been proved promising. Up to 5.6 mJ of Q-switched output energy with pulse duration of 216 ns has been generated. Further development will focus on optimization of optical damage properties of key components within the laser cavity and a cavity design that avoids optical damage.

Ho-lasers, due to their longer wavelength, are more efficient in pumping ZGP based OPOs near 2 µm, but no diode pumping of such lasers has been demonstrated so far. The concept followed in this project is based on in-band pumping of Ho:YAG. This will make the laser design simpler and more effective, without the use of an intermediate Tm-laser. Ho:YAG is a particularly attractive laser material for achieving high energy levels (10-100 mJ) at 2 µm with Q-switching operation, owing to a longer lifetime of the upper laser level with respect to that of Tm:YAG, for example.

Key components for the proposed new technology development are 1.9-µm (AlGaIn)(AsSb) laser diode arrays. Such devices have been developed recently and their performance had to be addressed in relation to the specific application. Critical aspects are their power-dependent wavelength shift and their relatively poor beam quality.

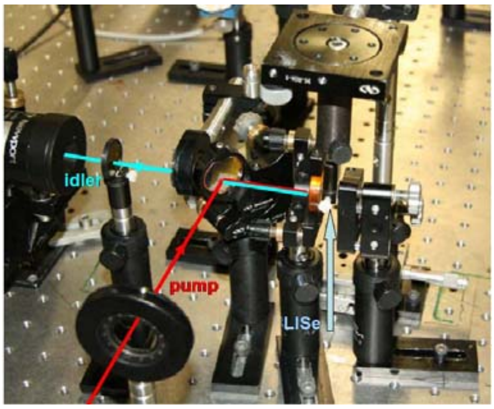
During the first year of the project, first high power (AlGaIn)(AsSb) multi-bar stack emitting at around 1910 nm were tested and characterized. The first diode-pumped cw Ho:YAG laser generated a maximum output power of 40 W and the corresponding slope efficiency with respect to the incident pump power was 40%. In addition, first Q-switched laser operation was achieved. Up to now, maximum Q-switched output energy of 3.5 mJ at a repetition rate of 1 kHz with 33% output coupling was reached. The pulse durations were around 150 ns. Experiments to obtain shorter pulses by electro-optic Q-switching and higher energy at lower (100 Hz) repetition rate are planned.

In parallel with the ongoing work on material research and pump laser development, during the first 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 pumping of a pulsed picosecond SPOPO, a modified oscillator-amplifier configuration for the flashlamp-pumped mode-locked Nd:YAG laser has enabled average pump power scaling to 3 W at 1064 nm, in macro-pulses of 2 μs at 25 Hz, with each macro-pulse containing around 200 micropulses of 15-20 ps duration at 100 MHz. Deploying this laser in combination with AGS has permitted the generation of ~20 mW at 6.45 μm with an average pump power of about ~500 mW. New concepts to minimize long-term material degradation and damage are under development towards utilizing the full available pump power.

In the second approach based on cascaded two-step synchronous pumping of a picosecond OPO, a 1st-stage cw OPO based on MgO:PPLN has already been successfully demonstrated using an Yb fiber laser at 1064 nm. Using a 50-mm crystal and 30 W of pump power, record idler powers of >8 W have been extracted in TEM_{00} spatial profile and tuning over 3-3.2 μm demonstrated. Direct translation of this experiment to a 20-W picosecond Yb fiber laser at 80 MHz is under implementation, where similar output powers and wavelength range are expected. This will provide the pump source for the 2nd-stage OPO based on ZGP under non-critical phase-matching to reach the target wavelength of 6.45 μm, where >1 W of average power for 8 W of pump are anticipated.

In another approach using direct single-step pumping of a pulsed nanosecond OPO, the main focus was on the extension of the tuning range of a LISe-based OPO to the mid-IR in order to reach the 6.45 μm wavelength directly, and on scaling the average power by increasing the repetition rate.



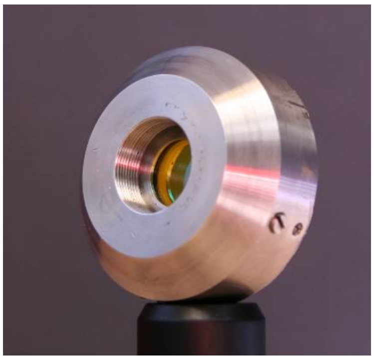
Photograph of the compact LISe OPO.

Using a diode-pumped, Q-switched Nd:YAG laser at 1064 nm, providing an average power of 10 W in 14-ns pulses of 100 mJ energy at a repetition rate of 100 Hz, a compact two-mirror cavity design for the OPO, and two LISe samples (17.6 and 24.5 mm long), idler tuning from 4 to 8.7 μm was achieved and maximum output pulse energies of 282 μJ at 6.514 μm and 116 μJ at 8.428 μm were obtained at external quantum efficiencies of 10.3% and 4.3%, respectively.

The maximum average power of 28 mW at 100 Hz represents more than an order of magnitude improvement over previous results, where ~2.5 mW at 3457 nm were achieved at lower repetition rates. Further power scaling is expected with better polishing and AR-coating of the LISe samples.

At the same time, there has been significant progress towards the cascaded generation of 6.45 μm radiation using two-step pumping by deploying a commercial diode-pumped Q-switched Nd:YAG pump laser providing pulses of 10 ns duration with an output energy of 170 mJ in an output beam with high spatial quality (M^2=1.7). The design parameters for optimum cascaded OPO and OPA (optical parametric amplifier) configurations have been established based on the use of bulk KTP, PPKTA, and bulk KTA for the 1st-stage OPO/OPA, and type-I and II ZGP for the 2nd-stage OPA. Performance characteristics of KTA crystal samples obtained from three different suppliers from Europe and China have been investigated to obtain damage threshold values for the 1st-stage OPO/OPA and design parameters for type-I and II ZGP crystals have been established for the final realization of the 6.45 μm radiation in this high-energy nanosecond pulsed regime.

Parallel to the OPO development, a mid-IR fiber delivery system was designed and constructed in preparation for laser-tissue interaction studies scheduled later in the project. To keep options open, the fiber delivery system can be used for a large range of fiber types and laser wavelengths.



Photograph of front side of entrance of the fiber coupler.

For initial testing, the system has been optimized for microsecond 10.6 μm CO_2 laser in combination with suitable hollow waveguides. The transmission loss through the coupling system itself is ~10%. The transmission loss through a rigid 1000 μm diameter hollow waveguide is only 3% which is near optimum. However, the more flexible 320 μm hollow waveguide has a loss of ~35% which increases by additional 10% when bending it. These results are in accordance which the theoretical predictions.

The delivery system will be adapted and tested for other wavelengths in the next phase and optimized towards 6.45 μm. The visualization setups for the study of the laser-interaction are being tested and optimized using lasers with similar tissue effects as expected from the 6.45 μm source.

The MIRSURG website www.mirsurg.eu has been created to inform about the project MIRSURG, both the projects 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 and unpublished reports with links to the corresponding media / events.

11 Printed Press Releases, 19 Online Press Releases, and one other (TV Videotext) announced the start of the project MIRSURG. In the 1st year, 12 scientific papers were published in peer-reviewed journals and results were reported at 9 International Scientific Conferences, in 5 different countries. The total number of conference presentations was 28, 6 of them were Invited Talks. A total of 2 seminars/lectures or colloquia (unpublished) were given at different events in 2 countries. Finally, a total of 9 Ph. Theses are being carried out fully or partially supported by the MIRSURG project.

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