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)**

D2.2: Solid-state ps laser system with macropulse format and 200 mJ energy (average output power of 20 W): Power and energy limitations of the diode and flash-lamp pumped stages

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Actual submission date: month 42

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Organisation name of lead contractor for this deliverable:	Bright Bright Solutions S. r. l.

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)	

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1. Outline

The following activities were scheduled for Deliverable 2.2 as in Annex I, and have been carried out at Bright Solutions S.r.l.:

- implementation of the DPSS picosecond oscillator with a rugged mechanical assembly
- design and preliminary test of the DPSS amplifiers (replacing the originally planned flashlamp system)
- integration of all parts and completion of the all-DPSS laser system
- detailed experimental characterization of the system performance
- numerical model and investigation of possible ways to improve the overall performance
- transportation of the laser system at ICFO, Barcelona (Spain)
- assistance with synchronous optical parametric oscillator (SPOPO) tests with CSP crystal, delivering 6.4-μm radiation

2. Overview of the laser architecture

The final implementation of the high-energy picosecond source developed for the MIRSURG project includes:

- high repetition rate Nd:YVO_4 seed laser with optimized new opto-mechanical layout, emitting ≈ 6-ps pulses at 450 MHz
- high gain low-power pre-amplifier based on two 200-W side-pumped Nd:YVO_4 slabs
- high power amplifier based on 1.2-kW side-pumped Nd:YVO_4 slab
- high power Nd:YAG 5-pass amplifier, side-pumped by two 2-kW laser diode stacks
- resonant saturable absorber mirrors (RSAMs) for suppression of ASE and low pulse background
- acousto-optic modulator (AOM) with programmable waveform for distortion compensations

Although the overall result is a unique and reliable laser system that has been developed for the generation of high-energy picosecond pulse trains much like a free-electron laser, but with a most compact footprint, with the added tunability offered by the SPOPO converter, few trade-offs have been necessary after departing from the "arclamp" architecture originally proposed.

- The reduced energy storage capability allowed by a competitively-priced laser-diode stacks amplifier module allowed lower energy than initially thought (50 mJ vs. 100 mJ)
- Suppression of ASE and low-amplitude cw pulse background requested the use of RSAMs (for the first time in such a high-energy ultrafast system to the best of our knowledge) that unfortunately are largely responsible for the output energy reduction
- However, the improved optical efficiency with respect to the flashlamp option allows to operate the laser system up to 50 Hz with reduced thermal lensing and beam distortions, compared to 10 Hz with our previous flashlamp setup delivering as much as 250 mJ
- It has to be remarked that RSAM technology proved a clever solution for tight packaging of the rather complex optical layout, without resorting to bulky spatial filters as in most traditional ASE suppression schemes

We note that the use of laser-diode stacks with 2% duty cycle should allow a repetition rate up to 100 Hz, although this is not recommended with the presently available pump modules in order to guarantee sufficient lifetime for the laser system in view of the planned SPOPO experiments.
One important thing to bear in mind is that the presently achieved amplifier performance (≈ 6% optical-to-optical efficiency) compares reasonably with that reported for much more conventional high-energy amplifiers for nanosecond seed pulses (≈ 8-10%), especially considering the specific constraints of this project. The most notable difference is the extremely low seed energy (45 nJ) requiring a total small-signal amplifier gain ≈ 90 dB, whereas conventional multi-mJ nanosecond amplifiers range between 20 and 40 dB. This accounts for the special attention that must be paid to suppress self-oscillations and ASE in our setup, leading to some efficiency trade-off.

3. Detailed characterization of the laser system and modeling

The 450-MHz picosecond oscillator has been confirmed to be a reliable performer, being intensively used for all the third year of the Project after its final housing into a specially designed metallic case.

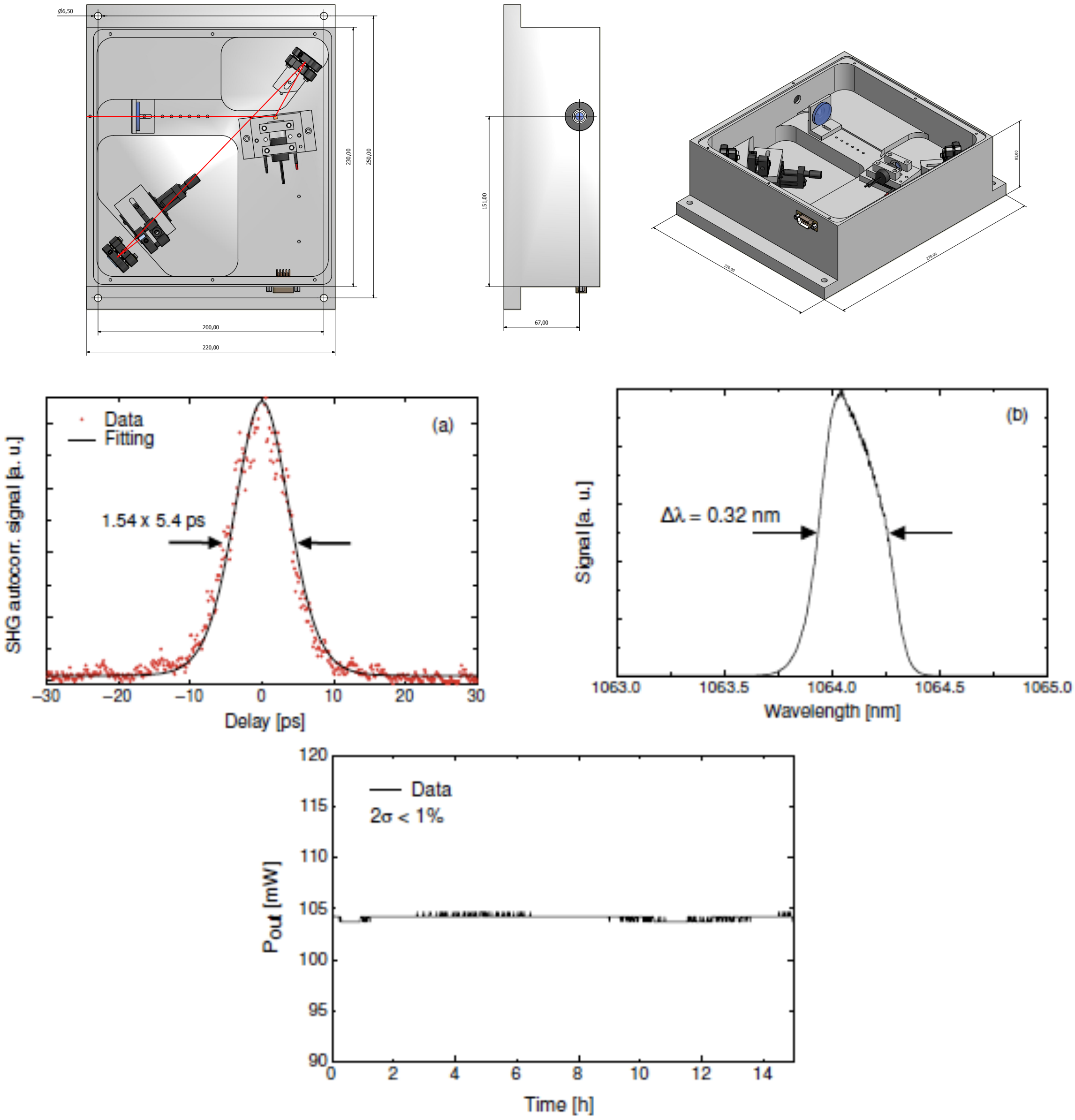

Fig. 1. Oscillator opto-mechanical layout as implemented, pulse autocorrelation, spectrum and output power stability.

The overall system layout, pictured in Fig. 2, has been slightly modified after preliminary tests appeared in the previous Annual Report: in particular, the first high-energy $Nd{:}YVO_4$ module was eventually configured as a single-pass amplifier, and a second RSAM has to be added to suppress ASE and tendency to self-oscillation. Both RSAMs have small-signal reflectivity of few percent, and saturated reflectivity of ≈ 80% at ≈ 10-ps pulses, with fast recovery of few tens picoseconds between consecutive micropulses.

The most effective configuration for energy extraction in the side-pumped Nd:YAG bounce amplifier was a 5-pass setup. Additional passes do not add significant output energy.

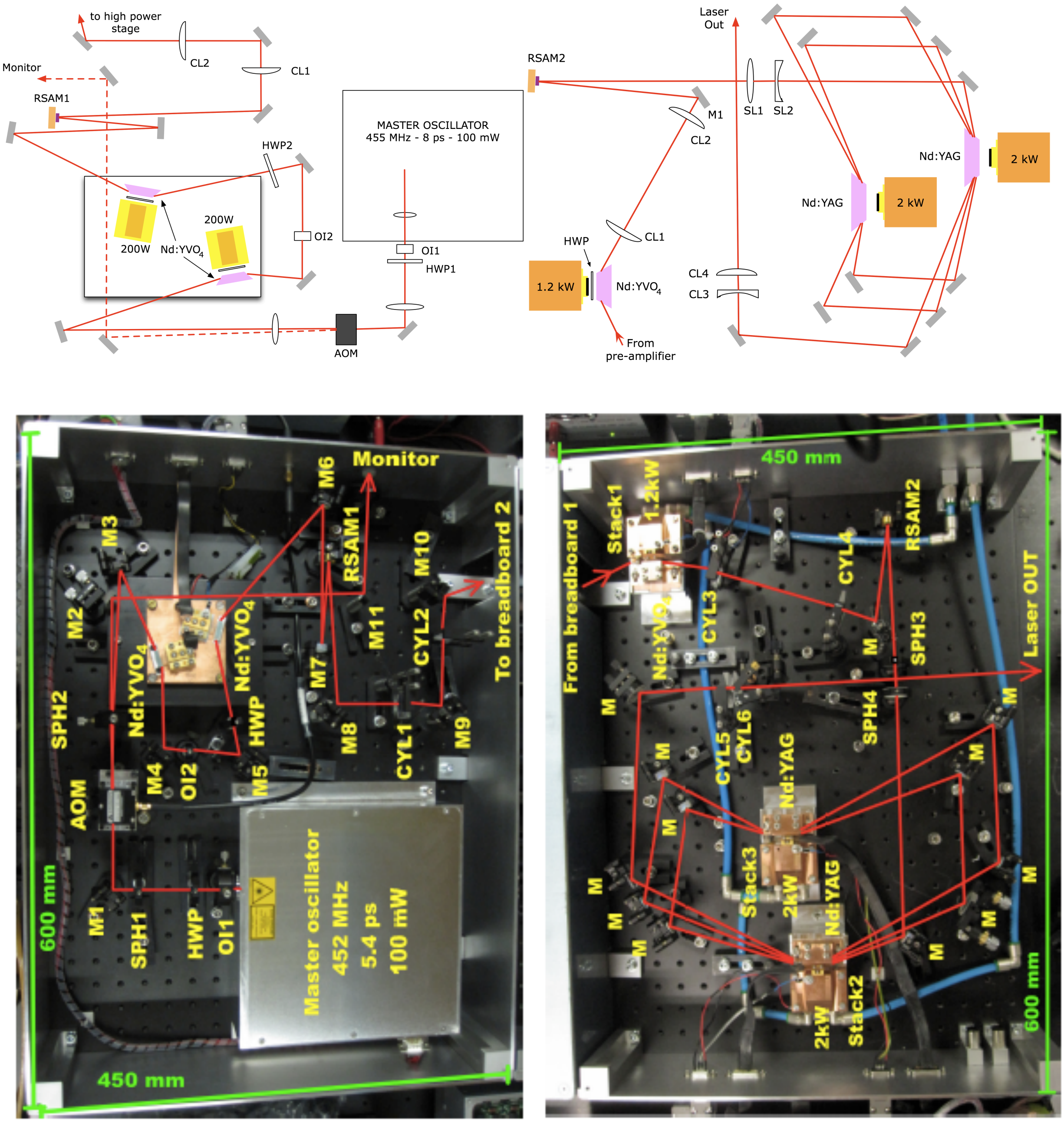

Fig. 2. Picture and layout of the laser system including the low-energy high-gain stage and the first high-energy module. AOM: pulse-picker allowing pre-compensation of amplifier distortions. OI: Faraday opto-isolators; CL: cylindrical lenses; SL: spherical lenses; HWP: half-wave plates.

Owing to the duty cycle rating at 1% for the high-power diode stacks, the repetition rate was set at 50 Hz maximum: the Nd:YVO$_4$ amplifiers were driven with 100-µs pulses, and the Nd:YAG amplifier was operated with 200-µs pulses to take advantage of the longer fluorescence time allowing higher energy storage. The macropulse output energy was 50 mJ (starting from ≈ 45 nJ after pulse-picker envelope shaping). ASE contribution as well as a leakage of the cw train owing to the static extinction ratio of the pulse picker (≈ 1:2000) were effectively suppressed by the RSAMs.

In order to characterize all single amplifying modules, we devised a particularly useful approach, taking advantage of the programmable AOM at the output of the seeder picosecond oscillator. Both the saturation energy E_{sat} and the small-signal gain G_0 of each module was determined by injecting an approximately flat-top input waveform and recording the saturated output. Hence a best-fit routine based on Frantz-Nodvik equations was run for each module to extract both E_{sat} and G_0:

$$P_o(t) = \frac{P_i(t)}{1-\left(1-1/G_0\right)\exp[-E_i(t)/E_{sat}]} \tag{1}$$

$$E_i(t) = \int_{-\infty}^{t} P_i(t')dt' \tag{2}$$

The example for the first 2 × 200 W Nd:YVO$_4$ module is shown in Fig. 3, while all the results are summarized in Tab. 1.

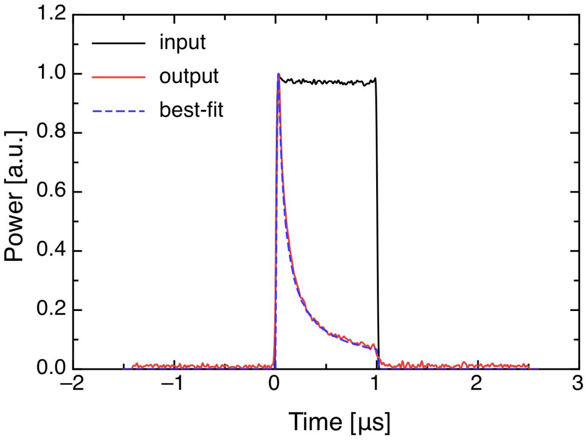

Fig. 3. Input and output waveforms for the 2 × 200 W pumped grazing-incidence Nd:YVO$_4$ crystals. The best fit result is also shown.

amplifier		**G$_0$ [dB]**	**E$_{sat}$ [mJ]**
stage	**pump module diode array(s)**		
I	2 x 200 W	49.0	0.60
II	1.2 kW	17.2	1.51
III	2 x 2 kW	22.6	19.0

Tab. 1. Saturation energy and small-signal gain for the three amplifier modules, according to the procedure outlined.

The same model was readily adapted for the reverse computation, i.e. to determine the input waveform required to produce a flat-top output:

$$P_i(t) = \frac{P_o(t)}{1-\left(1-G_0\right)\exp[-E_o(t)/E_{sat}]} \tag{3}$$

$$E_o(t) = \int_{-\infty}^{t} P_o(t')dt'$$

(4)

This was applied to the first and later to the first two modules to determine the AOM pre-compensation allowing for nearly flat-top input for the second and later for the third stage, to perform the characterization reported in Tab. 1. Eventually, the complete model of the amplifier chain including the RSAM nonlinear elements (according to specifications by the manufacturer) was used to predict the input waveform allowing a nearly flat-topped output (Fig. 4).

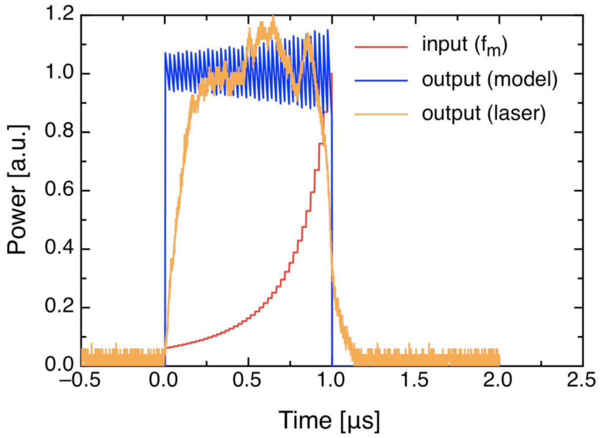

Fig. 4. Input and output waveforms for the whole chain. Actual output macropulse is also shown.

Whereas input pulse shaping has some effects on output energy (pre-compensation reduces the seed energy to ≈ 25%), it has to be remarked that the overall efficiency is significantly influenced by the RSAMs, due to the high dynamics of the pre-compensated seed waveform. Indeed, while their saturated output would approach 80%, the pre-compensating input shape yields integrated reflectivity of 35-40% for the RSAMs (about 50% of the saturated reflectivity, as expected for the reason stated above). A comparative analysis carried out with the Frantz-Nodvik model allows to identify readily the sources of inefficiency in our system:

- output energy = 81 mJ with flat-top input and no RSAMs
- output energy = 75 mJ with pre-compensating input and no RSAMs
- output energy = 50 mJ with pre-compensating input and with RSAMs

Another important aspect in view of SPOPO pumping is the output beam quality as well as the spectral quality, which turned out to be nearly diffraction- and Fourier-limited (Fig. 5).

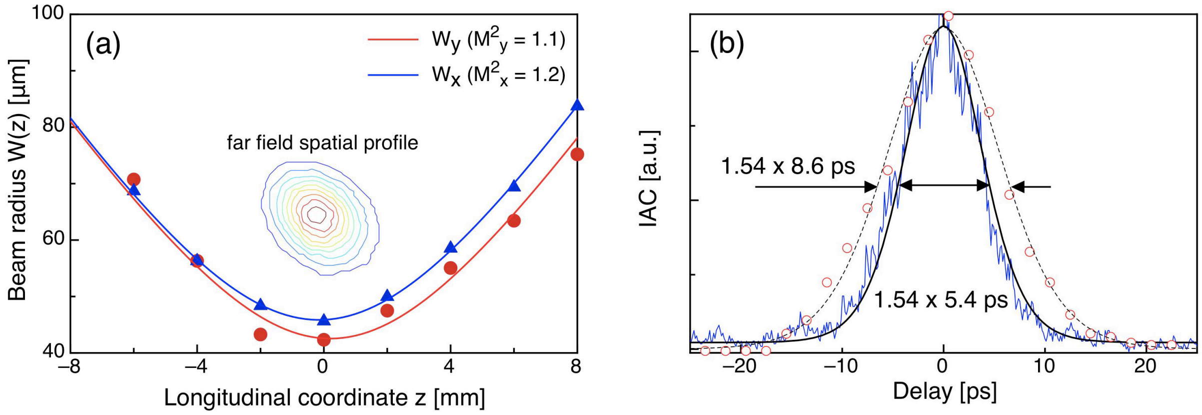

Fig. 5. Beam quality measurement for the amplified output macropulse and output pulse autocorrelation.

4. Summary and outlook

With reference to the Annex I of the Grant Agreement (GA) and the revised 2nd Annual Report (incorporating the target agreed for the all-diode-pumped system implementation), the final system performance can be summarized as in the following Table:

	Target Specifications	Present System Performance	Comments
micropulse fwhm [ps]	~ 10 - 20	12	OK
micropulse rep. rate [GHz]	~ 0.5 - 1	0.45 or 1.0	OK
macropulse length [µs]	~ 1	0.5 - 1	OK
macropulse energy [mJ]	~ 100 mJ (after decision to implement all DPSS instead of flashlamp amplifiers)	50 mJ	limited by ASE and self-oscillations with the present layout; other pumping geometry investigated, yielding the same G_0 but larger E_{sat}
macropulse rep. rate [Hz]	100 Hz	50 Hz	only limited by precaution of using laser diodes at 1% duty cycle nominal rating (2% duty is presently allowed by last-generation devices)
polarization	linear	linear	OK
beam quality M^2	< 2	≤ 1.2	OK

The diode-pumped laser system delivering macropulses of high-repetition-rate picosecond pulses at 1064 nm has been completed and transferred at ICFO (Barcelona, Spain) in December 2010, where a CSP-SPOPO near 6.4 µm emission wavelength have been successfully tested.

Indeed, most of the activity in the last period was concentrated on assistance at ICFO for running the SPOPO experiments with the ps laser system, whereas new solutions are under investigation for improving the present performance. For example, a straightforward option (but definitely more expensive!) would be the replacement of the low-energy module with a 10-W picosecond fiber laser and a fast electro-optic pulse-picker, reducing the overall gain requirement by 20 dB.

A simpler solution, surely less expensive, would be to increase the output energy by adding another (or two) 2-kW pump module in the last stage, thus increasing the overall gain volume (and beam cross section) without increasing the gain (and ASE).

However, it is worth noticing that the geometric size and the coating resistance of the presently available nonlinear crystals (CSP) do not allow full-energy pumping (50 mJ is already above the damage threshold), therefore the SPOPO activity is not slowed down by the energy level presently available from the pump laser system.

Commercial development for the overall system as well as for the subsystem modules are currently under way at Bright Solutions. A new product line of high-energy Q-switched DPSS oscillators are also under development based on the experience gained in this research activity.

5. Publications

Journals

1) A. Agnesi, C. Braggio, L. Carrà, F. Pirzio, S. Lodo, G. Messineo, D. Scarpa, A. Tomaselli, G. Reali, C. Vacchi "Laser system generating 250-mJ bunches of 5-GHz repetition rate, 12-ps pulses" Opt. Express 16, pp. 15811-15815 (2008)

2) A. Agnesi, P. Dallocchio, F. Pirzio, G. Reali "Sub-nanosecond single-frequency 10-kHz diode-pumped MOPA laser" Appl. Phys. B 98, pp. 737-741 (2010)

3) A. Agnesi, L. Carrà, P. Dallocchio, F. Pirzio, G. Reali, S. Lodo, G. Piccinno "50-mJ macro-pulses at 1064 nm from a diode-pumped picosecond laser system" Opt. Express 19, pp. 20316-20321 (2011)

4) S. Chaitanya Kumar, A. Agnesi, P. Dallocchio, F. Pirzio, G. Reali, K. T. Zawilski, P. G. Schunemann, M. Ebrahim-Zadeh "1.5 mJ, 450 MHz, $CdSiP_2$ picosecond optical parametric oscillator near 6.3 μm" Opt. Lett. 36, pp. 3236-3238 (2011)

5) A. Agnesi, C. Braggio, G. Carugno, F. Della Valle, G. Galeazzi, G. Messineo, F. Pirzio, G. Reali, G. Ruoso "A laser system for the parametric amplification of electromagnetic fields in a microwave cavity" Rev. Sci. Instrum. 82, 115107 (2011)

Conference proceedings

1) A. Agnesi, L. Carrà, S. Lodo, F. Pirzio, G. Reali, D. Scarpa, A. Tomaselli, C. Vacchi "High-energy picosecond tunable solid-state laser system with GHz repetition rate" Paper TuoB.5, Europhoton Conference 2008, 31 August - 5 September 2008, Paris, France

2) A. Agnesi, P. Dallocchio, C. Di Marco, F. Pirzio, G. Reali "Sub-nanosecond passively Q-switched multi-kHz MOPA laser system" Paper CA5, CLEO/Europe-EQEC, 14-19 June 2009, Munich, Germany

3) A. Agnesi, F. Pirzio, G. Reali, G. Piccinno "Table-top all-diode-pumped MOPA laser for generation of high-energy, high-frequency picosecond pulse trains" Laser Optics Berlin, Berlin (Germany), March 22-24, 2010

4) A. Agnesi, F. Pirzio, G. Reali "High gain solid-state modules for picosecond pulses amplification" ***(Invited Paper)*** Photonics Europe, Brussels (Belgium), April 12-16, 2010. SPIE Proceedings 7721, 77210C (2010)

5) A. Agnesi, P. Dallocchio, S. Dell'Acqua, F. Pirzio, G. Reali "High peak power sub-nanosecond MOPA laser system" Paper WeB4, Europhoton 2010, August 29 - September 3, 2010 Hamburg, (Germany)

Book chapter

A. Agnesi, F. Pirzio "High gain solid-state amplifiers for picosecond pulses" in "Advances in Lasers and Electro optics", pp. 213-238, M. Grishin ed., IN-TECH Publisher (2010), ISBN 978-953-7619-80-0