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Development of a Pulsed Laser System for Laser-induced Breakdown Spectroscopy (LIBS)

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***Abstract*—A prototype of a compact light-weight passively Q-switched diode pumped Nd:YLF solid-state laser system for harsh environments has been developed. It emits 2ns pulses at a wavelength of 1053nm with a repetition rate of up to 50Hz and an energy of 1.5mJ. The beam propagation factor M²-has a value of 1.2. The total mass of the prototype electronics, consisting of an electronic board including pump diodes and thermal control to be accommodated with other electronics in a shared electronics box, and the complete solid-state laser head is 189g with further potential for mass reduction with respect to a flight model development. Applications of this laser system are amongst others laser-induced breakdown spectroscopy (LIBS) for planetary surface exploration or short range altimetry.**

***Index Terms*—Solid-state laser, space technology, LIBS**

I. Introduction

Laser-induced breakdown spectroscopy (LIBS) is a versatile tool for the analysis of the geophysical composition of planetary surfaces. For some space missions there are severe mass and power limitations, which do not allow for remote LIBS with a measurement range of several meters as included in the payload of the Mars Science Laboratory [1]. Placing an optical head of a LIBS instrument, e.g. on a robotic arm providing a short distance towards the sample, allows for small spot sizes in the range of 50µm. Therefore, only moderate laser pulse energies of ~1mJ at 1µm wavelength with pulse durations of a few nanoseconds are necessary in order to reach the required power density for plasma formation of several GW/cm². Shortening of the laser pulse duration for increasing the peak power and decreasing the total required laser pulse energy only works to a certain extent, because LIBS experiments under low pressure atmosphere reveal that a minimum laser pulse duration of 2ns is desired to generate a good LIBS signature. Typically, the laser pulses are applied in bursts containing e.g. ~20 pulses at a frequency of 50Hz. The total number of shots for the instrument lifetime is in the range of 10^5.

A compact diode pumped solid-state laser system has been developed to meet the requirements for this application.

II. Conceptual Laser Design

In order to design such a laser system several trade-offs have to be performed. The required specification can be most easily achieved by a diode pumped solid-state laser, which is Q-switched. In order to achieve a good beam quality, which enables tight focusing on the sample, an end-pumped laser scheme is preferred. Delivery of the laser pulse via an optical fiber to the sample is not feasible, because laser pulse energy in the mJ range with ns duration could only be transmitted through a large core fiber. These types of fiber deteriorate the good beam quality and prohibit tight focusing at a sufficient distance to the sample, which avoids contamination of the focusing lens by the dust generated from the sample due to the laser impact. Since the laser head, therefore, has to be placed near the sample, it can be advantageous to separate the electronics and the temperature controlled pump diodes from the laser head. In an end-pumped configuration using a fiber coupled pump diode, the laser head can be accommodated near the sample in a thermally uncontrolled environment and only the pump light with pulse durations in the range of a few hundred microseconds and peak power levels of a few tens of Watt is transmitted via an optical fiber to the solid-state laser head. This approach has the additional advantage of homogenizing the pump light in the fiber, i.e. the pump light distribution in the fiber and in the laser crystal is not changing, if a part of the pump diode emitters fails.

Compared to electro-optical Q-switches, a passive Q-switch being inserted in the laser resonator based on a crystalline saturable absorber such as Cr:YAG is a very simple scheme. It has negligible mass and requires no high-voltage power supply as e.g. a Pockels cell.

For laser crystal selection, Nd:YAG, Nd:YLF, Nd:YVO_4 and Yb:YAG have been considered, because these crystals have a good availability and can be grown at good and reproducible quality. Moreover, mature laser diode technology is available to optically pump these crystals. However, since the Yb:YAG laser is a quasi-three level laser scheme, laser operation is quite sensitive to the environmental temperature conditions, which is detrimental to the application environment. Compared to Nd:YAG with a fluorescence lifetime of 230µs at 1% doping level and Nd:YVO_4 (90µs), Nd:YLF has a much longer fluorescence lifetime of 480µs, which allows for a longer storage of the pump light in the laser crystals. Therefore, less pump peak power and less mass for the pump diodes is needed. Although Nd:YAG has multiple space heritage and superior mechanical properties, Nd:YLF shows only small degradation under moderate ionizing irradiation [2] and seems to be suitable for pulsed laser systems with only a few roundtrips of the light in the cavity.

To verify these conceptual design considerations, at first two end pumped passively Q-switched laser systems (Figure 1) – one using a Nd:YAG crystal and one using a Nd:YLF crystal- were set up for comparison with similar resonator configurations in order to achieve approximately the same pulse parameters (Table 1). The solid-state lasers were optically pumped in pulsed (qcw) mode at a repetition rate around 10 Hz.

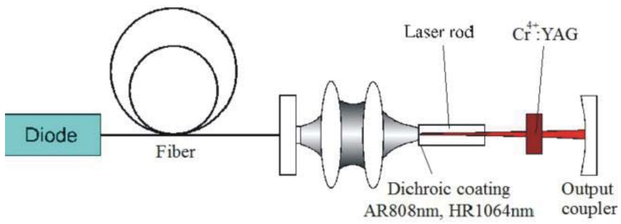

Figure 1: Laser setup.

While achieving similar pulse energies, the pulse duration of the Nd:YLF system is longer due to the lower cross section for stimulated emission, which is more favorable for the LIBS application. The most significant difference is that roughly half of the peak power, which is required for pumping Nd:YAG, is sufficient for pumping Nd:YLF at the cost of longer pump pulses corresponding to the fluorescence lifetime of the laser material.

TABLE I. COMPARISON BETWEEN ND:YAG AND ND:YLF LASERS

	Nd:YAG	Nd:YLF
Pulse energy (mJ)	1.9	1.8
Pulse duration (ns)	1.5	2.2
Peak pump power (W)	90	36
Pump duration (µs)	180	470
Pump energy (mJ)	16	17
Opt.-opt. efficiency	12	11
Peak pump power/mJ output	~50	~20-25

Assuming an optical peak pump power of 20-25W/mJ around a wavelength of 806nm deduced from the experiments, a pump power in the range of 40-50W is needed, if accounted for a sufficient margin for compensation of potential degradation of optical elements towards the end of life of the laser system.

Typical fiber coupled diode laser modules with this output power level contain either a single diode laser bar or some free space combined single emitters with several Watts of output power each. However, the disadvantage of diode laser bars turns out to be that their driving voltage is only 2V at a current of more than 50A. This requires from the electrical point of view more mass for capacitors, which store the electrical energy for the pump diode pulses, compared to driving several single emitters at 2V each and <10A in series. Combining single emitters via a free space coupling with mirrors and beam splitters requires a very rugged housing to keep the alignment for fiber coupling. This results also in appreciable mass consumption for packaging. A third possibility is the use of several hermetically sealed fiber coupled single emitter modules, which are combined by a fiber-based pump combiner to a single output fiber. Typical geometries of these pump combiners allow for the combination of the 7 105µm core NA=0.15 multimode standard output fibers of single emitter diodes to a single fiber. This output fiber can be either a 125µm core NA=0.46 or a 200µm core NA=0.22 fiber. For the latter type also space compatible versions, e.g. with polyimide instead of acrylate coating, are available. By using this approach the least mass is consumed and one can additionally profit for the pump diodes as well as for the pump combiner from Telcordia qualified packaging technology including MIL-STD 883 procedures, which already cover several aspects of space qualification. Furthermore, this type of single emitter pump diode is under space qualification for other projects. However, since these pump diodes are designed only for continuous wave (cw) operation at 5-6A, a pre-qualification campaign for the quasi-cw (qcw) operation was carried out. Commercial available fiber-coupled single emitter diodes of 5 different suppliers have been tested with pulsed currents up to 20A (Figure 2).

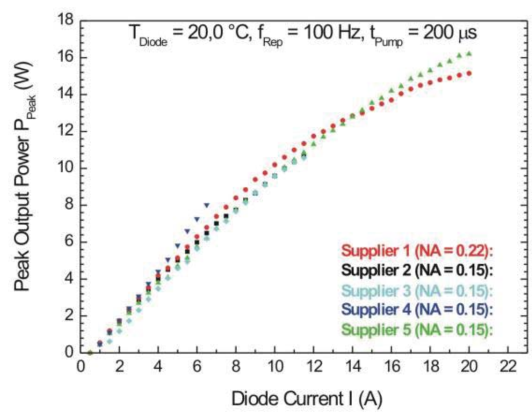

Figure 2: Pre-selection of single emitter diode lasers.

The diodes of two suppliers survived 20A pulsed operation under emission of ~15W peak power out of the fiber, which demonstrates that the current limitations for cw operation are mainly due to thermal limitations of the package, but not due to peak current.

Assuming a typical pump combiner efficiency of 90%, operation of 7 diodes with 7W output power at 7A each, results in a combined output peak pump power of 44W. Using the previous estimation of 20-25W pump power per mJ solid-state laser energy, 44W leaves sufficient margin for potential degradation of the solid-state laser optical components or redundancy in case of failure of a single emitter diode. Long term testing of the pulsed diodes of supplier 1 up to 20A did not reveal any sign of degradation after more than 10^5 shots and assures sufficient pump diode de-rating of more than 50%. For potential dry heat sterilization in the context of planetary protection, storage tests for 5h at 125°C did not show any degradation of the diodes of supplier 1, whereas for supplier 5 a degradation of 7% was observed.

All other components of the solid-state laser system such as dielectrically coated fused silica mirrors and windows as well as the saturable absorber Cr:YAG have multiple space heritage. Therefore, the baseline for further development is a longitudinally passively Q-switched Nd:YLF laser pumped by 7 fiber coupled single emitter laser diodes.

III. BREADBOARD LASERS

A breadboard laser system was set up in a laboratory environment with commercially available optomechanics in order to verify the conceptual laser design. 7 single emitter pump diodes of supplier 1 were used with a slightly different package, i.e. with a 105µm, NA=0.15 fiber instead of the initially tested NA=0.22 fiber. All pump diodes were manufactured from the same wafer in order to keep wavelength variation among each other small. This enables mounting of the diodes on the same heat sink and tuning of the diode temperature and their emission wavelength towards a region with a good spectral overlap to the Nd:YLF absorption. A 7:1 pump combiner with a 125µm/NA=0.46 output fiber was used. The fiber tip was mapped by two lenses in the laser crystal in order to enable a good spatial overlap between the laser mode and the pump light. A 1% doped Nd:YLF crystal in c-cut configuration emitting at 1053nm was used as laser crystal. The AR806nm/HR1053nm pump mirror was directly coated on the laser crystal. A Cr:YAG crystal served for passive Q-switching. The resonator outcoupling was realized by a partially reflecting mirror at 1053nm (Figure 3).

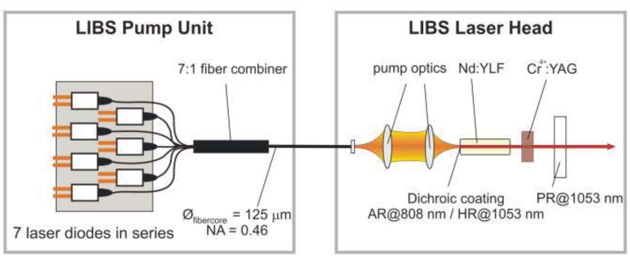

Figure 3: Laser setup of the laboratory model.

Laser operation was optimized by tuning the pump spot size in the laser crystal, by changing the initial transmission of the Cr:YAG and by optimizing the reflectivity of the outcoupling mirror. When operating the pump diodes at ~7A for a pump duration of 750µs, the solid-state laser pulse was released by the passive Q-switch after ~500µs (pulse release time) with an output pulse energy of 1.8mJ and a duration of 2.1ns (Figure 4). The optical-to-optical efficiency of the solid-state laser was around 10% when taking only the pump time until pulse release into account.

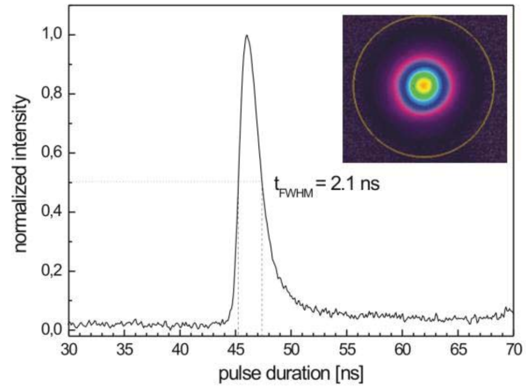

Figure 4: Temporal pulse shape and beam profile (inset)

A circular beam profile was measured as depicted in the inset of Figure 4. An M²-value of 1.2 was determined for the beam quality. Simple focusing experiments revealed that the beam can easily be focused by a single lens to a Gaussian beam diameter below 50µm at a distance of more than 50mm, which is a suitable distance to protect the lens from the dust generated by the laser pulse impact. Due to the long absorption path in the laser crystal, diode temperature variation in the range of +/-5K has only a minor effect on the pulse release time, and almost no effect on the pulse energy.

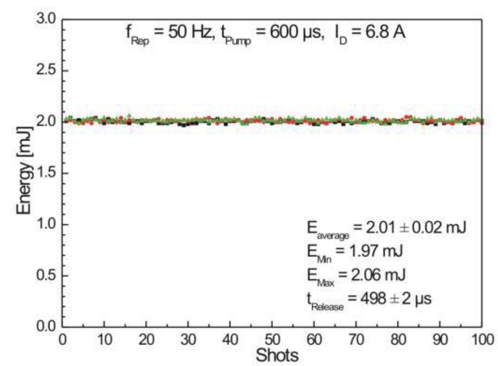

Figure 5: Burst operation:100 pulses at 50Hz

The laser system was again operated at a fixed repetition rate of 10Hz for >10^5 shots. Operation in burst modes such as 100 pulses at 50 Hz reveal only small energy fluctuations <0.1mJ (Figure 5) and prove stable laser operation.

IV. LASER PROTOTYPE

After verifying the optical properties of the laser system in the laboratory setup, an adequate packaging was designed. The electronic board for controlling the laser system comprises a serial communication port, which the laser can be commanded with, and electronics for driving the pump diodes. It was built by von Hoerner & Sulger GmbH (vH&S), Schwetzingen, Germany. The diodes were placed at the electronics board on a heat spreader bracket (Figure 6) and thermally controlled by a heating-only approach, i.e. the diodes were operated at a temperature of >30°C, which is above the highest possible operating temperature of the laser system. This approach consumes least mass and is also more reliable compared to the use of thermo-electrical coolers. The specific diode laser modules, used in the prototype model, were operated at 36°C emitting at a wavelength of around 805nm. The temperature-induced wavelength shift of the diodes was measured to be 0.21nm/K. The spectral full width at half maximum of the 7 combined diode lasers was ~3.5nm. The spectrum exhibits no significant change when increasing the repetition rate up to 50Hz.

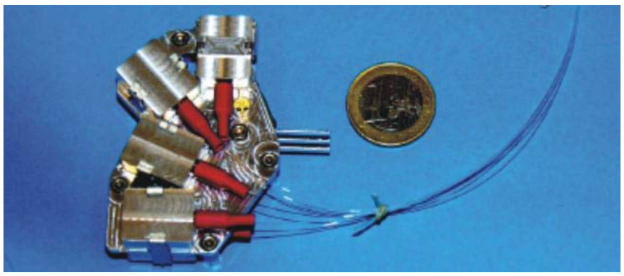

Figure 6: Bracket with dummy diode lasers built by vH&S.

The solid-state laser part (Figure 7) was built by Laser Zentrum Hannover e.V. We pursued a modular concept. This allows for some modifications of the prototype model, e.g. for the implementation of different pump optics according to the used pump fiber specification. Moreover, laser crystals and saturable absorbers of different lengths can be implemented. A slightly different optical configuration of Cr:YAG compared to the breadboard was chosen leading to lower pulse energies, since only >1mJ pulse energy is required.

Figure 7: Solid-state laser head prototype.

For the prototype mechanics, all the optical elements were clamped in order to avoid any outgassing materials inside the laser cavity, which can lead to molecular contamination of the optical surfaces and subsequently to laser-induced damage. The solid state-laser housing itself is hermetically sealed in order to keep an artificial air atmosphere inside the laser, which is also favorable in order to avoid laser induced damage [3]. For this reason, an input window for the pump light and an output window for the solid-state laser pulse were added compared to the laboratory model. The input window was located in the almost collimated pump light beam between the two pump lenses (Figure 3). However, in order keep the prototype as flexible as possible, the hermetical sealing of the housing was established by metal o- and c-rings instead of welding, which allows for later optimization and refurbishment of the prototype, but causes an extra mass of 15g as listed in Table II, because more massive mechanics due to the required high clamping forces had to be used. These sealings can be replaced in future models by welding and brazing. A total mass breakdown of the complete prototype laser is given in Table II.

TABLE II. MASS OF THE LASER PROTOTYPE SYSTEM

	Mass/g
Bracket with 7 pump diodes including fiber, fiber combiner, heater & 4 standoffs	88g
Pump electronics board	63g
Solid-state laser head	23g+15g
Total	**174g+15g**

A pulse energy of 1.5mJ was measured at a pulse duration of 2.1ns. The M²-value was again 1.2. The laser was operated at a repetition frequency of 10Hz for $7 \cdot 10^5$ pulses, which is seven times the requirement. Only small energy variations, but no degradation has been observed (Figure 8).

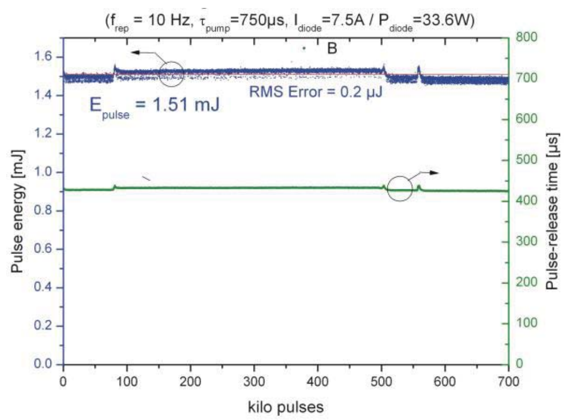

Figure 8: Longterm test of the laser prototype.

The laser head prototype model was operated also at a fixed repetition rate (instead of burst operation) up to 50Hz with laboratory electrical driver and single emitter pump diodes. Since this fixed repetition rate is outside the requirements and since the laser head was not thermally designed for this operating condition, its working point was shifted for 50Hz operation towards longer pulse release times and higher pulse energies around 1.8mJ.

V. SUMMARY

In summary, a diode pumped passively Q-switched Nd:YLF laser system was developed, which is suitable for LIBS in the context of planetary exploration. The laser system including the solid-state laser head, the pump diodes and the complete electronics has a mass of only 189g. The laser system is suitable for further optimization towards flight qualification.

Acknowledgment

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