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Enhancement of the Design of a Pulsed UV Laser System for a Laser-Desorption Mass Spectrometer on Mars

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***Abstract*—A laser-desorption mass spectrometer will be part of the ESA-led ExoMars mission with the objective of identifying organic molecules on planet Mars. A UV laser source emitting nanosecond pulses with pulse energy of about 250 µJ at a wavelength of 266 nm is required for the ionization of non-volatile soil constituents. A passively q-switched, diode-pumped Nd:YAG laser oscillator with external frequency quadrupling has been developed. The basic optical concept and a previously developed flight-near prototype are redesigned for the engineering qualification model of the laser, mainly due to requirements updated during the development process and necessary system adaptations. Performance issues like pulse energy stability, pulse energy adjustment, and burst mode operation are presented in this paper.**

Keywords - Solid-state laser; space technology; LDMS; frequency conversion

I. INTRODUCTION

One of the main objectives of ESA's ExoMars rover mission is to search for traces of past or present life on Mars. The Mars Organic Molecule Analyzer (MOMA) is one of the major instruments on the rover's payload Pasteur. It consists of a gas chromatograph for the analysis of volatile constituents and a laser-desorption mass spectrometer (LDMS) for the analysis of non-evaporable components [1-3]. For the ionization of large organic molecules in samples of soil from Mars' surface or sub-surface, a pulsed ultraviolet laser is needed. Nanosecond pulses with a pulse energy of 250 µJ at a wavelength of 266 nm and a fairly good beam quality of $M^2 < 4$ are required. The concept of the laser head which we developed is based on a passively q-switched, longitudinally pumped Nd:YAG laser oscillator operating at the wavelength of 1064 nm. For reasons of system modularity, the pump light is delivered via an optical fiber from a 120 W qcw pump diode which is located in a separate electronics module. The pulses of the oscillator with duration of approximately 1.5 ns and pulse energy of 2 mJ are externally frequency-quadrupled by two nonlinear crystals, i.e. a KTP (potassium titanyl phosphate) and a BBO (beta barium borate) crystal. Flight-near prototypes have been developed in a compact, lightweight and ruggedized design and already been presented [4,5]. A first set of environmental tests has been performed on these prototypes in order to assess the feasibility of its design details for a later flight model. This laser system will be the first one in space emitting at the wavelength of 266 nm.

The development process is advancing towards the engineering qualification model design. A focus of the development activities has been laid on aspects concerning the adaptation to changed requirements and operation conditions, advancement of technologies towards a qualifiable design and improvement on performance characteristics, in particular energy stability issues. The pulse energy stability of the longitudinally single-mode emitting laser resonator is mainly influenced by thermal effects inducing mode hops. Burst operation of the laser head further hampers the stability due to thermo-optical effects in the optical components. Different variations of the oscillator design with respect to longitudinal mode selection have been compared such as using diffusion-bonded crystals, optical elements with different wedges, or volume Bragg gratings. In addition to the selection of the appropriate resonator design, thermal control of the oscillator is necessary in order to stabilize the output of the passively q-switched laser along the whole operation temperature range of -50°C to +25°C. For variation of the UV pulse energy between the maximum and several lower levels, the feasibility of adjusting the efficiency of the second harmonic generation processes in the nonlinear crystals by temperature tuning is being investigated. Further activities involve design adaptations for the mounting of the laser head and beam deflection for accommodation on the payload system.

II. LASER CONCEPT

The optical requirements for the LDMS laser are a wavelength of 266 nm, pulse duration of about 1 ns, a pulse energy of approximately 250 µJ at a beam propagation factor M^2 of below 4. The operation mode on the mission has developed from an initially assumed continuous pulsing at 1 to 2 Hz to a burst mode with up to 50 pulses at 100 Hz. The basic laser concept is shown in Fig. 1, as it was already presented in [4]. It is based on a Nd:YAG laser crystal which is longitudinally pumped by a fiber-coupled pump diode. By using two lenses, the light out of the 600 µm diameter fiber is imaged into the laser crystal. The anti-reflective entrance surface for the pump light on the laser crystal is at the same time highly-reflectively coated for the laser wavelength of 1064 nm. Pulsing is achieved by passive q-switching using a saturable absorber crystal (Cr^{4+}:YAG). A Brewster window serves as the polarizing element for achieving stable polarization output for the two resonator-external nonlinear second harmonic generation (SHG) stages. Each of these crystals, i.e. a KTP (potassium titanyl phosphate) and a BBO (beta barium borate) crystal, doubles the frequency of its input such that laser pulses at 266 nm are generated. The passive q-switching scheme makes the laser concept very simple and compact, since no larger component or further electronics is required like in e.g. EOM-based actively q-switched lasers.

Subsequent to the frequency conversion by the SHG crystals, separation of the UV beam from the remaining 1064 nm and 532 nm components is accomplished. Part of the converted signal is branched off to photo diodes which are used for signalling successful laser pulse generation and for measurement of the UV pulse energy.

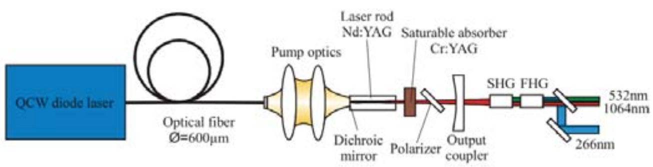

Figure 1. Optical setup of the pulsed UV laser.

A flight-near prototype as shown in Fig. 2 has already been developed and assembled [4]. It is very compact with just 13 cm of length and lightweight with below 120 g of mass. The thermal concept involves thermal insulation of the laser interior by the titanium housing, and thermal control is just accomplished by one internal heater at the frequency conversion stage in order to keep the internal operational temperature for all environmental cases. The prototype was intended to demonstrate the feasibility of the optical concept within a very compact and rugged mechanical structure coping with the mechanical, thermal, and radiation-related environmental conditions of the mission. It has successfully undergone several laboratory and environmental tests. Nevertheless, several design aspects still have to be accounted for in the development process towards the engineering qualification model and the flight model. Some of these, mainly which are related to operational issues, are discussed in the following.

III. PULSE ENERGY STABILITY

For the operation of the LDMS instrument, a certain pulse energy stability of the optical UV output is desired. Fluctuations toward lower energy values are acceptable, while higher values can be critical. Thermal tests with setups of the initial optical design revealed energy fluctuations in the UV output during operation with changing thermal environmental conditions. These fluctuations often occur in form of jumps due to mode hops.

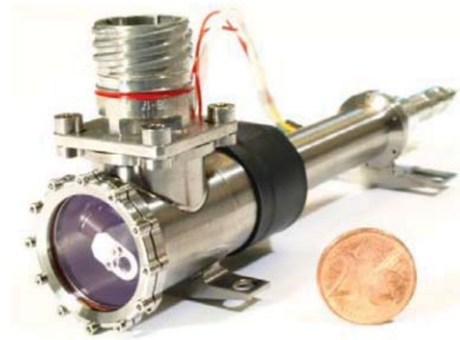

Figure 2. Realization of the laser head prototype.

The IR oscillator generally operates on a single longitudinal mode except in transition regions between two modes where two or even three modes can occur simultaneously, leading to higher peak energies both in the IR oscillator output and, usually with amplified relative effect due to the nonlinear behaviour, after frequency conversion in the UV output. The modal behaviour was investigated in the initial optical design of the laser oscillator. While the temperature of the oscillator was varied, pulse energy, wavelength and further parameters were measured at the 1064 nm output. Fig. 3a) shows the typical behaviour with mode jumps of about 23 to 90 pm, which is a multiple of the longitudinal mode spacing of this oscillator of approx. 7.5 pm. In the transition regions energy spikes in the IR wavelength by more than 15% can be observed which are associated with the mode transition regions.

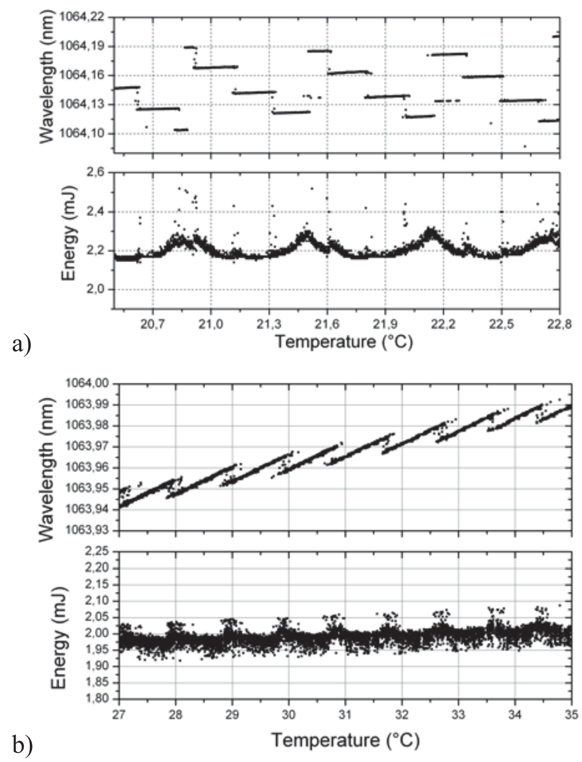

Figure 3. Wavelength and pulse energy fluctuation vs. variation of the oscillator temperature. a) Oscillator with plane optical components. b) Oscillator without subresonators.

The wavelength pattern strongly deviates from the ideal sawtooth-like pattern as it is known e.g. from stable nonplanar ring oscillators. The pattern is caused by weak but sufficiently strong subresonators formed by parallel surfaces of optical elements and the residual reflectivities of their anti-reflective coatings. A common way to circumvent this is to use wedged optical elements. Using slightly wedged laser crystals and output couplers leads to the oscillator behaviour shown in Fig. 3b). In certain ranges the wavelength exhibits the sawtooth-like behaviour with jumps by just one neighbouring longitudinal mode of approx. 7.5 pm. The pulse energy at 1064 nm is also much more stable; energy fluctuations are considerably reduced to just few percent around the average value. It can also be observed that the temperature range of mode-hop free operation has increased from below 0.1 K to about 0.5 K which gives much better possibilities of thermal control for the oscillator.

For comparison, further methods of wavelength stabilization have been investigated [6]. The first is the use of a volume Bragg grating (VBG) as output coupler. Although this grating already has a quite low bandwidth of 50 pm and was expected to enforce the generated mode into a small central region of the VBG spectrum, the mode hopping behavior still expands over several longitudinal modes (up to 40 pm), associated with energy fluctuations by more than 10%. Also a compound crystal consisting of a saturable absorber crystal, which is diffusion-bonded on the laser crystal in order to get rid of the optical faces between the two crystals was tested. Again, hops in the wavelength spanning a range of about 50 pm with corresponding pulse energy spikes of up to 15% towards positive values in transition regions between two modes were observed. Obviously, the residual reflectivity of the outer surface of the saturable absorber still has a noticeable influence on the mode behavior. As the experiments with the wedged components exhibited the best results, this variant was chosen as the baseline design.

A further energy stabilizing measure is the implementation of additional thermal control of the oscillator. The initial flight-like design just contains one single thermal control, i.e. for the frequency conversion stage. During operation, the temperature of the oscillator passively acquires a varying intermediate temperature between the maximum temperature located at the nonlinear crystals and the minimum temperature outside of the laser head. Implementation of a further thermal control loop for the oscillator in the revised laser design has the following positive effects: the pulse energy fluctuations caused by mode hops as discussed above are considerably reduced, and also the temperature-dependent pulse energy drift, which is typical to passively q-switched lasers is reduced.

IV. PULSE ENERGY ADJUSTMENT

Depending on the material composition in the samples of soil on Mars's surface, threshold levels for the optical intensity to ablate and weakly ionize the materials for subsequent analysis in the mass spectrometer differ from each other. An intensity level too low does not produce a sufficient number of ions, and a level too high may have further undesired physical effects such as an optical breakdown accompanied by full ionization on the surface of the sample. Thus, a typical LDMS measurement sequence approaches the threshold level from lower intensity levels upwards. The capability of pulse energy adjustment is desired. As mass, volume, and power resources are limited on the rover payload, a trade-off between different methods of pulse energy adjustment has to be made. The optical concept of the laser had already been chosen with respect to minimization of mass, size and electronics resources, but the output pulse energy of a passively q-switched laser is fairly a constant. External attenuators like, e.g., filter wheels require additional resources and qualification effort, and a simple method was sought. Thus, the possibility of pulse energy variation by changing the temperature of the nonlinear conversion crystals and, in turn, the optical conversion efficiency of the crystals is investigated.

As the maximum environmental operation temperature for the laser head is 25°C, the thermal design was chosen in that way, that by heating the nonlinear crystals to an operation point of about 30-35°C efficient conversion can be achieved. This approach can be achieved by using resistive foil heaters. This is a much simpler concept than e.g. using thermo-electric coolers which would be necessary when also cooling had to be accomplished. Of the two nonlinear crystals, KTP has a quite large temperature acceptance range[1] of 52 K, while BBO is the more sensitive crystal with an acceptance range of 20 to 30 K, depending on the finally chosen crystal length. Both crystals are mounted near to each other and are commonly controlled by a single thermal control. Detuning the temperature from the optimum operation point decreases the efficiency of the nonlinear conversion and, thus, can be utilized to adjust the UV pulse energy. A change of the temperature by approximately 15 K results in reduction of the pulse energy from the maximum level down to about 10%. The beam shape behavior has to be observed here: detuning the temperature means operating the crystals, and in particular the BBO crystal, off the phase matching condition. The spatial direction of optimum phase matching shifts off the beam center, and a deterioration of the beam profile can be observed.

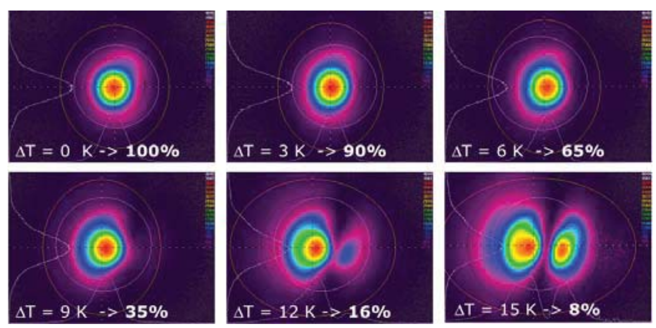

Figure 4. Beam profiles for different temperature deviations Delta T from nominal operation point. Percentage figures state relative pulse energy values.

Fig. 4 shows six beam profiles at different temperatures, starting at the optimum operation temperature with maximum conversion efficiency and UV pulse energy (set to 100%), and ending with a detuning by 15 K at less than 10% UV pulse energy in the output. At the lowest energy levels, even a beam

[1] The temperature acceptance range here is the full double-sided range terminated by the zeros in the conversion efficiency function.

split can be observed. The line separating the two beam portions can be explained by the spatial region of zero SHG efficiency (the first zero of the sinc^2 function which describes the conversion efficiencies in dependence of the phase matching condition). When detuning from 100% to 10%, the point of maximum intensity moves accordingly to the side, by approximately half a beam width as can be seen in the pictures (the camera position was fixed). Down to approximately 20-30% the deterioration of the beam profile is fairly small. But also the disturbed beam profile at lower energy values can be regarded as further intensity reduction within the field of view of the mass-spectrometer ion trap.

V. Burst operation

During initial development phases of the optical concept, the laser was expected to be operated in continuous pulsed mode with a constant 1 or 2 Hz repetition rate or bursts with a low number, i.e. 10 at 10 Hz, of pulses with a larger pause, ending again at the average pulse repetition rate of 1 Hz. Pulse energy considerations from the above sections are mainly related to continuous uniform operation with constant pulse repetition rate (in the lab, usually 5 to 10 Hz are applied). During further development, a new requirement of a high-repetition rate mode with 50 pulses at 100 Hz emerged to improve LDMS operation. After every burst, sufficient pause can be taken in order to end at a low average pulse repetition rate which the laser head and also the pump diodes are designed for.

a)

b)

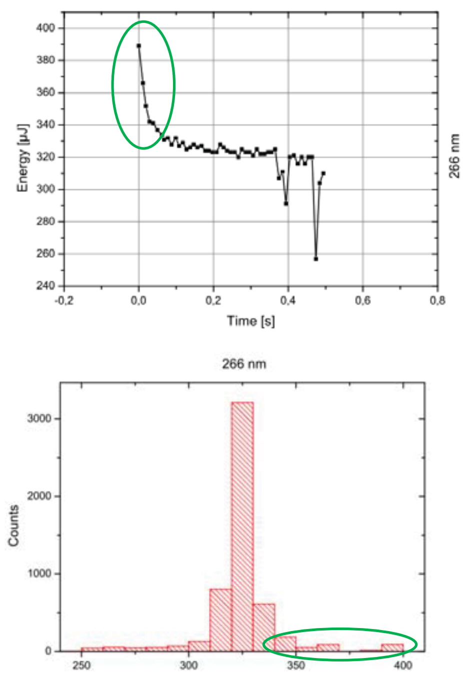

Figure 5. a) Typical UV pulse energy evolution during a burst. b) Histogram of pulse energy distribution. In green circles: energy values omitted by pre-pulsing.

During the start of a longer or shorter sequence of laser pulses, thermal dynamics due to absorption of pump power in the laser crystal cause varying optical parameters of the pulses until a stable thermal state is reached. This can be observed during virtually every burst, like in the pulse energy dynamics of a typical burst shown in Fig. 5a). Typically, a burst starts with higher-energy level pulses, and approaches a fairly stable level, with the exception of single pulses with lower pulse energies caused by mode hops. In Fig. 5b) a corresponding histogram of the energy levels, acquired over a larger number of bursts is depicted. As stated above, the lower values do not perturb the LDMS measurement, whereas higher values should be avoided. This can be achieved by application of a series of pump light pulses directly before every burst. These pre-pulses have the purpose of pre-heating the laser crystal by pump absorption and have to be shorter in duration than the pulse release time of the passively q-switched laser head, i.e. no laser pulse is generated. As a result, higher-energy-level pulses are repressed to a good portion; the pulses in the green circles in Fig. 5 are mostly omitted. The thermal and design-related measures from Sec. 3 improve the stability of the resulting statistics for all environmental conditions.

VI. Outlook: EQM Development

Mainly based on the existing design of the flight-near prototype model and the improvements in the optical and thermal issues as explicated above, the mechanics of the laser head is being redesigned. Due to issues of laser-induced contamination (LIC) in combination with high fluence on optical elements and their coatings, the laser head interior shall be as free of organic compounds as possible. Clamping techniques instead of using organic adhesives for mounting of the optical elements are adopted already in the prototype design, where the (mostly cylindrical) optical components are supported both on the barrel face and on the rim of the end faces. In the redesign, clamping for several elements from the barrel surface only is applied in order to reduce the amount of possible particulate contamination on the end faces during assembly. The mounts of the nonlinear crystals the alignment of which is very critical have been improved. The mounting concept of the laser head to the mass spectrometer is being adapted according to system requirements. The housing of the laser head will be hermetically sealed to keep an atmosphere of synthetic air inside for the reduction of LIC effects. Appropriate joining techniques like brazing and welding are developed and qualified e.g. by accomplishment of leakage tests during thermal cycling in vacuum. Further qualification activities are being accomplished with coatings, components, and processes.

VII. Summary

The pulsed UV laser source is an important part of the ExoMars LDMS instrument MOMA for the analysis of organic molecules. For reasons of compactness and restriction of system resources, a concept with a passively q-switched Nd:YAG oscillator with external frequency quadrupling has been chosen. The design of a first functional, flight-near prototype is enhanced with respect to several operational issues, like pulse energy stability or output pulse energy adjustment which are important for successful LDMS operation. The mechanical concept is experiencing a redesign on the way to an engineering qualification model.

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REFERENCES

[1] F. Goesmann, F. Raulin, L. Becker, R. Ehrenfreund, and M. Hilchenbach, „MOMA, the Martian Organic Molecule Analyser; current Developments and Capabilities of a combined GC/MS and LD-MS Instrument," Geophysical Research Abstracts, vol. 9, 05953, 2007

[2] R. J. Cotter, S. Swatkoski, L. Becker, and T. Evans-Nguyen, "Time-of-flights and traps: from Histone Code to Mars", Europ. J. Mass Spectrom., vol. 16, pp. 331-340, 2010

[3] L. Becker, T. Cornish, M. Antione, R. Cotter, T. Evans-Nugyen, V. Doroshenko, F. Goesmann, F. Raulin, and P. Ehrenfreund, "MOMA-Ldms: Instrument concept and results", Geochim. Cosmochim. Acta, vol. 73, A101-A101, 2009

[4] C. Kolleck, A. Büttner, M. Ernst, T. Hülsenbusch, T. Lang, R. Marwah, S. Mebben, M. Priehs, D. Kracht, and J. Neumann, "Development of a pulsed UV laser system for laser-desorption mass spectrometry on Mars", 8th International Conference on Space Optics (ICSO) 2010, Rhodes, Greece, 2010

[5] J. Neumann et. al., "Development of a pulsed ultraviolet solid-state laser system for Mars surface analysis by laser desorption/ionization mass spectroscopy," European Planetary Science Congress, EPSC Abstracts, vol. 4, 624, 2009

[6] T. Hülsenbusch, A. Büttner, M. Ernst, T. Lang, C. Kolleck, D. Kracht, and J. Neumann, "Mode fluctuations in end-pumped passively Q-switched solid-state lasers", Advanced Solid-State Photonics (ASSP), San Diego, CA, 2012