# Feasibility and performance study for a space-borne 1645 nm OPO for French-German satellite mission MERLIN

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## ABSTRACT

We present a theoretical and experimental analysis of a pulsed 1645 nm optical parametric oscillator (OPO) to prove the feasibility of such a device for a spaceborne laser transmitter in an integrated path differential absorption (IPDA) lidar system. The investigation is part of the French-German satellite mission MERLIN (Methane Remote Sensing Lidar Mission). As an effective greenhouse gas, methane plays an important role for the global climate.

The architecture of the OPO is based on a conceptual design developed by DLR, consisting of two KTA crystals in a four-mirror-cavity. Using numerical simulations, we studied the performance of such a setup with KTP and investigated means to optimize the optical design by increasing the efficiency of the OPO and decreasing the fluence on the optical components. For the experimental testing of the OPO, we used the INNOSlab-based ESA pre-development model ATLAS as pump laser at 1064 nm. The OPO obtained 9.2 mJ pulse energy at 1645 nm from 31.5 mJ of the pump and a pump pulse duration of 42 ns. This corresponds to an optical/optical efficiency of 29%. After the pump pulse was reduced to 24 ns, a similar OPO performance could be obtained by adapting the pump beam radius. In recent experiments with optimized optical design the OPO obtained 12.5 mJ pulse energy at 1645 nm from 32.0 mJ of the pump, corresponding to an optical/optical efficiency of 39%. Two different methods were applied to study the laser damage thresholds of the optical elements used.

**Keywords:** frequency conversion, spaceborne lidar, IPDA lidar, KTP, non-linear crystal, optical parametric oscillator, LIDT

## 1. INTRODUCTION

Methane is one of the most important anthropogenic greenhouse gases in the atmosphere [1]. To understand atmospheric processes and to develop models to predict climate development, it is fundamental to know the sources and sinks of methane. To explore these, long-term and global data with high spatial resolution on gas abundances are required. A spaceborne IPDA lidar-system has been found to be potentially suited to obtain these data, because it allows data acquisition globally at all times. Within the scope of a German-French cooperation, a methane remote sensing lidar mission (MERLIN) was initiated. The transmitter of the lidar system has to provide a single-frequency output at a defined and specific central wavelength that depends on the absorption lines of methane. A suitable multiplet is around 1645.6 nm [2], but there is a lack of mature laser systems directly emitting in the required wavelength range. Thus, the favorable sources are based on frequency conversion techniques like optical parametric oscillators (OPO) and amplifiers (OPA). In former airborne lidar systems, OPO/OPA systems were used to obtain the pulse energy needed [3]. To simplify this system, the OPO has to be optimized to emit pulse energies over 9 mJ. In this work a numerical model was developed to simulate the OPO and the results were compared to the following measurements.

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## 2. OPTICAL DESIGN

The conceptual design of the OPO was based on the setup of DLR-IPA for the CHARM-F project [3]. In the four-mirror ring-cavity, potassium titanyl phosphate (KTP) was employed as nonlinear medium. The two crystals were cut in a critical phase-matching direction for wavelengths around 1645 nm and arranged in a walk-off compensated configuration. The pump beam was coupled into the cavity at mirror 1 and coupled out at mirror 4. All four mirrors had a high transmission of the idler wave to reduce possible thermal effects and back conversion at high intensities. The OPO could be injection seeded through mirror 3, which is partial reflective for 1645 nm. At the same mirror the signal was coupled out.

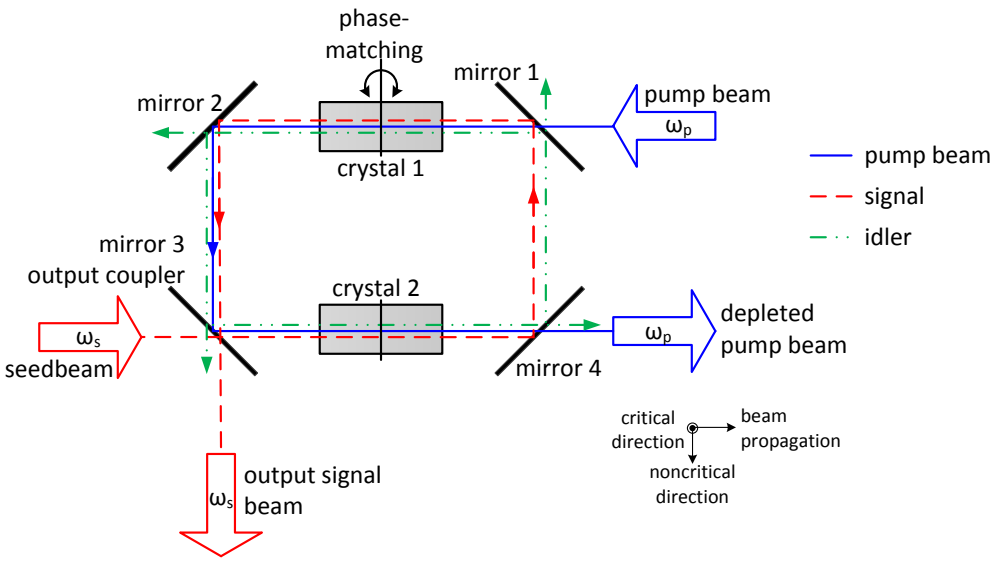


Figure 1. Optical design of the OPO

Based on this conceptual design, a numerical computer model was implemented that simulates the transition of one pump pulse through the OPO. The pulse is cut into time slices that are propagated through the OPO along the direction of beam propagation. In this model several parameters can be varied to optimize the OPO and to investigate their effect. In addition to the crystal material, these are the crystal and cavity length, the diameters of pump and seed beam, the energy and duration of the pump pulse, the power of the seed beam and the reflection coefficients of all four mirrors. To analyze the alignment and the pointing stability tolerances, the mirrors and the input beams can be virtually tilted and displaced in parallel to each other. The model of the OPO was used to calculate a favorable working point starting from the values in [3].

## 3. EXPERIMENTAL SETUP

The INNOSlab-based ESA pre-development model ATLAS was used as the pump laser at 1064 nm [5]. This Nd:YAG laser was Q-switched and the pulse duration was 41.6 ns. Since the OPO was not cavity-controlled at the beginning of the measurements, it was not necessary to run the pump laser in single-frequency operation. The maximum output energy generated by the laser is 45 mJ and the beam quality factor $M^2$ was measured to be in the order of 1.3. The repetition rate chosen was 25 Hz as the MERLIN system will be running at 12-25 Hz double-pulse, depending on the available power. The pump beam was shaped using a cylindrical telescope to avoid astigmatism and a zoom telescope for variation of the beam diameter.

For injection seeding, a DFB laser was used that allows mode-hop free tuning between 1643 nm and 1649 nm. The maximum power at the input coupler was 8.4 mW. To prove the feasibility of such a system, it was not necessary to perform our experiments at the exact absorption line of methane. Nonetheless, we adjusted the OPO and the seeder to

signal wavelengths between 1645 nm and 1646 nm to be close to the absorption line at l645.6 nm. The seed beam was shaped by a similar zoom telescope as the pump beam.

The mechanical setup of the bread-board OPO was mounted in a stable housing, which allowed the macroscopic variation of the resonator length. All four mirrors and the crystals were adjustable for maximum flexibility. With this setup all parameters in the simulation could be varied. Mirror 2 was provided with a piezo-element and a heterodyne-based cavity control was employed. The procedure of this control method is explained in [3].

## 4. MEASUREMENTS

### 4.1 Conversion efficiency

With this setup the characteristic curves in Figure 2 were measured. The maximum output energy was 9.2 mJ at 31.5 mJ pump pulse energy. The optical/optical efficiency is 29 % and the quantum efficiency 45 %. The threshold of the OPO at a pump beam radius of 0.62 mm was measured to be 12.5 mJ and the slope efficiency was 50 %. This result is in good agreement with the numeric model so that we were able to simulate every set of parameters.

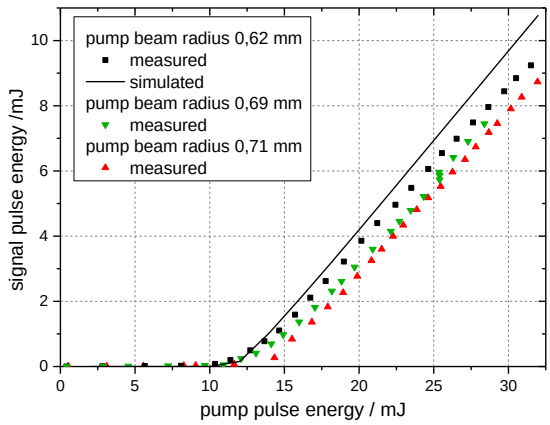


Figure 2. Signal pulse energy of the OPO as a function of the pump energy at different pump beam radii, measured and simulated

The requirements of the IPDA lidar system in MERLIN are shown in Table 1. The minimum pulse energy of 9 mJ was achieved at the required wavelength and the optical/optical efficiency was higher than required. The pulse width of the signal was also in the required range although the measurement was carried out at lower pulse energy to avoid damage of the optical elements. Higher pump energy would lead to a longer pulse but the maximum duration is given by the pump pulse duration of 41.6 ns. Although the pump did not run in single-frequency mode, the line width of the output wave was two to three times below the required value and the beam quality is better than required, as well. On the other hand, those two measurements were carried out close to the threshold and the line width and the beam quality are likely to degrade at higher pulse energies.

Table 1. Requirements of MERLIN and comparison to the measurements

| Parameter | MERLIN | KTP (18 mm, 41.6 ns pump pulse) |
|---|---|---|
| Wavelength | 1645 nm | Seeded at 1645 nm, tunable |
| Pulse energy | 9 mJ | 9.2 mJ |
| Optical/optical efficiency | 25 % | 29 % |
| Repetition Rate | 10-25 Hz (double pulse) | 25 Hz (single pulse) |
| Pulse width (FWHM) | 15 ns < t < 40 ns | 25 ns (at 3.1 mJ signal pulse energy) |
| Line width (FWHM) | <100 MHz | 39 MHz (at 3.3 mJ signal pulse energy) |
| Beam quality $M^2$ | <3.5 | <1.3 (at 3.7 mJ signal pulse energy) |

### 4.2 Seed power and output coupler

Increasing the reflection of the output coupler decreases the threshold of the OPO. To analyze this connection, two mirrors with different coatings and reflection coefficients were supplied. The available reflection coefficients were 60 % and 73 %. The characteristic curves of the OPO in seeded and unseeded operation with both mirrors are shown in Figure 3. As predicted by the model, the higher reflection led to a reduction of the threshold and a small increase of the slope efficiency. Seeded operation decreased the threshold by ~4 mJ in both cases.

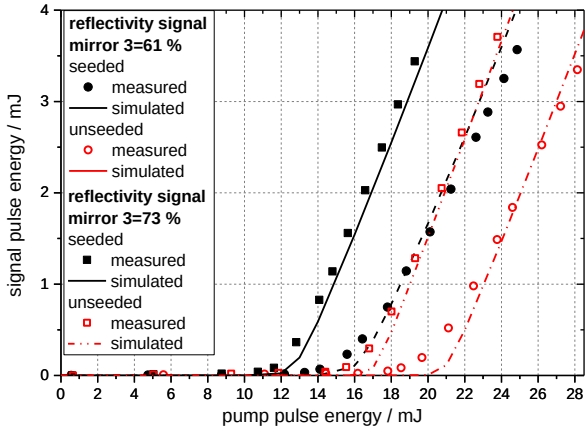


Figure 3. Signal pulse energy of the OPO as a function of the pump energy at different output reflection and in seeded and unseeded operation, measured and simulated

To investigate the influence of the seed power on the output pulse energy, this parameter was varied between 0 mW and 8 mW at a constant pump pulse energy (see Fig. 4). The measured output pulse energy in seeded operation was more than twice as high as in the unseeded case. Above a seed power of ~3 mW, a further increase only had a negligible impact on the pulse energy. This relation was also predicted by the simulation where especially the ratio of seeded and unseeded operation was almost the same as in the measurement.

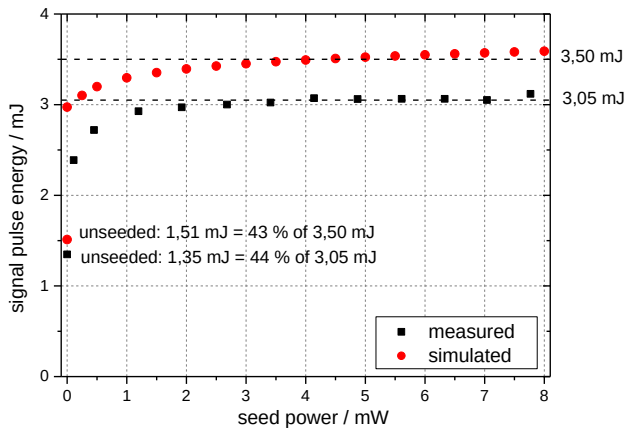


Figure 4. Signal pulse energy of the OPO as a function of the seed power, measured and simulated

### 4.3 Pump pulse duration

In order to analyze the influence of the pump pulse duration, it was decreased to 23.8 ns. Without changing the pump radius and, thus, keeping the same pump fluence, the threshold was reduced to 8.1 mJ. Then, the pump radius was increased to compare it with a measurement at a pulse duration of 41.6 ns while keeping the pump intensity constant.

The results of those two measurements are comparable with only small deviations of the threshold and the slope efficiency (see Fig. 5). By means of this decrease in pump pulse duration, the fluence on the optical elements could be reduced from 6.8 J/cm$^2$ to 4.2 J/cm$^2$ at 30.8 mJ pump pulse energy to avoid damage while keeping the same conversion efficiency.

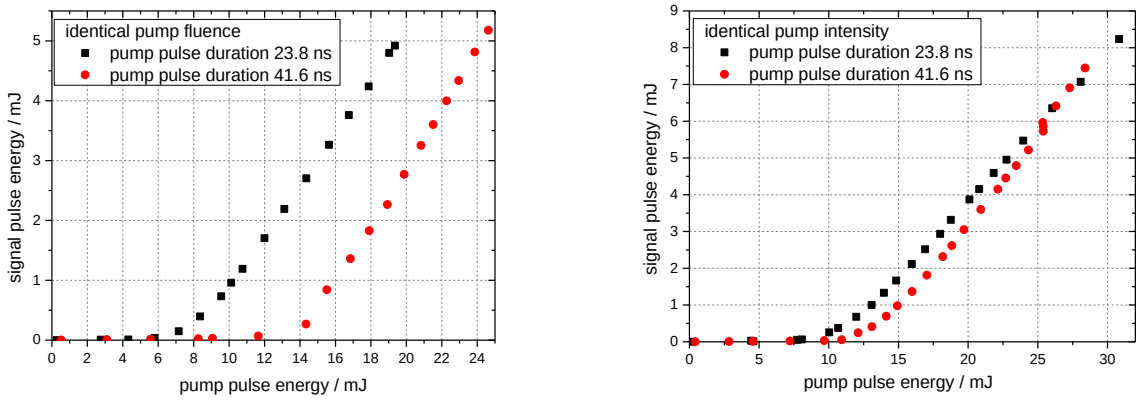


Figure 5. Signal pulse energy of the OPO as a function of the pump energy at different pulse durations and radii to compare the efficiency at constant pump fluence and intensity

### 4.4 Crystal Length

Another possibility to increase the efficiency is to use longer crystals. To investigate this effect the 18 mm KTP crystals were replaced by 23 mm long KTP crystals. Additionally, the optics were further optimized and the cavity control system of the pump laser was implemented, which reduced the pump pulse duration. The threshold of the OPO was measured to be 5.6 mJ and the slope efficiency was 54 % (see Fig. 6). A maximum output energy of 12.5 mJ was achieved at 32.0 mJ pump pulse energy. This corresponds to an optical/optical efficiency of 39 % and a quantum efficiency of 60 %.

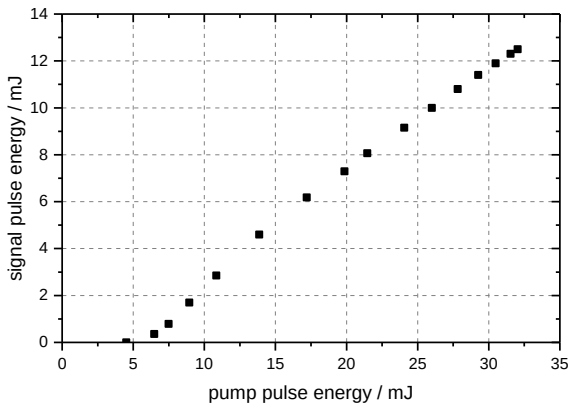


Figure 6. Signal pulse energy of the OPO as a function of the pump energy

### 4.5 Investigation of the damage threshold of the optical components

To minimize the risk of damage during long term operation and optimization of the working point it is important to know the laser induced damage thresholds (LIDT) of the optical components. To investigate the LIDT values of the optics used in the former experiments, damage threshold measurements were performed applying two different methods. Initially, the optical components were tested in an automated LIDT setup at the ILT, which was built for the space-qualification of optical components for the laser altimeter transmitter of the ESA mission “BepiColombo” [6]. This setup is suitable for ISO 11254-2 compliant LIDT-measurements at the pump wavelength of 1064 nm. In these experiments mirror 2 was identified to be the most critical component with a LIDT of approximately 6 J/cm².

This value may not indicate the real damage threshold of the optics during OPO operation, because the influence of the other appearing wavelengths (signal/idler) is not considered. For this reason LIDT measurements were performed during OPO operation by gradually increasing the fluence in the OPO. This was realized by gradually shrinking the pump beam radius. The first damage was observed on mirror 2 at a pump pulse energy of 27.1 mJ (see Fig. 7) corresponding to a total fluence F = 6.2 J/cm² ($F = F_{pump} + F_{signal} + F_{idler}$). The good agreement between the two LIDT values indicates that the wavelength dependence of the damage threshold might be low here.

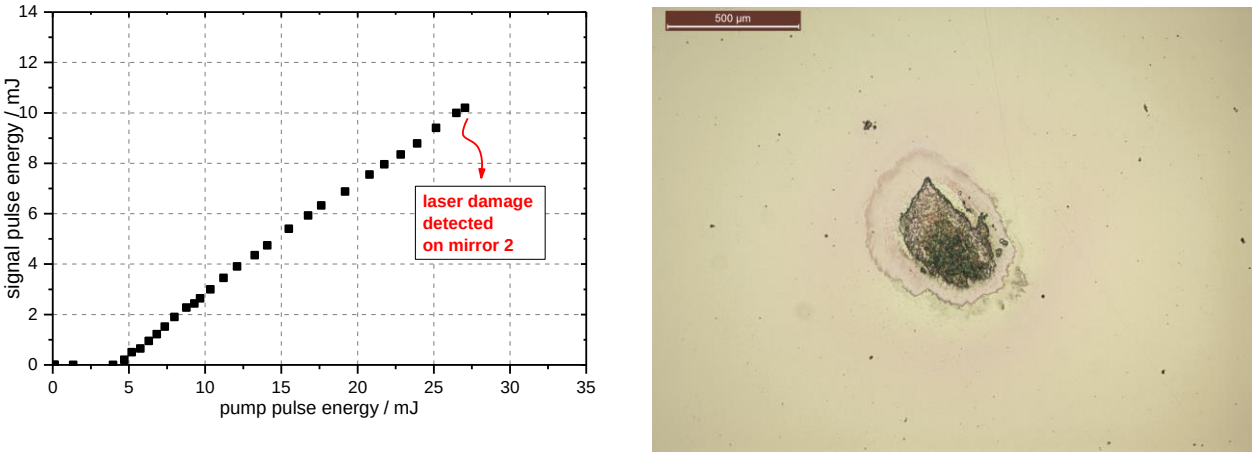


Figure 7. Signal pulse energy of the OPO as a function of the pump energy, microscopy image of mirror 2 after LIDT-tests

## 5. CONCLUSIONS AND OUTLOOK

To summarize, an optical parametric oscillator was demonstrated that emits 12.5 mJ of output energy at 1645 nm pumped by a Nd:YAG laser with 32.0 mJ at 1064 nm. This corresponds to an optical/optical efficiency of 39 %. The crystal material KTP was chosen. To optimize the system, a model was implemented and compared to the experimental setup at different input parameters.

In this paper the variations of seed power and reflectivity of the output coupler were presented. To increase the efficiency, the pulse duration was shortened and longer crystals were employed. Then, when the pump beam diameter was increased, the same efficiency was observed while at the same time the fluence was lowered so as to prevent damaging the optics.

After this demonstration of feasibility, further work will include measurements of spectral characteristics and beam quality at the working point of the lidar system. Further investigations of the damage threshold of the optics will be performed. For this reason a new LIDT laser source at 1645 nm will be developed and built. The optimization of optical components with respect to the damage threshold will be addressed. The assembling and adjustment of the OPO, which is very sensitive to misalignment will also be optimized.

## 6. ACKNOWLEDGEMENTS

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