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) conducted 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. One of the cavity mirrors is piezo-driven to provide single frequency operation of the OPO. Using numerical simulations, we studied the performance and alignment tolerances of such a setup with KTP and KTA and investigated means to optimize the optical design by increasing the efficiency 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. At a pulse frequency of 25 Hz this MOPA delivers a pump energy up to 45 mJ with a beam quality factor of about $M^2 = 1.3$. With KTP as nonlinear crystal 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.

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

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.

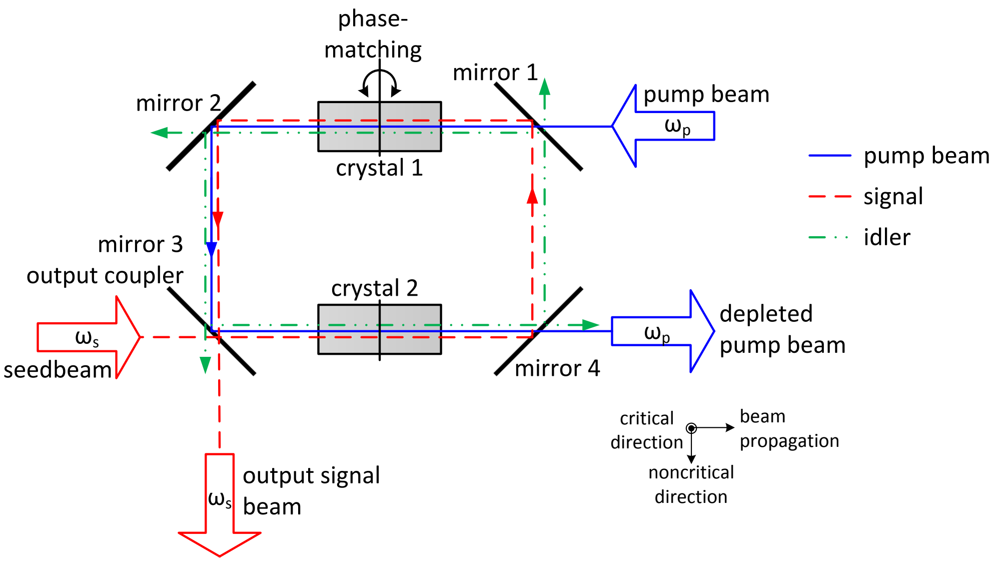

Figure 1. Optical design of the OPO

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.

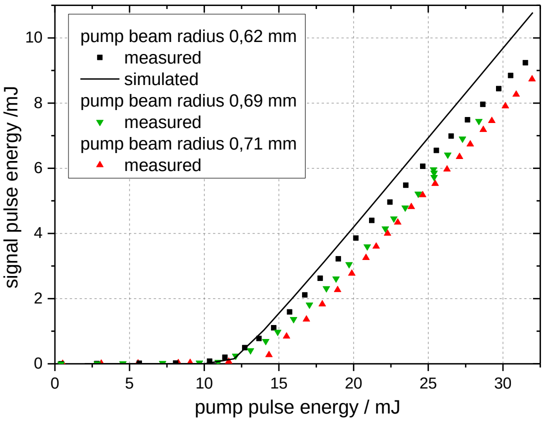

Figure 2. Signal pulse energy of the OPO as a function of the pump energy at different pump beam radii, measured and simulated

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.

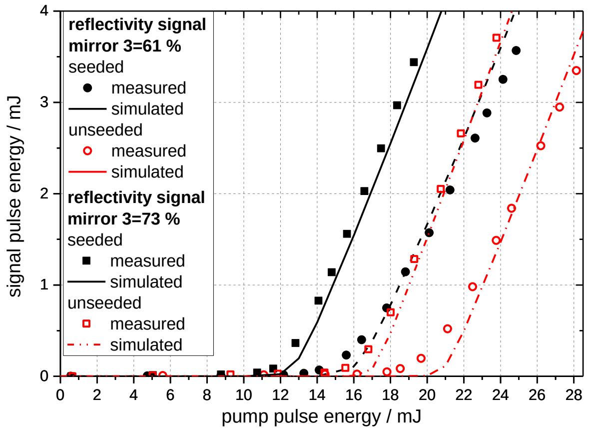

Figure 3. Signal pulse energy of the OPO as a function of the pump energy at different output reflection and in seeded and unseeded operation, measured and simulated

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.

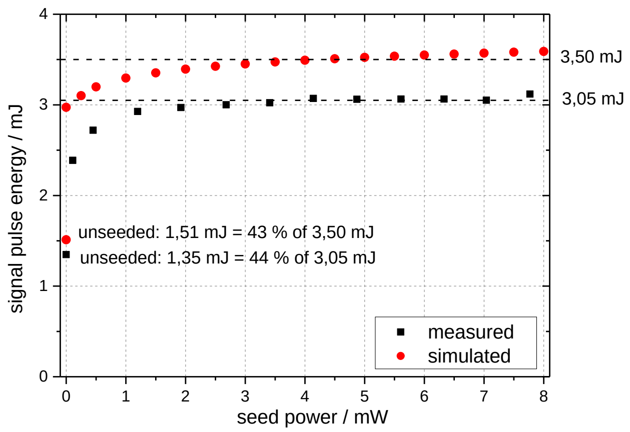

Figure 4. Signal pulse energy of the OPO as a function of the seed power, measured and simulated

4.3 Adjustment tolerances

For the later operation of the OPO, it is very important to know how misalignment of the optics changes the efficiency and the pointing of the output beam. Tilting the output coupler by 135 µrad in the critical direction (in the phase-matching plane) led to a drop of output energy of 50 % in seeded operation (see Fig. 5). In the perpendicular direction the mirror was less sensitive and the same decrease of the energy was observed at 210 µrad tilting. The simulation predicted a similar behavior comparing both directions, but the sensitivity of the mirror in the model was much higher than measured. It was not possible to give a more precise analysis, because the simulation did not allow a tilting of the output mirror greater than 50 µrad.

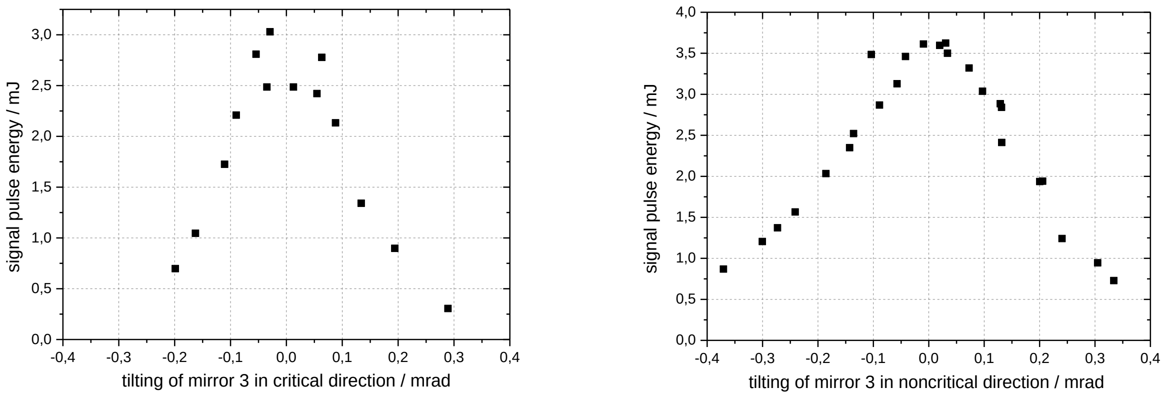

Figure 5. Signal pulse energy as a function of the tilting of mirror 3 (output coupler) in critical and noncritical directions

Not only does misalignment of the cavity impact the efficiency of the OPO and the pointing of the output beam, but also the pointing error of the pump beam has a similar effect. Tilting the pump beam in the critical direction decreased the output energy more than in the noncritical direction (see Fig. 6). This was comparable to the misalignment of the cavity. The overall sensitivity, however, was over three times lower. The FWHM of a pointing error in the noncritical direction could not even be measured, but was larger than 2.7 mrad in seeded operation. Further tilting might have damaged the optics. The pointing error of the pump beam led to a change of pointing of the output beam that is 14 % smaller. Both measurements were in good agreement with the model.

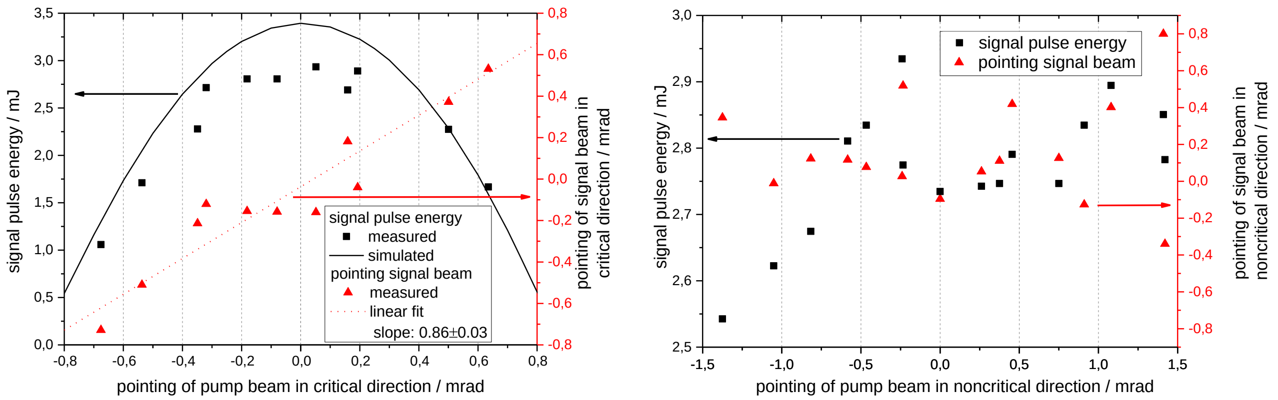

Figure 6. Pulse energy and pointing of the signal beam as a function of the pointing of the pump beam in critical and noncritical directions

4.4 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. 7). 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.

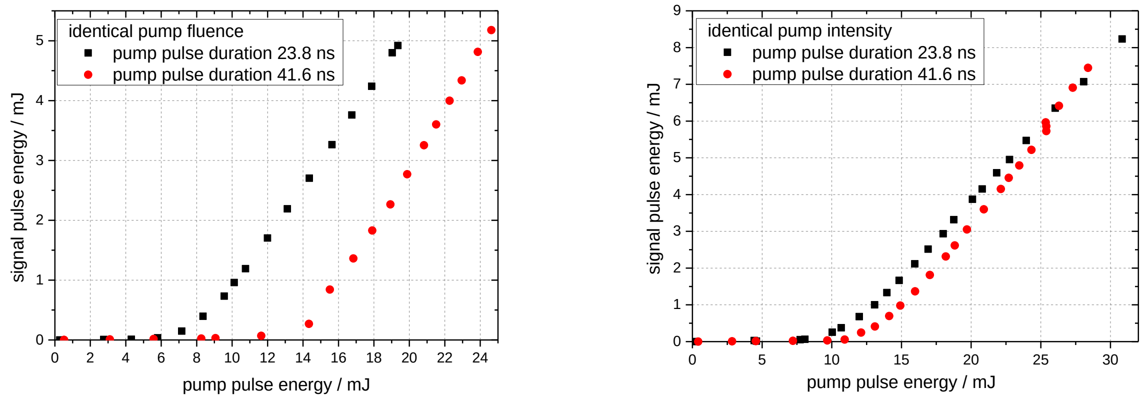

Figure 7. Signal pulse energy of the OPO as a function of the pump energy at different pulse durations and radii to compare the efficiency at constant pump fluence and intensity

4.5 Comparison with KTA

Besides KTP, the comparable crystal material KTA was taken into account for the OPO as both crystals have a small walk-off of the idler wave and are transparent for both signal and pump waves. Although KTA has a lower effective nonlinearity than KTP for the analyzed process (KTP: -3.2 pm/V; KTA -2.9 pm/V [4]), its advantage is a lower absorption of the idler wave.

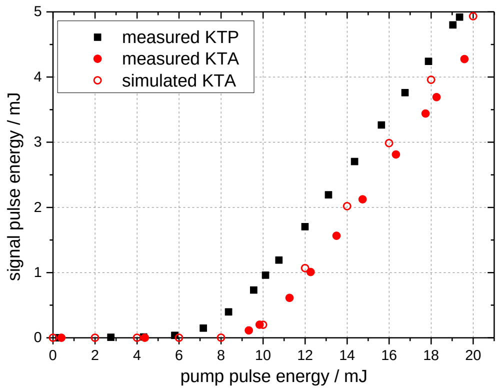

Figure 8. Signal pulse energy of the OPO as a function of the pump energy for KTA and KTP crystals at a pump pulse length of 23.6 ns

Compared to KTP, KTA had a 2 mJ higher threshold at 10 mJ and a comparable slope efficiency of 45 % (see Fig. 8). This threshold shift was also predicted by the model. Simulations showed that the order of magnitude of the pulse intensities used in this setup was too low to have measurable influence on both thermal lensing and phase mismatch of the nonlinear process.

4.6 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 6.6 mJ and the slope efficiency was 55 % (see Fig. 9). A maximum output energy of 9.3 mJ was achieved at 26.3 mJ pump pulse energy. This corresponds to an optical/optical efficiency of 35 % and a quantum efficiency of 54 %.

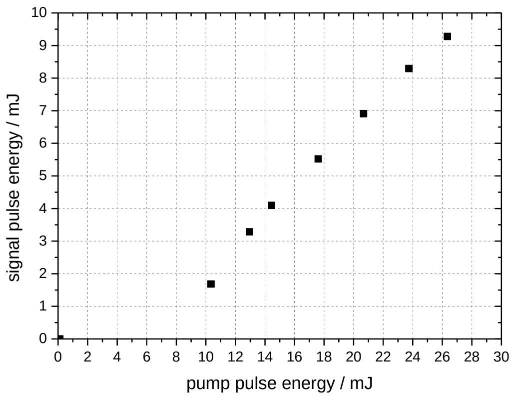

Figure 9. Signal pulse energy of the OPO as a function of the pump energy

5. CONCLUSIONS AND OUTLOOK

To summarize, an optical parametric oscillator was demonstrated that emits 9.3 mJ output energy at 1645 nm pumped by a Nd:YAG laser with 26.3 mJ at 1064 nm. This corresponds to an optical/optical efficiency of 35 %. The crystal material KTP was chosen, but also the similar KTA was measured. 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 the pump beam diameter was increased and the same efficiency was observed while at the same time decreasing the fluence in order to prevent damage of 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. Additionally, the damage threshold of the optics will be measured to further optimize the working point of the OPO and to minimize the risks of damaging it during long term operation in spaceborne environment. The assembling and adjustment of the OPO that is very sensitive to misalignment will also be optimized.

6. ACKNOWLEDGEMENTS

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