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# Demonstration of a 100-mJ OPO/OPA for future lidar applications and laser-induced damage threshold testing of optical components for MERLIN

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**Abstract.** In the field of atmospheric research, lidar is a powerful technology that can measure gas or aerosol concentrations, wind speed, or temperature profiles remotely. To conduct such measurements globally, spaceborne systems are advantageous. Pulse energies in the 100-mJ range are required to achieve highly accurate, longitudinal resolved measurements. Measuring concentrations of specific gases, such as $CH_4$ or $CO_2$, requires output wavelengths in the IR-B, which can be addressed by optical-parametric frequency conversion. An OPO/OPA frequency conversion setup was designed and built as a demonstration module to address the 1.6-$\mu$m range. The pump laser is an Nd:YAG-MOPA system, consisting of a stable oscillator and two subsequent Innoslab-based amplifier stages that deliver up to 500 mJ of output pulse energy at 100 Hz repetition frequency. The OPO is inherited from the OPO design for the $CH_4$ lidar instrument on the French–German climate satellite methane remote-sensing lidar mission (MERLIN). To address the 100-mJ regime, the OPO output beam is amplified in a subsequent multistage OPA. With potassium titanyl phosphate as nonlinear medium, the OPO/OPA delivered more than 100 mJ of output energy at 1645 nm from 450 mJ of the pump energy and a pump pulse duration of 30 ns. This corresponds to a quantum conversion efficiency of about 25%. In addition to demonstrating optical performance for future lidar systems, this laser will be part of a laser-induced damage thresholds test facility, which will be used to qualify optical components especially for the MERLIN. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.57.2.021205]

## 1 Introduction

Methane is one of the most important anthropogenic greenhouse gases in the atmosphere.[1] Within the scope of a German–French cooperation, methane remote-sensing lidar mission (MERLIN) was initiated, which employs an integrated path differential absorption lidar system.[2] A preliminary design of the laser transmitter was developed at Fraunhofer Institute for Laser Technology (ILT) and is currently in the detailed design review phase. The concept is based on an Nd:YAG-MOPA system, consisting of a injection-seeded stable oscillator and a subsequent Innoslab-based amplifier. The 1-$\mu$m output is used as the pump source for an optical-parametric oscillator, which delivers pulses at the selected absorption line of methane around 1645 nm. A similar system developed at Fraunhofer ILT and the DLR Institute of Atmospheric Physics (IPA) was tested on board of the German High Altitude and Long Range Research Aircraft.[3,4]

Since the MERLIN mission lasts 3 years, it requires a very stable and robust optomechanical and optical design of the laser transmitter. The future laser (FULAS) platform demonstrates the feasibility of the developed optomechanical components for the use under such conditions.[5] To minimize

the risk of damage during long-term operation and optimize the working point, it is important to know the laser-induced damage thresholds (LIDTs) of the optical components. Recently, an existing LIDT setup[6] was equipped with a 500-mJ Innoslab-based MOPA system, which was designed and built at ILT.[7,8] To qualify the optical components at 1645 nm with an ISO 11254-2 compliant LIDT measurement, pulse energies up to 100 mJ are required. Furthermore, for future spaceborne Earth-observation missions, the 100-mJ energy range is also very interesting to enable highly accurate, longitudinal resolved lidar measurements.

Optical-parametric oscillator (OPO)/optical-parametric amplifier (OPA) converters can deliver pulse energies up to 50 mJ, while satisfying the other requirements for lidar measurements.[9] Here, an OPO/OPA converter was designed and set up to demonstrate the scalability to the 100 mJ regime. It is also possible to achieve output pulse energies in the 100 mJ regime with erbium-doped solid-state lasers.[10] Here, we setup a scaled MERLIN laser to be able to measure the LIDT values at all three MERLIN relevant wavelengths (1064, 1645, and 3011 nm) with almost identical optical output parameters (spectral, temporal, and spatial).

## 2 Setup

The frequency conversion unit is built as a breadboard setup with optomechanics off the shelf and completed with some

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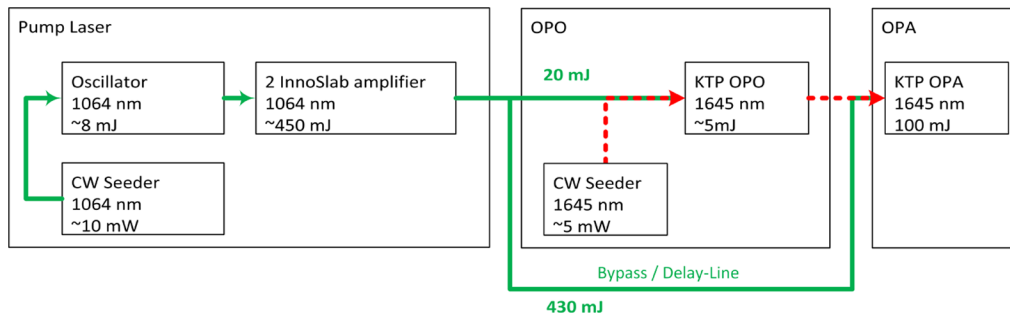
**Fig. 1** Functional groups of the beam generation chain.

customized mechanics, mainly for the OPO/OPA crystal mounts and the OPO mirror mounts. The functional groups of the beam generation chain are shown in Fig. 1 and a photo of the OPO/OPA converter is shown in Fig. 2.

## 2.1 Pump Laser at 1064 nm

The pump laser is an Nd:YAG-MOPA laser,[7,8] which can be injection-seeded and cavity-controlled to achieve single-longitudinal mode (SLM) operation. The spectral, temporal, and the main spatial beam properties are generated in the low-energy Q-switched Nd:YAG-based oscillator. The pulse energy of 7.5 mJ from the oscillator is amplified in two subsequent Innoslab-based amplifier stages. The system delivers up to 500 mJ of output pulse energy at 1 $\mu$m, a repetition rate of 100 Hz and a pulse duration of 30 ns. The output beam is shaped using a cylindrical telescope to obtain a symmetrical beam with a beam quality $M^2$ of $1.8 \times 1.4$.

## 2.2 Frequency Conversion Unit

To avoid back reflections into the amplifier, a Faraday isolator is inserted into the beam path. About 20 mJ of the pump beam is extracted to pump the OPO. The beam is shaped with a spherical telescope to achieve a radius that guarantees an efficient working point of the OPO. The OPO setup is inherited from the MERLIN setup.[11] In the four-mirror ring cavity, potassium titanyl phosphate (KTP) was used as the nonlinear medium. All four mirrors had a high transmission of the idler wave to reduce possible thermal effects and back conversion at high intensities. The OPO was injection-seeded by a distributed feedback diode laser at 1645 nm through the signal outcoupling mirror. The cavity length of the OPO can be varied by a piezoelectric element and is actively controlled by a heterodyne detection scheme to guarantee SLM operation. The procedure of this control method is explained in Ref. 9.
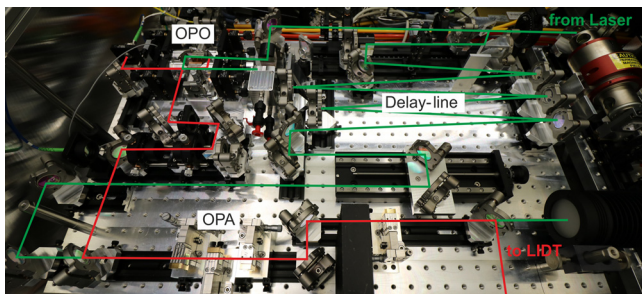


**Fig. 2** Photo of the laboratory setup of the OPO and OPA stage with the pump beam (1064 nm, green) and converted beam (1645 nm, red).

The output signal beam is shaped with a spherical telescope to match the pump beam size in the OPA. The OPO signal beam and the main part of the pump beam are then combined using a dichroic mirror, so that a good temporal overlap can be achieved between pump and signal beam in the OPA. A delay line is inserted into the beam path of the pump. The optical path length of the delay line is set in a way that the pulse build-up time of the OPO can be compensated.

To investigate the amplification properties of the OPA for different setups, the OPA consists of up to four 15-mm long KTP crystals, with the possibility of removing the idler beam between them. According to the work of Arisholm et al.,[12] this can improve beam quality and output power. The KTP crystals are cut in a critical phase-matching configuration ($\theta = 76$ deg, $\phi = 0$ deg). After the last OPA stage, the signal beam is separated from the residual pump and idler beam by dichroic mirrors.

## 3 Performance

### 3.1 Optical Parametric Oscillator

The energetic output characteristic curves of the OPO are shown in Fig. 3. When it was injection-seeded and had an active cavity-length stabilization, the system achieved a maximum output energy of 8 from 21 mJ of the pump. This corresponds to an optical/optical efficiency of almost 40% and a quantum efficiency of almost 60%. The output bandwidth of the signal beam was measured using a heterodyne detection scheme and was around 40 MHz.
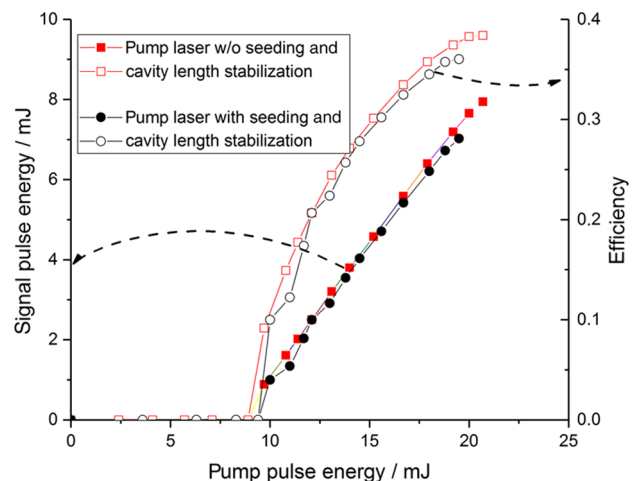


**Fig. 3** Output pulse energies and efficiency of the OPO stage over pump pulse energy.
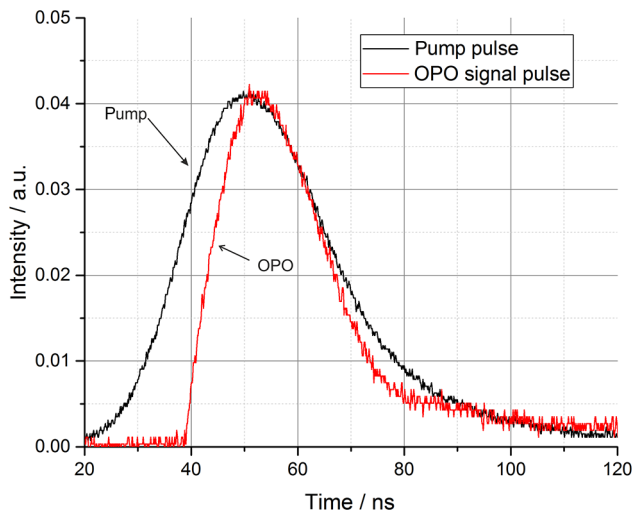
**Fig. 4** Temporal shape of the pump pulses (black) and the OPO output pulses (red).



**Fig. 6** Comparison of output pulse energies for unseeded, free-running and seeded, longitudinally single-mode pump laser with three OPA stages.

Thus, the performance of the OPO is similar to that of the MERLIN setup.

The output pulse energy does not depend on the mode of operation of the pump laser, which can be operated in single-longitudinal frequency mode (seeded and with cavity-length stabilization) or in free-running mode (unseeded, no cavity-length stabilization).

The pulse duration of the OPO output was measured to be around 23 ns (full width at half maximum), which is 25% shorter than the pulse duration of the pump laser due to the build-up time of the OPO. The temporal shapes of the pump and signal pulse are shown in Fig. 4.

### 3.2 Optical Parametric Amplifier

The amplification of the OPO signal output was measured for a different number of OPA stages. Figure 5 shows the OPA output pulse energies for one to four OPA stages. A maximum signal pulse energy of 111 mJ was achieved at 400 mJ of the pump energy. This corresponds to more than 26% conversion efficiency.
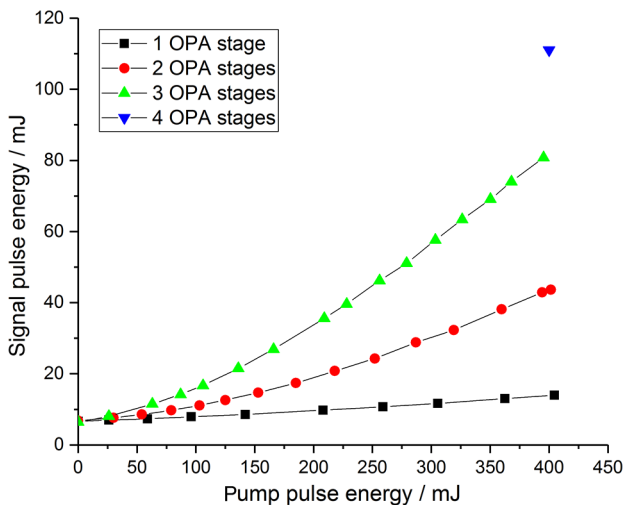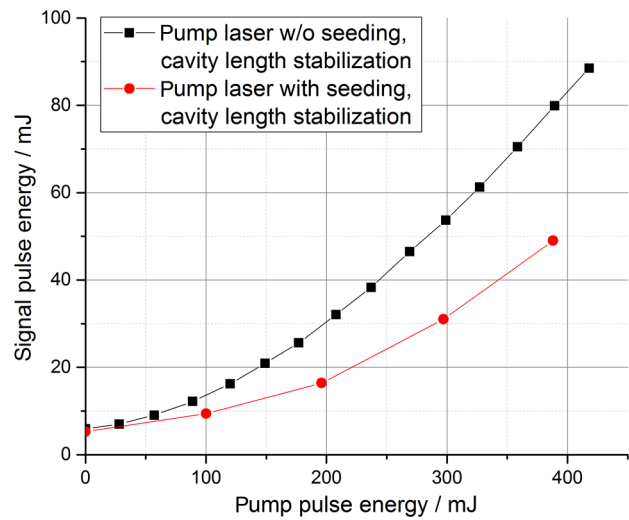


**Fig. 5** Output pulse energies after a different number of OPA conversion stages. Inset: output beam profile at 1645 nm.

These results were obtained when the pump laser was operated without injection seeding and without cavity-length stabilization, hence running on multiple longitudinal modes. When the laser was operated with injection seeding and cavity-length stabilization, and hence running in SLM, the output energies of the OPA stages decreased as can be seen in Fig. 6 (here shown for three OPA stages).

Since the other input characteristics of the OPA, such as input signal pulse energy (see Fig. 3), beam profile, pulse width, and temporal delay between signal and pump, etc. were unchanged, the spectral input characteristics of the OPA were the only parameters that changed between the two different operating modes. This effect is well reproducible. Further investigations showed that the gain in every single OPA stage decreased by a factor of 1.5, if the pump laser is operated in SLM. Therefore, optimizing the output energy in SLM operation should be achievable due to adaptions of the beam radius and crystal length. This and further investigations on the reasons for this effect are currently being conducted.

## 4 Summary and Outlook

For the next generation lidar systems with pulse energies in the 100 mJ regime, a demonstrator of a high-energy OPO/OPA was set up on a breadboard. The OPO/OPA emits a maximum of 111 mJ output energy at 1645 nm pumped by an Nd:YAG laser with 420 mJ at 1064 nm, which corresponds to a conversion efficiency of more than 26%. To date, this efficiency could be demonstrated only when the system is pumped by a multiple longitudinal mode beam. When it is pumped by a SLM beam, the OPA gain is decreased by a constant factor of ~1.5.

In addition to its function as a technology demonstrator, this setup is part of an LIDT test facility for the qualification of optical components, in particular for current space missions. The LIDT test facility will be operated at both 1064 and 1645 nm, especially for the MERLIN mission.

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Biographies for the authors are not available.