EPJ Web of Conferences **362**, 01009 (2026) https://doi.org/10.1051/epjconf/202636201009
ILRC31/CLRC22-2024

Novel emitter for a compact general-purpose Doppler lidar based on diode-pumped Alexandrite

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Abstract: We present an overview of a narrow-bandwidth, compact and efficient emitter for a general-purpose atmospheric Doppler lidar based on diode-pumped Alexandrite. The laser operates in single-longitudinal-mode with a very narrow linewidth of 3 MHz at the resonance line of potassium (770 nm) and with an average output power of 2.4 W. The high electro-optical efficiency >2 %, the excellent beam quality of $M^2 = 1.1$, the repetition rate of 750 Hz and the pulse energy of 3.2 mJ are tailored to the autonomous long-term operation of the lidar system. Four demonstrator lasers were built and integrated into mobile lidar systems and measurements were conducted during several field campaigns from summer 2022 to spring 2023.
The transfer of the technology to the deployment in an iron lidar operating in the UV is demonstrated in the laboratory by intra-cavity frequency conversion. Remarkably, all parameters of the IR laser, especially the efficiency, are almost preserved.

1. Introduction

Given the increasing impact of anthropogenic climate change, there is a growing need for data on wind velocities and temperature distribution in the atmosphere at altitudes above 5 km. This data is crucial for developing detailed models of atmospheric physics. Lidar systems capable of monitoring wind velocities and temperatures at these altitudes have become increasingly important, especially following the successful AEOLUS mission, which profiles Earth's wind from space. For measuring the atmospheric parameters, different scattering processes are utilizable: Doppler-Mie (at aerosols < 25 km), -Rayleigh (at air molecules 25-80 km) and -resonance (metal atoms 80-120 km). Assuming a suitable laser emitter, it is possible to use a combination of multiple scattering mechanisms in a single lidar instrument like VAHCOLI [1] . However, in order to separate the Mie and Rayleigh signals and minimize uncertainties, it is necessary to use narrowband spectral filtering that is significantly narrower than the full-width-half-maximum (FWHM) of Rayleigh scattering. This is crucial because a mixture of both signals result in increased uncertainties.

To build a compact and portable lidar system that is highly accurate, it is advantageous to use a beam source with a high electro-optical efficiency to minimize energy consumption. It is necessary to have a narrow bandwidth (<10 MHz) in order to effectively separate Mie and Rayleigh signals with a high separation ratio. Additionally, the laser wavelength should be tunable to address specific atomic lines. In the last ten years the Leibniz Institute of Atmospheric Physics (IAP) and the Fraunhofer Institute for Laser Technology (ILT) have developed a technology for a compact multi-frequency Doppler lidar instrument that occupies a volume of only 1 m^3. The key component of this system is a diode-pumped Alexandrite laser that emits at the potassium resonance line at 770 nm, with a bandwidth of ~3 MHz and a pulse energy of up to 3.2 mJ and average power of 2.4 W [2] .

For enhanced daylight operation and Rayleigh signal, the iron resonance wavelength in the UV is preferable, allowing for superior performance over current wind lidar technology like AEOLUS. By a careful adaption of the laser concept without changing the basic advancements one benefits from the heritage of the IR lasers and the wide continuous tuning range of Alexandrite (700-800 nm). Following that approach an intra-cavity frequency-doubled Q-switched diode-pumped Alexandrite ring-laser directly emitting in the UV at 386 nm is presented [3] .

2. Design

The Alexandrite laser resonator that operates in single longitudinal mode forms a ring to avoid spatial hole burning. A schematic setup and photo of the laser are shown in Figure 1.

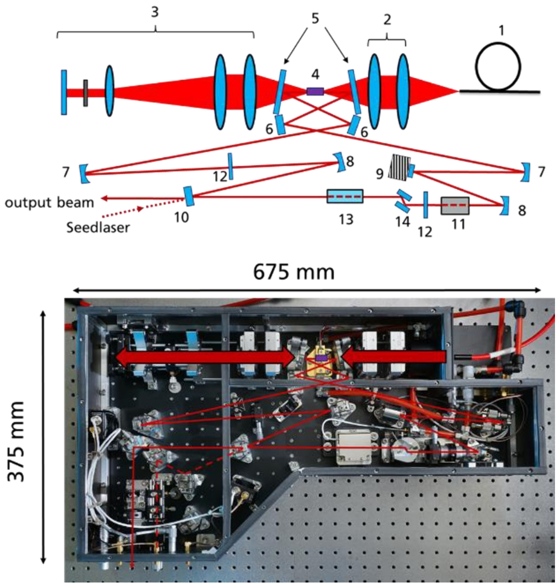

Figure 1: above: Schematic setup of the ring cavity with numbered cavity elements: optical fiber guiding the pump light (1), pump light collimation and focusing lenses (2), pump light back-folding unit (3), Alexandrite crystal (4), flat, dichroitic pumping mirrors (5), flat folding mirrors (6), curved mirrors ROC=1500mm (7), curved mirrors ROC=1200mm (8), flat folding mirror on piezo actor for stabilization of the cavity length (9), flat output coupler (10), Faraday rotator (11), half-waveplates (12), Q-switch (13), and thin-film polarizer (14).
below: IR laser prototype without cover

It contains one Alexandrite crystal that is end-pumped by a fiber-coupled diode module (@ 638 nm). As the absorption of the pump light is strongly polarization-dependent and the pump light from the fiber is unpolarized, a pump light back-folding unit is used. A symmetric ring resonator with a total length of 2 m is designed with two pairs of curved mirrors with radii of curvature of 1500 and 1200 mm each. The resonator mode size is matched to the pump diameter of 800 µm in the laser crystal and twice as large on the internal optical components. A Faraday rotator, two waveplates and TFPs guarantee unidirectional laser emission and an AOM is used for Q-switching. SLM operation is achieved by injection seeding with a narrow-bandwidth cw diode laser and an advanced cavity-control technique.

Four rugged prototypes of Alexandrite lasers operating at the potassium resonance in the IR (@ 770 nm) were constructed and integrated for remote long-term operation with a compact Doppler lidar. The optical and mechanical design allow for these prototypes to be built within a volume of 1 m^3. The laser beam source, housed in a closed but not air-tight enclosure, has dimensions of 375 mm × 675 mm × 175 mm. To account for remote operation in harsh environmental conditions that may cause resonator misalignment due to vibrations or shock, one of the curved mirrors is mounted in a piezo mirror mount that enables remote alignment. Commercial off-the-shelf optical mounts were used in the resonator to minimize complexity and costs of the prototypes.

For intra-cavity frequency doubling, the LBO crystal is placed between the AOM and the output coupling mirror. The output coupling mirror for the fundamental light in the IR (R@770 nm = 97 %) is replaced by a mirror, highly reflective for the IR-light and highly transmissive for the frequency doubled light in the UV. Thus, the output coupling transmissivity of the resonator is given by the conversion efficiency while there is no other output coupling for the fundamental wavelength. The output coupling transmissivity of 3% for the IR laser is therefore the designated conversion efficiency for intra-cavity SHG. Such a low conversion efficiency is easy to achieve even with low pulse energies, large beam diameters, and short conventional nonlinear crystals.

The experiments for the UV laser are conducted in the lab with a setup that is not housed and thereby, air turbulences from the flow boxes causes higher energy jitter and disturbance during cavity-controlled operation.

3. Results

The measured output parameters for the latest prototype operating in the IR and the laboratory setup operating in the UV are summarized in Table 1, additional information can be found in [2] and [3] .

The output energy of the latest IR laser prototype, optimized for maintenance-free long-term operation, is 3.2 mJ (see left in Figure 2) with a pump energy of 32.9 mJ, resulting in an optical-to-optical efficiency of 9.75 %. The pulse energy is very stable (0.2 % RMS) within the housing. With a repetition rate of 750 Hz the average output power is 2.4 W.

Table 1. Performance of the Alexandrite lasers

Laser type	latest IR prototype	UV lab setup
Parameter	**Achieved value**	
Wavelength	770 nm	386 nm
Pulse energy	3.2 mJ	3.0 mJ
Repetition rate	750 Hz	500 Hz
Average power	2.4 W	1.5 W
Energy stability (rms)	0.2 %	1 %
Pump duration	85 µs	82 µs
Pump energy	32.9 mJ	33 mJ
e-o efficiency	2.1 %	2.0 %
M^2 (x/y)	1.1/1.1	1.1/1.1
Pulse length	1040 ns	920 ns
Spectral bandwidth	~ 3 MHz	<< 20 pm

The beam quality of the round and stigmatic output beam is excellent with $M^2 = 1.1$ in both directions, as shown in Figure 2 right. The pulse duration is rather long with 1040 ns allowing for very narrow linewidth. With the latest models of the diode pump modules, the electro-optical efficiency of the laser is 2.1 %.

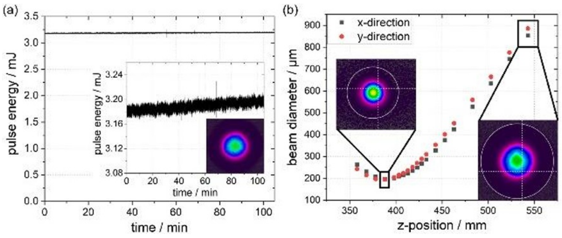

Figure 2: Pulse energy of the prototype in the IR with a repetition rate of 750 Hz (left) and its caustic with a derived beam quality of $M^2 = 1.1$ (right)

The spectrum is determined by injection seeding and an advanced cavity control technique that guarantees single-longitudinal-mode operation at the resonance wavelength of potassium at 770 nm. The bandwidth of the laser is measured by deconvolution of the transmission spectrum of a confocal etalon with known bandwidth and the pulsed laser itself, as shown in Figure 3, resulting in approximately 3 MHz, depending on the environmental disturbances. Both, frequency shift against the seed laser and the jitter are below 1 MHz.

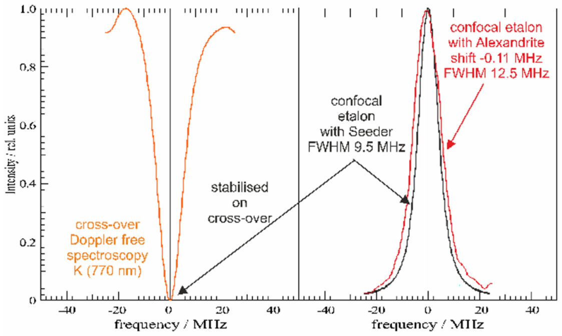

Figure 3: Spectrum of a confocal etalon with 9.5 MHz bandwidth stabilized on a potassium crossover line (left) and transmission spectrum of Alexandrite laser, resulting in a linewidth of 3.3 MHz (right).

The UV laser is currently operated with a repetition rate of 500 Hz and yields 3.0 mJ pulse energy in the UV with a pump pulse energy of 33 mJ (see left in Figure 4), resulting in an optical-to-optical efficiency of 9.1 %. The efficiency is almost unchanged compared to the same laser without the LBO crystal operating in the IR yielding 3.6 mJ with 38.5 mJ of pump energy. The beam quality in x- and y-directions are consistently excellent with $M^2 = 1.1$, shown on the right in Figure 4, due to negligible walk-off effects in the short LBO crystal.

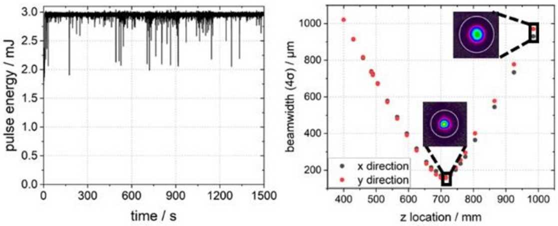

Figure 4: Pulse energy of the lab setup in the UV with a repetition rate of 500 Hz (left) and its caustic with a derived beam quality of $M^2 = 1.1$ (right)

The temporal shape of the UV pulse is smooth and without any fluctuation and shows a pulse length of 920 ns, shown left in Figure 5.

The spectrum of the frequency-doubled output without seeding and seeded with cavity-controlled operation is shown on the right in Figure 5. While the unseeded spectrum has a linewidth of 0.2 nm, the seeded spectrum is < 20 pm, which is the limit of the spectrometer in the UV spectral region. The exact linewidth cannot be measured yet without a matched narrow-bandwidth confocal etalon for this wavelength. These measurements require a high spectral stability of the laser emission which can only be achieved with an enclosed laser system that is not disturbed by air movement and disturbances.

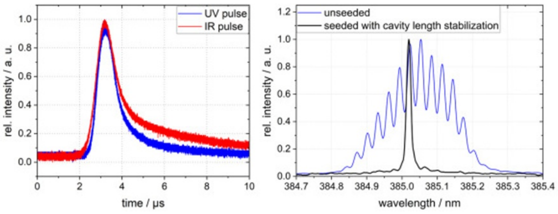

Figure 5: Temporal shape of the fundamental (IR) and frequency-doubled (UV) laser pulse (left) and UV spectra unseeded and seeded with cavity length stabilization (right)

The measurements are planned for near future with a housed prototype operating in the UV at a resonance line of iron (@386 nm) that will be integrated into an adapted lidar system.

4. Summary and outlook

Four rugged mobile prototypes based on the optical design of the diode-pumped Alexandrite lasers operating at the resonance line of potassium in the IR were built and implemented in mobile lidar systems with a volume of ~1 m^3 [2] [4] . Several successful measurement campaigns from summer 2022 to spring 2023 were conducted. To enhance the capabilities for monitoring dynamical phenomena in the atmosphere, the lidar system can be reconfigured with up to five telescopes to get a lidar system with several fields of view. First experiments with such a lidar system were successful, and the results are shown in [5] .

The technology transfer of the lidar instrument operating in the IR to a consortium of SMEs is prepared in the frame of the BMBF-funded Rubin project LidarCUBE (ID: 03RU2U08D).

Based on the demonstrated design, rugged prototypes will be built to be integrated in novel Doppler Mie, Rayleigh, and iron resonance lidar systems with multiple fields of view, currently also under development in the EU-funded project EULIAA (grant ID: 101086317). These lidar systems will be used to demonstrate the potential of a lidar array for simultaneous measurements with an extensive field campaign at different locations throughout Europe [6] .

The demonstrated performance of intra-cavity frequency doubling and the tuneability of the fundamental Alexandrite laser enable the targeting of other resonance lines within the UV region. This technology platform allows for the addressing of interesting tracers such as Ca^+ at 393 nm, which is the only metallic ion observable from the ground in the upper atmosphere (80-120 km). Additionally, N_2^+ at 391 nm can be targeted to extend the measurement altitude up to 300 km. Furthermore, metastable Helium at 389 nm can be utilized for thermosphere applications.

The technology is also advantageous for spaceborne lidar missions such as follow-on of AEOLUS [7] and is in line with the technology platform for spaceborne lasers developed by Fraunhofer ILT for the Merlin Mission [8] .

5. References

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