

Tuneable narrow-linewidth diode-pumped Alexandrite laser transmitters for multi-species resonance lidar

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ABSTRACT

Diode-pumped Alexandrite lasers provide tuneable, narrow-linewidth transmitters for Doppler-Mie, Doppler-Rayleigh, and resonance lidar. This paper reports packaged infrared and ultraviolet laser prototypes integrated into compact lidar systems developed within the EULIAA project. The injection-seeded Alexandrite ring lasers generate Q-switched pulses with durations of about 1 μ s at repetition rates up to 750 Hz. The fundamental wavelength can be tuned from 740 to 800 nm. Intra-cavity second harmonic generation extends the operating range to 370–400 nm. Operation at the potassium line at 770 nm and the iron line at 386 nm provides millijoule pulse energies, near-diffraction-limited beam quality, and highly efficient diode-pumped operation with low pulse fluence.

A wavelength-stabilised confocal etalon is used to measure the spectral behaviour during the Q-switched pulse. The measurements show a reproducible wavelength chirp that broadens the pulse-integrated spectrum under standard operating conditions. Adjustment of the cavity-control operating parameters compensates the wavelength evolution over the energetic central part of the pulse. Under compensated conditions, pulse-integrated linewidths below 1 MHz were obtained. Residual wavelength shifts occur mainly in low-energy pulse wings. Injection seeding in the infrared also narrows the emission after frequency conversion to the ultraviolet.

The wavelength range supports resonance lidar measurements of several atmospheric metals and ions, including potassium, iron, and Ca^+ . It can also address selected species relevant to studies of re-entering space debris. Low pulse fluence, high repetition rate, diode-pumping, and narrowband wavelength control make the transmitter concept suitable for further assessment for spaceborne lidar.

Keywords: Alexandrite laser, diode-pumped laser, tuneable laser, injection seeding, frequency conversion, resonance lidar, Doppler lidar, spaceborne lidar

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1. INTRODUCTION

Measurements of wind, temperature, aerosols, and metal layers over a wide altitude range require lidar systems with complementary measurement modes. Doppler-Mie lidar uses aerosol backscatter, Doppler-Rayleigh lidar uses molecular backscatter, and resonance lidar addresses selected atomic transitions. A common lidar platform for these modes requires a pulsed laser transmitter with narrow and reproducible spectral emission, stable absolute wavelength, sufficient pulse energy, and access to relevant wavelengths. The lidar technology, its applications, and recent field deployments are described in [1].

Diode-pumped Alexandrite lasers developed by Fraunhofer ILT and Leibniz IAP over the last decade provide a suitable and versatile laser platform. The lasers use a unidirectional ring resonator, injection seeding with an advanced cavity-control (CC) method to achieve single-longitudinal-mode (SLM) operation, and an acousto-optic modulator (AOM) for Q-switching. The present transmitter platform is designed for fundamental wavelengths from 740 to 800 nm and covers, amongst others, the potassium resonance line at 770 nm. Intra-cavity second-harmonic generation (IC-SHG) in lithium triborate (LBO) extends the accessible range to 370–400 nm. This range includes the iron resonance line near 386 nm, the Ca^+ line near 393 nm, and further metallic resonance lines. The Alexandrite gain bandwidth and IC-SHG therefore enable operation at several resonance wavelengths without changing the basic laser architecture.

Rugged IR laser prototypes for compact lidar systems and the scaling of pulse energy and repetition rate have been reported previously [2],[3]. Efficient IC-SHG was demonstrated in a laboratory UV laser at the iron wavelength [4]. The IR and UV lasers provided millijoule pulse energies, near-diffraction-limited beam quality, and pulse durations of about 1 μ s. Earlier IR prototypes showed pulse-integrated linewidths of about 3 MHz. Initial seeding experiments in the laboratory showed that spectral narrowing of the IR laser is retained after frequency conversion to the UV [4]. A first assessment of the laser concept for spaceborne lidar was reported in [5].

The present work concerns the subsequent development of packaged IR and UV transmitter prototypes for the European Lidar Array for Atmospheric Climate Monitoring (EULIAA) project [6]. The lasers have been integrated into compact lidar systems operating at the potassium and iron resonance wavelengths. The completed and ongoing field campaigns demonstrate the stability of the packaged transmitters during transport, installation, and unattended operation. The two UV lidar systems have so far accumulated more than 750 h of atmospheric measurements without laser realignment or major maintenance. The lidar platform, receiver, retrieval methods, and atmospheric measurements are described in the accompanying contribution [7].

This paper focuses on spectral characterisation and control of the injection-seeded laser pulse. A wavelength-stabilised confocal etalon is used to resolve the wavelength evolution during the Q-switched pulse. The measurements show a reproducible wavelength chirp that broadens the pulse-integrated spectrum. Adjustment of CC operating parameters compensates the chirp over the energetic central part of the pulse and reduces the integrated linewidth. The resulting spectral properties, wavelength range, field-proven laser packaging, low pulse fluence, and diode-pumped architecture are also relevant for future spaceborne lidar transmitters.

2. ALEXANDRITE LIDAR TRANSMITTER PLATFORM AND FIELD DEPLOYMENT

The EULIAA lidar systems use diode-pumped Alexandrite ring lasers as their transmitters. The laser heads are mounted on separate breadboards and enclosed in sealed housings with defined optical, electrical, and cooling interfaces. The housing isolates the laser alignment from mechanical loads on the lidar structure. This arrangement permits transport and installation of the lidar without realignment of the laser resonator.

The laser is pumped by a fibre-coupled diode module at 638 nm through an 800 μ m core fibre with a numerical aperture (NA) of 0.22. The module provides up to 400 W peak power. The ring resonator is operated unidirectionally by a Faraday rotator and uses an acousto-optic modulator (AOM) for Q-switching. Injection seeding and cavity control (CC) provide single-longitudinal-mode (SLM) operation at the wavelength of a narrow-linewidth cw diode seed laser. The present transmitter platform is designed for fundamental output from 740 to 800 nm. The IR version is used for the potassium resonance line at 770 nm. For UV operation, an LBO crystal is inserted into the resonator, and the IR output coupler is replaced by a dichroic mirror that is highly reflective in the IR and highly transmissive in the UV. Intra-cavity second-harmonic generation (IC-SHG) then provides output in the range from 370 to 400 nm. The UV prototypes operate near the iron resonance line at 386 nm. Table 1 summarises the output parameters of the latest IR and UV prototypes. Both systems provide millijoule pulse energies at 750 Hz with near-diffraction-limited beam quality and electro-optical efficiencies close to 3 %. The listed spectral bandwidths refer to pulse-integrated emission under standard operating conditions. The laser concept and the IC-SHG design were described in detail in previous work [2]-[5].

Table 1: Performance of the latest Alexandrite laser prototypes.

Parameter	IR prototype	UV prototype
Wavelength	770 nm	386 nm
Pulse energy	3.2 mJ	2.9 mJ
Repetition rate	750 Hz	750 Hz
Average power	2.4 W	2.2 W
Energy stability (rms)	0.2 %	0.2 %
Pump duration	69 μ s	60 μ s
Pump energy	27.6 mJ	22.6 mJ
Electro-optical efficiency	2.8 %	3.1 %
Beam quality, M^2 (x/y)	<1.1/1.1	1.1/1.1
Pulse duration	1040 ns	710 ns
Pulse-integrated spectral bandwidth	$\sim$ 3 MHz	$\sim$ 15 MHz

Pulse durations and spectral bandwidths are FWHM values. Spectral bandwidths refer to deconvolved pulse-integrated emission under standard operating conditions without chirp compensation.

The IR and UV configurations use the same basic resonator concept and opto-mechanical setup. Apart from the LBO crystal, the dichroic output coupler, and wavelength-dependent operating parameters, the UV version uses the established components and control scheme of the IR laser. Seeding is applied at the fundamental wavelength. The spectral properties are therefore controlled in the IR, while the UV output follows through frequency conversion. Figure 1 shows a packaged UV laser prototype with the schematic beam paths.

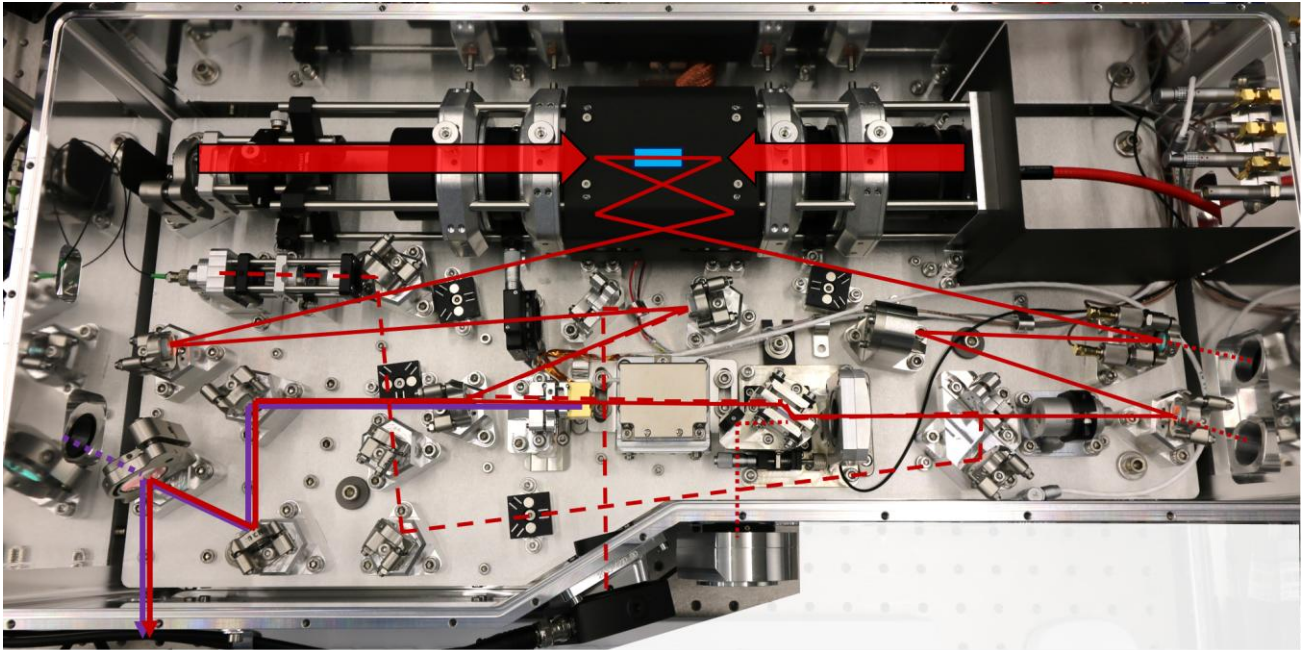


Figure 1. Photo of an injection-seeded diode-pumped Alexandrite laser with schematic beam paths. The packaged UV version was prepared for integration into an EULIAA lidar system. The fundamental output is tuneable from 740 to 800 nm. For UV operation, an optional LBO crystal provides IC-SHG to 370-400 nm.

The transmitter concepts have been tested in three EULIAA lidar systems. Further details of the EULIAA lidar systems, the spectral requirements of the retrieval methods, and campaign data illustrating the improved resolution obtained by signal-decomposition analysis using the time-resolved laser spectrum are given in [1] and [7].

EULIAA-IR operates at 770 nm and was transported from Germany to the ALOMAR observatory in northern Norway. It was installed and returned to operation without laser realignment. The system has accumulated more than 600 h of atmospheric measurements during ten months of autonomous operation. Routine work was limited to lidar-level service, such as refilling the chiller and cleaning telescope windows. No laser realignment or major laser maintenance was required.

The first UV system, EULIAA-UV1, was deployed to the Observatoire de Haute-Provence (OHP), France, shortly after final assembly. It completed a ten-week campaign with more than 500 h of atmospheric measurements. The campaign included high ambient temperatures during a heat-wave period and a temporary cooling interruption following a power failure. After cooling was restored, the lidar continued operation without realignment and with unchanged signal levels. EULIAA-UV2 was designed for helicopter transport and installed at the Sphinx station of the High-Altitude Research Station Jungfraujoch at 3578 m altitude. The system started operation within hours after installation. So far, it has accumulated more than 250 h of atmospheric measurements without laser realignment or major maintenance. Valid atmospheric parameters were retrieved during more than 40 percent of the total deployment time. Laser operating time was higher than the valid-data time because weather conditions sometimes prevented retrievals with sufficient data quality.

Together, the campaigns exposed the transmitters to transport shocks, non-stabilised temperatures during transport, high-alpine conditions, strong winds, icing, thunderstorms, and high ambient temperatures. All systems operated without laser realignment after transport or during the campaign. The deployed lidar systems experienced temperatures from about -17 to +43 °C. These results do not constitute space qualification, nor does the present mounting technology based on commercial off-the-shelf components. They show, however, that the packaged IR and UV transmitters can operate for

several hundred hours under field conditions without realignment. A detailed tolerance analysis and an assessment of the suitability of Fraunhofer ILT space-qualified soldering technology are reported in [5]. This experience is relevant to the development of future spaceborne transmitters.

3. PULSE-RESOLVED SPECTRAL CHARACTERISATION AND CHIRP COMPENSATION

The pulse-integrated spectral bandwidth does not fully describe the emission of a Q-switched laser. For the EULIAA lidar systems, the spectral width and wavelength shift during the laser pulse are relevant to the receiver model and the signal-decomposition analysis. The latter uses the measured time-resolved transmitter response together with the receiver characteristics to improve spectral and range resolution [7].

The pulse-integrated linewidth depends on the laser working point and the CC operating parameters. Relevant parameters include resonator alignment, pump energy, Alexandrite crystal temperature, waveplate orientation, and the timing of the CC method. Consequently, identical CC parameters do not necessarily produce identical linewidths after a change of laser setup or operating point.

A seed-referenced confocal Fabry-Perot interferometer (FPI) is used to measure the spectral behaviour of the injection-seeded IR laser. The transmission function of the FPI is determined with the narrow-linewidth cw diode seed laser. During the measurement, the wavelength of the seed laser is scanned across an FPI transmission peak while the transmitted Alexandrite pulses are recorded with a fast photodiode (PD). The recorded signal provides the pulse shape as a function of time and seed wavelength. The laser spectrum is determined by deconvolution with the measured FPI transmission function.

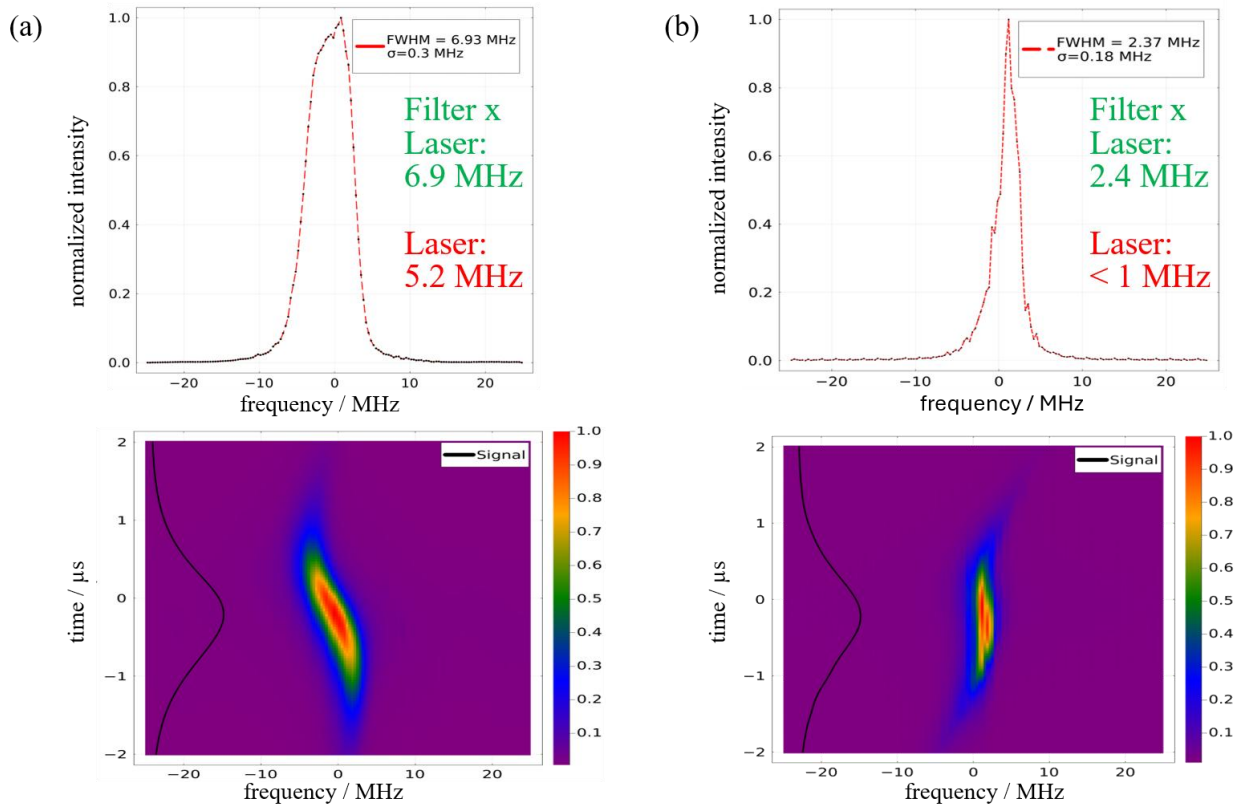


Figure 2. Integrated (above) and pulse-resolved (below) spectral characterisation of the injection-seeded Alexandrite laser at 770 nm. The labels "Filter x Laser" denote the measured spectra including the FPI transmission function. The laser linewidths were obtained by deconvolution. (a) Standard CC operating parameters result in a reproducible wavelength chirp during the Q-switched pulse. (b) Chirp-compensated CC operating parameters reduce the wavelength change over the energetic central part of the pulse. The pulse-integrated spectra were obtained after deconvolution of the measured FPI transmission function.

Figure 2 shows representative integrated and pulse-resolved measurements for standard and chirp-compensated CC operating parameters. The wavelength shift is shown as an equivalent frequency offset. Under standard conditions, the

laser wavelength changes reproducibly during the Q-switched pulse. The instantaneous emission in the central part of the pulse is narrow, but the wavelength shift broadens the pulse-integrated spectrum. For the laboratory laser and operating point shown in Fig. 2(a), the measured FPI-convolved spectrum has a FWHM of 6.9 MHz. Deconvolution gives a laser linewidth of 5.2 MHz. The latest IR prototype was adjusted to a different working point and achieved a pulse-integrated linewidth of about 3 MHz under standard operating conditions, as listed in Table 1. A comparable wavelength chirp has been reported for injection-seeded Alexandrite lasers [8].

The wavelength shift can be changed by adjusting CC operating parameters. A compensated operating point is selected to minimise the wavelength change during the central part of the pulse, where most of the energy is emitted. The remaining wavelength shift occurs mainly in the low-energy leading and trailing pulse wings. For the result in Fig. 2(b), the FPI-convolved pulse-integrated spectrum has a FWHM of 2.4 MHz. Deconvolution of the FPI response gives a linewidth below 1 MHz.

The measurements in Figure 2 were performed at the IR fundamental wavelength. The UV laser is seeded and controlled at the fundamental wavelength before IC-SHG. Earlier measurements showed that injection seeding narrows the UV emission as well [4]. The standard UV prototype currently shows a pulse-integrated bandwidth of about 15 MHz, as given in Table 1. Further work will address pulse-resolved UV measurements and the transfer of chirp compensation through frequency conversion.

4. TUNEABILITY AND MULTI-SPECIES LIDAR

Alexandrite has a broad gain bandwidth that supports wavelength-tuneable operation over a wider range than required for the present lidar application. The optical coatings and operating parameters of the current transmitter platform are designed for fundamental wavelengths from 740 to 800 nm. The highest laser performance is expected near 755 nm due to the gain spectrum. Pulse energy decreases towards the limits of this range. For example, preliminary measurements at 780 nm showed a pulse-energy reduction of about 10 % compared with operation at 770 nm. IC-SHG extends the expected operating range to 370-400 nm. The phase-matching condition of the LBO crystal can be adapted by crystal angle and temperature.

The current field systems operate at 770 nm for potassium and at 386 nm for iron. Figure 3 shows the relevance of the UV range for further resonance-lidar applications. Figure 3(a) shows selected atomic transitions between 360 and 400 nm for elements that may originate from anthropogenic spacecraft material. Recent analyses of stratospheric aerosol particles have identified metals associated with spacecraft re-entry and indicate that their atmospheric impact requires further investigation [9],[10].

Figure 3(b) shows exemplary seeded and unseeded UV spectra recorded at several manually adjusted operating points between about 385 and 398.5 nm. The spectra demonstrate that the same laser and frequency-conversion concept can be operated across a relevant part of the UV range without exchanging any resonator components.

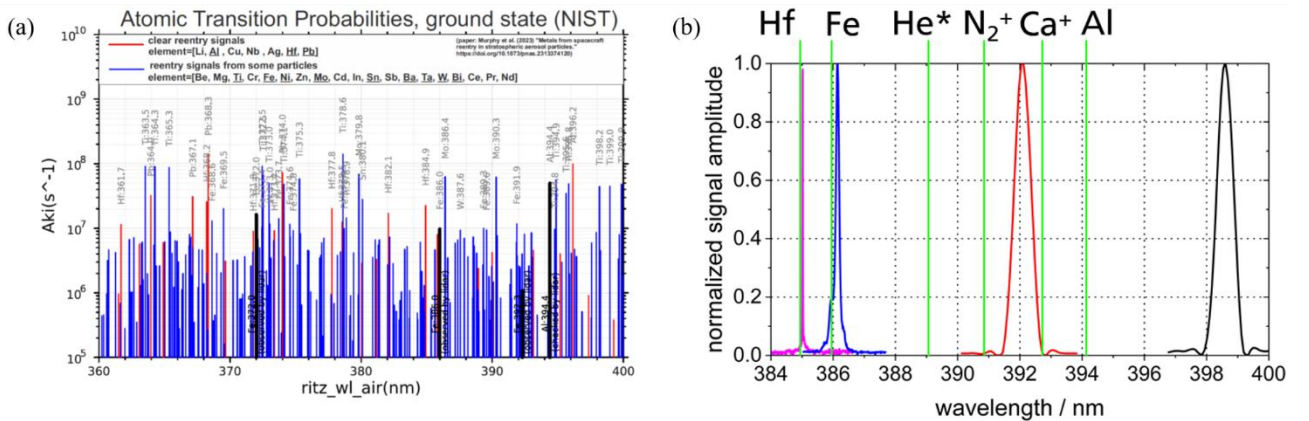


Figure 3: Tuneability of the UV Alexandrite laser and selected atomic transitions. (a) Atomic transition probabilities of selected elements between 360 and 400 nm. The marked transitions include species of interest for atmospheric studies and possible tracers of anthropogenic spacecraft material [9],[10]. Atomic data are taken from the NIST Atomic Spectra Database [11]. (b) Exemplary seeded and unseeded UV spectra of the Alexandrite laser at several manually adjusted operating points between about 385 and 398.5 nm. Vertical lines mark selected resonance wavelengths of Hf, Fe, metastable He, N₂⁺, Ca⁺, Al.

The marked wavelengths include transitions of Hf, Fe, metastable He, N^{2+} , Ca^+ , Al, and further species. Iron and Ca^+ are established natural tracers for the mesosphere and lower thermosphere. Metastable helium and N^{2+} may permit observations at higher altitudes up to 250 km and even above. Aluminium is of particular interest because it is a major constituent of spacecraft structures. Hafnium may provide a more specific tracer for selected spacecraft materials. The suitability of individual tracer lines depends on atmospheric abundance, chemical state, transition strength, atmospheric transmission, and the lidar receiver configuration. A lidar designed for a specific tracer would require corresponding adaptations of the seed source, receiver filters, and retrieval method. The tuneability of the transmitter is therefore a central requirement for a common lidar platform.

Remote wavelength tuning requires reliable control of the fundamental laser and the IC-SHG process. In the UV configuration, frequency conversion provides the nominal resonator outcoupling. During wavelength changes, controlled outcoupling must therefore be maintained throughout the tuning procedure. Safe and repeatable tuning methods are under development. A detailed investigation of laser performance across the fundamental and UV tuning ranges, including a wavelength-dependent performance model, is in progress as part of an ESA OSIP activity [12] and will be reported separately.

A tuneable resonance lidar could support long-term observations of natural metal layers as a reference and of material released during spacecraft re-entry. Such measurements are of increasing interest in the context of ESA Clean Space activities and the rapid growth of space operations. Ground-based resonance lidar is presently the only technique that can provide continuous, altitude-resolved observations of relevant metal species in the mesosphere and lower thermosphere. The same capability could also be relevant to a future spaceborne lidar, where global coverage and reduced attenuation by the lower atmosphere would complement ground-based observations.

5. RELEVANCE FOR SPACEBORNE LIDAR

The laser architecture is also suitable for further assessment for spaceborne lidar. The present prototypes provide pulse energies of about 3 mJ at 750 Hz with electro-optical efficiencies close to 3 % and near-diffraction-limited beam quality and wide, continuous wavelength tuneability in the IR and UV. The resulting average power is comparable to that of higher-energy laser transmitters, but the pulse energy, peak power, and optical fluence are substantially lower. This reduces the optical load on laser and frequency-conversion components, which is of relevance for UV operation. Injection seeding and CC provide narrowband emission at a defined wavelength. Together with matched narrowband receiver filters, this permits efficient suppression of solar background and molecular scattering for Doppler-Mie and resonance measurements. The tuneable transmitter concept can address deep Fraunhofer lines and selected resonance transitions with the same basic laser platform. A spaceborne implementation could combine Doppler-Mie and Doppler-Rayleigh measurements in the lower and middle atmosphere with resonance measurements in the mesosphere and lower thermosphere [1],[5],[13],[14].

The EULIAA campaigns demonstrate that the packaged IR and UV lasers can be transported and operated for several hundred hours without realignment. This field experience does not constitute space qualification. The present laser heads use commercial opto-mechanical components and would require replacement by space-qualified mounting technology. Fraunhofer ILT has developed soldered, low-outgassing optical mounts and related laser technology for spaceborne lasers, including FULAS and MERLIN. A previous tolerance analysis indicated that the Alexandrite resonator is compatible with the expected alignment stability of these components [5]. The present laser prototypes and field campaigns therefore provide a basis for a future space-qualified transmitter development.

For a resonance lidar addressing material from re-entering spacecraft, a spaceborne platform could complement ground-based measurements through global coverage and reduced attenuation by the lower atmosphere. The transmitter tuneability would allow a mission concept to be adapted to selected metal tracers as their atmospheric relevance becomes better understood.

6. CONCLUSION AND OUTLOOK

Diode-pumped Alexandrite ring lasers provide a tuneable transmitter platform for Doppler-Mie, Doppler-Rayleigh, and resonance lidar. The latest IR and UV prototypes provide pulse energies of 3.2 mJ and 2.9 mJ, respectively, at 750 Hz, with electro-optical efficiencies close to 3 % and near-diffraction-limited beam quality. The packaged transmitters have been integrated into three EULIAA lidar systems. The field campaigns demonstrate operation after road and helicopter transport and several hundred hours of measurements without laser realignment or major laser maintenance. Pulse-resolved FPI measurements show that the wavelength chirp during the Q-switched pulse contributes to the pulse-integrated linewidth. Adjustment of CC operating parameters reduces the wavelength shift over the energetic part of the

pulse. At a suitable laboratory working point, pulse-integrated linewidths below 1 MHz are obtained after deconvolution. The current transmitter platform supports continuous wavelength tuneability from 740 to 800 nm in the IR and, with IC-SHG, from 370 to 400 nm in the UV. It can therefore address potassium, iron, Ca⁺, and selected tracer species relevant to studies of natural metal layers and re-entering spacecraft material.

Future work will address safe and repeatable remote wavelength tuning, wavelength-dependent performance across the full IR and UV ranges, and pulse-resolved spectral measurements in the UV. The field-tested transmitter packaging and the available Fraunhofer ILT heritage in space-qualified laser technology provide a basis for a future space-qualified Alexandrite transmitter.

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