The Alexandrite Ring Laser: A Spectrally Narrow Lidar Light Source for Atmospheric Fluorescence and Absorption Observations

S. C. Collins[1], T. D. Wilkerson[1], V. B. Wickwar[1], D. Rees[1]
J. C. Walling[2], D. F. Heller[2]

[1] Center for Atmospheric & Space Sciences, Utah State University
Logan, UT 84322-4405, USA. E-mail: collins@aeronomy.cass.usu.edu
[2] Light Age Incorporated, Somerset, NJ 08873, USA. E-mail: Lightage@aol.com

Abstract. The Atmospheric Lidar Observatory (ALO) at Utah State University has recently acquired an alexandrite laser, developed by Light Age Incorporated, that is a relatively new type of configuration, ideal for resonance lidar and DIAL observations. Unidirectional ring lasing is established in a two-rod cavity, producing single longitudinal and transverse mode (TEM_{00}) pulses up to 200 mJ in energy and having a pulse length of 100 nsec or greater. This paper is, in part, a progress report on the advanced technology behind this new type of alexandrite laser, and how the new performance level will impact atmospheric lidar observations. We have not yet operated the USU alexandrite laser as a lidar transmitter, but have carried out the construction and testing of this and two other similar lasers, one of which is lidar-operational, and the other is currently being installed for the same purpose. This paper reviews some of the salient features of alexandrite as a laser medium, provides details on the current state-of-the-art of this tunable frequency-stabilized laser, and outlines the capabilities for geophysical lidar measurements using the alexandrite laser.

1. Alexandrite

Alexandrite, the common name for chromium-doped chrysoberyl ($Cr^{3+} : BeAl_2O_4$), is a solid-state crystal that was first made to lase upon a vibronic sideband at the Allied Corporation in 1977 [1]. It is a four-level, low-gain, and broadly tunable laser (nominal range 700–820 nm) using the energy levels of trivalent chromium in the crystalline host. The synthetic alexandrite rods are produced by Czochralski techniques, similar to those used for ruby and YAG, in which the rod is slowly pulled from a liquid melt, after the growth has been initiated by a high-quality crystalline seed. Cr^{3+} replaces a certain fraction of the Al ions, and the chromium concentration can be adjusted according to the intended laser application.

The combination of the chromium dopant and chrysoberyl host offers very favorable qualities. Chromium is favored over other transition metals because of its chemical stability, broad pump bands, large energy level splitting, and reduced excited state absorption [2]. The alexandrite crystal is mechanically very strong, and a relatively good thermal conductor. This allows it to be Q-switched, able to withstand higher repetition rates, and emit a higher average output power, when compared to other Cr^{3+} lasers. It has a low threshold and high slope efficiency resembling that of

Nd:YAG. Unlike other tunable lasers, alexandrite lases at room temperature, and its performance actually increases with elevated temperature.

Alexandrite lasers are vibronic, or phonon-terminated lasers, which describes an intimate coupling between vibrational and electronic states in the crystal lattice. This leads to a coupling between the emission of photons and the creation of phonons over the lasing transition. The total energy of the lasing transition is constant, yet divided between these photons and their corresponding phonons in a continuous manner. This coupling allows the laser to be tunable, making it extremely versatile for various applications.

2. Technology

2.1 Diode Laser Injection Seeder

Pulse lengths in the range of 20-300 nsec have been reported for Q-switched alexandrite lasers, offering the prospect of spectrally very narrow output as well as tunability, assuming careful control of the longitudinal and transverse modes. In early alexandrite lasers built as linear resonators, narrow-band tuning was attempted by adding etalons to the broader-band tuning elements in the resonator cavity (birefringent plate assemblies and gratings), while striving to minimize losses that were particularly harmful with this low gain laser medium. The present philosophy is quite different, namely to take control of the *gain* of the resonator by seeding the laser with narrow-band radiation, injected by a frequency-stabilized cw diode laser (DLIS). Moreover, the diode injector and the alexandrite resonator cavity are carefully matched, both spatially and spectrally, with the result that Q-switched pulses have been obtained with linewidths less than 30 MHz. This has been possible to accomplish only by utilizing a ring cavity design, in which the use of travelling waves removes the vexing problem of hole-burning.

The laser control exercised by the injected photons is due to their concentration being much higher when the Q-switch opens, than the concentration of spontaneous emission photons in the cavity. The subsequent amplification of the injected photons proceeds exponentially and outraces the growth of the population of all other photons, so the laser output simply becomes an amplification of this external source. Therefore, the output is as spectrally narrow and well defined in frequency as the DLIS itself. Semiconductor diode lasers are extremely narrow in spectral linewidth and relatively easy to control in frequency, making them the ideal source for the seed radiation.

In the case of the alexandrite ring laser, coarse frequency tuning is accomplished by means of an intra-cavity birefringent tuner. However, for resonance lidar and DIAL observations, one must be able to scan this frequency on a much finer scale. Fine tuning is accomplished by systematically varying the frequency of the DLIS to which the resonator is frequency-locked. Tuning on this scale is done by slight adjustments of the current across the diode’s semiconductor junction. Stabilization is maintained by means of a feedback loop to the current controller, providing compensation in current, keeping the DLIS locked to a certain frequency. This lock is provided by sampling the seed beam and locking it to the maximum passband of an etalon.

At the ALO, frequency stability is extremely important, and therefore its DLIS utilizes a highly sophisticated *capacitance-stabilized etalon* (CSE), produced by Hovemere, Ltd. This etalon is pressure and temperature stabilized in order to prevent drifting, and a constant plate separation is maintained by sampling and controlling the capacitance across the piezo-controlled spacers. Diode stabilization is obtained by locking the diode laser frequency to the etalon, allowing diode scanning to occur by changing the piezo-controlled plate separation. In this manner, the frequency output of the DLIS may be scanned, and ultimately, then, the output of the alexandrite laser.

2.2 Frequency Shifting

By manipulating alexandrite's broad tuning range along with various frequency-shifting devices, such as frequency doubling crystals and Raman cells, emission over much of the visible and UV spectrum can be obtained. Table 1 shows various metallic species whose resonance lines can be reached by these means.

The ALO will initially make observations of the mesospheric sodium layer, in which case radiation at nominally 589 nm is required. Here, the alexandrite laser output is frequency-shifted *via* stimulated Raman scattering (SRS) in a cell of hydrogen. There are two possible methods available that are being compared at present: frequency doubling the first Stokes shift starting with laser output at 791 nm, or using directly the first anti-Stokes shift from 780 nm.

Table 1. [3, 4]

Constituent	Metallic Wavelength ν_o(nm)	Laser Wavelength ν_L(nm)	Method to produce ν_o from ν_L
Na(D_2)	589.0	790.9	Raman Shifted(1) & Frequency Doubled
Na(D_2)	589.0	779.9	Raman Shifted(1,2)
K	769.9	769.9	Direct
Ca	422.7	769.6	Raman Shifted(3) & Frequency Doubled
Ca^+	393.4	786.8	Frequency Doubled
Al	396.2	792.4	Frequency Doubled
Mg	383.5	767.0	Frequency Doubled
Mg^+	448.1	755.5	Raman Shifted(3) & Frequency Doubled
Fe	384.1	768.2	Frequency Doubled
Fe	372.0	744.0	Frequency Doubled

(1) Raman Shifted in H_2 (4155 cm^{-1}), (2) First Anti-Stokes
(3) Raman Shifted in N_2 (2330 cm^{-1})

2.3 Beam Analysis

To actively probe and determine a spectral structure, it is necessary to have the capabilities to analyze the spectrum of the incident beam. At the ALO, this is done by sampling the lidar beam with a laser wavelength meter (LWM) designed and built by Hovemere, Ltd. This wavemeter consists of a temperature and pressure stabilized etalon of large spacing (15 cm) and a resolution of 25 MHz (finesse = 40). The etalon fringes are formed on a CCD linear array and saved in a computer. For every single laser pulse, the computer can save the fringe pattern, the relative wavelength, the spectral width, and the power. These are useful for later analysis and determining the pulse quality.

3. Resonance Scatter Lidar

Because of meteoritic decay, metallic layers such as sodium are formed high in the atmosphere, between 80 and 105 km. Remote sensing of these layers, using the resonance lidar technique, involves the active probing of an atmospheric constituent's hyperfine structure. In resonance scattering, a photon is absorbed and re-emitted at the same frequency, allowing the constituent's spectral structure to be determined by scanning the laser.

Figure 1 shows the sodium lineshape's strong dependence upon the temperature. If the hyperfine structure is probed in a few places, a least squares fit can be done to the data, determining the temperature in a sequence of range gates through the layer [5]. Doppler shifts in the spectrum also allow one to calculate the horizontal wind speeds in the mesosphere when the lidar system looks at an angle sufficiently off-zenith. To accurately measure the shape of the spectrum, or the Doppler shift, an extremely narrow-band light source is needed.

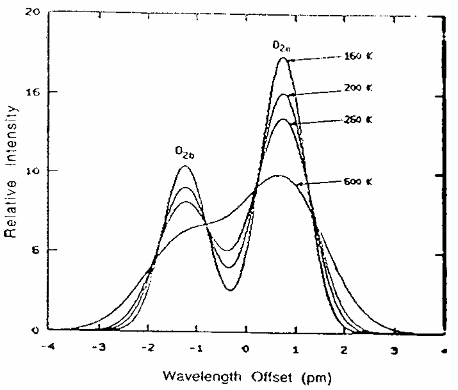

Fig. 1. Doppler broadened hyperfine structure of the Na D_2 resonance line [3].

4. Conclusion

This particular lidar system is a combination of the combined efforts of the laser industry with that of the airglow community. Temperatures have recently been reported using one of these lasers on potassium [6]. We hope to be able to report sodium temperatures and winds within the year.

References

1. Walling, J. C., Peterson, O. G., Jenssen, H. P., Morris, R. C., O'Dell, E. W.: Tunable Alexandrite Lasers, IEEE Journal of Quantum Electronics **16** (1980) 1302–1315.
2. Koechner, W.: Solid-State Laser Engineering, 4th edn., Springer Series in Optical Sciences, Springer-Verlag, Berlin, Heidelberg, (1996) pp 708.
3. Gardner, C. S.: Sodium Resonance Fluorescence Lidar Applications in Atmospheric Science and Astronomy, Proceedings of the IEEE **77** No. 3 (1989) 408–418.
4. Megie, G.: Laser Measurements of Atmospheric Trace Constituents, in Laser Remote Chemical Analysis, ed. by R. M. Measures, John Wiley & Sons, New York, (1988) 333–408.
5. Fricke, K. H., and von Zahn, U.: Mesopause Temperatures Derived from Probing the Hyperfine Structure of the D_2 Resonance Line of Sodium by Lidar, J. Atmos. Terr. Phys. **47** (1985) 499–512.
6. von Zahn, U., Höffner, J.: Mesopause Temperature Profiling by Potassium Lidar, Geophys. Res. Lett. **23** (1996) 141–144.