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Measurements of Spectral Purity of an Injection Seeded Alexandrite Ring Laser for a DIAL Temperature Lidar

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A differential absorption lidar operating in the oxygen A band near 760 nm is used for high accuracy atmospheric temperature measurements (Korb, et al, 1993). The NASA-GSFC pressure-temperature oxygen DIAL lidar utilizes two tunable pulsed alexandrite lasers (Schwemmer, et al, 1987) operating at 10 Hz. Earlier analyses of the temperature measurement method (Korb and Weng, 1982) have determined that for a measurement accuracy of ≤ 1K, the on-line laser frequency stability has to be better than 0.002 cm^{-1} over the duration of the experiment, its spectral bandwidth ≤ 0.01 cm^{-1}, and its spectral purity has to be ≥ 99.9%. Spectral impurity is a major source of experimental error in DIAL measurements (Cahen and Megie, 1981, Ehret, et al, 1993, Ismail and Browell, 1989, Theopold and Bosenberg, 1993).

By injection seeding a standing wave alexandrite laser with a stabilized diode laser (Schwemmer, et al, 1991) the required frequency stability and spectral bandwidth were achieved (Prasad, et al, 1992). However, a significant amount of out-of-band radiation was present giving a spectral purity of ≤ 94%. To improve the spectral purity, a travelling-wave three mirror ring alexandrite laser was recently integrated into the pressure-temperature lidar to replace the standing wave on-line laser. The seed laser and optics were modified to eliminate some sources of spectral impurity. A significant improvement in the spectral purity resulted from these changes. In this paper we present the details of the injection seeded alexandrite ring laser and some measurements of its spectral purity.

A spectral purity relevant to DIAL measurements is defined as the ratio of the laser energy contained within a narrow bandwidth (of the order of a few linewidths of the absorption line), to the total output energy. Hence a long path cell filled with oxygen (absorption linewidth ≈ 0.1 cm^{-1} at one atmosphere pressure), will act as a narrow band notch filter centered on the absorption line. The extent of spectral impurity in the laser output is determined by a measurement of the transmittance, τ, of the laser beam through the cell. By choosing a strong absorption line with an absorption coefficient, α, and a long path length, l, such that $exp\ (-\alpha l) \approx 0$, the residual transmittance is then the amount of spectral impurity. A multi-pass White cell containing an atmosphere of pure oxygen with a total path length of about 60 m was used. To fully saturate the absorption at the line center the laser beam was directed along a horizontal atmospheric path at a retro-reflecting target board placed 850 m away. The $^{P}P_{11}$ line at 764.07 nm, with a line strength of 7.6 cm^{-1}/molecule/cm^2, was chosen. All transmittance measurements were normalized for the laser energy (or power for the cw laser) and also for the transmission through the same path at a nearby non absorbing (off-line) wavelength.

Spectral impurity in an injection seeded laser can arise from spatial hole burning in a standing wave resonator cavity, an imperfect match between the transverse modes of the seed and slave lasers, impurities in the seed laser, or the seed laser frequency not being resonant with the slave laser longitudinal modes. By using a traveling wave ring laser spatial hole burning normally encountered in a standing wave resonator is avoided. The tendency of the ring laser to oscillate in both directions is suppressed by the injected seed laser beam that ideally forces the oscillations along the direction of the seed beam. When the transverse modes of the two lasers are not matched, the slave laser is free to oscillate in the unseeded modes over the entire spectral bandwidth of the laser in both directions, giving rise to spectral impurities. A good mode match is obtained when both the seed and slave lasers are operating in the TEM_{00} mode.

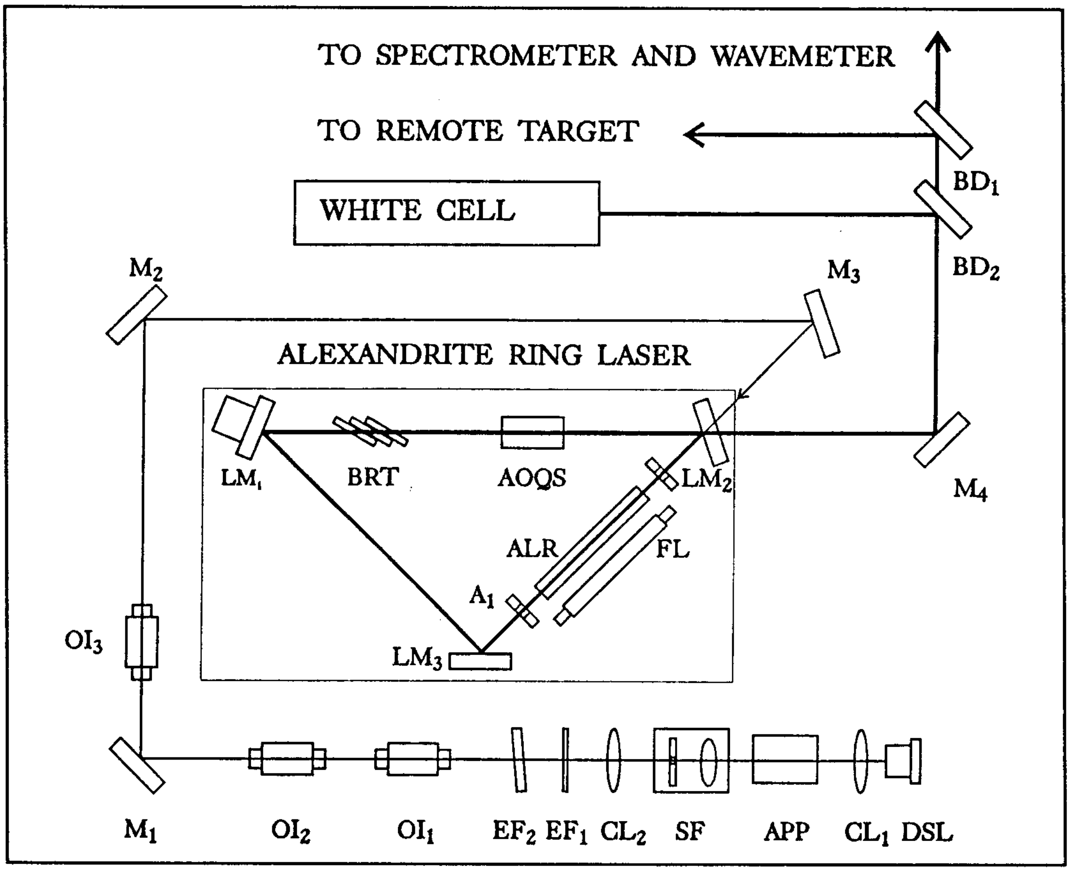

Figure 1. Schematic of the injection seeded ring laser. A_1, A_2: Apertures; ALR: Alexandrite Laser Rod; AOQS: Acousto-optic Q Switch; APP: Anamorphic Prism Pair; BD_1, BD_2: Beam Dividers; BRT: Birefringent Tuner; CL_1, CL_2: Collimating Lenses; DSL: Diode Seed Laser; EF_1, EF_2: Etalon Filters; FL: Flashlamp; LM_1 - LM_3: Ring Laser Mirrors; M_1 - M_4: Mirrors.

A stable single longitudinal mode (SLM) diode laser is used to injection seed the alexandrite laser. Commonly available single mode AlGaAs diode lasers operate mostly at 780 nm at 25°C and can be tuned over the 760 - 770 nm O_2 band by cooling them with multi-stage thermoelectric coolers by about 40 to 60°C (Schwemmer, et al, 1991). It is evident that any spectral impurities present in the seed laser would give rise to spectral impurities in the slave laser output as well. Commercial SLM AlGaAs diode lasers with 3 mW and 30 mW output were found to contain several weaker lines (from different longitudinal modes of the cavity) which contribute a significant fraction to the output ($\approx$ 2 to 3%). Broadband radiation of the order of 1% over the entire bandwidth of the laser diodes is also present. External cavity diode lasers which are expected to have high spectral purity were not available for this study. In order to achieve a high spectral purity in the seed laser we used a 100 mW, index guided, single mode AlGaAs laser, with a wavelength of 776 nm at 25°C, in a specially designed vacuum enclosure with multistage thermoelectric coolers.

The wavelength of the diode laser is coarsely tuned to the middle of the P branch of the

O_2 A band by cooling the diode to approximately -30°C and then precisely tuned by a combination of temperature and current control. In the experiments reported here the diode laser wavelength was passively maintained constant by using an ultra stable current source and a temperature controller. Its output contained many weaker lines spaced at ≈ 0.095 nm whose combined output power was about 5% of the total. The spectral impurity of the diode laser was determined by tuning it to the $^PP_{11}$ line and measuring its transmittance through the White cell. Three solid etalons of lengths 0.1mm (90% R), 1 mm (75% R), and 2 mm (75% R) were used to filter out the side bands. The spectral impurity was reduced to about 0.35% after filtering with the three etalons.

Figure 1 shows the schematic of the alexandrite ring laser together with the optical train used for injection seeding, and the diagnostics used in our experiments. A TEM_{00} transverse mode distribution across the seed beam is obtained by utilizing a collimating lens CL_1, an anamorphic prism pair APP, a spatial filter SF, a 10X microscope objective lens and a 16 μm pinhole, and a second collimating lens CL_2. Optical feedback from the slave laser is prevented from reaching the seed laser by three optical isolators OI (each consisting of a Faraday rotator and two polarizers) providing more than -90 db isolation. A three mirror ring resonator configuration is employed for the alexandrite ring laser. Two intracavity sapphire apertures (a 2.5 mm and a 4 mm dia) were placed on either side of the pump chamber to force the laser to operate in the lowest order transverse modes. A 100 mm long x 5 mm diameter alexandrite laser rod is pumped by a single flashlamp.

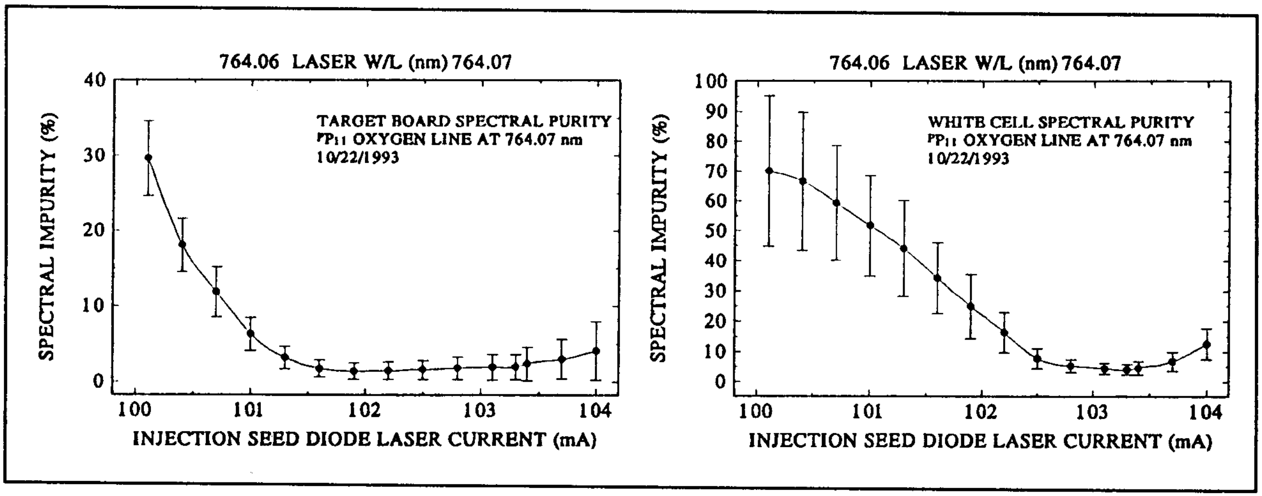

Figure 2 Mean spectral impurity of injection seeded alexandrite ring laser measured using: a) target board. b) White cell. Each point is the average of 1000 shots.

The laser output spectra were analyzed with a spectrometer having 0.25 cm^{-1} resolution and a wavemeter consisting of a 5 cm Fizeau etalon and having a resolution of about 0.004 cm^{-1}. The effect of various operating parameters on the spectral purity of the injection seeded alexandrite laser was investigated. The parameters that were varied included: spectral filtering of the diode beam to remove side-bands, broadening the linewidth of the diode laser, and the beam divergence of the seed laser beam. Before incorporating the limiting apertures in the alexandrite laser and optical filters for filtering the diode sidebands, the spectral purity was found to be as low as 85 to 90%.

Continuous nitrogen purge was used to remove the atmospheric oxygen present in the laser cavity in order for the low-gain alexandrite laser to operate on an oxygen line. The spectrum of the unseeded Q-switched alexandrite laser output shows a sharp dip at all oxygen lines, which disappears after 30 to 40 minutes of purge. Absorption by oxygen lowers the laser gain at the line center causing the laser to oscillate over the entire bandwidth of the BRT, severely reducing the spectral purity. It may be noted that it is not possible to totally eliminate all the oxygen in the laser cavity, but only reduce it to a low level. The spectrum of the injection seeded laser contains a number of lines corresponding to the side bands of the diode. When etalons were used to filter the diode beam, except for one or two weak side bands that appeared on some of the shots all other side bands were filtered out. The best spectral purity measured was about 96.3% using the White cell, at the center of the ${}^{P}P_{11}$ line. The intrinsic linewidth of the diode laser is only 15 MHz and is comparable to the linewidth of the slave laser. Without an active cavity length control the seed laser wavelength is resonant with the slave laser for only some of the shots. For the rest of the shots a small fraction of the total seed power in the cavity will be utilized by the slave laser modes, which are spaced by 200 MHz. To increase the useful seed power the diode linewidth was broadened by the addition of white noise to the diode laser power supply. The experiment was limited in scope because of the 2 MHz bandwidth of the laser power supply. Even with these limitations the spectral purity improved to 97.5%.

In the final set of measurements the frequency of the seed laser was scanned in steps across the oxygen line at 764.07 nm. The off-line wavelength was set at 764.3 nm. For this set we did not broaden the diode laser line and the spectral filtering of the diode beam was optimized at a slightly different wavelength. Data was collected simultaneously from the target board as well as from the White cell. Figures 2a and 2b shows the residual spectral impurity as the seed laser is scanned across the ${}^{P}P_{11}$ line. The mean spectral impurity measured at the line center was 1.9% using the target board data and 4.5% using the White cell data. When shots that had high values of transmittance (4 standard deviations away from the mean) were filtered out the mean spectral purity was 98.6% for the target board and 95.8% for the White cell at the line center. By incorporating active cavity length control and a feedback system to keep the slave laser in resonance with the seed laser frequency further improvements of the spectral purity are expected.

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