Construction of a High Power OPO Laser system for Differential Absorption LIDAR

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Abstract

Our goal is to develop and characterize optical measurement technology to enable accurate quantification of greenhouse-gas emissions from distributed sources and sinks. We are constructing a differential absorption LIDAR (DIAL) system that will be sensitive to the three primary greenhouse gases, carbon dioxide, methane, and nitrous oxide. Our system uses a high energy optical parametric oscillator (OPO) operating from 1585 nm to 1646 nm. Here we describe this OPO system and initial characterization of its output. The OPO uses a Rotated Image Singly-Resonant Twisted RectAngle (RISTRA) design. The commercially available RISTRA cavity is machined from a solid block of aluminum. The compact single piece cavity design requires no mirror adjustments and image rotation provides efficient light conversion efficiency and excellent beam quality. The injection seeded OPO has demonstrated total output energy of 50 mJ/pulse when pumped with 220 mJ/pulse of 1064 nm radiation. The pump laser has a repetition rate variable from 1 Hz to 100 Hz and a temporal pulse width of 4.2 ns. In the current configuration the seed laser is locked to a mode of the cavity.

Keywords: DIAL, LIDAR, greenhouse gas, laser, optical parametric oscillator, remote sensing

1. Introduction

A quantitative measure of the greenhouse gas (GHG) inventory, both sources and sinks, is of critical importance to understanding the science of global climate change and to facilitate sound environmental decision-making regarding GHG levels and trends. Current inventory methods rely on estimates and emission factors. Their quantitative performance can be improved with improved measurement capabilities that will also provide a validation method useful in a variety of settings [1]. A major challenge for assembling an accurate inventory of GHG fluxes is in the estimation of fluxes from large distributed sources; for example landfills, agricultural sites, and large scale industrial sites where point-based measurements may fail to give an accurate picture due to the heavy reliance on models. Active optical remote sensing using DIfferential Absorption Light detection and ranging (DIAL) is an attractive method to meet this and other measurement challenges[1, 2].

We are developing a DIAL system with laser emission in the eye-safe region near 1600 nm. The major greenhouse gases CO_2, CH_4, and N_2O all have vibrational absorption bands here and the measurements are simplified due to low interference from water vapor absorption. The targeted spectral region in the near infrared is illustrated in Fig.1. This region also features the availability of sensitive detectors, the ability to generate high energy laser pulses, and the availability of off-the-shelf technology from the telecom industry.

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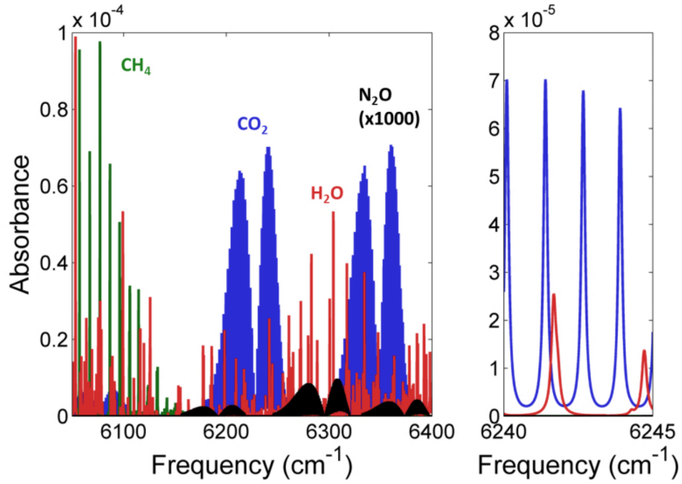


Fig. 1 Left: The near IR spectrum of relevant greenhouse gases methane (green), carbon dioxide (blue), and nitrous oxide (black) are illustrated using their respective globally averaged concentrations and at atmospheric pressure and temperature with 50% relative humidity. The simulated spectrum is based on HITRAN[3]. The weak spectrum of nitrous oxide is multiplied by a factor of 10^3. Absorption due to water (red) makes much of the near IR spectrum opaque, but is only a minor inference in the spectral region near 1600 nm (6225 cm^{-1}). Right: A subregion of the spectrum showing a region of the spectrum where suitable choice of frequencies can result in DIAL measurements free from the confounding effects of water vapor.

The fundamental component of a DIAL system is a suitable laser source. There are currently many groups developing laser sources to perform DIAL for the measurement of greenhouse gases. Koch et al and Gibert et al have developed high energy sources operating at 2000 nm for use in heterodyne or coherent DIAL[4-7]. These systems were developed to measure carbon dioxide concentration and wind speed. There are several groups developing laser sources in the same 1600 nm spectral region that is of interest to us for the detection of carbon dioxide, methane, water vapor, ozone, and to perform aerosol characterization.

To produce the 1600 nm light, several groups are using quasi-phase matching (QPM) methods that use periodically poled materials. The QPM method is attractive because of the ease of alignment and high efficiency of light conversion, but has limited tuning and low pulse energies. Burris et al has demonstrated pulse energies of 180 μJ/pulse at 2 kHz repetition rate using a two stage optical parametric amplifier (OPA) that implements periodically poled lithium niobate (PPLN)[8]. Numata et al has constructed a fiber based system that uses a single stage PPLN OPA to generate 10 μJ/pulse energies at 6 kHz repetition rate[2]. Recently available large area periodically poled materials have been used by Sakaizawa et al in a four mirror OPO ring cavity to generate pulse energies of 10 mJ/pulse at 110 Hz repetition rate[9]. Other groups that have been developing methods that use a high energy OPO systems to generate pulse energies on the order of 10 mJ/pulse[10] to 100 mJ/pulse at repetition rates of about 10 Hz[11].

To perform DIAL remote sensing over large distances in the near IR a high energy laser pulse is required to achieve sufficient single-to-noise in the collected backscatter photon counts and a high repetition can minimize integration time so that measurements can be made under constant atmospheric conditions. The high energy is needed to overcome the $1/R^2$ power loss and the weak elastic backscatter cross sections. In the 1km to 3 km range of interest to us, we estimate that sufficient signal-to-noise can be achieved with pulse energies in the 10 mJ/pulse to 100 mJ/pulse range. A laser system based on an optical parametric oscillator (OPO) can achieve these pulse energies.

Laser systems based on OPOs have many features that make them suitable for a field-deployable DIAL system. These include frequency agility, solid-state construction, and the ability to generate high energy output. The major drawback in conventional OPO systems is poor beam quality at output energies greater than a few mJ/pulse. At the pump energies required to achieve output in the mJ/pulse range the pump beam diameter needs to be made large to avoid optical damage. A pump beam with a large diameter entering a cavity can oscillate on multiple transverse modes and thus the output is degraded. We chose to base our system on the Rotated Image Singly-Resonant Twisted RectAngle (RISTRA) cavity design pioneered by Armstrong and Smith[12]. This ring cavity design induces a 90 degree image rotation on every round trip, which maintains excellent beam quality with demonstrated M^2 values as low as 1.1 even at high pulse energies[13-18]. The RISTRA is machined from a solid block of aluminum which makes the cavity robust. We have recently assembled a 1064 nm pumped high power RISTRA OPO with signal output in the range from 1585 nm to 1646 nm (6050 cm^{-1} to 6400 cm^{-1}) which corresponds to the spectral region illustrated in Fig. 1.

2. OPO System Elements

2.1 Pump Laser

The pump laser for the OPO is a Coherent Infinity 80-100 Nd:YAG [12]. The fundamental output at 1064 nm is used to pump the OPO. The Infinity has a variable repetition rate from 1 Hz to100 Hz and a maximum average output power of 40 Watts. The repetition rate and high energy make the laser well suited for a DIAL system. The Infinity is a hybrid between a solid-state laser and a flash lamp pumped system. The combination of the solid-state design and use of an internal spatial filter typically provides a high quality beam profile and pulse-to-pulse energy fluctuations near 1 %. The beam profile of the pump laser is shown in Fig. 2 and has a measured $1/e^2$ diameter of 6.2 mm. This image indicates a hot spot in the beam which will be remedied with realignment.

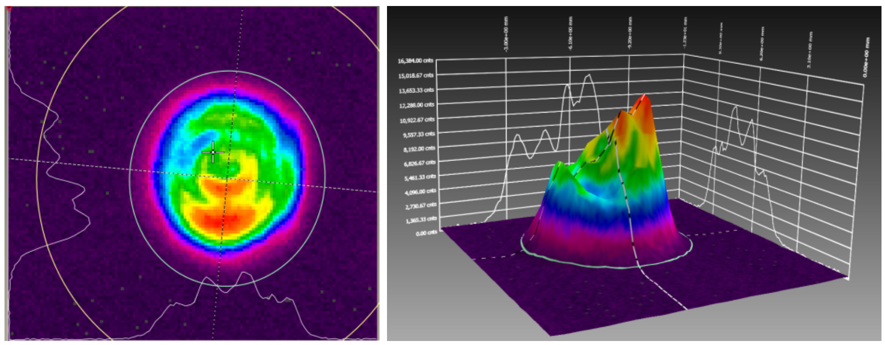
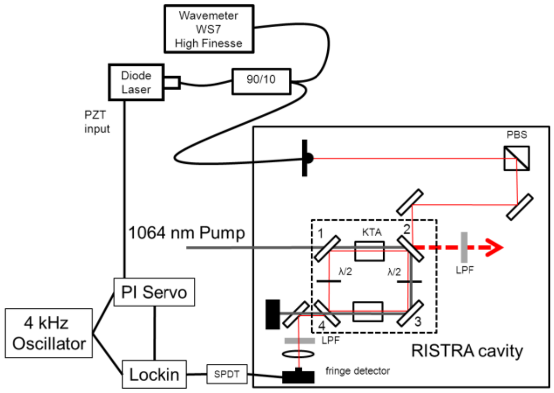


Fig. 2 The pump laser spatial fluence profile is shown as a contour and surface plots.

All beam profile images shown in this paper were recorded using a Pyrocam III camera and acquired and analyzed using Beamgauge software (OPHIR-Spiricon) [12]. The Nd:YAG laser was set to a 30 Hz repetition rate, a flash lamp setting of 480 Volts, and had an output energy of 210 mJ/ pulse. These same settings were used in all experiments. The pulse duration of the Infinity also varies slightly with output energy. For the settings described the pulse duration was roughly 4.2 ns.

2.2 Seed Laser

The RISTRA OPO is injection seeded at 1630 nm using an external cavity diode laser (New Focus Velocity series) [12]. The diode laser operates from 1650 nm to 1580 nm and is fiber coupled to single-mode polarization maintaining fiber and a 90 % / 10 % fiber splitter. The 10 % portion is used to monitor the wavelength and the 90 % is used to seed the RISTRA. The optical layout is illustrated in Fig. 3.



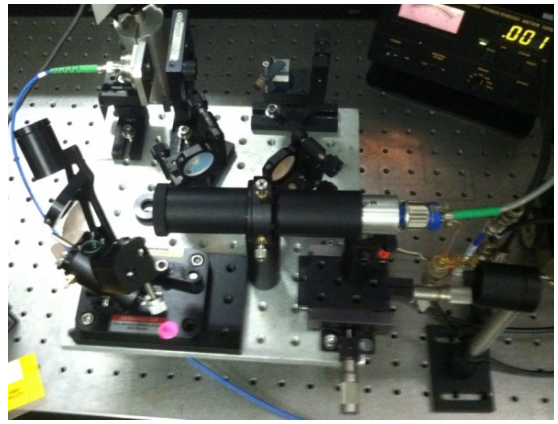


Fig. 3. Mounted to a 9" x 9" breadboard are the fiber output from the seed laser, polarizing beam splitter cube, seed alignment mirrors, RISTRA cavity (lower left in picture), and the fringe detector. Long pass filters (LPF), (OD 6 at 1064 nm) are used to attenuate the residual pump pulse. Mirrors 1- 4 are labeled.

The output power of the seed laser into the RISTRA ranges from 1 mW to 3 mW. A beam profile of the seed laser immediately before entering the OPO cavity after exiting the single-mode polarization maintaining fiber is illustrated in Fig. 4 and has a measured $1/e^2$ diameter of 4 mm.

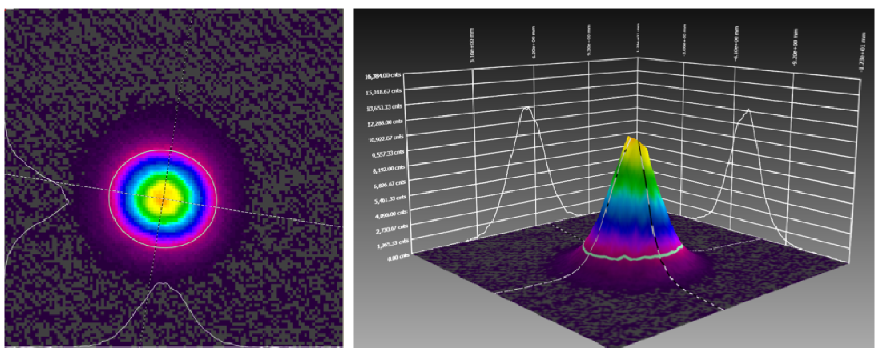


Fig. 4. Seed beam spatial fluence profile is shown as a contour and surface plots

A polarizing beam splitter cube (PBS) was used to ensure high polarization purity. The wavelength was monitored using high resolution (10 MHz) wavelength meter (High Finesse, WS7 IRII) [12]. The wavelength meter can be used to monitor the wavelength but also contains a servo to stabilize the diode laser to a desired wavelength. This method has been used to stabilize the output frequency of the diode laser to sub MHz precision for several hours (Fig 5). Absolute accuracy can be achieved by use of dual wavelength stabilized He/Ne laser.

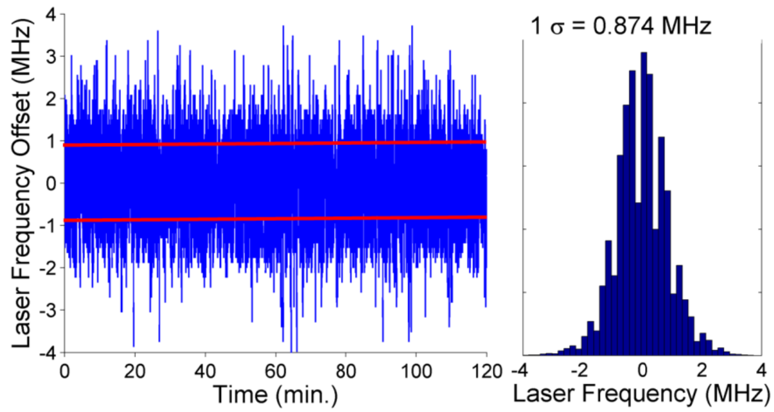


Fig. 5. Long term wavelength stability showing a time trace of the laser frequency and a histogram of the amount of time spent in different frequency bins over the 120 minute observation period.

Other servo methods could stabilize the frequency to a few hundred kHz [19]. These methods will be needed for locking to the peak of the desired absorption signal during the DIAL experiment.

2.3 Optical Parametric Oscillator

As stated above the OPO cavity design implements 90 degree image rotation. Typically, when a pump beam with poor quality is used to pump an OPO it generates a low quality output beam (signal). The image rotation properties of the cavity minimizes rotational asymmetry in output beams when non-ideal pump laser sources are used. Our implementation of the RISTRA OPO uses two KTA 10 mm x 10 mm x 15 mm crystals in the cavity with type II phase matching conditions[17]. The crystals are xz-cut at 67.4 degrees for phase matching at normal incidence at 1625 nm where 3082.0 nm (e) + 1625.0 nm (o) = 1064.0 nm (o), the e and o are the extraordinary and ordinary waves. The RISTRA allows ±10 degree rotation of crystal for optimally phase-matched operation from 1595 nm to 1650 nm. The crystals were obtained from Crystal Associates Inc [12]. It is noted that one of the crystals has a defect in the upper corner, an issue which is not uncommon[17]. It remains to be seen if this will impact the ultimate performance of the OPO.

The pump beam propagates in a ring from mirror 1 to mirror 4. (The mirrors are numbered 1 – 4 going clockwise and starting with the pump beam input mirror, See Fig. 3.) The input/output coupler (mirror 2) is coated for 60% reflection for the signal beam. Leakage of the seed beam through mirror four is used to monitor the cavity fringes. Mirror four also transmits the pump beam so a second mirror that transmits the pump is used to send the seed beam through a long pass filter (OD 8) and then a 25mm focal length lens is used to collect the light on a germanium photodiode. An InGaAs photodiode was initially used but was damaged when only an OD 6 filter was used.

Alignment of the seed beam to the OPO was achieved by translating the beam and optimizing the cavity fringes by monitoring the fringe detector on mirror 4. The mode pattern of the cavity is shown Fig. 6. The finesse of the cavity is approximately 9 and its free spectral range is 2.00 GHz at 1625 nm.

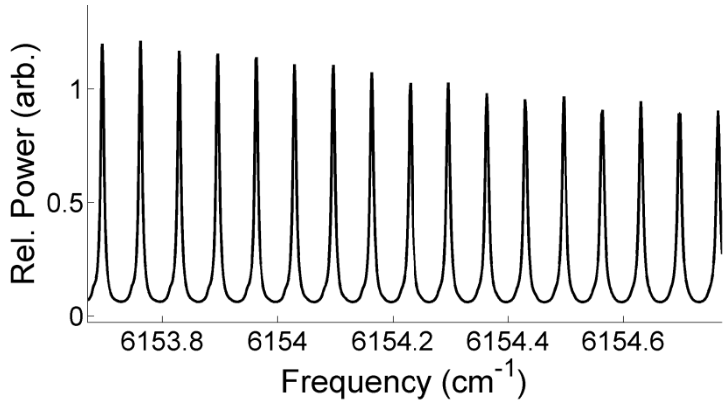


Fig. 6 Measured longitudinal mode structure of RISTRA cavity. The data was acquired by scanning the diode laser through the fringes of the cavity while recording the output power on the fringe detector and the frequency of the diode laser.

With the seed aligned to the cavity a servo system was used to lock the laser wavelength to the RISTRA cavity. Before the cavity can be used for DIAL, mirror 3 of the cavity will be mounted on a PZT to enable locking the cavity length to the laser frequency. With the cavity locked the beam profile of the transmitted seed (from mirror 2) was observed and further optimized to ensure that the cavity was not aligned on a vortex mode. A series of beam profile images are shown in Fig. 7 that illustrate optimizing the seed beam alignment.

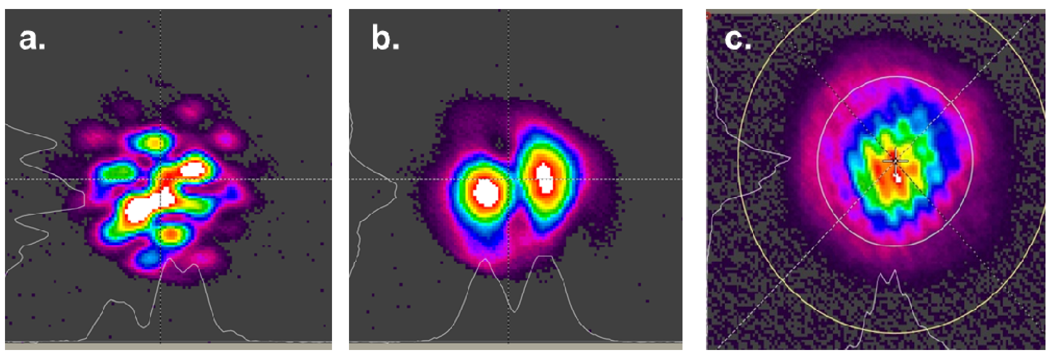


Fig. 7. These images depict the various states of seed beam alignment a. grossly misaligned, b. aligned to higher order modes, c. aligned and locked to the cavity. The distortion observed in c. is due to interference on the output coupler

The laser was locked to the RISTRA cavity by means of a dither lock. The diode laser was modulated at 4 kHz over a single fringe of the cavity. The output of the fringe detector was measured using a lock-in to generate an error signal. The error signal was input to a proportional – integral (PI) servo. The servo output was used to feed back to the diode laser frequency. An electronic switch located on the output of the fringe detector was used to remove the residual pump and or signal pulse, which improved the servo lock.

3. Results and Discussion

The performance of the RISTRA OPO can be modeled with freely available software.[20] The components described above (pulse energy, pulse duration, pump beam diameter, crystals length and cut) were used as inputs into the RISTRA2 modeling software[12]. The software predicted that with a pump pulse energy of 200 mJ/pulse the RISTRA should have an output energy of 70 mJ/pulse of signal (1625 nm) and 30 mJ/pulse of idler (3082 nm) with a beam diameter of 2 mm. The threshold energy lasing with seeding was observed to be roughly 110 mJ/pulse achieving output energy of a few hundred μJ/pulse. A measure of the pump efficiency is shown in Fig 8.

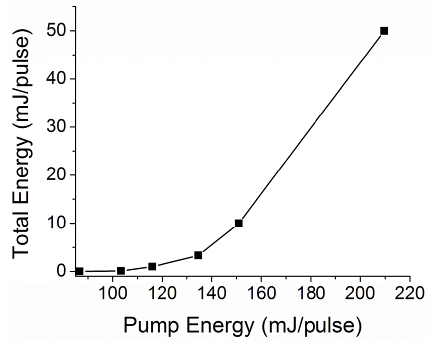


Fig. 8. Efficiency curve using two critically phase matched KTA crystals and with seeded input. The seed laser was locked to a mode of the RISTRA cavity for all measurements.

The maximum energy used to pump the RISTRA was 210 mJ/pulse generating a total output energy of 50 mJ/pulse. The beam profile of the 50 mJ/pulse output beam is illustrated in Fig. 9. The small beam size and shape are typical for this type of image rotation cavity.

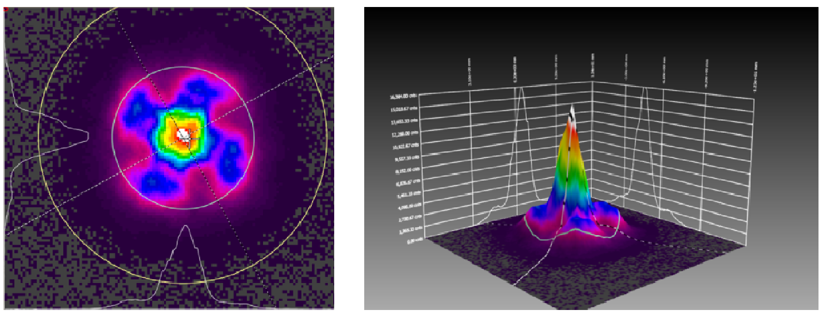


Fig. 9 The RISTA OPO output spatial fluence profile is shown as a contour and surface plots. We believe that an improvement in our pump laser mode quality will result in improved mode quality from the OPO.

A portion of the signal beam was analyzed using a high finesse etalon (67 MHz resolution) to measure the spectral width. The results are shown in Fig. 10 and the bandwidth was determined to be approximately 200 MHz.

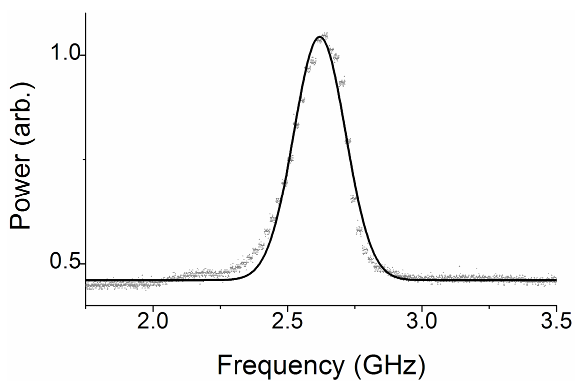


Fig. 10 Measured (gray dots) and fit (black line) of the spectral width of generated signal beam.

In a previous RISTRA design operating with injection seeding at 1550 nm and using similar KTA crystals the threshold for lasing was observed near 200 mJ/pulse[17]. We observe threshold just above a 100 mJ/pulse and believe the difference arises from both the hot spot (see Fig. 2) and possibly the shorter pulse duration (4.2 ns vs. 10 ns) of the pump laser. The poor quality pump beam may also explain some of the higher order structure of the seen in Fig. 9 of the OPO output. This may be due to lasing on vortex modes of the cavity, which is known to be an issue in image rotation cavities due to the four-fold symmetry. In the near future we will realign the pump laser system in order to eliminate the hot spot and anticipate that our pump and signal beam profiles will be significantly improved.

4. Summary and Future Applications

We are currently working to develop a DIAL system for the measurement of carbon dioxide, methane, and potentially nitrous oxide. The work is in support of climate change research and efforts to support measurement of the greenhouse gas inventory to meet the needs of regulators, policy makers, and industry. The needs are largely driven by cost, ease-of-use, and robustness. We have demonstrated the construction of tunable near IR laser source generating output energies near 50 mJ/pulse and operating near the transform limit with a spectral width of 200 MHz. The completion of the laser source is only the first step in the construction of the full DIAL system. Assembly of the data acquisition, receiver system, and new measurement methodologies are currently in progress. Upon construction of the DIAL system, it will be placed in a 100 meter long indoor facility that will be used for validation and characterization of the DIAL system and various analysis algorithms to provide a rigorous measure of uncertainty. In addition to the indoor facility NIST also has a calibrated burn facility, where the precise contents of the exhaust from a smoke stack are well known and characterized. Future work may include performing DIAL measurements on the plume release from the NIST smoke stack to perform realistic test conditions for the DIAL system.

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