Design and Testing of a Compact Widely Tunable Cascaded Master Oscillator Power Amplifier (MOPA) Diode Laser Based Micro Pulse Differential Absorption Lidar (DIAL) for Water Vapor Profiling in the Lower Troposphere

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ABSTRACT

Atmospheric water vapor is an important driver of cloud formation, precipitation, and cloud microphysics. Water vapor profiling in the lower troposphere is important for understanding complex weather and coupled climate processes including the aerosol direct and indirect effects. A compact, widely tunable semiconductor based master oscillator power amplifier (MOPA) water vapor differential absorption lidar (DIAL) has been built, tested, and deployed at Montana State University (MSU). The laser transmitter uses a tunable external cavity diode laser (ECDL) with a center wavelength of 830 nm to injection seed two cascaded tapered semiconductor optical amplifiers (SOA), producing up to 2 micro joules per pulse at a pulse repetition frequency and pulse width duration of 20 kHz and 1 μs respectively. The low average power and high pulse repetition frequency of the DIAL transmitter allows for shot to shot backscattered returns up to ~10 km and water vapor number density retrievals up to 4 km with averaging times approaching 5-10 minutes. Pulsing of the DIAL transmitter is achieved by modulating the forward current to the second SOA. The DIAL receiver utilizes a commercial 28 cm diameter Schmidt-Cassegrain telescope, a fiber coupled photon counting avalanche photodiode (APD) detector, a 250 pm narrow band optical filter, and a multi channel scalar (MCS) to collect, discriminate, and measure the scattered light.

Water vapor number density profiles collected with the MSU water vapor DIAL instrument will be compared with co-located radiosonde measurements, demonstrating the instruments ability to measure water vapor profiles in the lower troposphere. Water vapor profiles can be collected with averaging times of less than ten minutes, providing sufficient signal to noise ratios for night time water vapor number density measurements up to ~ 4 km and day time measurements up to ~ 1.5 km. Performance characteristics as well as night time and day time water vapor number density profiles derived from the MSU DIAL instrument will be presented. Continuation of future work towards the development of a next generation semiconductor based compact micro pulse water vapor DIAL instrument will also be discussed.

1. INTRODUCTION

The Earth's climate is driven by incoming solar radiation that is distributed and eventually reemitted back into space. Understanding how the incoming solar radiation is distributed and reemitted back into space provides insight and understanding of the complex climate system. Understanding the details of how this redistribution of energy occurs provides insight into the complex climate system of the earth and is used as a starting point for climate models.

Aerosols play an important role in the Earth's complex climate system. The increased aerosol loading of the atmosphere due to anthropogenic sources produces a negative radiative forcing similar in magnitude to the positive radiative forcing associated with the increase in anthropogenic greenhouse gases [1]. According to the Fourth Assessment Report (FAR) of the Intergovernmental Panel on Climate Change (IPCC) [2], the radiative forcing due to aerosols currently has a "low level of scientific understanding" [2], resulting in the largest uncertainties in our understanding and modeling of the Earth's climate system. The radiative forcing of aerosols depends on three coupled components of the climate system, including atmospheric aerosols, water vapor, and clouds. To better understand and model the role these atmospheric constituents play in the climate system, new observational instruments and techniques are needed to reduce these uncertainties [2].

Aerosols affect the climate system both directly and indirectly. In the aerosol direct effect, aerosols interact directly with the incoming solar radiation, reflecting the incoming solar radiation back into space, causing a net negative radiative forcing, which lies in the range of (-0.5 ± 0.4 W/m^2) [2]. This large uncertainty (±80%) associated with the negative radiative forcing due to the aerosol direct effect is an indication of the uncertainty in understanding of how aerosols influence the climate system. The large uncertainty of the radiative forcing due to aerosols is in contrast to the "high level of scientific understanding" [2] for radiative forcing due to the increase of greenhouse gases such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), responsible for trapping thermal long wave radiation that heats the atmosphere [2].

In the aerosol indirect effect, aerosols can also influence cloud microphysical properties, which in turn indirectly affect the climate system. Twomey suggests that an increased concentration of atmospheric aerosols will result in a higher concentration of cloud condensation nuclei (CCN). The increased concentration of CCN then leads to a higher cloud droplet concentration that will suppress drizzle formation and lead to more reflective clouds. However, as noted by Eichel et al. and Wulfmeyer and Feingold, this chain of events is not a foregone conclusion but rather depends on properties associated with the aerosols, including the aerosol composition and hygroscopicity in the atmosphere. The changes in the cloud micro-

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physical structure due to the interaction of aerosols and water vapor produce more reflective clouds, resulting in more incoming solar radiation being reflected back into space, leading to an overall negative radiative forcing that is estimated to be (-1.8 W/m^2 to -0.3 W/m^2) [2]. This large range for the radiative forcing by the aerosol indirect effect also reflects the uncertainty in the understanding of the aerosol indirect effect. To better understand the aerosol indirect effect, Wulfmeyer and Fiengold noted that lidar measurements of aerosol properties can provide important information to enhance our understanding of the role of aerosols in the climate system.

The LIDAR group at Montana State University has initiated a program to simultaneously study aerosols, water vapor, and cloud formation in the atmosphere. Aerosol distributions are currently being studied with a two-color LIDAR system. In addition, a three color, high spectral resolution LIDAR system has also been developed and is starting to take initial data. Water vapor number densities are currently being studied with an external cavity diode oscillator/diode amplifier based differential absorption lidar (DIAL) instrument at the 828.187 nm water vapor absorption line. This system is taking data both for night time and day time measurements. Cloud formation studies are being done by a simultaneous, spatially correlated digital camera imaging system. Furthermore, two commercially available instruments including the sun/sky scanning solar radiometer (CIMEL 318) as part of the NASA run AERONET program as well as the MPL-4 micropulse lidar as part of the NASA run MPLNet are being used to study aerosol loading and radiative transfer through the atmosphere respectively.

A promising avenue of research toward development of DIAL instruments for water vapor studies is to use semiconductor laser transmitters. Diode lasers are compact, inexpensive, can be tuned, and have good spectral coverage in the near infrared spectral region where water vapor has many absorption lines. Several numerical studies of diode-laser-based transmitters and photon counting avalanche photodiode-based receivers have been performed, but few systems have been built. Combining the DIAL instrument with other atmospheric remote sensing instruments available at Montana State University provides the tools needed for studying the role water vapor plays in the complex climate system.

This paper gives a brief update on the progress of the MSU water vapor DIAL system and previews future work towards a high power next-generation compact field deployable DIAL instrument. Section 2 provides a detailed physical description of the current water vapor DIAL instrument as well as recent data taken over Bozeman, Montana, with a comparison to collocated radiosonde measurements. Concluding remarks as well as future work towards a more compact, higher-power injection-seeded multi-laser transmitter for a next-generation MSU water vapor DIAL instrument will be presented in section 3.

2. DIAL Instrument and Experimental Results

2.1 DIAL Technique

DIAL instruments are capable of making range resolved measurements of molecular number density. DIAL instruments use a tunable pulsed laser transmitter that can be tuned to an on-line wavelength for an absorption line for the molecule of interest and then tuned to an off-line wavelength with no molecular absorption. The on-line and off-line wavelengths of the DIAL transmitter are chosen so that the ratio of the return signal from these wavelengths is directly related to the absorption from the molecules of interest. The difference in the strength of the return signals for the on-line and off-line wavelengths at different altitudes can then be related to a number density for the molecule of interest using the DIAL equation shown in equation 1.

$$N(r) = \frac{1}{2\left(\sigma(\lambda_{on}, r) - \sigma(\lambda_{off}, r)\right)\Delta r}\left[\ln\left(\frac{P(\lambda_{on}, r)P(\lambda_{off}, r+\Delta r)}{P(\lambda_{on}, r+\Delta r)P(\lambda_{off}, r)}\right)\right] \quad (1)$$

Ranging information is obtained by measuring the time difference between when the laser pulse leaves the laser transmitter and when the scattered light is collected by the DIAL receiver.

2.2 Instrument Description

A first generation water vapor DIAL instrument has been developed at Montana State University demonstrating the capabilities of diode laser based DIAL instruments [3]. A schematic of a second generation water vapor DIAL is shown in figure 1. The output from an ECDL in the Littman-Metcalf configuration is used to injection seed a tapered semiconductor optical preamplifier. The output from this preamplifier is incident on a half have plate (HWP) and a polarizing beam splitter (PBS). Light passing through the PBS is sent to a wavemeter to lock the laser transmitter's wavelength to either the on-line, side-line, or off-line wavelength of a water vapor absorption feature. Light rejected by the PBS is used to injection seed a second tapered semiconductor optical amplifier that is operated in saturation mode. The drive current to this second tapered amplifier is pulsed with a 1 µs pulse width at a 20 kHz pulse repetition frequency, yielding up to 1-2 µJ of energy per pulse and an average power of approximately 50 mW. After the tapered amplifier, the light is expanded and is then incident on a wedged window. Light reflected from the wedged window is

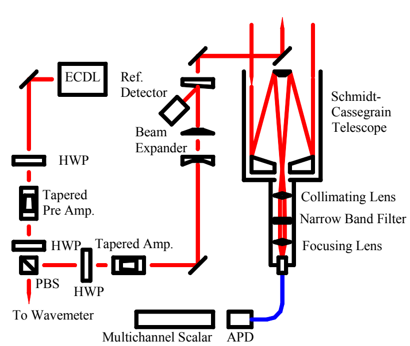

Figure 1. *Schematic of the second generation water vapor DIAL built at Montana State University.*

sent to a reference detector used to monitor the output power of the DIAL laser transmitter while light passing through the wedged window is sent into the atmosphere. A 28 cm diameter Schimdt-Cassegrain telescope is used to collect the backscattered light. Light collected by the telescope is next collimated, sent through a narrow band optical filter with a 0.25 nm passband and is then focused into a 105 µm diameter multimode fiber that delivers the light to an avalanche photodiode (APD) detector that is operated in Geiger mode. The APD is monitored using a 20 MHz multichannel scalar card data acquisition system, yielding a minimum range resolution of 7.5 meters. A summary of the MSU water vapor DIAL transmitter and receiver specifications are shown in table 1, the laser transmitter requirements for water vapor retrievals with an error due to individual laser properties of < 3% are also shown for comparison.

Table 1. *DIAL transmitter and receiver specifications*

Parameters	Measured Values	Requirement
λon, λside-line, λoff (nm, Vacuum)	828.187 / 828.1936 / 828.287	
Pulse Repitition Frequency (kHz)	20.0	
Pulse Width (µs)	1	
Pulse Energy (µJ)	1.0-2.0	
Transmitter Linewidth (FWHM; MHz)	< 0.300	< 296
Frequency Stability (MHz)	± 88	± 160
Spectral Purity	0.995	> 0.995
Telescope Diameter (cm)	28	
Far-field Full Field of View (µrads)	~85	
Filter Bandwidth (FWHM; pm)	~ 250	

2.3 Experimental Results

Night-time and day-time testing of the actively pulsed second generation water vapor DIAL instrument over Bozeman, Montana are being tested against collocated radiosonde measurements to verify instrument operation and accuracy. Results from the MSU water vapor DIAL instrument can be seen in figure 2 where water vapor number density profiles for 10 minute averaging times are plotted as a function of altitude for the nights of 03 March, 2009 (left) and 10 August, 2009 (right). The red dashed lines are results from the MSU DIAL, which show good agreement in both data sets with the collocated radiosonde measurements

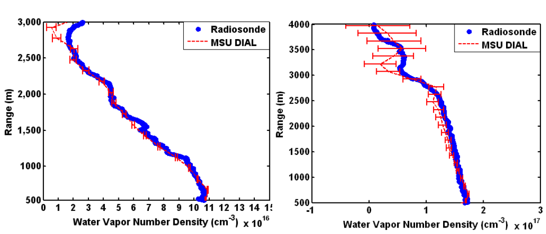

Figure 2. (*Left) 10 minute avg. vertical water vapor number density profile taken starting at 2130 LT 03 March 2009 calculated using 150-m vertical range bins.* (*Right) 10 minute avg. vertical water vapor number density profile taken starting at 2334 LT 10 August 2009 calculated using 150-m vertical range bins.*

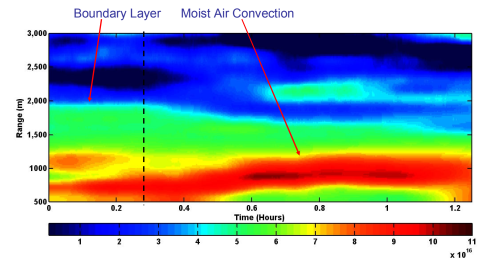

Figure 3. *False color time-height plot of water vapor number densities in the lower troposphere obtained with the MSU water vapor DIAL instrument starting at 2110 LT 03 March 2009. Ten minute running averages and vertically interpolated smoothing yielding 21.5-m range resolution is displayed. The dashed line indicates the launch of a collocated radiosonde measurement.*

displayed as the solid blue lines.

Micro-pulse DIAL instruments such as the water vapor DIAL that is deployed at MSU exploit high pulse repetition frequencies (PRF) and spatial averaging to obtain reasonable SNR's such that number density or mixing ratio measurements of the particulates of interest can accurately be calculated. The power of MSU's narrow field of view high PRF low power DIAL instrument lies in its ability to measure range and time resolved water vapor number densities up through the lower troposphere given clear conditions. False color time height plots capturing boundary layer water vapor dynamics have been recorded with averaging times approaching ten minutes. The good correlation between the DIAL and in situ measurements shown in figure 3 illustrates sufficient instrument operation such that time resolved water vapor DIAL data could be retrieved with ~10 minute running averages. Two nighttime false color time-height plots of water vapor number densities centered on the two profiles from March 3 2009 and August 10 2009 are shown in figures 3 and 4 respectively. Radiosonde derived temperature and pressure profiles measured temporally at approximately the dashed lines in figure 3 and 4 were utilized to calculate the differential absorption cross section of water vapor up through the lower troposphere as well as to verify the DIAL measurements as shown in figure 2. Relatively low integration times have allowed for time resolved transport of warm moist air carrying water vapor from the near surface up to the top of the planetary boundary layer around the 2-3 km of the lower troposphere in both data sets. The DIAL instrument has also demonstrated the ability to consistently measure the height and homogeneity of the planetary boundary layer as shown by the green data in both false color time-series plots. Furthermore, the MSU DIAL has demonstrated to be to our knowledge the first daytime operating diode laser based DIAL instrument.

The water vapor DIAL instrument built and deployed at Montana State University demonstrates the potential of diode laser based DIAL instruments for making range resolve molecular number density profiles up to and potentially past the planetary boundary layer during both nighttime and daytime operation. However, this first generation water vapor DIAL instrument can be improved by addressing three major issues including increasing the laser transmitter pulse energy, de-

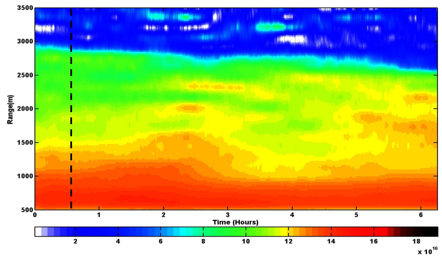

Figure 4. *False color nighttime time-height plot of water vapor number densities in the lower troposphere obtained with the MSU water vapor DIAL instrument starting at 2300 LT 10 August 2009. Ten minute running averages and vertically interpolated smoothing yielding 21.5-m range resolution is displayed. The dashed line indicates the launch of a collocated radiosonde measurement.*

creasing the switching time between the on-line and off-line wavelengths, and packaging the DIAL instrument for field deployment.

3. Future Work and Concluding Remarks

The first generation water vapor DIAL instrument operates with a pulse energy of 1-2 μJ. This pulse energy is sufficient for range resolved number density profiles to approximately 3 km with an averaging time approaching10 minutes. For each factor of two improvement in the laser transmitter power, either an increase in range by a factor of the square root of two or a decrease in the averaging time by a factor of two will be achieved.

The MSU water vapor DIAL instrument collects data at the on-line wavelength for one minute, is tuned to the off-line wavelength, and collects data at the off-line wavelength for one more minute. This data collection scheme is dictated by the time it takes the laser transmitter to tune between the on-line and off-line wavelengths, which is approximately five seconds [4,5]. This data collection scheme runs into difficulty when clouds rapidly move into and out of the field of view of the water vapor DIAL instrument on a time scale that is much shorter than the switching time associated with the master ECDL. A future work plan aims at developing a next generation water vapor DIAL instrument that addresses the limitations of the second generation water vapor DIAL instrument in terms of laser transmitter pulse energy, switching time, and packaging.

The proposed next generation diode laser based water vapor DIAL instrument is shown schematically in figure 5. In the next generation water vapor DIAL, two custom built high power Littrow configured ECDLs will be used for the laser transmitter. One ECDL will actively be locked to the on-line wavelength while the second ECDL will be operated at the off-line wavelength. The output from each of these ECDL's will be launched into one of the input fibers of a 2x1 fiber optic switch. The fiber optic switch will be used to switch between the on-line and off-line wavelengths at 1 s intervals. The 1 s averaging time and rapid switching between the on-line and off-line wavelengths will allow the next generation water vapor DIAL instrument to make measurements in the presence of clouds moving into and out of the field of view of the DIAL instrument. The output from the fiber optic switch will be used to

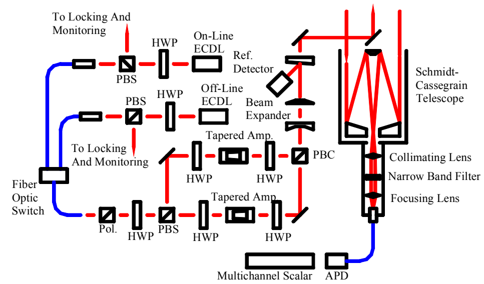

Figure 5. *Schematic of the proposed second generation diode laser based water vapor DIAL instrument.*

injection seed two beam combined, pulsed tapered amplifiers, doubling the output pulse energy of the DIAL transmitter. Because of the high output power from each of the two ECDLs, the need for the preamplifier's are eliminated, hence decreasing the footprint of the DIAL transmitter and allowing for field deployment packaging on a 1' x 1' optical bread board. The improved performance of the next generation laser transmitter has the potential to lead to compact low power DIAL instruments that in the future may be acceptable candidates for use in multi-point lidar networks.

Acknowledgments

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