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"New Concepts for an Environmental LIDAR" and "Doppler LIDAR for Tropospheric Wind Measurements"

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New Concepts for an Environmental LIDAR

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ABSTRACT

A development activity is in progress to renew the ENEL DIAL with the aim to obtain a reliable multipurpose system, able to control different pollutants (SO_2, NO, NO_2, O_3, Hg, CO and so on), together with important meteorological parameters such as water vapor concentration and temperature.

The system is based on a Nd:YAG pumped Titanium:Sapphire laser, with the possibility to be tuned from UV to IR by frequency mixing. The frequency control is obtained by means of stabilized laser diode injection into the Titanium:Sapphire laser. The Nd:YAG pump laser, designed for spaceborne use in the framework of an ESA contract, is a very compact device, based on a Master Oscillator Plus Amplifier (MOPA) configuration with a Gaussian resonator. The main feature of the transient recorder is the high dynamic range (18 bit, i.e. a dynamic range of 250,000) with a 10 MHz sampling rate and a reduced jitter for the laser pulse emission (less than 10 ns). The receiver photomultiplier follows a quadratic gain versus range law in order to reduce the LIDAR signal dynamic range.

Most of the work concerned with these critical LIDAR components (laser, wavelength control, receiver) will be presented.

1. INTRODUCTION

During the last 15 years, the Thermal and Nuclear Research Centre (CRTN) of ENEL (Italian Electricity Generating Board), in co-operation with CISE and the National Research Council (CNR), has been the leader in Italy in testing, validating and developing optical and acoustic remote sensing techniques for the control of thermal power plants environmental impact.

To this purpose, a mobile UV-DIAL system for SO_2 monitoring has been developed. It makes use of a doubled dye laser pumped by the second harmonic of a Nd-YAG laser with 20 Hz repetition rate. Fully automatic measurements can be made by means of a computer-controlled electronic device.

This system has been used since 1982 during experimental campaigns in different places (industrial and urban sites)[1] to track plumes near power plants, monitor SO_2 over large zones[2] and also to measure gas emissions from soil and fumaroles in volcanic areas[3].

After ten years of activity, it is possibile to assess the real role of this instrument and to define stringent operational requirements in order to utilize it, not only for a research activity but for routine operation. Since 1984, a Central Intelligent Unit (CIU), using remote sensing instrumentation and the chemical-meteo network around the power plant, was implemented to provide in real-time detailed analysis, allowing a sort of feed-forward action on plant operations[4]. Important modifications are required in order to allow automatic measurements, to increase the operational time of the DIAL and to reduce the maintenance costs. The block diagram of the system is shown in Figure 1.

2. LASER

The main requirement for this unit is the need to emit at different wavelengths, covering the UV, Visible and NIR ranges. Although the existing dye lasers allow this wide frequency tuning, nevertheless they require frequent dye replacement when degraded or whenever a different range of wavelengths is required for a new measurement. The use of tunable solid state laser overcomes these troubles, which are the main limitation to a completely automated and maintenance-free LIDAR .

The best choice for the laser source is now the Titanium:Sapphire, tunable in the range 700-1000 nm. To emit in the required frequency ranges and to fulfill the DIAL requirements, it can be practically implemented in different configurations and options:

- with flashlamps or laser pumping;
- with an oscillator/amplifier configuration;
- with an injected amplifier;
- with second and third harmonic generation;
- with frequency mixing using another laser.

The solution we adopted is based on a Nd:YAG pumped Titanium:Sapphire injected regenerative amplifier; it can be tuned from UV to IR by means of frequency mixing (using BBO crystals) with the radiation emitted by a single mode Nd:YAG laser (see Figure 2). The Titanium:Sapphire frequency control is obtained by means of stabilized laser diode injection into the ring amplifier.

The chosen configuration allows the following advantages:

- stable frequency control of the laser by monitoring the temperature and the drive current of the laser diodes;
- narrow band emission (single longitudinal mode) at all wavelenghts;
- possibility to efficiently extend the tuning range into the UV and IR by frequency mixing the relatively low output power of the Titanium:Sapphire with the large output power of a single mode Nd:YAG;
- 10 ns laser pulse duration, which allows good conversion efficiency in second harmonic generation and frequency mixing;
- use of high efficiency and high damage threshold, angle tuned, BBO crystals for frequency conversion (the crystal orientation is computer-controlled).

The Nd:YAG lasers used for frequency mixing and pumping are nearly identical: the former has single longitudinal mode emission obtained by injection of a CW diode pumped Nd:YAG laser, the latter is efficiently doubled by means of a KTP crystal. They are based on a MOPA configuration with a Positive Branch Unstable Resonator (PBUR) and a Gaussian reflectivity profile output coupler mirror (these devices had been formerly designed for spaceborne use in the framework of an ESA contract). Up to now, the Nd:YAG rods are flashlamp pumped; diode pumping would offer a better electrical-to-optical efficiency and a much longer lifetime. On the other hand, the cost of pumping laser diodes is still too high in comparison with the overall cost of the whole system; we expect that they will become competitive in a few years, due to a further costs reduction and increase of reliability and lifetime. Table 1 reports the main specifications of the laser.

3. WAVELENGTH CONTROL

The wavelength control is performed by injection locking the Titanium:Sapphire regenerative ring amplifier with single mode emission of two sets of three laser diodes, relevant to λ_{on} and λ_{off} respectively. Each set is contained in a temperature controlled box (computer adjustable from -35 °C to +35 °C); each laser diode covers a limited wavelength range corresponding to one or more gases. The alternate emission at λ_{on} and λ_{off} is obtained by switching the current on the selected diode. A precise computer control of both temperature and current for each diode allows automatic and repetible laser frequency setting.

However, in order to further increase the DIAL reliability, a set of calibration cell is utilized for SO_2, NO, NO_2, Hg with a real-time measurement of the absorption coefficient.

The measurements of water vapor concentration and atmospheric temperature (using oxigen absorption lines), which require a more critical frequency stability, are to be performed by directly locking the diode emission to the relevant absorption line.

The use of these low cost and reliable devices, with no mechanical parts, offers a better frequency stability and narrow band in comparison with any other practical device.

4. RECEIVER

The design of the receiver has to deal with the high dynamic range of a LIDAR signal, which can be much larger than the dynamic range of the detector or of the transient recorder. This effect is particularly evident when the laser beam penetrates smoke plumes: initially, a sudden increase of the signal due to the high scattering can cause detector saturation. On the contrary, after crossing the plume, the light signal can be smaller than the less significant bit of the transient recorder because of the attenuation due to scattering or gas absorption.

The variability of a LIDAR signal is due to different causes:
- the signal decreases as the inverse of the range square;
- the attenuation due to aerosol extinction or gas absorption;
- the high variability of the aerosol backscattering.

Only the first term is constant and can be exactly compensated: the correction is automatically performed by rapidly changing the gain of the detector (a photomultiplier), so that it is proportional to the square of the time. This function is obtained by means of a fast time modulation of the photomultiplier dynode voltage. The initial low gain (i.e. 10^3) allows the detector to avoid the saturation due to the strong near-field signal, whilst the larger gain (i.e. 10^6) after 20 μs allows maximum sensitivity in the far-field.

The standard transient recorders used up to now have a typical dynamic range of 10^3 (10 bits) at a sampling rate of about 10 MHz. To overcome the problems due to such limited performances we decided to develop a dedicated instrument, able to perform a real-time and automatic gain control in order to digitize with the same accuracy both low and high level LIDAR signals.

The main feature of this transient recorder are the high dynamic range (18 bit, i.e. a dynamic range of 250,000) at a sampling rate of 10 MHz, the reduced jitter with reference to the laser pulse emission (less than 1 ns), a less significant bit of 80 μV and a full scale of 10 V (bipolar).

The use of both the above devices really simplifies DIAL operation and extends the system operational range.

5. CONCLUSIONS

With these advanced characteristics, also the DIAL can be connected to a CIU for an overall assessment of the air quality both in industrial and urban areas Nowadays, some acoustic and electro-acoustic remote sensing devices are already installed in different sites in the Po Valley[5] and their data are collected in real-time at a regional node, giving the possibility to have a overview of most important meteorological situations: the DIAL can cover the needs of local pollution control correlated to small and mesoscale climate changes.

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6. ACKNOWLEDGMENTS

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TABLE 1
LASER SPECIFICATIONS

TITANIUM:SAPPHIRE LASER
configuration : regenerative ring amplifier with Gaussian reflectivity output coupler mirror
pump energy : 400 mJ at 532 nm
output energy : 100 mJ from 750 to 850 nm
> 10 mJ in the UV
bandwidth : single longitudinal mode
repetition rate : 20 Hz

Nd:YAG PUMP LASER
configuration : oscillator + amplifier
resonator type : PBUR with Gaussian reflectivity mirrors
output energy : 600 mJ at 1064 nm
400 mJ at 532 nm
repetition rate : 20 Hz

Nd:YAG LASER FOR FREQUENCY MIXING
configuration : oscillator + amplifier
resonator type : PBUR with Gaussian reflectivity mirrors
output energy : 500 mJ at 1064 nm
bandwidth : single mode
repetition rate : 20 Hz

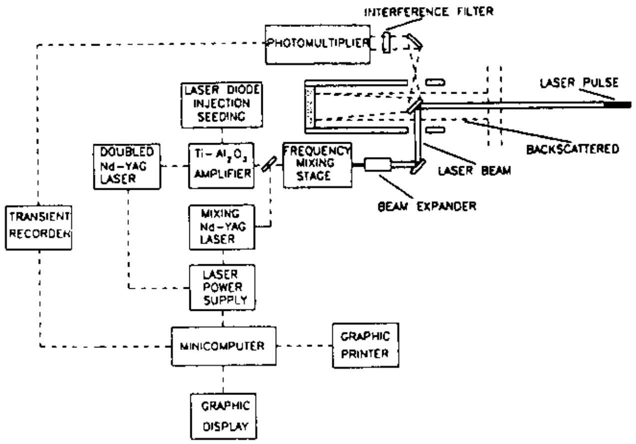

Figure 1. Block diagram of the ENEL DIAL system

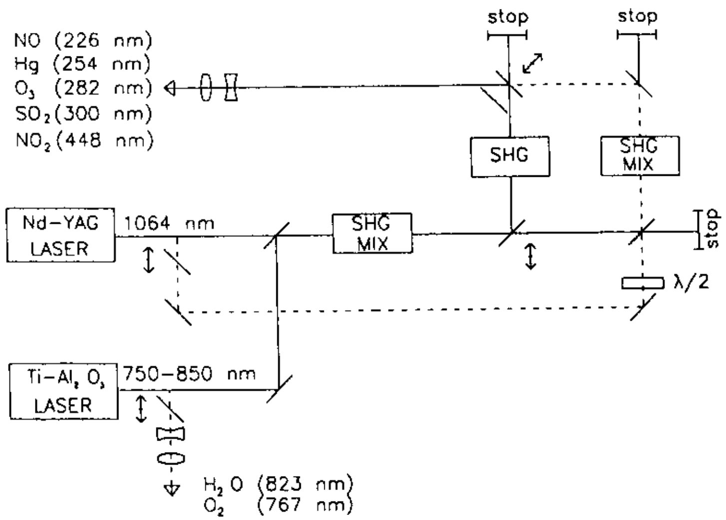

Figure 2. Block diagram of laser sources

Doppler Lidar for Tropospheric Wind Measurements

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ABSTRACT

A ground-based Doppler Wind Lidar for Tropospheric Wind speed measurement is being developed for environmental applications such as pollutants distribution studies and climatology investigations preceding the choice of sites for power plants and factories. This paper gives a short overview on specifications and design concepts of the system and reports the obtained results about the developing and testing of the pulsed CO_2 TEA laser source. The Lidar system is scheduled to be ready for laboratory measurement next year and for field use within a couple of years.

1. INTRODUCTION

The increasing reliability of conventional instruments and the development of remote sensing devices to measure meteorological parameters in the Planetary Boundary Layer (PBL), coupled with advances in numerical modelling methods, has led to great improvements in our understanding of this region of the atmosphere.

The analysis of the problems, arising during the power plant operations connected to environment protection, emphasized the possibilities of remote sensing measurements. Because of this need, to improve the knowledge of the PBL and to better the forecasts of ground impact, ENEL/CRTN was induced to promote studies and build up remote sensing systems.

The operation of large scale power plants (rated 1000 - 2000 MWE) supplied by oil and/or fossil coal raises some problems concerning the environment and its pollution. From this point of view, the most important phenomenon is the air and soil pollution due to fall-out of smokes and particulates with a concentration level higher than the one allowed by current laws and/or local regulations. This situation arises when some adverse meteorological conditions, like the well known phenomenon called "thermal inversion", hinder the long range dispersion capability of the site.

Ground measurements do not allow to distinguish the contribution of power plants among other sources of pollution (industrial and urban) located in the same area, and this fact may cause some useless but expensive actions.

It has been demonstrated the necessity of vertical profiles (wind and temperature fields), avoiding, for example, the installation of "expensive" meteorological towers and with the aim to increase the maximum measurement height of traditional instrumentation. The remote sensing "construction" of these profiles gives a strong improvement in evaluating the "effective" plume pattern due to wind effects and presence of thermal inversion.

For all these reasons, a Doppler LIDAR for tropospheric wind measurements was recognized as a key instrument to be designed and at present it is in advanced development.

2. SYSTEM DESIGN OVERVIEW

2.1. System design concepts

A preliminary system study started two years ago to define the required performances for an effective use of a ground based Wind Lidar for environmental application and to evaluate the technological state of the art as well as the next future advances which were most likely to affect the system. The results of this work were first the listing of some guidelines about the required performances (Table 1) and second the choice of a CO_2 Doppler instrument as the most promising way to obtain significative results in the short period.

The main technical aspects which led us to this option have been related to atmospheric propagation with turbulence and low visibility, laser source availability and reliability, eye safety, electronics and optics feasibility.

The eye safety requirement implies the use of an ultraviolet or an infrared wavelength, but the choice of this latter one is forced by jointly asking for good atmospheric propagation with haze and smog, due to the high value of the beam extinction coefficient for ultraviolet radiation which is typical of these environmental conditions. Turbulence related phenomena, like beam wandering and scintillation, also have a better trade-off on system performances when evaluated at infrared wavelengths. On the other hand, the typical particulate loading in the aerosol of the lower troposphere above industrial areas is likely to give good lidar echoes in this spectral region.

The above mentioned considerations about wavelength dependent propagation effects still applies for the choice among infrared wavelengths, thus pushing toward longer ones.

Solid state mid-infrared laser sources are being developed quickly, nevertheless the more established CO_2 technology looks more reliable to have a system available in the short term, even considering the work still required to get a CO_2 laser which is suitable for the Wind Lidar application.

The choice of the longer wavelength is also suggested by other considerations. First, the use on an heterodyne receiver is required to get good electrical noise performances in the infrared, but the demanded alignment accuracy and stability for efficient heterodyning are more easily obtainable when the wavelength is large. The heterodyne detection gives also an easy way to measure the doppler shift, but the beating frequency corresponding to the same wind velocity increases inversely with wavelength and thus less stringent requirements for processing electronics have to be fulfilled when it is longer.

2.2. Preliminary system design

The work carried out up to now has been mainly related to the laser source prototype development and testing, which is reported in the next section. In the meanwhile a preliminary project of the whole system has been prepared, whose block diagram is shown as Figure 1. It is now in progress the detailed design of the whole instrument, which is scheduled to be operative from a laboratory site next year and ready for field use within a couple of years.

The conceptual scheme of a coherent Doppler Wind Lidar is well known[1,2], but our aim is to build it exploiting present technology to get maximum reliability and technical longevity. So, the design of the system takes in account the need for a user friendly instrument as learnt by authors' companies

during ten years experience in developing and operating different Lidars for pollution monitoring[3,4] and other electro-optical instruments, as well as other wind remote sensing systems[5].

All the more relevant instrument building blocks have computer interfaces to allow an easier check of their function and an on-line computer aided diagnosis of hardware problems; as well as to get a fully computer controlled measurement procedure.

The pulsed laser source is frequency stabilized by continuous wave (CW) injection using an automatic control loop to track resonator length variations. The heterodyne local oscillator is frequency locked to the injection laser by means of a digital Phase Locked Loop (PLL) to settle the beat frequency of the two CW lasers, which is obtained by mixing on a room temperature Mercury Cadmium Telluride (MCT) detector some power spilt from them.

Taking advantage of the fast developments in high speed electronics for data acquisition and processing the lidar return will be digitized at an early stage, in order to avoid problems with the analog complex demodulation to baseband before sampling. Using heterodyne intermediate frequency in the order of some tens of Mhz there is no strong limitation in availability of a suitable 8 or 10 bits digitizer using hybrid or monolithic ADC, while the heavy duty to extract the needed information from the resulting high data volume can be handled on-line by a software programmed parallel processor. This choice gives also maximum flexibility in using different algorithms to compute wind parameters estimators and to perform scattering calculations. Data displaying and recording will be performed on-line by the main computer with choice among different measurement procedures like line-of-sight velocity versus time plot, raster scanning or Velocity Azimuth Display (VAD) three dimensional wind measure.

3. LASER SOURCE DESIGN AND TEST

3.1 Laser source requirements and design guidelines

The laser sub-system is known to be a key apparatus of a Doppler Lidar, being its characteristics strongly related to the whole system performances, first of all wind speed measurement accuracy and spatial resolution. The main laser requirements for this application are summarized in Table 2 and are not fulfilled by most of the commercially available units. Being CISE an experienced designer of laser sources for electro-optical measurement system, the first development stage of our Wind Lidar project has been devoted to the study of the CO_2 pulsed laser considering both the discharge channel requirements as well as the resonator configuration options.

The main guidelines for this work have been the reliable achievement of an output pulse with a suitable output energy level and good temporal and spectral properties.

The first choice we made is the use for the active medium pumping of a self-sustained discharge instead of an electron beam sustained one, because for our application the first is cheaper, being easier to be designed and manufactured, smaller and easier to be operated and maintained.

To obtain an high output energy, a relatively long pulse and a low pulse frequency chirp using a self-sustained discharge it is necessary to find the right compromise among discharge cross-section and volume, gas mixture composition and pressure, excitation field and resonator losses. In spite of the comprehensive literature about CO_2 laser design[6], the optimization of this laser for a Doppler Wind Lidar is not trivial and requires an extensive research and development program moving from theoretical considerations which need experimental validation.

3.2. Discharge channel design and tests

The discharge channel is the most peculiar element of the Doppler Lidar pulsed laser source and its characteristics strongly influence the overall system performances. The adopted configuration is the Transversely Excited Atmospheric (TEA) amplifier with a rather fast transverse gas flow to assure mixture refreshing between pulses to avoid short term effects due to mixture overheating and discharge induced gas decomposition. The long term degradation of the active medium due to CO_2 dissociation is reduced using a solid catalyst inside the gas flow loop, while an heat exchanger provides to stabilize the active medium mean temperature.

Literature data survey and previous experience led to define an active volume of 4 by 4 cm^2 cross section and 40 cm length to fulfil the pulse energy requirement. These values came out from a compromise among the needed volume for demanded energy, a minimum length to get a reasonable small signal gain and the need to use a large cross section to minimize Laser Induced Perturbation (LIMP) effects[7,8]. As known, the changes in active medium refractive index due to the laser action itself (LIMP) causes a frequency change in the laser output which badly affect its spectral properties, being this frequency chirping a modulation of the output carrier. The theory shows that this effect goes inversely with the square of the medium cross section.

Another frequency modulation effect which needs to be considered is the plasma chirp[9], which is related to the refractive index variation due to changes in free electron concentration in the active medium while the discharge is ending. To reduce this effect it is necessary to shorten the excitation current pulse to avoid any significant overlapping with the optical output, i.e. the discharge has to be shorter than the build-up time of the laser pulse.

We have tested different high voltage circuits, with and without capacitive voltage doublers and different saturable pulse transformers, looking to the laser efficiency using a stable multimode resonator. Eventually we decided to use the simplest configuration employing a single capacitor, a thyratron switch and a saturable pulse transformer to give an extra voltage to start the discharge. To assure a uniform glow discharge, we chose a corona pre-ionization scheme[10] of the active medium, using two alumina tubes with a conductive rod inside placed near the high voltage electrode and with an optimized resistive and capacitive connection to ground. A typical discharge current pulse shape of our device is shown in Figure 2.

To avoid pulse degradation related to electrodes' shock waves[7] which propagates with sound velocity after the beginning of the discharge, the actual size of the active volume has been fixed at 4.4 by 4.4 cm^2 to get some margin while designing for a 4 cm diameter laser mode.

The discharge channel performances have been tested using different gas mixtures at different pressures, obtaining optimization plots like that shown in Figure 3.

Some problems with discharge uniformity and with high voltage sparks within the gas chamber emerged during pumping unit and resonators tests, the latter being now solved with better internal lay-out and insulation. The present electrodes have a modified Chang profile and theoretically assure a very high field smoothness, but some problem could be related to mechanical tolerances in electrodes' mounting. Small signal gain tests are in progress to get more information about pumping spatial distribution.

3.3. Laser resonator design and tests

The laser resonator design for a CO_2 Doppler Lidar has to fulfil strict requirements about mode purity and energy extraction efficiency. We chose to make extensive tests using Positive Branch Unstable Resonators (PBUR) and Variable Reflectivity Mirrors (VRM) as output couplers in order to achieve high mode diameter, Single Transverse Mode (STM) operation and a compact laser assembly. The Single Line working of the source has to be assured by a diffraction grating to retain line tuning capability, while Single Longitudinal Mode (SLM) can be controlled by CW injection with a proper tuning of the resonator length on the selected wavelength.

Three different resonators have been tested up to now (Table 3), two with a Gaussian Reflectivity[11] (GM) and one with a Super-Gaussian Reflectivity (SGM) profile[12], looking to output energy, STM, near and far field properties. The discharge channel has been closed by two Brewster angle windows to minimize losses and to assure linear polarization and all the tests have been carried out on the 10P20 line at 10.6 μm. The pulse energy results are very similar for the three cases with a mean value of 1 J obtained using 3:2:1 $He:N_2:CO_2$ mixture at a pressure of 0.4 atm, trapezoidal current pulse shape about 0.8 μs long and 2 kA high, 25 kV excitation and 31 J total pumping energy, thus with an electrical to optical efficiency greater than 3 %. Further testing is in progress to improve energy output working at a little bit higher pressure and voltage, having now solved the above referenced sparking problems inside the pumping unit.

SLM operation has been obtained by CW injection through the grating zero order with a cavity CW power level in the tens of mW range. Three main effects are related to injection as shown in Figure 4: pulse is SLM, its build-up time is shorter and the gain switching spike is lower. The strong disturbances before laser pulse start are related to the electrical noise produced by the discharge. The small residual modulation on the pulse tail is also due to some electrical noise and not to mode beatings, because it is present even when the beam is blocked.

4. CONCLUSIONS

Even though a great effort is presently turned towards the reduction of the emissions, environment protection is required nowadays and probably also in the next future, as well fundamental demands as:

- greater knowledge of the phenomena which take place in the lower atmosphere, through the development of research tools;
- possibility of intervention on the power plants during critical meteorological conditions and singling out the impact areas in cases of accident discharges
- necessity to classify the conditions within PBL on a climatological basis.

Consequently, it is expected that new meteorological networks will use, on an ever increasing scale, information of wind and temperature profiles of the atmosphere obtained by means of remote sensing devices. The Wind Doppler LIDAR, coupled with other remote sensing systems such as the Doppler SODAR and the RASS able to give a better resolution in the layers closer to the surface, will give a useful contribution for the solution of these problems.

5. ACKNOWLEDGMENTS

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Table 1. Main requirements for a ground based Tropospheric Doppler Wind Lidar for environmental applications

Minimum operating range	≥ 20 km
Minimum operating altitude	≥ 5 km
Required spatial resolution	≤ 0.5 km
Wind speed dynamic range	± 50 $m\ s^{-1}$
Wind speed measure accuracy	± 1 $m\ s^{-1}$
Pulse repetition rate	≥ 10 Hz
Eye safety class	3A max
Operative requirements	- Real time data processing, displaying and recording - Working with low visibility - Extensive computer control

Table 2. Main requirements for the CO_2 pulsed laser source subsystem

Energy output	≥ 1 J
Pulse length	≥ 3 μs
Mode purity	SLM & STM
Pulse frequency chirp	≈ 200 kHz
Electro-optical efficiency	> 3 %
Pulse repetition rate	≥ 10 Hz
Active medium lifetime	≈ weeks, sealed off with solid catalyst
Heterodyne offset	automatic control

Table 3. Summary of resonators' tests

R_1 [m]	R_2 [m]	w_m [mm]	w_i [mm]	n	M	N_{eq}	L [m]	ρ_0	E_{out} [J]
-15	19	22.8	20	2	1.26	3.27	2	0.7	1.1
-15	19	15.2	20	10	1.26	1.45	2	0.7	1.1
- 6	8	22.8	20	2	1.33	8.17	1	0.8	0.9

Output coupler reflectivity profile:

$$R(r) = \rho_0 \, e^{-2\left(\frac{r}{w_m}\right)^n}$$

Intensity profile:

$$I(r) = I_0 \, e^{-2\left(\frac{r}{w_i}\right)^n}$$

R_1 : output coupler radius of curvature (RoC)
R_2 : total reflector RoC
w_m : mirror soft radius
w_i : cavity intensity soft radius
n : reflectivity order
M : resonator magnification
N_{eq} : resonator equivalent Fresnel number
L : resonator length
ρ_0 : output coupler peak reflectivity
E_{out} : output energy

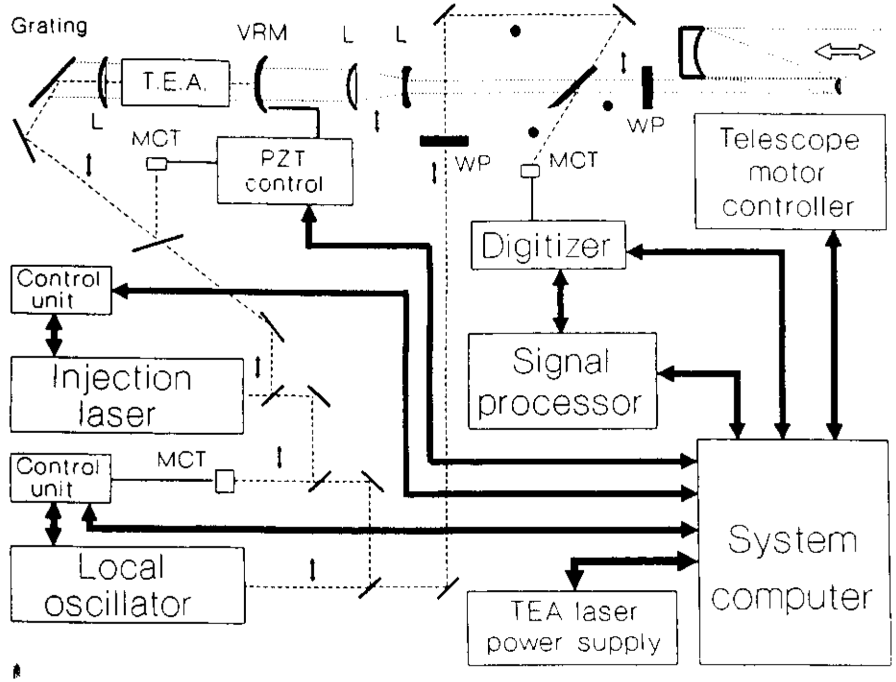

Figure 1. Block diagram of the Tropospheric Doppler Wind Lidar, showing main optical paths and electronics connections.

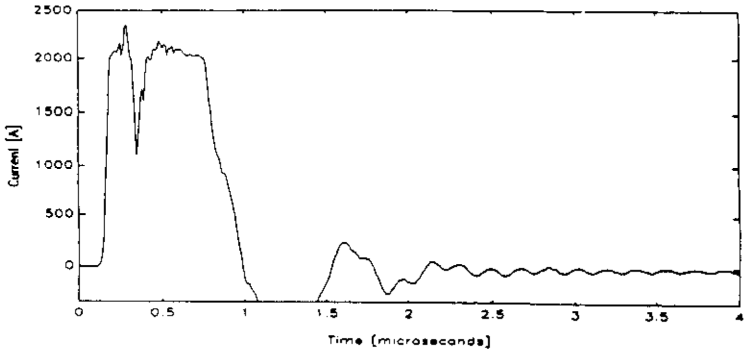

Figure 2. Measured waveform of TEA discharge current.

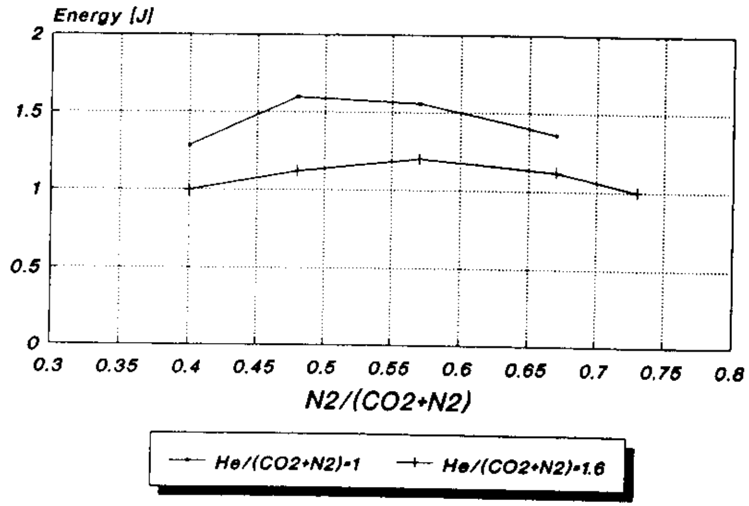

Figure 3. Experimental dependence of output energy on gas mixture composition at P=0.25 atm.

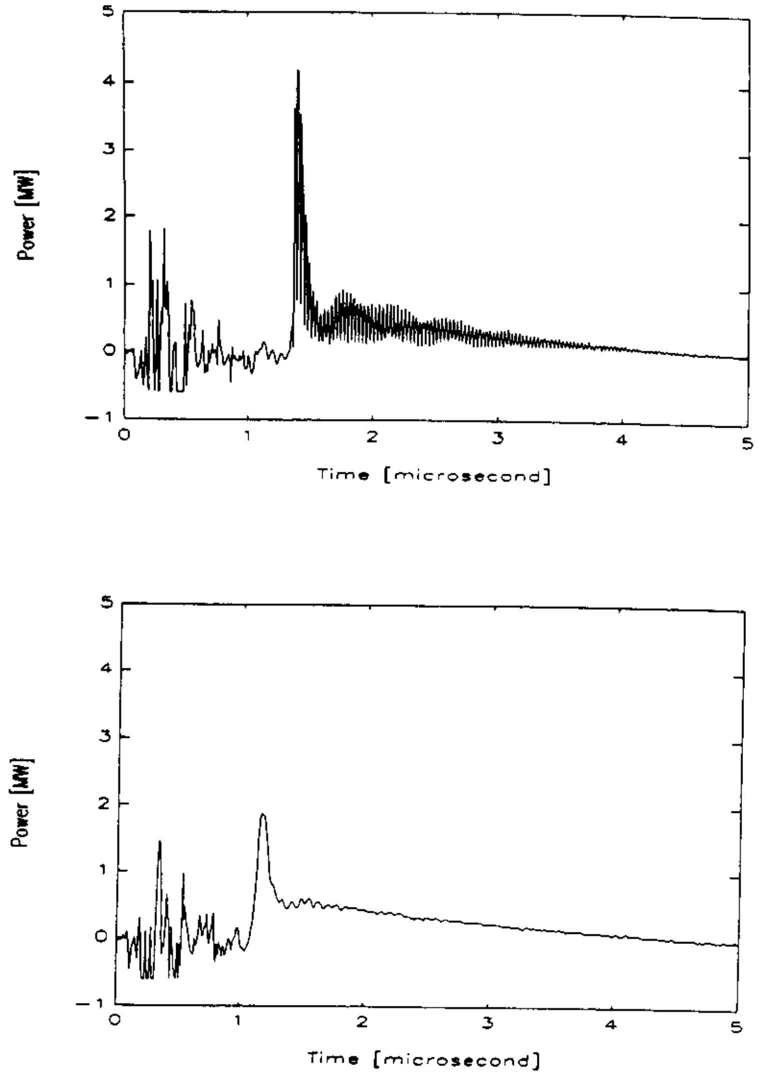

Figure 4. Experimental laser output pulses without (top) and with (bottom) CW injection.