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Laser Remote Sensing, a 20 year Perspective

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Introduction

Next year the 20[th] International Laser Radar Conference will be held. This year saw the meeting of the 10[th] Conference on Coherent Laser Radar. From the beginning, the field of laser remote sensing has been international in its reach and global in its technical scope.

It is not possible in this brief review to cover all aspects and progress of laser sensing. Therefore, I will highlight key concepts and progress in technical achievements that have taken laser radar from its beginnings to the present. I will attempt to present a view of where the field may go in the near future.

Edwin Land admonished us "don't undertake a project unless it is manifestly important and nearly impossible." Global earth observations and in particular global wind sensing fits that description. Why has progress been so slow in meeting the nearly impossible task of achieving global wind sensing? What are possible future approaches to meet the transmitter-receiver requirements at a cost and performance that will allow satellite based measurements? Seeking an answer to these questions has drawn my research group back into remote sensing after more than one decade absence.

Early Remote Sensing progress

Prior to the invention of the tunable laser sources based on laser dyes and optical parametric oscillators, remote sensing experiments using lasers probed the turbidity of the atmosphere in analogy with radio wave detection and ranging. The acronym LIDAR for Light (Laser) Detection and Ranging was adopted to describe the activity. Early reviews of LIDAR progress was presented by Inaba, Kobayshi and Ichimura [1]. Inaba and Kobayashi discussed the detection of molecules by Raman scattering [2] and presented early experimental results [3].

The availability of the tunable laser source opened additional laser remote sensing possibilities for atmospheric probing and molecular detection. Kildal and Byer published a review paper in 1971 [4] on the comparison of laser methods for remote detection of atmospheric pollutants. The paper discussed and compared the sensitivity of Raman and resonance fluorescence detection methods. Interestingly, differential absorption detection, first discussed by Schotland in 1966, [5] was not considered in detail until two years later in 1972 [6] and in 1973 [7]. The differential absorption method (DIAL) provides depth resolution by laser backscatter from distributed particles in the atmosphere and sensitivity by probing absorption transitions of molecules.

A summary and overview of remote sensing methods, including a discussion of signal to noise and sensitivity was given by Byer in 1975[8]. Both direct detection and heterodyne detection approaches introduced by Menzies [9] were treated.

Tunable Lasers in Remote Sensing

The need for tunable laser sources was evident from the beginning. However, in addition to appropriate spectral coverage in the infrared for the detection of molecules, there was a need for high peak power, narrow-linewidth transmitters. These requirements were slow in being met and led to a decade of demonstration remote sensing experiments with progress in the tunable laser sources and in the system detection and data processing.

The lead salt laser diodes, cryogenically cooled, were used early in double-ended absorption measurements by Hinkley [10]. Of course, line tunable CO_2 lasers were also used for sensing [11].

Differential absorption measurements using a parametric tunable laser were demonstrated by Henningsen et al who detected CO at a range of 107m at 2.3μm wavelength in the near infrared [12].

Measurements of NO_2 in the violet spectral region using dye lasers were conducted by Igarshi [13], Rothe et al [14], and by Grant et al [15]. The combination of sensitive photomultiplier detectors and mJ pulse energy dye lasers allowed two dimensional mapping of pollutants above a factory.

The Quanta Ray Nd:YAG and $LiNbO_3$ OPO

The weak backscatter return from particles in the atmosphere coupled with the need for tunable infrared for molecular detection led to the application of the unstable resonator concept invented by Siegman to the Nd:YAG laser oscillator amplifier [16]. The resulting Nd:YAG laser that generated 1J per pulse at 10Hz was commercialized by Quanta Ray in 1976 and later sold by Spectra Physics. More that one thousand lasers have been sold many of which have been used for remote sensing applications.

The Nd:YAG laser pumped a $LiNbO_3$ optical parametric oscillator (OPO) [17,18] followed by an optical parametric amplifier [19] to generate tunable output from 1.4 to 4.3μm at up to 100mJ per pulse at 10Hz repetition rate. This source was transmitted into the atmosphere across the Bay Area from Stanford University campus. The transceiver used a cro-cooled IR detector at the focus of a 16 inch telescope.

The computer controlled tunable source allowed remote sensing measurements of SO_2, and CH_4 [20]. An improved 0.1cm^{-1} linewidth $LiNbO_3$ OPO later allowed the simultaneous measurement of atmospheric temperature (0.1C) and humidity (1% accuracy) at 1.77μm [21].

The challenge to improve sensitivity of acquired data over an area with two dimension mapping suggested alternative remote sensing approaches such as fiber delivered and detected signals proposed by Inaba and two dimensional mapping via optical tomography [22].

However, as the decade of the 1980s began, the question of remote sensing from space platforms became increasingly of interest and with it the possibility of global remote sensing of wind [23]. This in turn raised the challenge of sub-megahertz linewidth solid-state lasers and the potential for demonstrating lasers with greater than 10% electrical efficiency, 100W average power, 10J per pulse at 10Hz, and operation at an eyesafe wavelength. The challenge of global remote sensing [24] led directly to a research program at Stanford on laser diode pumped solid state lasers with high coherence at high average output power.

Laser Diode Pumped Solid State Lasers

The appearance of 1W power laser diode arrays in 1978 [25] suggested the possibility of Laser Diode (LD) pumped solid state lasers that could operate at high average power and efficiency.

The first LD pumped Nd:YAG laser operated at Stanford in 1984 with 2mW of output power at 25% slope efficiency [26]. However, progress was rapid with LD array power increasing from 1W to 120W in one decade [27] at operating efficiencies in excess of 50%. The progress in the early years of LD pumped solid state lasers was reviewed by Byer in 1988 [28]. Of particular interest was the combination of the LD pump sources with the potential for power scaling using the slab-geometry laser concept [29].

Further, the high brightness LD pumping allowed new laser systems to be operated including the three level lasers such at 946nm Nd:YAG [30], the 2.1μm Ho:YAG [31], and the Yb:YAG laser introduced by Fan [32]. For the first time it appeared possible to develop an eyesafe laser that might meet the requirements for global wind sensing.

Solid State Laser Coherent Wind Sensing

The potential for an all-solid state laser for coherent Doppler wind sensing was evaluated by Kane et al in 1984 [33]. The key system requirements were a highly coherent local oscillator, an amplifier for power scaling, and a heterodyne receiver system. Kane set out to invent each of these sub-systems and succeeded first with the NonPlanar Ring Oscillator, or NPRO, which is a monolithic Nd:YAG single frequency ring oscillator [34]. This single invention led solid state laser linewidths to decrease from MHz to less than 1 Hz in less than four years. The slab laser amplifier [35] and the fiber optic based heterodyne receiver formed the technical basis for the first coherent wind sensing experiment in a solid state laser system using Nd:YAG [36].

Considerable research and development aimed at developing an eyesafe laser transmitter followed the early demonstration of LD pumped Ho:YAG. Recent progress is summarized by the group from Coherent Technologies [37] with respect to the proposed NASA SPARCLE mission to conduct a technical readiness- demonstration of coherent laser wind sensing from the Space Shuttle. The Tm:YAG and related two micron lasers have been used in a number of coherent wind sensing experiments from the ground and from aircraft. The challenge is to develop a 2J laser transmitter with pulse width of 1μsec at 10 Hz repetition rate for heterodyne Doppler detection of wind from a space platform. Excited State Absorption (ESA) processes in the Ho:Tm:YLF laser system must be overcome to increase the extracted pulse energy from the current values near 100mJ to the 2J level.

However, progress has been made on the development of narrow bandwidth, single mode local oscillators that are tunable over the GHz range. Hale et el [38] report on METEOR local oscillators at 2μm and at the Yb:YAG 1.03μm wavelength with output power levels in excess of 50mW. Taira et al [39} has described an Yb:YAG single frequency oscillator with an extended tuning range of 8.2THz with greater than 1W of output power.

Progress in power scaling of LD pumped Yb:YAG lasers has also been promising. Early work by Giesen et al [40] has led to the thin disk Yb:YAG laser concept that has operated at better than 50% optical to optical efficiency and has now reached 1kW of cw output power. Meanwhile, Brusselbach et al [41] have operated an LD pumped Yb:YAG rod master oscillator power amplifier with more than 1kW of output power.

Yb:YAG is a three level laser that must be pumped by high brightness LDs. The pump band at 940nm is broad and easily pumped by available laser diodes. However, the three-level Yb:YAG does favor operation below room temperature unless the laser is pumped at very high intensities. Yb:YAG does not suffer from Excited State Absorption (ESA) or from up-conversion loss processes. Thus it is an almost ideal laser especially for cw operation with a potential for an electrical efficiency of greater than 20%.

The upper level storage time for Yb:YAG is 950μsec compared to only 240μsec for Nd:YAG. The low gain cross section of Yb:YAG, 2.1×10^{-20}, allows for energy storage without parasitic oscillation. The drawback of Yb:YAG is the corresponding high saturation fluence of 9.2Jcm^{-2} compared to Nd:YAG saturation fluence of 0.67Jcm^{-2}. This is important because a Q-switched laser operates at twice the saturation fluence at three times above threshold where efficient energy extraction occurs. Thus Nd:YAG can operate under Q-switched conditions and yield greater than 1J per pulse at 1.2 Jcm^{-2} which is below the damage threshold for 10nsec Q-switched pulses. This is not the case for Yb:YAG where Q-switched operation would damage the laser gain medium at the 18Jcm^{-2} output fluence level.

Proposed Laser Transmitter for Global Wind Sensing

Given the potential for Yb:YAG to operate at high average power levels and at electrical efficiencies of greater than 20%, the question faced is how to take advantage of the 1.03μm wavelength laser oscillator and still meet all of the requirements for global wind sensing. Of these requirements, the generation of 2J of pulse energy at 10 Hz repetition rate at an eyesafe wavelength (λ>1.4 μm) is very challenging.

We propose to meet this challenge by taking advantage of two recent technological breakthroughs: the edge-pumped slab laser concept with the potential for power scaling at high efficiency, and quasi-phasematched nonlinear optical interactions based on recently developed nonlinear crystals such as periodically poled $LiNbO_3$ (PPLN).

The key idea is to extract 4J of energy from an LD pumped Yb:YAG amplifier in a 1μsec pulse and to convert the 4J of 1.03μm output to the 1.5μm wavelength using the high gain periodically poled LiNbO3 nonlinear material. This combination should yield 2J of output energy at 1.5μm for 8J of LD pump energy. The parametric amplifier can be tuned to 1.5μm to take advantage of coherent local oscillators developed for laser communications or it can be tuned to 2μm to take advantage of the existing Tm:YAG local oscillators.

The LD edge-pumped Nd:YAG slab laser has been demonstrated by Tulloch et al [42] at the 120W average power level at 55% slope efficiency. This laser is pumped by fiber coupled LDs that allows the laser head to be located remotely from the power supplies and the LDs. The laser head is conduction cooled, very compact and reliable. Work is underway to pumped Yb:YAG using the same edge-pumped geometry. Modelling studies show that average power levels in excess of 10 kW are feasible using the edge-pumped conduction cooled design [43].

The key technical issue for the laser transmitter is the extraction of 4J of energy without inducing optical damage. This is accomplished by extracting the energy at the 1μsec pulse length where the damage fluence is in excess of $100Jcm^{-2}$ because of the well known increase of optical damage fluence with the square root of the pulse length. The Yb:YAG amplifer slab dimensions for generating 4J per pulse output energy are 2.2mm thick, 5.6mm wide, and 13.5mm long. This very small slab operates well below the thermal fracture limit which is in excess of 10kW average power for a slab of these dimensions.

The second key technical issue is efficient frequency conversion to $1.5\mu m$. This is now possible because of the progress in nonlinear optical materials in particular periodically poled $LiNbO_3$ [44]. The increase in parametric gain by a factor of 20 in PPLN relative to bulk crystals allows master-oscillator, parametric power amplifiers to be constructed based on the earlier work of Baumgartner [19].

Experimental work has been initiated to confirm the expected performance of the edge-pumped Yb:YAG slab laser. Work has also begun to demonstrate efficient parametric frequency conversion to the eyesafe $1.5\mu m$ wavelength at the $1\mu sec$ pulse duration. A description of this approach has been presently recently by A. K. Sridharan et al [45].

Future Developments

The challenge of global wind sensing is manifestly important and has proven over that past twenty years to be nearly impossible.

The recent progress in laser diode output power and improved reliability at greater than 50% electrical efficiency may open the door to meeting the challenge. Based on fifteen years of commercial progress, the cost of Laser Diodes is decreasing at 30% per year and is projected to be $1 per Watt by 2005. Meanwhile, the operating lifetimes have been extended to tens of thousand of hours. With increasing power per device and high brightness fiber delivery, commercial laser diodes will enable high pulse energy solid state lasers.

At the same time, the development of reliable solid-state laser local-oscillators and power amplifiers has opened the way to meet the demanding transmitter requirements for global remote sensing. What remains to be demonstrated is the efficient parametric conversion to eyesafe wavelengths using the recently developed PPLN nonlinear crystals. Perhaps after twenty years of continued research and development, the members of the global remote sensing community finally will meet the nearly impossible challenge of global remote sensing

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