349-nm Source for Direct Detection Measurement of Winds

Yelena Isyanova and Peter F. Moulton
Q-Peak Inc.
135 South Rd.,
Bedford, MA 01730

***Abstract* – We report on work carried out under a NASA SBIR Program, whose objective was to develop an efficient 349-nm source suitable for Doppler Lidar direct detection measurement of winds. The essential part of the program was to design a stable, single-frequency, 1047-nm Master Oscillator-Power Amplifier (MOPA) laser system and nonlinear devices for conversion the near-IR beam into the UV. In the course of the program Q-Peak developed, designed, and built a packaged, ruggedized, water-cooled prototype laser system with the following major characteristics: pulse energy - 4 mJ at 349 nm; repetition rate - 1 kHz; beam quality - M^2 <1.2; single-frequency operation; wall-plug efficiency - 3%.**

I. INTRODUCTION

The continued need to reduce the weight and improve the performance and efficiency of airborne and spaceborne lidar systems requires innovations in laser devices. One such system is a Doppler lidar for wind profiling, which provides altitude-resolved wind-velocity measurements.. These measurements are especially important in providing data for meteorological forecasting and overall global circulation models. Wind profiler data are also critical in identifying possible dangerous weather conditions for aviation. Wind profiling lidars can use either coherent detection followed by electronic signal processing or the “edge-filter” or “double-edge” direct-detection technique to determine Doppler frequency shifts of signals backscattered from aerosols in the planetary boundary layer. UV-wavelength, direct-detection lidars using molecular scattering can provide accurate global wind measurement, even in those areas of the atmosphere where the aerosol density is too low to yield good infrared backscatter signal.

There are two missions currently being contemplated for direct-detection wind-sensing lidars, airborne and spaceborne. Our development was directed towards satisfying the airborne system requirements for a UV source, which are summarized in Table I below. We developed an efficient, single-frequency, diffraction-limited, 349-nm laser source for use as a Doppler lidar transmitter for direct-detection measurements of winds. [*] The laser source is based on a quasi-cw diode-pumped, ring-cavity, near-diffraction-limited, electro-optically Q-switched 1047-nm Nd:YLF laser. The ring cavity is injection-seeded and frequency-locked using a single-frequency, cw diode-pumped laser and control electronics based on the pulse build-up-time reduction technique. The system feature consecutive doubling and tripling to convert the near-IR output of the Q-switched Nd:YLF laser into the UV.

TABLE I
AIRBORNE LASER TECHNOLOGY REQUIREMENTS

Parameter	Requirement
Output wavelength(s) (nm)	355
Output pulse energy (1064 nm)	30 mJ
Output pulse energy (355 nm)	10 mJ
Repetition rate	1-2 kHz
Pulsewidth (ns)	10-20
Spectral linewidth (FWHM)	< 300 MHz at 355 nm < 40 MHz at 1064 nm
Beam quality (M^2)	< 1.2
Wallplug efficiency to IR	3-5 %
Lifetime (shots)	3 x 10^9

Our design approach allows us to scale the UV output to higher energies. A prototype system producing single-frequency, 4-mJ pulses at a 1-kHz repetition-rate at 349 nm was built and delivered to NASA GSFC at the end of the Phase II NASA SBIR program (in 2004).

II. SYSTEM DESCRIPTION AND PERFORMANCE

The technical approach we chose was to use (1) Nd:YLF as the laser material, which has a number of advantages listed below; (2) a scalable master oscillator – power amplifier (MOPA) configuration; (3) our multipass side-pumped laser design for the amplifiers that provides high efficiency and high beam quality. This design will be enhanced to meet the pump-laser energy requirements.

Nd:YLF is high-gain laser material that is particularly well suited for amplifying pulses with energies above a few mJ. An important advantage of Nd:YLF over alternative gain media (including Nd:YVO_4 or Nd:YAG) is the potential, at low pulse rates, to generate higher pulse energies at a given pump power. This is a direct consequence of the longer upper-state lifetime (~480 μs; ~5x that of Nd:YVO_4 and ~2x that of Nd:YAG). Compared to Nd:YAG, the longer upper-state lifetime reduces by half the number of diode pump lasers required to produce a given energy, and that has a

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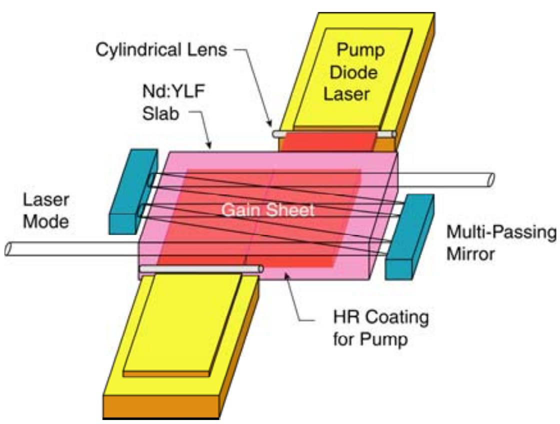
significant impact on system size, complexity and ultimate cost.

Also, since YLF is a birefringent material, stress induced birefringence (which can cause deleterious depolarization effects) is a second-order effect, unlike YAG where it is a serious concern. This allows the generation of linearly polarized light without pump-induced losses in the laser material. Nd:YLF has also significantly lower thermal lensing compared to Nd:YAG and other oxide host crystals. This simplifies laser designs in which high beam quality is desired and reduces changes in beam properties (size and pointing) with changes in pump power. One of the disadvantages of Nd:YLF is that its mechanical strength is lower than that of Nd:YAG, and thus, ultimately, the material cannot produce as much average power per unit volume. We have been developing high-power, diode-pumped, 1047-nm Nd:YLF lasers since 1994, and find that the advantages of Nd:YLF outweigh the disadvantages. Our MPS design, shown schematically in Figure 1, takes care to minimize any thermal stresses in the host crystal through the use of finite-element analysis of the thermal gradients and the resultant stresses. Our thin, rectangular Nd:YLF slab, conduction cooled on the top and bottom surfaces, has consistently produced high powers without mechanical damage.

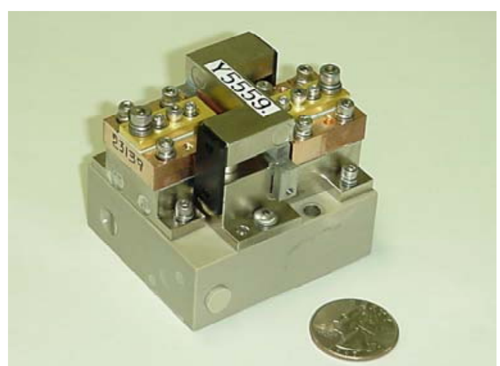
The starting point of our MPS design is a multi-pass gain element, with external high reflectors. The laser crystal is transversely pumped by a pair of 1-cm long, 20-40-W CW or QCW diode-laser bars. The diode-laser bars are coupled to the gain element through a single cylindrical lens attached directly to each bar package. These lenses minimize the divergence of the pump light in the plane perpendicular to the linear emitter. The pump geometry is a central feature of the design in that it yields a laser that is relatively insensitive to the alignment, spectra, and temperatures of the diode-laser bars. This is in contrast to some of the complex, multi-element imaging schemes that have been developed for similar purposes, and benefits both the reliability and cost of the technology.

Power is extracted efficiently and high gain per pass is obtained by passing a TEM_{00} laser beam a few times though the gain sheet that is produced in the slab, with no deterioration of the spatial characteristics of the beam. The Nd:YLF slab geometry developed at Q-Peak is unique in providing high gain while avoiding many of the difficulties encountered in end-pumping laser media (such as achieving good overlap between the pump and laser mode and thermal aberration of end faces).

As was mentioned above, we use a Master Oscillator-Power Amplifier (MOPA) design and nonlinear devices. Figure 2 shows a schematic layout of our MOPA and nonlinear systems. For our oscillator, we chose to use a four-mirror ("rectangular") ring resonator using spherical and flat mirrors in combination with cylindrical lenses. The design goal was to shape the laser mode in the vertical and horizontal planes to provide good overlap of the laser mode with the gain sheet produced in the gain module to ensure TEM_{00} mode operation. We used two high-reflection (HR) 40-cm-radius spherical mirrors and two flat mirrors, one of which was HR-coated and another was an output coupler of 70-% reflection. Two -14-cm focal length cylindrical lenses were placed at the distance approximately two times the focal length of the cylindrical lens. The angle of incidence on each of the mirrors was 45 degrees.



Multi-Pass Slab (MPS)
US Patent 5,774,489
40% optical-optical efficiency



"Gain Module"

Fig. 1. The Nd:YLF MPS design and picture of the Gain Module. Efficient operation in a side-pumped configuration is achieved by multi-passing the laser mode through the Nd:YLF slab.

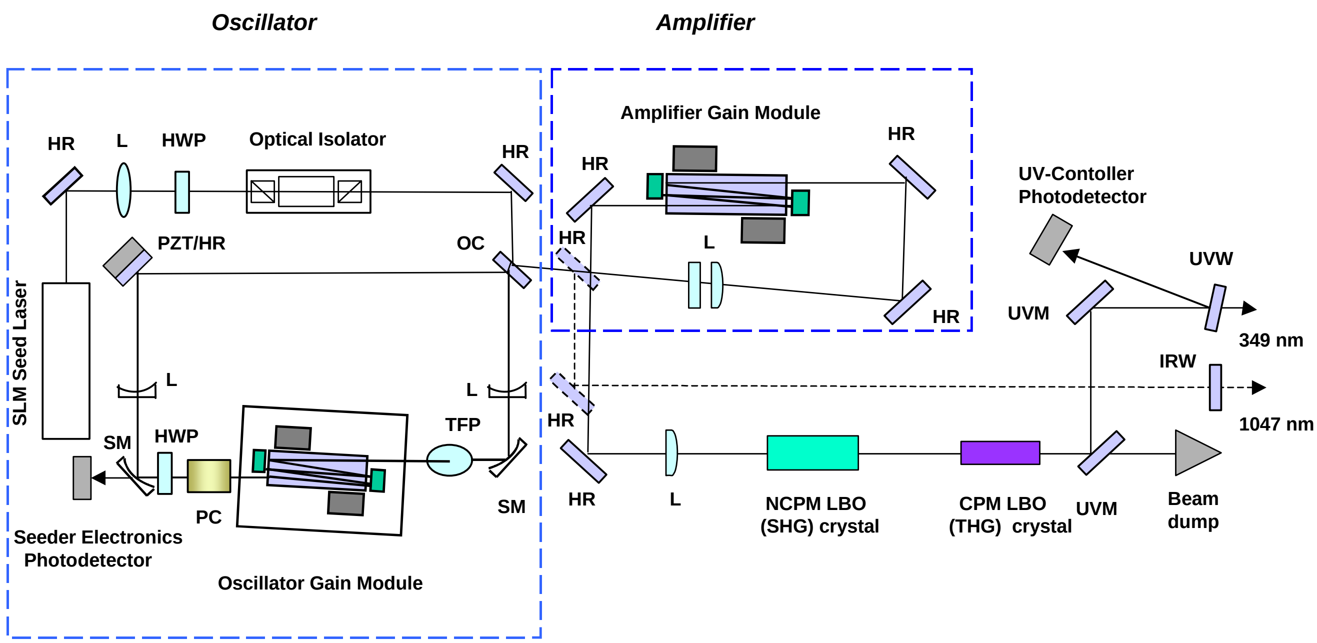


Fig. 2. Schematic layout of the UV Transmitter optical head.

The proper choice of mode size allows us to generate a high-power, TEM_{00} beam with a M² of <1.1.

Precise temperature control of the diodes and heat removal from the Nd:YLF crystal is accomplished through conduction cooling by water-cooled copper blocks. For pulsed pumping of the diode laser bars we used quasi-CW drivers. The pump pulse duration of 500 μsec was chosen to match the upper state lifetime of Nd:YLF. The diode drivers were controlled by the pulse generator producing square-wave pulses at a 1 kHz rate.

The Q-switch consisted of a KD^*P Pockel's cell, PC (Cleveland Crystals, Inc. Model Impact 8) and a Brewster-angled thin-film polarizer, TFP. The TFP was introduced into the resonator so that the plane of its transmission was parallel to the c-axis of the slab and coincided with the plane of π-polarization (1047-nm component). In such a configuration, the polarizer performs two functions. First, along with the Pockel's cell, it allows Q-switching of the resonator for the 1047-nm component. Second, it suppresses the 1053-nm component due to reflection from the polarizer. We used an additional element, a half-wave plate (HWP), in the resonator that allowed us to use a half-wave-voltage PC. The Q-switch was controlled by a fast solid-state Q-switch driver (Behlke Model FQD 80-01-ON).

In order to provide stable single-frequency operation of our oscillator, we utilized injection seeding and locking techniques. We developed and/or tested a few seeding sources: our own fiber-coupled-diode end-pumped 20-mW cw Nd:YLF laser, a commercial single-longitudinal laser from CrystaLaser, Inc., and a KTP Bragg-waveguide-stabilized semiconductor laser, Model GTL-1047 from AdvR Inc. The latter was found to provide the best wavelength stability of the master oscillator when seeded.

A pulse-build-up-time-reduction (PBUTR) technique was used to frequency lock a longitudinal mode of the ring laser to a longitudinal mode of the seed laser. The operating principal of the PBUTR technique is that the build-up time of the Q-switched pulses is shortest when a longitudinal mode of the ring laser corresponds to the seed-laser frequency. One of the HR flat mirrors of the ring was mounted on a PZT to allow control of the cavity length. This mirror was dithered by a small fraction of a free spectral range of the ring cavity about the locked position at a 1-kHz rate thus changing the build-up time. A photodiode monitors a small fraction of the cavity beam through one of the mirrors to provide the optical pulse trigger for a seeder controller. The buildup-time is measured by using the time difference between the Q-switch trigger pulse and the optical pulse. The PZT and photodiode are part of a seeder control electronics that provides buildup time minimization.

For the delivery system, we utilized a locking electronics from Lightwave Electronics Co. (Model 101-OPN-ELE). We designed an assembly consisting of the Lightwave Electronics' PZT and a 45-degree HR mirror, and also implemented a Lightwave Electronics' photodetector. In order to "lock" the laser to a seed laser frequency, we adjusted the PZT offset and the power of the beam incident on the photodetector. We were able to receive single-frequency operation of the ring laser with no reduction of output power as compared to unseeded operation. The maximum energy per pulse achieved in the injection-locked mode was 5.8 mJ. The temporal properties of the Q-switched pulses in perfect resonance (marked as seeded), not perfect resonance (marked as mismatch), and in unseeded operations are presented by oscilloscope traces in Figure 3. Although the pulse amplitudes are drastically different, the buildup time difference is very small, on the order of a few nanoseconds.

The spectra of the oscillator beam were analyzed using a Fabry-Perot (FP) interferometer and a Beam Analyzer combined with a Cohu CCD camera. To resolve adjacent longitudinal modes of the ring cavity, we set the space between the FP mirrors at 12.4 cm so the FSR was equal 0.0403 cm^{-1} or ~ 1.2 GHz. The optical length of the ring cavity was equal 73 cm thus providing the spacing between adjacent longitudinal modes of 0.0136 cm^{-1} or 0.4 GHz. Thus, with this setting, at least 3 adjacent longitudinal modes could be resolved. The interferograms of the beam in injection-seeded mode contained a single line in each spectral order, which is indicative of single-frequency operation of the Q-switched laser (Figure 4). With no seeding and locking, there were a few lines in each. Seeding also improves the spatial beam profile of the oscillator as can be seen from Figure 4.

The output of the laser is passed through the collimating optics into the MPS-type amplifier gain module, which uses 90-W QCW diode bars (Coherent model Lightstone PV 10196). In order to avoid damage to the slab, we chose to collimate the output beam of the diodes in vertical (fast) plane with cylindrical lens (LIMO 1.1.1 FAC) providing a 1.1~ mm wide beam at the input surface of the slab, which is ~ 1.6 times that of the 40-W bars. We tested a few Nd:YLF slabs with different Nd dopings (0.65%, 0.8%, and 1.%) and found that the 0.8% Nd-doped slab is the optimal choice for our power amplifier.

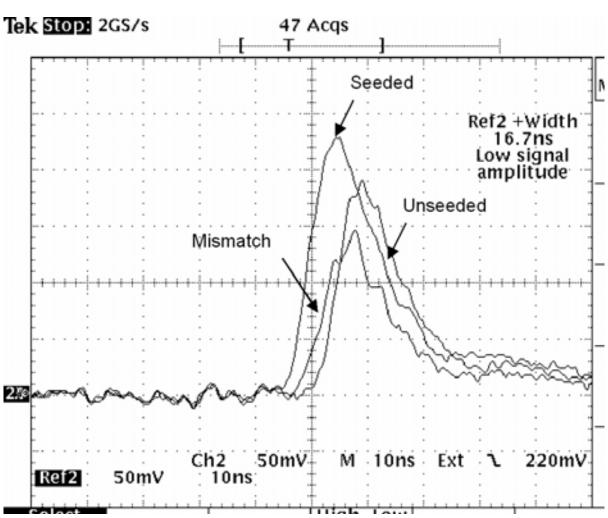
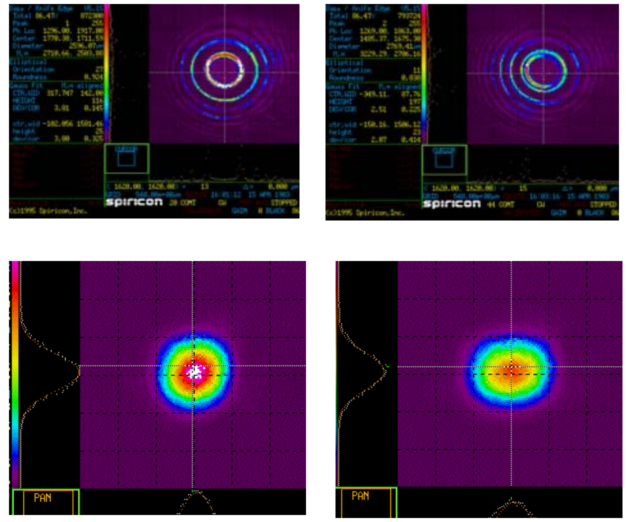


Fig. 3. Oscilloscope traces of ring-cavity pulses in different modes of operation.



(a) (b)

Fig. 4. Interferograms and beam profiles of Q-switched pulses with (a) injection-locking and (b) no injection-locking.

The highest energy per pulse received with this slab was 16.1 mJ at a 1 kHz repetition rate.

The output of the amplifier was frequency doubled in a non-critically phase-matched (NCPM) LBO crystal mounted in an oven that is maintained at approximately 170°C. The temperature controller was incorporated in the laser head.

The next nonlinear device in the optical train was a critically phase-matched LBO crystal for third harmonic generation (THG), which was mounted in an oven maintained at ~ 35°C. The 523-nm beam and residual 1047-nm beam were interacting in the THG crystal to yield 349-nm light. The 349-nm beam was directed to the laser head output by two 45-degree mirror HR-coated at 349 nm (UVM). A small fraction of the UV light reflected from the output window (UVW) is monitored by a UV photodetector. The photodetector signal was sent to a UV controller, which was positioned inside the laser head. The UV controller automatically adjusts the crystal temperature thus maintaining stable UV output power at any level between 2.5 W to 4.5 W. The controller was connected to the 9-pin RS-232 serial interface, which can be connected to an external computer. If the desired output power level is below 2.5 W, the UV controller can be computer-operated using Q-Peak supplied interface software.

The UV Transmitter delivered to NASA is a stable 349-nm single-frequency source producing 4-mJ, 15-ns pulses at a 1 kHz repetition rate in a nearly diffraction-limited beam. It consists of a Laser Head, Laser Controller including a Control unit and a Cooling Unit. The Control Unit is operated by the Q-Peak Laser Interface software and provides QCW pumping for the oscillator and amplifier gain modules and Q-switching for the oscillator. Temperature control is accomplished using the Cooling Unit, which is a closed-loop water-cooling system.

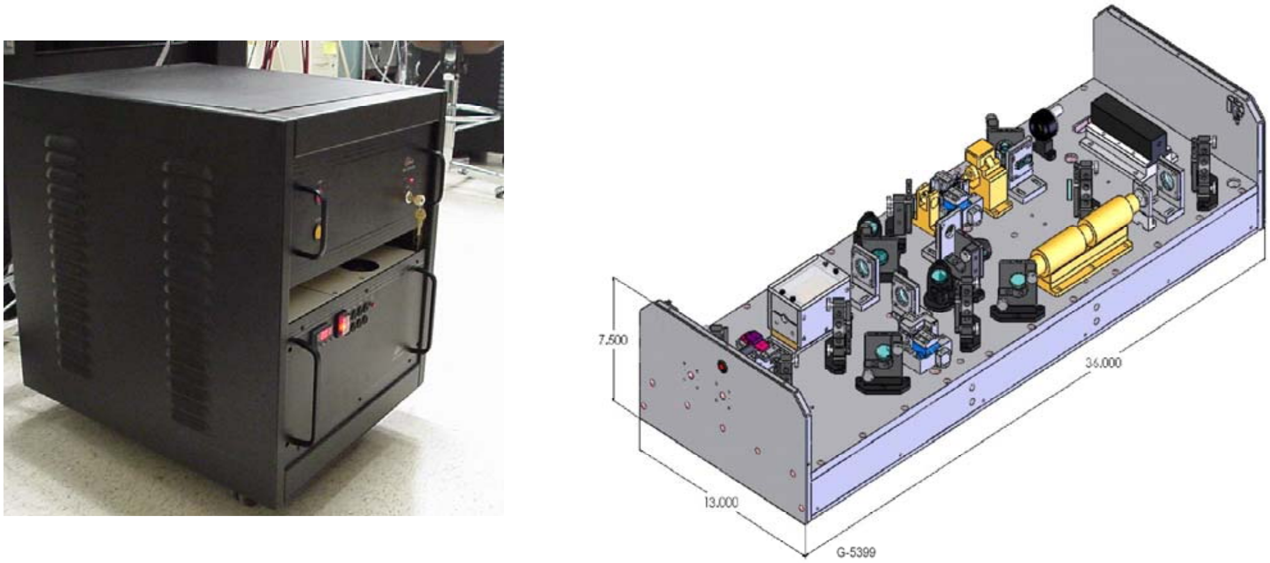


Figure 5. UV Transmitter: Photo of power supply and CAD drawing of laser head

The mechanical design of the delivery system including the power supply and optical head is demonstrated in Figure 5.

III. Conclusion

Currently, the prototype is being rebuilt by Q-Peak through the NASA SBIR Phase III program with the goal of continuing the development of the 349-nm source. The emphasis of the program is on achieving a frequency stability that meets the Doppler airborne lidar requirements, namely, a short-term drift should be < ± 1MHz over 30 s and long term drift within hours to days should be < ± 200 MHz.

The technology developed is of particular use to the NASA for lidar transmitters. Specifically, the pulsed UV source can be used for wind measurements or Raman probing of the atmosphere based on direct detection of Rayleigh or aerosol-scattered light.

Other NASA applications could include space-based aerosol sensing using the laser fundamental and harmonic wavelengths, similar to the LITE mission that flew on the STS. We note that much of the Nd:YLF technology we are developing for aircraft-based sensors can be scaled to spaceborne sensors.

For the commercial market, this technology could be used as a low-cost driver for a solid state, pulsed UV source for via drilling, and other precision micro-machining applications.