

A Modular Control Platform for a Diode Pumped Alkali Laser

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Abstract: Many of the difficulties of creating compact, high power laser systems can be overcome if the heat dissipating properties of chemical lasers can be combined with the efficiency of diode lasers. Recently, the novel idea of using solid state diode lasers to pump gaseous gain media, such as is done in diode pumped alkali lasers (DPALs), has been proposed and early experiments have shown promising results. However, a number of technical issues need to be overcome to realize high output power from these lasers. In order to achieve higher power, the efficiency of coupling between pump laser energy and the chemical cell must be increased, and eventually multiple high power diode pumps must be combined and synchronized so that their energy can pump the chemical cell. Additionally, an inter-cavity adaptive optics system may be a requirement to be able to propagate these lasers with high efficiency.

DPAL systems are complex and require a significant amount of data fusion and active feedback to control and optimize their performance. There are a wide range of components including pump lasers, gain cells and monitoring points needed to study and refine the overall laser system. In support of this dynamic development environment, we have developed a hardware framework using commercial off the shelf (COTS) components which supports the rapid assembly of functional system blocks into a cohesive integrated system. Critical to this system are a simple communication protocol, industry standard communication pipes (USB, Bluetooth, etc), and flexible high level scripting. Simplifying the integration process has the benefit of allowing flexible “on the fly” modifications to adapt the system as needed and enhance available functionality. The modular nature of the architecture allows scalability and adaptability as more pieces are added to the system. Key components of this system are demonstrated for selected portions of a DPAL system using a USB backbone.

Introduction

A smart instrument is composed of modules arranged hierarchically with a top level management unit. Processing and control requirements are delegated down the hierarchy to the module closest to the functional unit as possible. A top level management unit instructs individual modules on when to execute their designated task and receives acknowledgment and results when those tasks are completed. Modules can send signals and information to each other as necessary. The smart instrumentation paradigm distributes processing requirements and data collection across a small network of specialized modules and concentrates management at a single point which issues commands to each module, collects results and stores them for later analysis. This architecture allows for robust fast, complete (in the sense that all data are fully described) data acquisition and control in a scalable framework made from affordable pieces.

A smart instrumentation approach allows the central management unit to query all of the devices in the experiment about their status, record a data set, and attach metadata to each data set fully describing the experimental conditions. The quality of the data is enhanced because the exact conditions of each module in the experiment are known at the time of data acquisition. The volume and quality of data generated using smart instrumentation means that measurement uncertainty can be reduced to negligible levels. The centralized control of the experiment means that independent data sets can be acquired in rapid succession giving the ability to explore trends on short time scales. The advantage of low uncertainty and high time fidelity have produced data which provides critical information for the development of a robust control system for a class of laser diodes being considered as pump sources for DPALs.

In this paper we report on a smart instrumentation package which provides the framework for characterization and control of the many components comprising a diode pumped alkali laser. The system enables high fidelity data acquisition using affordable commercially available modules and easily scales as additional complexity is introduced into the system. The instrumentation package is initially being used to characterize and understand the diode pump sub-system of the DPAL. The characterization scripts can easily be replaced with control scripts while simultaneously introducing new sub-systems to be studied and eventually controlled.

DPAL Overview

Although diode pumping has greatly improved the efficiencies of many solid state lasers, they are still limited by the thermal loading of the gain medium. The advantage of using a gas phase gain media is that it can flow through the head, removing the heat. Alkali metal vapors offer an excellent opportunity for use as a laser gain media. The single valence electron can be efficiently excited from its ground state to the $P_{3/2}$ energy level, and then quickly relaxed to the $P_{1/2}$ energy level creating a population inversion. Stimulated emission then lasing occurs from the $P_{1/2}$ to $S_{1/2}$ transition as shown in fig. 1. The energy lost in the transition from $P_{3/2}$ to $P_{1/2}$ is a small fraction of the total transition energy ($\sim 2\%$ for Rubidium) reducing the amount of heat generated in the system. The cycling time of the electrons through the excitation, relaxation, stimulated emission process is very rapid, thus the alkali vapor can convert pump energy to laser energy as fast as it is applied, suggesting the potential for high power output[1,2].

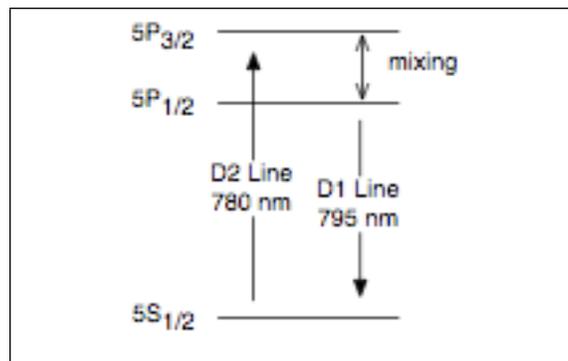


Fig. 1. Energy level diagram of a rubidium atomic vapor laser.

One challenge in using an alkali vapor lies in matching the linewidth of the absorption band of the alkali (~ 500 MHz at room temperature) with the emission bandwidth of the laser pump sources. Currently this spectral overlap is met by using a combination of pressure broadening of the alkali transition and spectral narrowing of diodes using gratings or other techniques. Recent breakthroughs in spectral narrowing and frequency locking lasers create the possibility of having high power, high efficiency diode pump sources that are spectrally dense in an alkali vapor absorption band.

Laser diodes still present considerable technical challenges which must be overcome before they can be used as efficient pump sources for DPALs. First, the natural bandwidth of a laser diode is on the order of 1000s of GHz. Special techniques must be employed to narrow the bandwidth of the laser emission to equal or less than the bandwidth of the alkali vapor pump transition. There are two primary methods of narrow banding a diode source. The common approach involves using an external grating to form an external cavity around the laser diode to select a narrow wavelength band for feedback. The laser wavelength is tuned by tilting the grating to select a different wavelength to optically feedback into the laser forcing resonance at a selected wavelength. A variety of configurations have been demonstrated and analyzed that offer narrow bandwidth and large tuning ranges, [3,5,6]. The other method uses light from a laser source of the desired frequency and bandwidth and injects it into a broad area laser diode, forcing it to resonate at the frequency of the injection source in a master-slave configuration. Grating based external cavity lasers offer narrow bandwidth and tunable wavelength, but their output power is limited by the power rating of the gratings and they are susceptible to a phenomenon called mode-hopping where the resonant longitudinal mode will jump due to mode competition between the diode and the external cavity. Injection locking offers the prospect of higher power output because multiple emitters can be cascaded and because the use of

sensitive optics exposed to high intensity light can be avoided, however it is far more difficult to achieve over long time periods because it requires precision optical alignment or special photo-refractive materials, and is extremely sensitive to disturbances[7-9].

Second, after the laser diode is narrowed, it must be locked to a specific transition frequency to maintain efficient pumping of the alkali transition. Typically, wavelength is controlled by directing a portion of the light into a wavelength reference, such as an etalon or a cell containing atomic vapor, and employing a feedback control loop to lock the laser to some absorption or emission feature of that reference [3,4]. This is normally only achievable by an experimenter intimately familiar with the laser's properties.

An appealing configuration would use an actively controlled grating stabilized laser as a master oscillator to injection lock multiple high power diode emitters which are then used as the pump source for the DPAL. The proposed system would require a stable pump source with active wavelength control, active monitoring of multiple broad band diode bar emitters to be injection locked and monitoring and control of the alkali vapor temperature and resonant cavity.

Instrumentation Platform

As shown in fig. 2, the data acquisition system in its current state consists of a computer connected via communication ports to three modules, one for controlling laser tuning parameters, and two for data acquisition modules. A signal is shared between the laser control module and one data acquisition module which transmits a high speed modulation signal required for data processing. The laptop computer uses Ruby [11], an extremely flexible object oriented programming language, to manage and conduct experiments. A Ruby script initializes communication with each module, queries the user for experimental parameters, and then issues control and data acquisition commands to modules while accumulating the results along with their metadata.

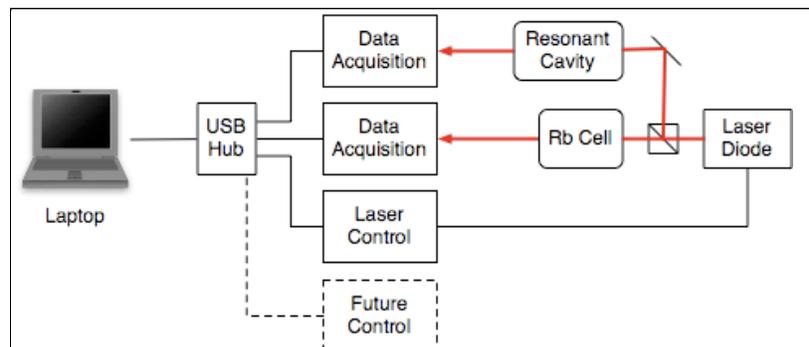


Fig. 2. Smart instrumentation system provides a scalable platform for studying and building DPALs.

Two data acquisition modules have been used, one a commercial product called a Labjack U12 which supports USB communication and low speed digital sampling, and a second module created from a Freescale MC9S12DP256 micro-controller on a commercially available evaluation board which performs multi-channel digital sampling, analog waveform generation and serial communication. The Labjack U12 lends itself well to strict data acquisition needs, but the custom device is more suited to a smart instrumentation paradigm because it can assume specialized processing tasks required immediately before and after data acquisition. Additionally the micro-controller based module has faster sampling rates and response times. This allows sampling at rates up to 20 kHz and acquisition of independent data sets with their own metadata at intervals less than one second.

The first stage of this project has been developing the instrumentation for monitoring, characterization and control of a potential laser diode pump source. In order to model and build an active control system which accurately positions the emission wavelength of the laser at a user specified power, it is crucial to know how the various control parameters affect the output wavelength. The instrumentation described allows asynchronous control of the laser,

measurement of an arbitrary number of outputs or environmental variables, and easy integration of any future elements necessary for robust control of the DPAL system. An added benefit of this instrumentation package will be the ability to evaluate the performance of potential pump sources from a large market of available products. A smart instrumentation system lends itself to an experimental process that allows for efficient integration and performance comparison of a variety of components making up a DPAL system such as pump sources, cavity mirrors and atomic vapor cells.

The diode laser we are currently evaluating as a pump source is a grating stabilized 1 Watt, < 10 MHz linewidth laser diode in an external cavity Littrow configuration (Sacher-Lasertechnik of Germany). The laser is driven by an original equipment manufacturer (OEM) control box which allows user control over the laser diode drive current, the grating angle via a piezo-electric actuator and the laser diode temperature. There are additional inputs for applying a modulation to either current or piezo voltage and the control box offers a serial port for remote control. Lasers of this variety are commonly used for laser cooling of atomic vapors and atomic spectroscopy.

As stated earlier, grating stabilized external cavity diode lasers suffer from mode competition between the desired operating modes within the semiconductor as established by the current, the temperature, the semiconductor physical geometry, and the resonant modes created by the external cavity between the grating and diode. The laser is susceptible to mode-hopping, where the operating wavelength and output power will spontaneously change as a particular resonant mode becomes more dominant inside the laser [5]. These mode-hops are problematic when attempting robust control of emission wavelength. If the wavelength is fluctuating and a control system is compensating by tuning the grating angle, there will eventually be a point where the laser mode hops, leaving the control system directionless. Likewise if the user decides they would like to run at a different output power, they must change the injection current. This changes the operating wavelength and potentially moves the laser through multiple mode hops.

The system has been used in two experiments providing valuable information about the operating points where the laser emits light at the desired wavelength and the location of mode-hops. In the first experiment, absorption of the light by a rubidium vapor reveals when the laser is emitting within the atomic absorption band. In the second experiment, the light is injected into a passive resonant cavity in order to measure how the wavelength changes as the laser control parameters are changed.

Absorption Experiment

Establishing the precise emission wavelength of a laser to GHz precision is difficult using optical devices such as monochromators. The easiest way to tell if the laser is emitting at a desired wavelength is to observe the interaction of the light with the species of interest using either absorption or fluorescence spectroscopy.

To measure the absorption, the laser light is split into two beams (signal and reference) of equal intensity. One beam is incident directly onto a detector, the other is detected after passing through a heated cell containing rubidium vapor. The relative intensities of the two beams are given by Beer's Law:

$$\frac{I}{I_0} = e^{-N\sigma(\nu)L}$$

where I is the intensity of the absorbed beam, I_0 is the intensity of the unabsorbed beam, which is equal to the reference beam, N is the number density of rubidium atoms, $\sigma(\nu)$ is the frequency dependent absorption cross section between a photon and the atom, and L is the column length of the vapor. The absorption cross section of the alkali for these experiments is a Voigt lineshape made from the superposition of the fine structure components containing both Gaussian and Lorentzian components. The Gaussian profile is due to Doppler broadening and the Lorentzian profile is due to pressure broadening [10]. For these experiments the sample cell contained Rubidium, 200 torr of Helium, and 100 torr of ethane. Because only the location and not the absolute intensity of the absorption feature was needed, only the Lorentzian component was fit to the observed features. This estimation should suffice in that the Doppler broadening is expected to be only ~ 0.75 GHz as compared to the ~ 10 GHz FWHM broadening due to collisions.

By adjusting the laser current, temperature and voltage and looking for absorption, we are building a map of regions where the laser emits light at the precise wavelength of the Rubidium D2 transition. Fig. 3 presents the data obtained by fixing the laser current at 2.1 Amps and varying the voltage on the piezo. The data presented are $\ln(I/I_0) = N \sigma(\nu) L$. The data are 0 for equal intensity and display a dip proportional to $\sigma(\nu)$ where the light is absorbed.

Modehops appear as clear discontinuities in the data set. The location of the peak absorption and the mode hopping has shifted between data sets revealing the wavelength drift of the laser emission and the complexity of building a control which finds the absorption peak if the laser has mode hopped to a region where the light is not being absorbed.

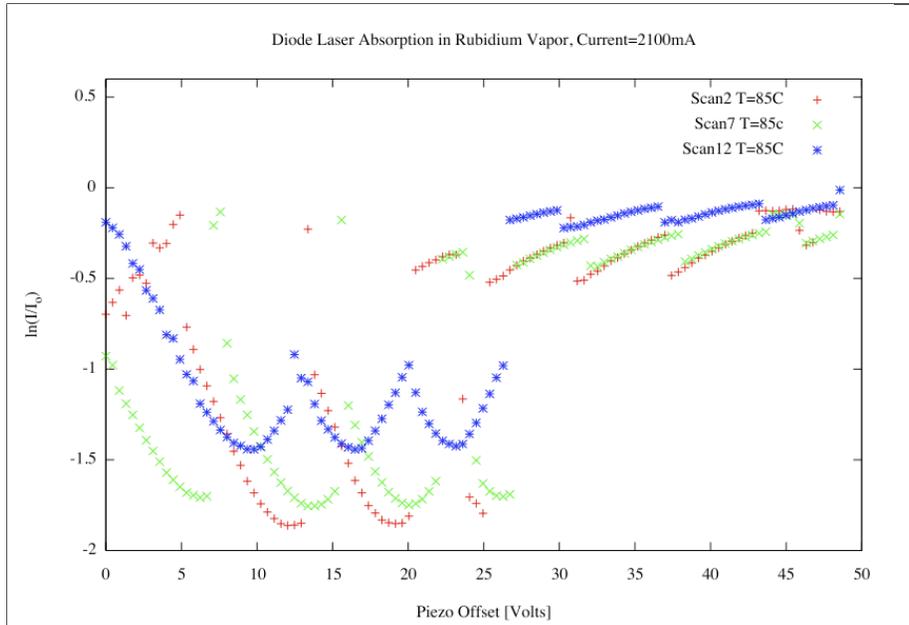


Fig. 3. Absorption of diode laser in Rubidium vapor. Laser wavelength is adjusted by changing piezo voltage while holding current constant.

Resonant Cavity Experiment

The absorption experiment reveals information about how changes to the laser input parameters (temperature, current, and piezo voltage) effect the laser wavelength when that laser emission wavelength is within the absorption band of the vapor. Otherwise, it is impossible to tell what is happening beyond the fact that the laser light is outside the absorption band.

An interferometric system was used to characterize the behavior of the laser emission wavelength when it cannot be absorbed by the alkali vapor. In these tests, laser light was injected into a confocal passive resonant cavity made of two high reflectors. The cavity acts as a comb filter for the incident laser light, only passing narrow bands of light with wavelengths which fit into the cavity an integral number of times. The laser light is rapidly scanned in wavelength using the piezo and a small amount of light is transmitted through the cavity and detected at a photodiode when the wavelength of the light corresponds to a resonant mode of the cavity. Plotting the detected light versus the wavelength displays narrow spikes, whose relative distance are fixed in frequency space by the length of the cavity. Specifically, the distance between the peaks in frequency space is known as the free spectral range, and is a function of the speed of light and the cavity length $FSR = c/2L$. For a 0.1 meter cavity, the free spectral range is 1.5 GHz.

The distance between transmission peaks can be measured as a function of voltage applied to the piezo, and the constant relating change in piezo voltage to change in laser wavelength can be computed. This particular experiment reveals how the wavelength changes as the injection current changes. By sequentially increasing or decreasing the laser current then scanning the wavelength with a modulation on the piezo, the movement of the peaks as transmitted through the cavity can be analyzed. Regions where multiple peaks appear or the distance between peaks diverges from the nominal indicate regions of wavelength instability or multimode operation. Fig. 4a shows a small portion of four such scans taken independently. Data taken at a given current were averaged, then the voltage at which peaks occurred were found by fitting a Gaussian function to the scan at the location of each point

over a threshold and recording the location of the fitted function. Compared to a similar scan as shown in fig. 4b where the current was not changed, the current has an obvious effect on wavelength. From these data we can extract the relationship between current and wavelength, which can be incorporated into the control, but more importantly, we can identify the regions of multimode operation and instability where the controller should avoid driving the current.

Most revealing, however is the analysis of the distance between the peaks at each setting of injection current. When multiple independent replicates are analyzed, fig. 5, a clear repeatable trend emerges showing that the function relating wavelength tuning to piezo voltage is not constant, but a function of current. The regions of multimode operation or instability are also evident as discontinuities in the reduced data.

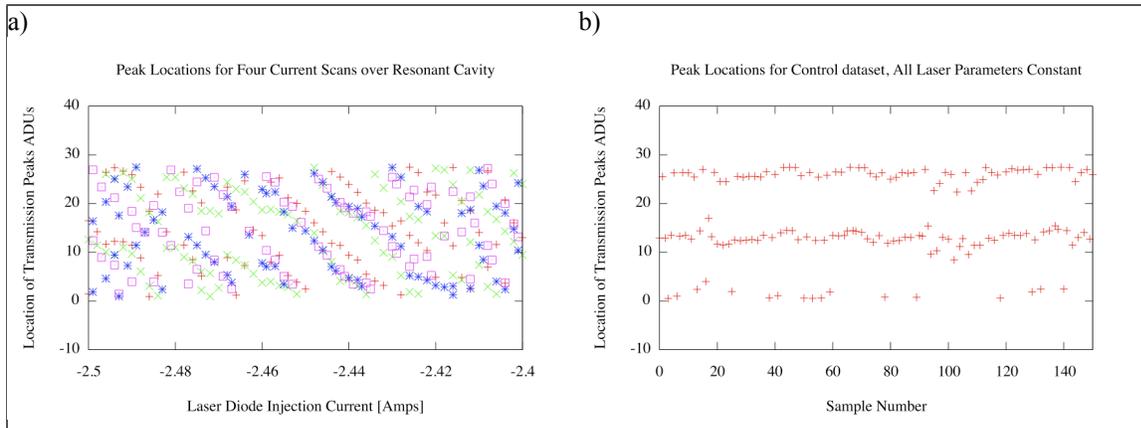


Fig. 4. a) Subset of a resonant cavity scan experiment demonstrating shift in laser wavelength due to change in laser injection current. Free spectral range of cavity is 1.5 GHz. Regions at either end of subset are multimode or unstable. b) Control experiment demonstrating drift in laser wavelength for constant laser injection current.

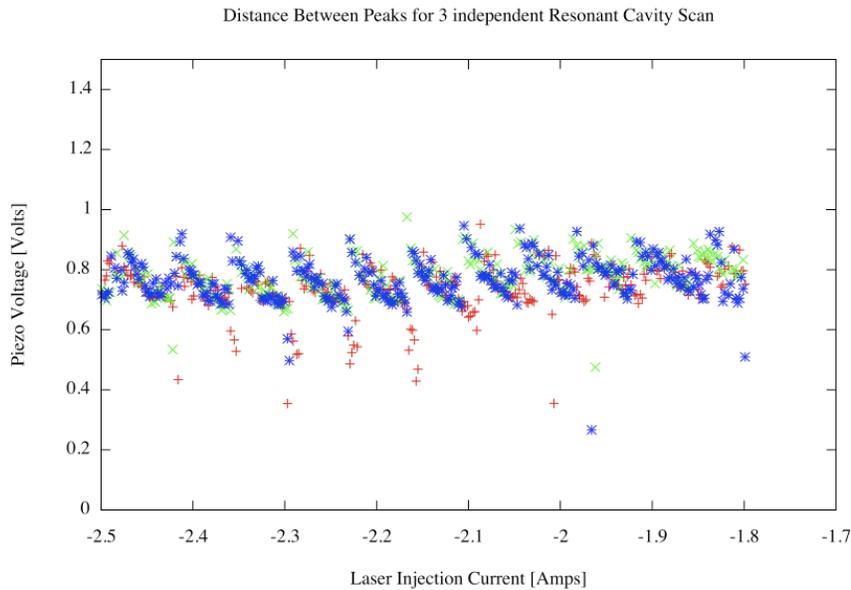


Fig. 5. Analysis of three resonant cavity scans showing distance between cavity transmission peaks in terms of piezo voltage vs. laser injection current. The tuning is not constant as one would expect. Clear regions of instability are evident.

This instrumentation platform has allowed for the acquisition of data such as those above which fully explore the multi-dimensional parameter space of the laser diode. Preliminary analysis has provided initial locations of the regions of stable and unstable wavelength emission, which is sufficient to enable the control system can to seek out stable regions of operation. Additional data acquired over time and more robust statistical analysis and pattern identification will provide a valuable comparison with working theories on external cavity laser operation. Collection of data of this quality is difficult if not impossible without an integrated smart instrumentation system.

Conclusion

The study of Diode Pumped Alkali Lasers is evolving rapidly and shows much promise as a new class of higher power laser. Stable and robust operation of DPALs requires stable and robust operation of the diodes pump sources. This means they must reliably operate at an exact wavelength tuned to the alkali vapor absorption band under a variety of environmental and operating conditions. Grating stabilized external cavity diode lasers are good candidates for DPAL pump sources or as injection seeds for high power laser diode arrays, but they suffer from non-linear instabilities and mode competition which make normal feedback control extremely difficult.

In this paper we report on the development of a modular smart instrumentation package consisting of inexpensive functional modules connected by USB to a central command and control which has been successfully used to map and characterize the stable operating regions of the diode laser. The system is powerful enough to provide high quality, complete data in sufficient volume to minimize uncertainty and the structure is flexible enough that it can be quickly and easily converted into a feedback control system, and additional functional modules can be attached to support the DPAL development effort. The system can be made portable by incorporating a laptop as the central processor. The system thus is able to scale with the complexity of the control of the DPAL, for instance as flow loop and active beam positioning become relevant in the study.

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