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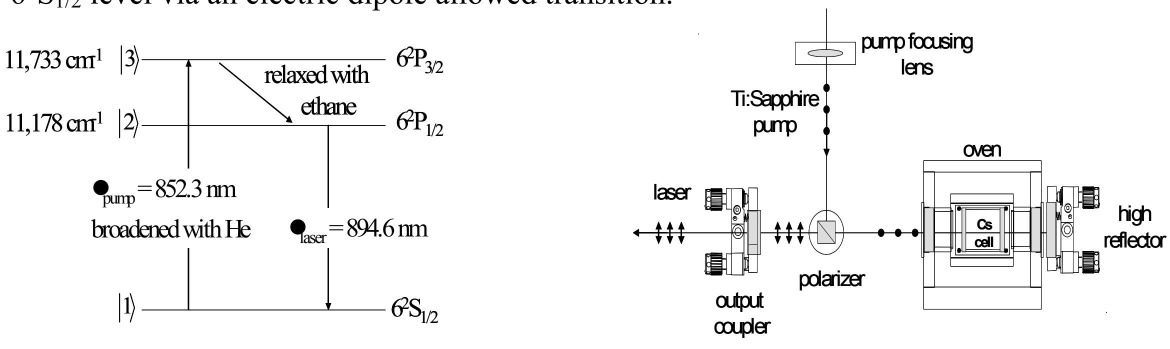
Abstract: A scientific demonstration of a Cs laser is described in which the measured slope efficiency is as high as 0.59 W/W using a Ti:Sapphire laser as a surrogate diode-pump. In addition to presenting experimental data, a laser energetics model that accurately predicts laser performance is described and used to model a power-scaled, diode-pumped system.
OCIS Codes: (140.1340) Atomic gas lasers; (140.3480) Lasers, diode-pumped

Since the advent of lasers over four decades ago, solid-state and gas lasers have followed largely separate development paths with gas lasers being based primarily on direct electrical discharge for pumping, and to a lesser extent luminescent chemical reactions; and dielectric solid-state lasers being pumped by flash lamps and more recently semiconductor diode laser arrays. Recently, an entirely new class of laser has been introduced by Krupke, combining features from both the gas and solid-state laser families, and based on diode excitation of atomic alkali vapors.[1] The approach utilizes the Alkali D_2 transition ($n^2S_{1/2} \rightarrow n^2P_{3/2}$) for pump excitation followed by rapid fine-structure relaxation between the $n^2P_{3/2}$ and $n^2P_{1/2}$ levels, facilitated by collisions with small hydrocarbon molecules,[2] and then finally amplification on the D_1 transition ($n^2P_{1/2} \rightarrow n^2S_{1/2}$). As proposed by Krupke, continuous-wave three-level alkali atom lasers were predicted using collisional broadening of the D_2 line in addition to collisionally-induced fine-structure mixing to render such systems practical and efficient when pumped by laser diode arrays having spectral emission widths up to several nm.[3] In the initial scientific demonstration of this concept, Rb was lased in a cell containing 500 Torr of He and 75 Torr of ethane, using an end-pumping geometry and a Ti:Sapphire laser as the pump excitation source.[1] Besides the Rb used in the original demonstration, both K and Cs are good candidates for diode pumping, with their D_2 transitions being wavelength compatible with well developed AlGaAs/GaAs based laser diode arrays. Here we present the results from the *first* scientific demonstration of a Cs based alkali vapor laser along with a comparison to the projected performance of the laser system made using a detailed energetics model. Without any adjustable parameters, the excellent agreement between model prediction and experimental performance indicate the underlying physics of the laser system is well understood and lend strong support to power scaling extrapolations based on the model and the known spectral properties of laser diode arrays.

Figure 1a shows the energy levels of Cs used for pump excitation and laser extraction in our experiments, and Fig. 1b shows a schematic layout of our experimental setup. The 2.5 cm long sealed cell used in our laser was commercially procured with uncoated optical windows on each end and filled at room temperature with 100 Torr of ethane and 475 Torr of He in addition to a small quantity of Cs metal prior to being sealed off. For the laser to be efficient, after excitation into the $6^2P_{3/2}$ level the population must be relaxed to the $6^2P_{1/2}$ level at a rate fast compared with the $3.3x10^7$/sec decay rate out of the $6^2P_{3/2}$ level (30.5 nsec lifetime), which decays radiatively back to the ground $6^2S_{1/2}$ level via an electric dipole allowed transition.

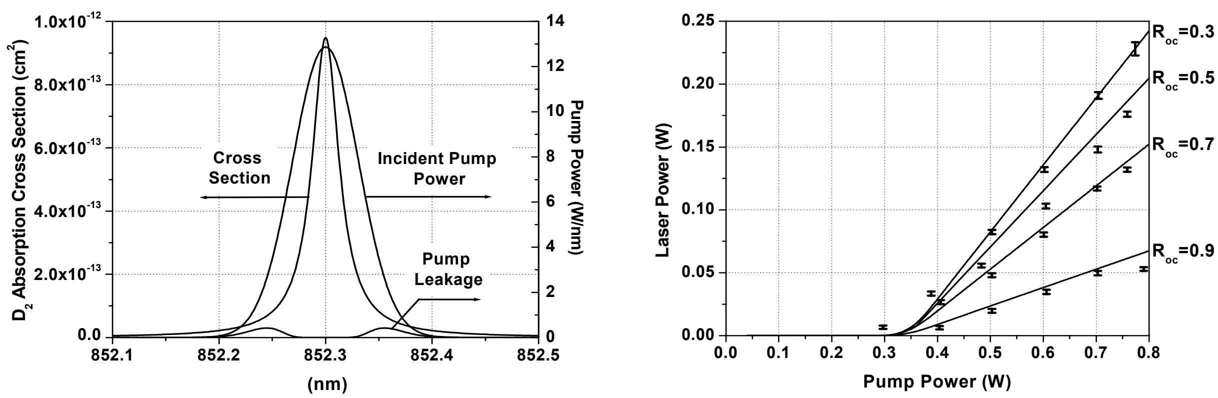


(a) (b)

Fig. 1. (a) Energy levels of Cs relevant to laser demonstration. The laser is pumped on the D_2 transition at 852.3 nm using a Ti:Sapphire laser and lased on the D_1 transition at 894.6 nm. (b) Schematic diagram of laser resonator. Optical elements are shaded. The two outer windows on the oven are AR coated at the pump and laser wavelengths, but the inner Cs cell windows are uncoated. The pump beam single-passes the laser cavity and propagates with orthogonal polarization to the intracavity laser radiation.

This rapid fine-structure mixing is accomplished using ethane collisions to transfer population between the $6^2P_{3/2}$ and $6^2P_{1/2}$ states. Walentynowicz et al. have measured cross section values for Cs $6^2P_{3/2}\rightarrow 6^2P_{1/2}$ population transfer via collisions with various hydrocarbons.[4] Their published cross section value for ethane at 110 ^oC is $5.2x10^{-15}$ cm^2, which for our experimental conditions gives a $6^2P_{3/2}\rightarrow 6^2P_{1/2}$ transition rate of $1.1x10^9$/sec, 33x greater than the competing radiative decay rate out of the $6^2P_{3/2}$. Laser experiments were performed with the cell held at 110 °C, giving an alkali number density in the cell of $2.7x10^{13}/cm^3$. At 110 ^oC, the Doppler width of the Cs D_2 line used for pump excitation is approximately 0.4 GHz FWHM, 75x narrower than our 30 GHz wide Ti:Sapphire pump excitation laser. The purpose of the He buffer gas in the cell is to collisionally broaden the pump absorption line, making it spectrally homogeneous, without electronically quenching the $6^2P_{(3/2,\ 1/2)}$ levels. As reported by Andalkar et al., the measured He collisional broadening rate of the Cs D_2 line is 19.3 GHz/amg at 21°C.[5] In our modeling, we correct this broadening rate for the difference in our cell temperature and the 21°C at which the rate was measured by including a √T factor, to account for the temperature dependence of the Cs-He collisions, $\Gamma_{D1\text{-}He}$=19.3 (GHz/amg)√T/294, where T is the absolute temperature in the cell. Using our known cell fill parameters and experimental temperature conditions, this predicts a FWHM D_2 absorption linewidth of 12.7 GHz, approximately 2.4x narrower than our 30 GHz wide Ti:Sapphire pump excitation laser as shown in Fig. 2a, where we have modeled the Ti:Sapphire pump laser as having a gaussian spectral profile. Even with this apparently unfavorable ratio of absorption linewidth to excitation pump linewidth of 2.4:1, the pump light is still efficiently coupled into the laser gain medium due to the very large *64 e-foldings* of unsaturated line-center single-pass absorption through the cell, and the very homogeneous character of the collisionally broadened absorption line that allows all absorbed pump power to contribute usefully to the lasing process. In our experiments the pump light was single passed through the cell and the absorption efficiency was 0.96.

To assess system performance we have measured output laser power against incident pump power for a series of output couplers having 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9 reflectivity at 895 nm. A Ti:Sapphire laser with a three-plate BRF tuning element was used to generate the pump light at 852.3 nm, giving a FWHM as measured on a scanning Fabry-Perot etalon of 30 GHz. The pump laser could deliver up 800 mW of pump light, and for each output coupler we measured laser output power for varying pump input power. The pump light was introduced into the laser cavity off a polarizer as shown in Fig. 1b and focused to a spot size of 150 μm at the cell center. The optical length of the laser cavity was 19.9 cm, the high reflector was flat, and the output coupler had a concave radius of 20 cm. This gave a fundamental beam waist at the location of the cell of 263 μm (526 μm diameter) as was confirmed by back-tracing the observed diffraction limited laser output beam through the various optical elements in the optics chain to the cell location. A one-way cavity transmission, sans output coupler loss, of 0.82 was measured with a Ti:Sapphire probe beam tuned to the 894.6 nm laser wavelength, with the cell cooled to room temperature to avoid Cs absorption. Plotted in Fig. 2b as data points, is our measured laser output against pump input for every other output coupler starting with the 0.3 reflectivity one. The pump power on this plot is measured before the cell and is delivered into the cell with an efficiency of 0.9 from that point. The best performance was achieved with the 0.3 reflectivity output coupler, giving a peak optical-optical conversion efficiency of 0.34 W/W and a slope efficiency of 0.59 W/W relative to the absorbed pump power.

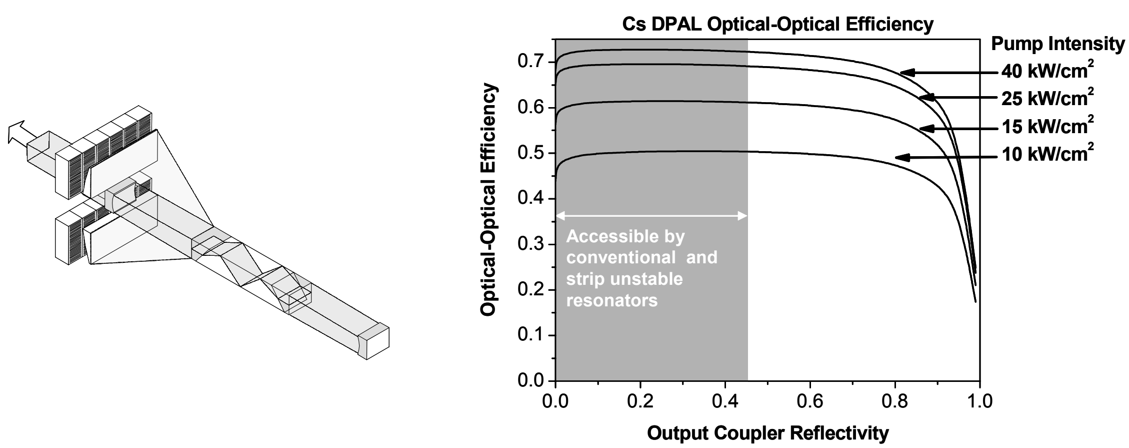


(a) (b)

Fig. 2. (a) Comparing FWHMs, our pump spectral profile is 2.4x wider than our collisionally broadened Cs D_2 absorption line. Even so, 96% of the incident pump is absorbed in single passing the Cs cell due to "wing absorption". (b) Shown as data points is laser output power vs incident pump power for output coupler reflectivities of 0.3, 0.5, 0.7, and 0.9. The pump power on the x-axis is delivered into the Cs cell with an efficiency of 0.9. The solid lines are our corresponding energetics model predictions for laser output power using no adjustable parameters.

Using the same methodology that we have previously used to model end-pumped Yb:YAG systems,[6] we have developed an energetics model for alkali lasers using an end-pumping geometry.[7] Taking literature reported values for various model input parameters such as the broadening rates due to He collisions, ethane-Cs fine-structure mixing cross sections, and excited state radiative lifetimes, and using directly measured values for other input parameters such as cavity length and pump spot focal sizes; we have compared model predicted laser performance with experimentally measured laser performance as shown in Fig. 2b. Importantly in the Fig. 2b data/model overlays, the good agreement between experiment and model is obtained without the use of any adjustable parameters, giving us confidence that we have correctly and completely included all the necessary physics relevant to the laser system, and can use the developed model to extrapolate system performance. Finally, to assure ourselves that the introduced ethane buffer gas in our laser cell did not introduce any significant electronic quenching of the excited $6^2P_{(3/2,\ 1/2)}$ levels, in a separate set of experiments using 3 nsec pulsed excitation, the radiative lifetimes of the $6^2P_{(3/2,\ 1/2)}$ levels were experimentally measured and confirmed.

Using our developed and anchored laser codes we are now in the process of designing and demonstrating diode-pumped alkali laser systems that are of interest because of their very favorable power scaling properties. Of primary interest is the pathway offered to high average power with high beam quality. When compared with conventional diode pumped solid-state laser system such as Yb:YAG or Nd:YAG, the presently considered Cs system has several distinct and advantageous differences. First, the quantum defect of Cs is less than 5%, so less thermal power will be generated per unit excitation than in competing solid-state systems. Second, the dn/dT that characterizes a typical baseline diode-pumped Cs system (system in which 10 atmospheres of He are used to broaden the pump absorption feature to make it efficiently accessible by diode arrays having several nm spectral extents) is negative and 10x smaller in absolute magnitude than the corresponding YAG value. As is well appreciated by solid-state laser designers, negative dn/dT's are more easily compensated for and often desired in constructing athermal resonators.



(a) (b)

Fig. 3. (a) Conceptual sketch of a power scaled DPAL laser in which the diode pump radiation is delivered through a hollow lens duct to a slab configured gain volume. (b) Optical-optical efficiency vs. output coupler reflectivity for a range of incident pump irradiances at the input end of the cell between 10 kW/cm^2 and 40 kW/cm^2.

The DPAL concept is compatible with multiple gain cell geometries, heat removal schemes, and laser architectures in general. For example, convectively cooled flowing gas-vapor cells are a possibility for removing heat from very high average power systems; and the gain and energetics characteristics of DPAL systems make them equally applicable to both oscillators and amplifiers. As a specific example of a system concept that offers a pathway to high average power with good beam quality, a conceptual design using a statically filled cell for a laser oscillator is shown in Fig. 3a. As shown, the slab-shaped gain volume is end-pumped through a hollow lens duct[8] and the cell is assumed to be filled with 10 atm of He, 100 Torr of ethane, and held at 93 ^{o}C. Using the laser energetics model that we have developed and baselined against our scientific Cs laser demonstration, Fig. 3b plots optical-optical efficiency vs. output coupler reflectivity of this laser for a series of input pump irradiances ranging from 10 kW/cm^2 to 40 kW/cm^2. In this modeling study, the delivery efficiency of the pump radiation from the laser diode array to the input end of the alkali cell is assumed to be 90%, and the 1-way (passive) cavity loss at the laser wavelength is assumed to be 90% neglecting the output coupling. A more complete description of this modeling is given in reference [7]. Of particular interest is the greater than 70% laser optical-optical efficiency that obtains with an incident pump irradiance of 40kW/cm^2, which is easily obtainable with today's commercially available laser diode arrays that are radiance-conditioned on their fast-axis using cylindrical microlenses and then have their output radiation delivered through a lens duct.[9] Additionally, the high gains that can be generated with our alkali approach are ideally matched to the requirements of conventional geometrically unstable and strip unstable resonators, making DPALs compatible with aperture scaling to reach high output powers.

In summary, we have performed detailed experiments on a surrogate diode-pumped Cs vapor laser and developed a comprehensive energetics model that faithfully predicts observed experimental performance with no adjustable parameters. The good agreement between experiment and model indicate the underlying physics in this system is well understood, and add credibility to our power scaling studies done using the model. DPAL systems based on Rb and Cs are distinguished from conventional solid state lasers in both the wavelengths they can generate and their projected high efficiency operation. Because DPAL systems offer a pathway to high average power with good beam quality and are compatible with today's laser diode arrays, we believe they will be of high interest to applications that require cw or quasi-cw laser radiation, which are today served by diode-pumped solid-state lasers.

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References

[1] W.F. Krupke, R.J. Beach, V.K. Kanz, and S.A.Payne, "Diode Pumpable Rubidium Laser," OSA TOPS Vol. 83, Advanced Solid-state Photonics pp. 121 (2003), and W.F. Krupke, R.J. Beach, V.K. Kanz, and S.A.Payne, "Resonance-Transition, 795 nm Rubidium Laser," accepted for publication in Optics Letters

[2] Z. Konefal, "Observation of collision induced processes in rubidium-ethane vapour," Optics Comm. **164**, 95-105 (1999)

[3] W.F. Krupke, "Diode-Pumped Alkali Laser," US Patent Application Publication, Pub. US 2003/0099272 A1, Pub Date: May 29, 2003

[4] E. Walentynowicz, R.A. Phaneup, and L. Krause, "Inelastic Collisions Between Excited Alkali Atoms and Molecules X. Temperature Dependence of Cross Sections for the $6^2P_{1/2}\leftrightarrow6^2P_{3/2}$ Mixing in Cesium, Induced in Collisions with Deuterated Hydrogens, Ehtanes, and Propanes," Can. J. Phys. Vol. 52, pp. 589 (1974)

[5] A. Andalkar and R.B. Warrington, "High-resolution measurement of the pressure broadening and shift of the Cs D_1 and D_2 lines by N_2 and He buffer gas," Phys Rev A, **65**, 032708-1 (2002)

[6] R.J. Beach, "CW Theory of Quasi-Three Level End-Pumped Laser Oscillators," Optics Communications 123, pp. 385-393 (1995)

[7] Raymond J. Beach, William F. Krupke, V. Keith Kanz, Stephen A. Payne, Mark A. Dubinskii and Larry D. Merkle, "End-Pumped CW Alkali Vapor Lasers: Experiment, Model and Power Scaling," manuscript in preparation for JOSA B

[8] E.C. Honea, R.J. Beach, S.C. Mitchell, J.A. Skidmore, M.A. Emanuel, S.B. Sutton, S.A. Payne, P.V. Avizonis, R.S. Monro, D.G. Harris, "High-power dual rod Yb:YAG laser," Optics Letters, 25, pp. 805-807 (2000)

[9] R.J. Beach, "Theory and Optimization of Lens Ducts," Applied Optics 35, pp. 2005-2015 (1996)