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Highly Efficient Cesium Vapor Laser

R. J. Knize,[1] T. Ehrenreich,* and B. Zhdanov

Department of Physics, U.S. Air Force Academy, Colorado 80840

The results of our work on optically pumped cesium vapor laser development are presented. We demonstrated efficient cesium laser operation with diode laser pumping. The measured optical efficiency was more than 32% with an overall electrical-to-optical efficiency of 15%. With an improved pump source we have demonstrated a Cs laser with slope efficiency of 81% and overall optical efficiency of 63%.

KEYWORDS: Alkali lasers, Diode pumped lasers, Optically pumped lasers

1. Introduction

There has been an extensive development of high-powered lasers for military applications over the past 35 years. Several successful high-power lasers have been developed, such as the chemical oxygen iodine laser (COIL) and the HF/DF laser. The COIL will be used in the airborne laser (ABL) for theater missile defense. There is also interest in an advanced tactical laser (ATL) for local defense. Both of these platforms require lasers with powers in excess of 100 kW. Although COIL is a highly successful laser system, it has some undesirable features, most notably its use of dangerous chemicals and its excessive size. There has therefore been a search for other high-power laser systems including other chemical lasers, and for alternative technologies including diode-pumped solid-state lasers, fiber lasers, and multiple-diode laser beam combining. Even after extensive research and development, none of these systems has achieved the necessary powers. In this paper we describe an optically pumped cesium laser operating at wavelength 894 nm. Scaling to very high power using diode laser pumping might be achievable.

Alkali vapors as a laser medium have attracted the attention of researchers since the very beginning of the laser era. Schawlow and Townes[10] first proposed an optically pumped potassium vapor laser (maser) in 1958. Laser gain in an optically pumped Cs vapor[4] was measured in 1961, and laser action at 7.18 μm was observed in 1962 using a radio frequency (RF)-powered helium lamp as a pump.[8] The lasing efficiency in these experiments was very low, and the output power did not exceed 50 μW. Considerably more efficient lasing has been observed in Rb and Cs vapors using an Ar^+ pumped dye laser,[11] a Ti:sapphire laser,[2,6] and a diode laser[3] for optical pumping. Krupke et al.[2,6] demonstrated Rb and Cs vapor lasers with Ti:sapphire laser pumping with a slope efficiency of up to 59% relative to the absorbed pump power. The first demonstration of a Cs vapor laser with a diode laser pump[3] showed a slope efficiency of 41% relative to the input power and an overall optical efficiency of 32%.

Optically pumped alkali lasers have a number of desirable features as compared with solid-state or fiber lasers. The quantum efficiency is high (95.3% for Cs as compared with

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*Corresponding author; e-mail: thomas.ehrenreich.ctr@usafa.af.mil.

[1] E-mail: Randy.knize@usafa.af.mil.

76% for a 1.06-μm Nd YAG laser), which is very important not only for increasing the overall laser efficiency but also for minimizing heating problems. In addition, thermal problems can be reduced since the gas gain medium can be flowed to remove heat. At the current powers the gas gain medium has an excellent optical quality that allows the generation of high-quality beam with diffraction-limited divergence. Further studies of the optical quality are needed to verify that no degradation of the active medium takes place at very high powers.

The Cs laser has also many advantages compared with chemical lasers, e.g., COIL. It does not use large quantities of hazardous materials. Its operational wavelength is shorter than the 1.315-μm COIL wavelength that makes the diffraction-limited spot size smaller. For the same power a cesium laser can have more than twice the intensity on the target compared with COIL. The alkali laser could be constructed in a closed cell, eliminating the need for vacuum pumping and discharge of chemicals. Finally, it is possible to easily change the alkali number density and buffer gas composition to optimize the laser performance.

Using high-power and highly efficient diode lasers and laser diode arrays for optical pumping of the alkali lasers opens a new prospective in high-power laser development. The power and efficiency of diode lasers and laser diode arrays have been increasing over the past decade. Highly efficient laser diodes arrays with continuous-wave (CW) powers of more than 50 W are readily available. The beam quality of laser diodes and laser diode arrays is unfortunately very poor, and therefore they cannot be used directly as laser weapons. Diode-pumped solid-state lasers and fiber lasers can be used to beam combine many diode lasers to produce a high-quality laser beam. Lasers with several tens of kilowatts have been produced. Solid-state lasers are limited due to thermal heating, and fiber lasers are limited by intensity damage and nonlinear effects. The alkali medium can be seen as a beam combiner that takes a spectrally and spatially incoherent diode laser and creates a spectrally and spatially coherent high-quality laser beam ideal for directed energy applications. Diode-pumped alkali lasers can be scaled to higher powers with additional pumping from commercially available high-power laser diode or diode arrays.

Although pumping with off-the-shelf lasers is possible (as proposed by Krupke et al.[7]), it would be preferable to use a technique to narrow the linewidth of the diodes (see, for example, Ref. 1). Since laser diodes are sensitive to optical feedback, several techniques use optical feedback to narrow the laser linewidth with minimal loss in power. It is possible to keep the pump diode lasers at the desired wavelength and narrow their linewidth with feedback from a grating, hologram, optical cavity, or similar device. Since diode arrays with "out of wall" efficiencies of more than 65% are commercially available, overall efficiencies approaching 50% should be possible.

2. First Diode-Pumped Cs Laser Demonstration

We used the three-level pump scheme suggested by Konefal[5] to create the population inversion on the D_1 transition in Cs atomic vapors ($6P_{1/2}$–$6S_{1/2}$; see Fig. 1). A narrowband diode laser operating at 852 nm pumps the atoms to the $6P_{3/2}$ state (D_2 line), which is then rapidly quenched to the $6P_{1/2}$ state by an ethane buffer gas. This creates a population inversion between the $6P_{1/2}$ and $6S_{1/2}$ states and lasing at 894 nm. The experimental setup consisted of an injection-seeded SDL-8630 diode laser used as a pump source and a Cs vapor cell positioned inside a stable laser cavity. The laser cavity was longitudinally pumped through the input cavity mirror. This mirror had a concave radius of 20 cm and about 99% reflectivity at 894 nm and 90% transmission at 852 nm. A series of flat output mirrors

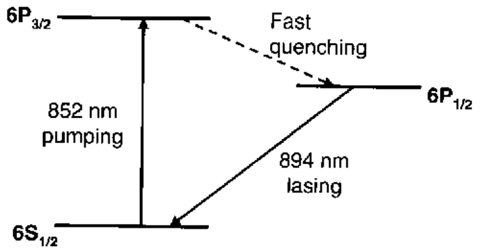

Fig. 1. Energy-level diagram of the Cs laser.

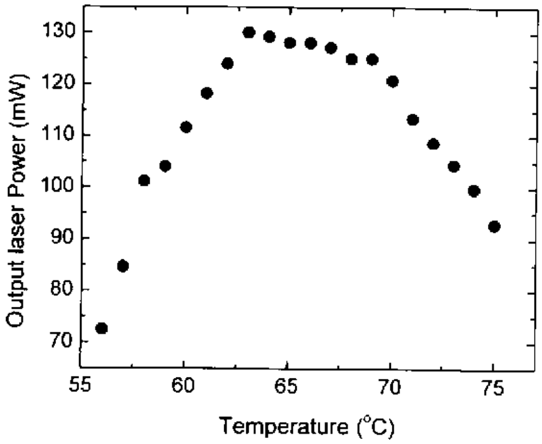

Fig. 2. Cs laser output power at 894 nm as a function of cell temperature.

were used, with reflectivities for both 894 and 852 nm ranging from 20% to 90%. The optimal output coupler reflectivity was 30% at 894 nm. The length of the laser cavity was 16.5 cm. The SDL-8630 pump laser had a maximum output power of 500 mW at 852 nm with full width at half-maximum (FWHM) of less than 1 MHz. The Cs vapor cell was 5 cm long, with Brewster windows at both ends. It was filled with metallic cesium and 100 torr of ethane at 20°C and was placed inside an oven. The oven was designed to keep the windows of the Cs vapor cell warmer than the cold finger of the cell, thereby minimizing window contamination. No degradation of the cell windows was seen during the course of the experiments.

Figure 2 shows Cs laser output power at 894 nm as a function of cell temperature with a 30% reflectivity output coupler. The graph shows a broad peak centered at 65°C. At this temperature the Cs vapor density is 1.3×10^{12} cm^{-3}. Figure 3 shows laser output power at 894 nm as a function of the incident pump power at 852 nm. A maximum slope efficiency of 41% was obtained in this experiment. The pump beam used had an elliptical cross section and did not match the laser cavity mode.

To determine the maximum value of the Cs laser slope efficiency, we performed a series of experiments on optimizing the cavity design and pump beam geometry. The results of these experiments are presented below.

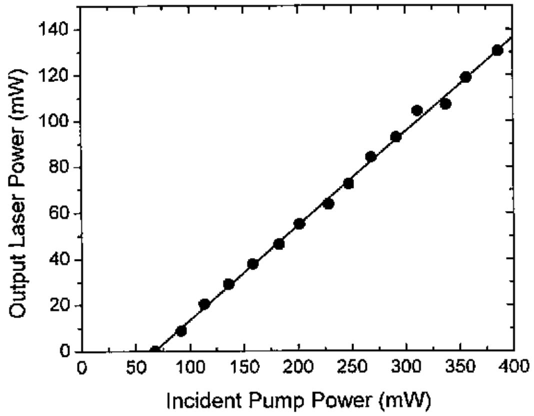

Fig. 3. Cs laser output power at 894 nm as a function of incident pump power at 852 nm. The laser threshold value is 67 mW, and the slope efficiency is 41%.

3. Cs Laser with Optimized Cavity and Pump Arrangement

The experimental setup consisted of a coherent MBR 110 Ti:sapphire laser used as a pump source and a 2-cm-long Cs vapor cell with antireflection (AR)-coated windows positioned in the center of a 16-cm-long stable laser cavity. The cell was filled with metallic cesium and 500 torr of ethane at 20°C and was placed inside a temperature-controlled oven, which had the same design as in the previous experiment. The laser cavity was longitudinally pumped through the input cavity mirror. Both cavity mirrors were concave, with a radius of 20 cm. The input mirror had a 99% reflectivity at 894 nm and 90% transmission at 852 nm. In our experiments we used several output mirrors with reflectivities at 894 nm ranging from 13% to 43% and a reflectivity at 852 nm of about 90%. Several experiments were performed to optimize laser and pump beam parameters that affect the laser efficiency.

The ratio of the pump beam waist w_P to the laser cavity mode waist w_L is important for three-level lasers because it determines the reabsorption losses.[9] The calculated laser cavity mode waist was $w_L = 167\ \mu\text{m}$. To vary the pump beam waist inside the Cs cell, we used several different external focusing lenses, and the pump spot size was measured with a beam profiler. We measured the laser slope efficiency for the pump beam radius in the range from 50 to 200 μm and found its optimal value of $w_P = 120\ \mu\text{m}$. The experimentally determined optimal value of the ratio w_P/w_L is 0.72.

We measured the laser slope efficiency for the cavity with several different output mirrors having reflectivities in the range from 13% to 43%. The optimal value of the output coupler reflectivity at the lasing wavelength of 894 nm was determined to be 23%. We optimized the density of Cs atoms in the gain medium by measuring the output power at different temperatures. The optimal temperature for the 2-cm-long cell was about 88°C, which corresponds to a Cs vapor density[12] of $7.8 \times 10^{12}\ \text{cm}^{-3}$.

Figure 4 shows the dependence of the output power on input pump power for the optimal pump waist, output mirror reflectivity, and cesium temperature as described above. The data show an 81% slope efficiency for the output power relative to the input power. The overall optical efficiency was 63% at 0.57-W input pump power.

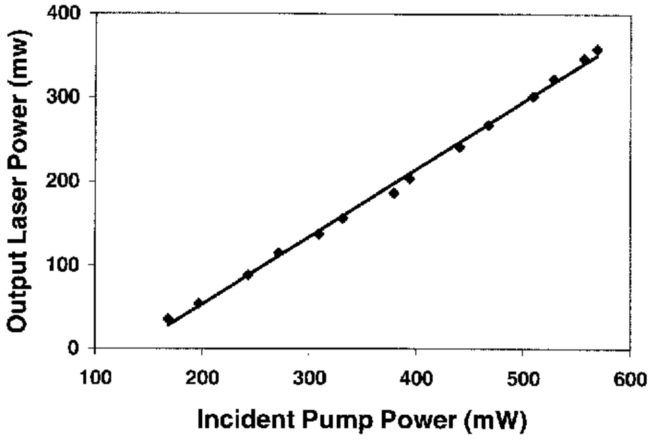

Fig. 4. Optimized Cs laser output power at 894 nm as a function of incident pump power at 852 nm. The laser threshold value is 127 mW, and the slope efficiency is 81%.

The slope efficiency dP_L/dP_P of a three-level laser can be calculated using the following equation[9]:

$$\frac{dP_L}{dP_P} = \frac{T}{L+T}\frac{\nu_L}{\nu_P}\eta_P\frac{dS}{dF}, \tag{1}$$

where T is the output coupler transmission, L is the round-trip losses, ν_L/ν_P is the quantum efficiency associated with pump-to-lasing conversion, η_P is the fraction of the incident pump power absorbed by the active medium, and dS/dF is the efficiency with which absorbed pump photons are converted to laser photons. The first three terms in Eq. (1), $[T/(L+T)](\nu_L/\nu_P)\eta_P$, determine the maximum possible slope efficiency. For our Cs laser, $T=77\%$, $L=8\%$, $\nu_L/\nu_P=95.3\%$, $\eta_P=99.4\%$, and the maximum possible slope efficiency is 85.8%. A perfect optically pumped gain medium would convert every absorbed pump photon into a laser photon and, thus, $dS/dF=1$. In our experiment we calculate $dS/dF=0.94$, which is close to unity. The reason that this factor is slightly less than unity is reabsorption.[9] It may be possible to improve the slope efficiency by further optimization, such as reducing the cavity losses. The round-trip losses can possibly be reduced with improved coatings of the intracavity optics.

4. Conclusion

We demonstrated a diode-pumped Cs vapor laser that showed a slope efficiency of 41% with a pump beam having an elliptical cross section that did not match the laser cavity mode. Using an improved cavity design and perfect pump beam allowed us to obtain the 81% laser slope efficiency and 63% overall optical efficiency with the 0.57-W pump power close to its possible maximum limit.

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