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Spin-exchange optical pumping using a frequency-narrowed high power diode laser

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We describe a method for frequency narrowing commercial high power diode lasers from 2 to 0.1 nm bandwidth with modest loss of power (<2 dB). The resulting laser light is well suited for spin-exchange optical pumping, and we demonstrate that the polarization produced by a 2.5 W narrowband laser exceeds that of a 15 W array by 40% in our optical pumping system. © *2000 American Institute of Physics.* [S0003-6951(00)00411-3]

Applications of hyperpolarized noble gases include magnetic resonance imaging,[1] precision measurements,[2] spin-polarized targets for nuclear physics,[3] and chemistry.[4] The noble gases are typically hyperpolarized via spin exchange with optically pumped Rb atoms.[5] Most current spin-exchange systems use high power, broadband diode arrays for the optical pumping. The poor match between the laser bandwidth (2–3 nm) and the absorption linewidth of the Rb atoms (≈17 GHz/amg) requires high buffer gas pressures and/or temperatures in order to utilize a significant fraction of the light.[6]

In this letter we demonstrate the use of external cavities to frequency narrow 1–5 W single and dual-stripe broad-area laser (BAL) diodes to <0.15 nm bandwidth, with <2 dB power loss. When applied to spin-exchange optical pumping in our system, such a narrowband 2.5 W laser produces 40% higher polarization than a commercial 15 W diode array, at a fraction of the cost.

Current spin-exchange devices use principally two types of laser sources: expensive narrowband lasers (e.g., Ar^+-pumped Ti:sapphire)[3] or broadband diode arrays.[6–8] Neither is optimum for optically pumping alkali vapors in spin-exchange optical pumping systems. High costs and large footprints make Ti:sapphire unattractive. Commercially available diode arrays, while compact and inexpensive, have bandwidths of typically 2–3 nm, far in excess of the 0.1–0.3 nm pressure broadened Rb absorption linewidth. For some implementations this mismatch can be compensated for by increasing the optical thickness of the alkali absorption line.[6] However, studies have also shown that the high-intensity off resonant light produces heating in high-pressure spin-exchange cells that is detrimental to noble gas polarization as well as to cell integrity.[9] For spin-exchange optical pumping at pressures much below 10 atm the 2.0 nm bandwidth of a diode array is too large to be efficiently used.

Recently, Levron *et al.*[10] frequency narrowed a custom 1 W diode to use for spin-exchange optical pumping of Xe using Cs instead of Rb. The resulting 0.3 W output with 0.12 nm bandwidth gave Xe polarizations of 2.5%. Here we achieve nearly a factor of 10 increase in power at the same linewidth using commercial BALs.

Commercially available high power BALs either have a single rectangular active region (typically 200 μm×1 μm) or two such active regions separated by a small isolation space. The emitted laser beams have a divergence of typically 10°×35°, with significant astigmatism. A 0.68 numerical aperture (NA) aspheric lens collimates the rapidly diverging direction of the diode laser beam. For a single active region, we used either a Littrow or Littman-Metcalf[11] external cavity with a 1800 lines/mm holographic diffraction grating for feedback. The diode laser is oriented with the long side of the active region parallel to the grooves of the grating. Due to the astigmatism, the other direction remains slightly divergent, but we found it unnecessary to correct for this. We often found the feedback from the grating excessive, so we introduced a half-wave plate to rotate the polarization of the light, with a consequent reduction in the diffraction efficiency of the grating and increased power output.[12]

Using a Coherent Semiconductor Group 2 W BAL (SS-79-2000C-150-H), for example, we attain 1.4 W with a 0.08 nm bandwidth (Fig. 1). The output frequency tuned smoothly from approximately 792 to 798 nm, and ran stably for days without requiring adjustment or realignment. No temperature control of the external cavity was used, and the components were mounted on low-cost commercial mounts. Similar re-

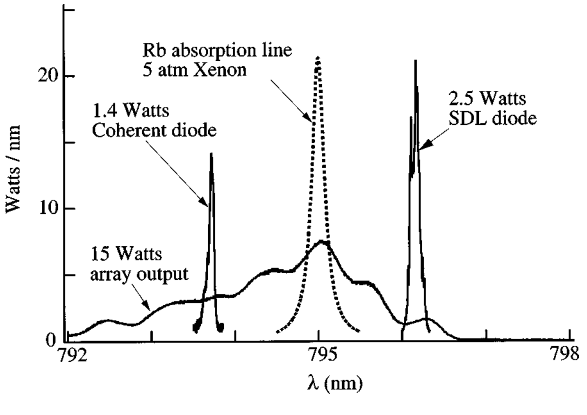

FIG. 1. Laser linewidths: The line shape of the array was measured using an 0.25 m monochromator with resolution of ∼0.2 nm. The narrowed diodes' line shapes were recorded using a homebuilt Fabry-Perot spectrometer with 0.3 nm free-spectral range and finesse of ∼20, and their peaks are shifted away from 795 nm for clarity.

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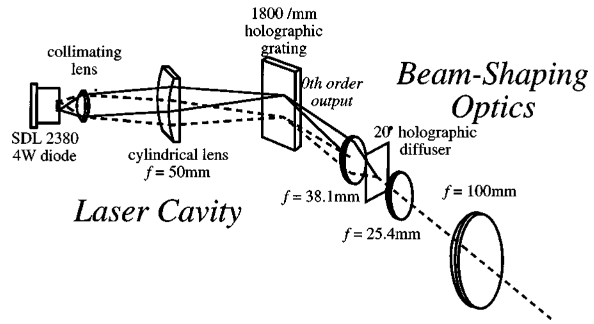

FIG. 2. Optical diagram of the frequency narrowed 4 W BAL. A λ/2 plate is often included in the cavity to optimize feedback and output power.

sults were attained with a 4 W Semiconductor Laser International BAL at 808 nm (SLI-CW-SLD-C1-808-4M-R).

Often higher power BALs, for example, a 4W Spectra Diode Labs diode (SDL-2380), have two active regions separated by an isolation space. The two regions are indeed isolated, since the simple cavity configuration described above could be used to narrow one of the active regions but not both. The laser intensity several centimeters from the collimating lens exhibits two spatially distinct lobes, corresponding to the two active regions of the diode. In fact, by using two separate gratings, we found that we could produce two independently tunable 1 W beams of 0.12 nm bandwidth. This simple configuration may be of interest for applications such as THz generation. We note that Hsu *et al.*[13] have recently reported a dual frequency laser of much lower power and narrower linewidth.

Inserting a cylindrical lens into the cavity allows us to narrow and tune both active regions with one grating. The key to this design (see Fig. 2) is the placement of the cylindrical lens. Rather than collimating the laser light, the lens images the diode onto the grating. In this way, the first order diffraction feedback forms an image of the diode back onto itself with positive unit magnification (in contrast to the negative magnification that occurs in a standard Littrow cavity). The result is that each of the two active regions is imaged back onto itself, rather than onto the other. In this way, we have produced a 2.5 W output beam with 70 GHz full width at half maximum, tunable over roughly 4 nm. (see Fig. 1). Note that for this particular commercial diode laser, light is polarized along the quickly diverging direction; adding the half-wave plate to the cavity allows us only to increase the feedback, resulting in lower power output with only modest gains in narrowing and tunability.

We compared the optical pumping performance of the frequency narrowed 4 W diode to a commercially available 15 W diode array (OPC-A015-FCPS, Opto Power Corporation). The optical pumping cell is a sealed uncoated Pyrex 4 cm diam sphere with a small stem. It contains 1.3 amagats of natural abundance Xe, 50 Torr of nitrogen quenching gas, and a small amount of Rb metal. It is located inside a forced air oven with an antireflective coated window, and is carefully centered in a pair of 1 m diam Helmholtz coils which provide the dc field. A custom pulsed nuclear magnetic resonance (NMR) system measured the relative polarization of the ^{129}Xe in the cell using free-induction decay following a $\pi/2$ resonant pulse.

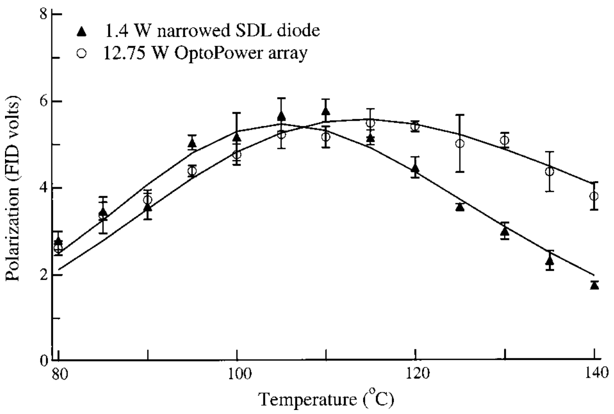

FIG. 3. Measured Xe polarization as a function of temperature using 12.75 W from a commercial diode array (open circles) and 1.4 W from a frequency narrowed BAL (closed triangles).

To compare the performance of the narrowed diode and the array, we measured the polarization of the Xe as a function of the oven temperature. Each of the two laser sources was used to illuminate the cell with a uniform 2 cm diam beam. The irregular beam profile of the narrowed diode necessitated the use of the beam-shaping optics shown in Fig. 2. Losses at the optics led to only 1.4 W actually being delivered to the cell. Nevertheless, the maximum polarization acheived with the 1.4 W narrowband laser is nearly identical to that of the 15 W array. Removing the beam shaping optics results in even higher Xe polarizations because the entire 2.5 W is delivered to the cell. The narrowband 2.5 W laser then produces polarizations 40% greater than that of the 15 W array.

Also shown in Fig. 3 are results of a detailed model of the spin-exchange process.[5,6] The model uses the measured laser line shape, known alkali vapor pressures, pressure broadening rates, spin-relaxation rates, and spin-exchange rates to calculate the expected Xe polarizations. The model accurately predicts the absorption of the light by the Rb in the cell to within a few percent accuracy. With two free parameters, namely, the polarization calibration and the wall-relaxation rate, the relative polarization of the Xe as a function of temperature for each of the two sources is well accounted for.

We note that Humphrey *et al.*[14] have recently successfully frequency narrowed a diode array via injection locking with a Ti:sapphire laser for use in spin-exchange optical pumping.

To summarize, we have demonstrated a simple and effective method to frequency narrow broad-area laser diodes with only modest loss in power. In this letter we have concentrated on a particular application, namely, production of hyperpolarized gases, but many other applications should benefit from the increased spectral brightness of our laser source. Examples include THz generation[15] and light detecting and ranging.[16] For applications requiring more power than that demonstrated here, it should be possible to daisy chain several such lasers.

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