Characterization and Stabilization of Opto Power Fiber-Coupled Laser Diode Arrays

D. F. Phillips, G. P. Wong, D. Bear, R. E. Stoner and R. L. Walsworth
Harvard–Smithsonian Center for Astrophysics, Cambridge, MA 02138

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Abstract

We have characterized the spectra and performance of an ensemble of eleven fiber–coupled laser diode arrays (LDAs) manufactured by Opto Power Inc. These high–power LDAs operate near 795 nm and are of a type commonly used for spin–exchange optical pumping of noble gases. We find the Opto Power LDAs to vary significantly in output power, spectral width, and other important characteristics, in a manner not correlated with age, operating lifetime, or information supplied by the manufacturer. In addition we have developed a two–loop feedback technique for use with LDAs that stabilizes the Rb magnetization in an optical pumping cell to better than one part in a thousand.

1 Introduction

High power near-infrared (795 nm) light is necessary for optical pumping of the D1 line of Rb, which via spin-exchange can polarize ^{3}He and ^{129}Xe nuclei [1]. These polarized noble gases have recently found numerous applications in physics [2, 3], materials science [4] and biomedicine [5]. To provide this optical pumping light, many groups, including ours, now use fiber-coupled multistripe laser diode arrays (LDAs) manufactured by Opto Power, Inc. [6]. The model of Opto Power LDA we use [7] nominally produces 15 watts of total power out of the fiber bundle, with a spectral width of 1-2 THz.

These Opto Power LDAs are composed of 24 diode arrays housed in a $12'' \times 7'' \times 8''$ box containing the hardware to control the injected current and the temperature of the diode lasers. Each array is coupled to its own fiber through a cylindrical microlens which transforms the highly asymmetric light of the bare diode array into an axially symmetric beam. The 24 fibers (typically 1– to 5–meters in length) are bundled together, emitting into a 12° cone. The fiber bundle enables light to be delivered several meters from the LDA, allowing, for example, the laser to operate at a distance from a high field NMR magnet while the light is provided to an optical pumping cell in the fringe field or bore of the magnet. A typical optical pumping cell used in these experiments is a 100 cm^3 pyrex cell containing Rb vapor and ^{3}He or ^{129}Xe gas at a pressure of several atmospheres, together with approximately 100 torr of N_2. The cell is heated to 80–150°C and the noble gas is polarized by spin–exchange collisions with Rb vapor atoms that have been spin–polarized by depopulation optical pumping driven by circularly polarized light from the LDA [1]. The Doppler broadened Rb absorption line (250 MHz) is further pressure broadened by the N_2 and noble gas by roughly 15 GHz/atm to widths of ≈ 50 GHz. Nevertheless, the 1–2 THz linewidth of the LDA is substantially broader than the pressure–broadened Rb absorption line (Fig. 1); thus less than 10% of the light is typically resonant with the Rb. Given this poor photon–efficiency, understanding the spectral structure and temporal stability of Opto Power LDAs is critical for maximizing the useful output light, and hence the rate of noble gas spin–polarization. To characterize the LDAs, we studied 11 units of the same model, looking at the dependence of the output spectra on diode temperature and current, total power, linewidth, time and age (see Table 1). Our ensemble of LDAs included lasers that had been used for less than ten hours as well as lasers that had been used for several years with "on" times up to 6800 hours (3/4 of a year).

Additionally, we present in this paper a method for simultaneously stabilizing the total power from an LDA and the power resonant with the Rb D_1 transition. Drifts in the LDA wavelength and power can lead to changes in the Rb magnetization and therefore the noble gas polarization in an optical pumping cell. By measuring the Rb magnetization and adjusting the laser operating point, the Rb magnetization in an optical pumping cell may be kept constant to within one part in one thousand.

2 Experimental setup

Opto Power LDAs were characterized using a power meter [8] and a Fabry-Perot cavity [9] of free spectral range (FSR) 2 THz (4 nm). The cavity had a finesse of approximately 100 corresponding to a resolution of 20 GHz. In most of our studies (Fig. 2), the beam from the fiber bundle was expanded with a telescope such that the individual elements of the fiber bundle were resolved. The beam was then steered with a mirror and an X–Z translational stage onto a pinhole which was used to select one fiber from the 24 in the bundle. In some studies we focussed the full beam from the 24 fibers through the pinhole. In all cases, the light passing through the pinhole was then reflected into the Fabry-Perot cavity.

A single–mode diode laser with spectral width (< 4 MHz) much smaller than the 20 GHz resolution of the Fabry-Perot cavity was used for spectral calibration. The calibration light entered the cavity in parallel with the LDA light by reflection from a beam splitter (Fig. 2). The absolute wavelength of the calibration laser was determined by observing fluorescence from a rubidium vacuum cell. The Rb absorption in the vacuum cell has a Doppler profile (≈ 250 MHz) that is much narrower than the resolution of the Fabry-Perot cavity.

If the LDA wavelength is changed by one FSR of the Fabry–Perot cavity (4 nm), the measured spectrum remains unchanged. Therefore, a mechanism

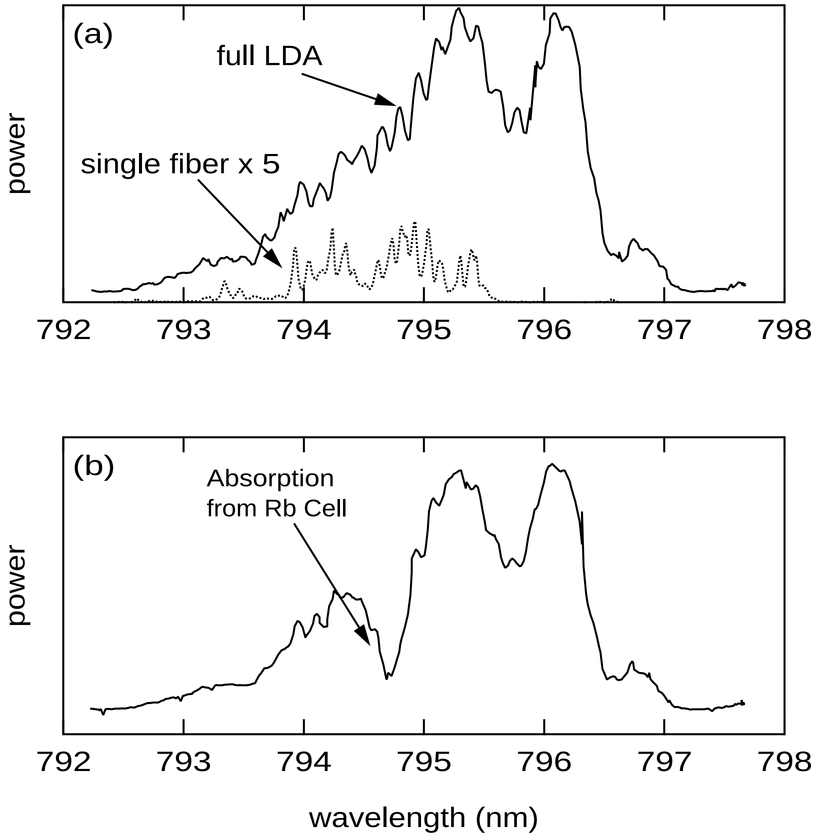

Figure 1: Typical Opto Power LDA spectra: (a) all 24 fibers (solid line) and a typical single fiber (dotted line) with the power multiplied by 5; and (b) all 24 fibers after passing through a Rb absorption cell that is pressure broadened with one atmosphere of nitrogen and heated to $\sim 100^\circ$ C.

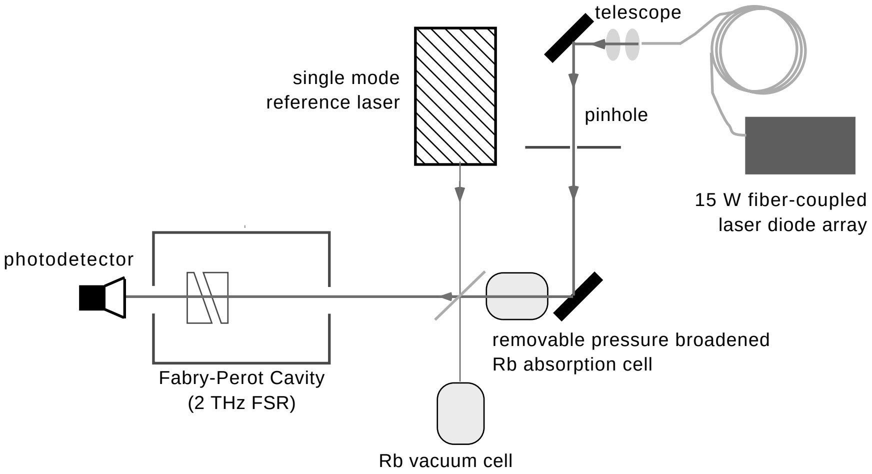

Figure 2: Schematic of LDA characterization setup

was needed for determining the absolute wavelength of the LDA. To this end, a Rb cell pressure broadened to $\sim$ 15 GHz with approximately 1 atm of N_2 (see Fig. 1b) was inserted in the path of the LDA. The absorption dip allowed us to tune the LDA onto the Rb resonance, guaranteeing that the LDA and the single–mode laser were in the same FSR of the Fabry–Perot cavity. After this procedure, the Rb cell was removed from the light path so that the LDA spectrum could be measured, free of Rb absorption.

3 Results

Among the 11 Opto Power fiber–coupled LDAs in the test ensemble (see Table 1), we measured the maximum output power to vary from 9 to 15 watts for diode currents of 25 amps, with an average of 12.8 watts. These powers are somewhat less than the value of 15 watts specified by Opto Power. We measured the threshold current (i.e., the current necessary to observe any output optical power) to vary from 6 to 9 amps for different LDAs. We did not find a correlation between the maximum output power and the age or operational lifetime of the LDA, or any information supplied by the manufacturer.

The measured LDA spectral structure is not smooth (e.g., see Fig. 1a). Each of the 24 diode arrays emits in many modes. External cavity effects from the fiber–coupling may further complicate the spectrum, which we found to be sensitive to strains on the fiber bundle at the connection to the microlens and LDA. The net spectrum from all 24 fibers of an LDA, while much smoother than that from individual fibers and diode arrays, is still irregular and a line center cannot be simply extracted by a fitting procedure. Instead, we defined the line center by integrating the spectrum of the LDA and locating the median wavelength such that half the LDA power is at longer wavelengths and half is

Table 1: Measured properties of the ensemble of studied LDAs. (Starred entries were not measured.)

laser	age months	operating hours	total power (watts)	$\frac{\partial\lambda}{\partial \mathrm{T}}$ (nm/°C)	$\frac{\partial \mathrm{P}}{\partial \mathrm{T}}$ (W/°C)	$\frac{\partial\lambda}{\partial \mathrm{I}}$ (nm/A)	$\frac{\partial \mathrm{P}}{\partial \mathrm{I}}$ (W/A)	linewidth (nm)
1	28	7578	13.8	0.25	-0.30	0.23	0.47	1.8
2	28	1083	10.6	0.19	-0.10	0.25	0.33	2.0
3	26	728	11.1	0.34	-0.31	0.18	0.39	1.3
4	28	6841	9.0	0.36	-0.22	0.30	0.43	1.5
5	25	*	13.9	0.41	-0.36	0.29	0.68	1.0
6	25	141	13.4	0.35	-0.24	0.32	0.38	1.7
7	25	1461	*	0.38	-0.22	0.42	0.29	3.1
8	25	47	13.0	0.34	-0.29	0.34	0.53	4.6
9	20	555	12.1	0.24	-0.10	0.30	0.24	1.3
10	0	10	14.9	0.20	-0.43	0.18	0.60	1.3
11	6	*	13.7	0.32	-0.15	0.28	0.75	1.5
Avg	21	2049	12.6	0.31	-0.25	0.28	0.46	1.9

at shorter wavelengths.

For optimal use of the LDAs in spin–exchange optical pumping of noble gases, it is crucial that both the diode current and temperature (i.e., the "operating point") be set such that the LDA's line center wavelength (or maximum power wavelength) is near the Rb resonance (i.e., within ~ 50 GHz). The measured operating points for our 11 LDAs differed by up to 7 amps and 5 degrees. The current tuning coefficients found in determining the LDA operating points varied from 0.18 nm/A to 0.42 nm/A for different LDAs The dependency of total radiated power on diode current varied from 0.24 W/A to 0.75 W/A for different LDAs (corresponding to a fractional change that varies from 2.0 %/A to 5.5 %/A). Both the wavelength and the power saturated at large currents. (Typical data from a single LDA fiber is shown in Fig. 3.) Thus, the smaller current tuning coefficients correspond to operating points closer to saturation of the LDAs. Temperature tuning was found to vary from 0.19 nm/°C to 0.38 nm/°C for different LDAs at our measured operating points, in rough agreement with the nominal value of 0.3 nm/°C provided by Opto Power. The dependency of power on diode temperature varied from -0.10 W/°C to -0.43 W/°C for different LDAs (corresponding to a fractional change in full power ranging from -0.8%/°C to -2.9%/°C). Note that in varying the current and temperature of the Opto Power LDAs over their full ranges, both typically provided 4 to 5 nm of tuning range.

We determined the LDA linewidth in a similar manner to the center wavelength. A measured spectrum was integrated to determine the wavelengths below which 16% and 84% of the LDA power resided. The difference of these two wavelengths was defined to be the linewidth, as it contains 68% of the LDA power. The manufacturer's nominal linewidth for this model LDA is 2 nm. Observed linewidths for different LDAs ranged from 1.0 up to 4.3 nm (see Fig. 4) with a mean of 1.9 ± 1.0 nm. These linewidths are not correlated with laser age or operational lifetime. We measured light emitted from individual fibers to have linewidths varying from 1 to 2 nm (see Fig. 1a). The line centers of the

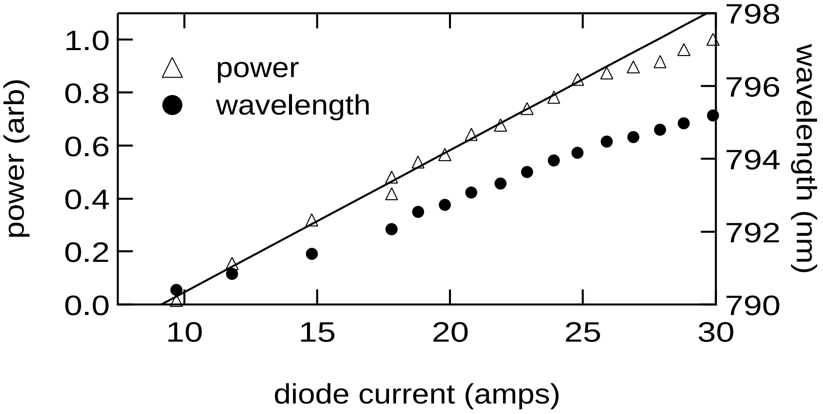

Figure 3: Typical dependence of the wavelength and power on diode current. The data is from one LDA fiber. Note the saturation effects at high currents (i.e., deviation from the straight line, added as a guide to the eye).

individual fibers also varied by 1 to 2 nm. Therefore, the net LDA linewidth is determined both by the spectral width of each of the 24 diode arrays and by the differences in center wavelengths between diode arrays, with roughly equal contributions.

Temporal stability is important for efficient use of the LDAs. Because of the irregular spectral structure of the LDAs, small fractional changes in the center wavelength (~ 0.1 nm) can have large effects on the Rb optical pumping rates and hence on the noble gas polarization rate. We monitored the spectra of each of the 11 LDAs for 2–15 hours. Drifts in the center wavelength of the LDAs varied from less than 0.02 nm/hour up to 0.2 nm/hour (see Fig. 5). The largest observed deviations from the set wavelength over any period of time were ~ 0.5 nm. We also observed drifts of up to 10% in the total LDA power over these periods. The mechanisms which degrade the wavelength stability and lead to these large drifts are not all understood, but can include operating the LDA in an environment too hot for the temperature regulator ($\gtrsim 27$°C).

4 Stabilizing the LDA Spectrum

As discussed above, we measured the center wavelength of free–running Opto Power LDAs to drift by up to 0.2 nm/hour, corresponding to a change in power resonant with the Rb D_1 line of at least 5%. In a cell in which the the Rb is not fully electron spin polarized, this LDA power drift can lead to significant changes in the Rb polarization (P_{Rb}). Changes in the total LDA power incident upon the cell can also effect the cell temperature and thus the rubidium vapor density (n_{Rb}). These two parameters determine the noble gas nuclear spin polarization

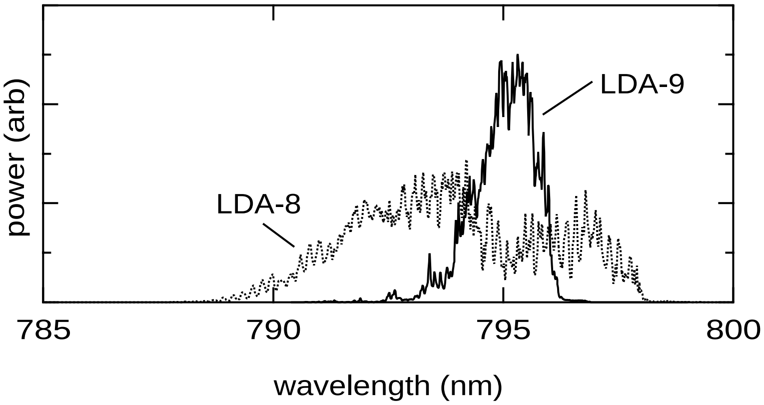

Figure 4: Extremes of spectral widths from the ensemble of 11 Opto Power LDAs used in the present study. LDA–9 has a linewidth of 1.3 nm and LDA–8 has a linewidth of 4.6 nm.

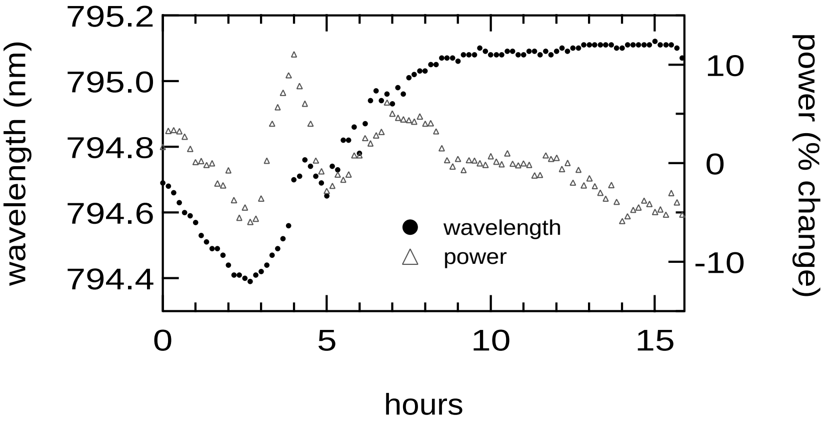

Figure 5: Typical temporal stability of an Opto Power LDA. Stable and unstable periods like those shown here were observed in many of the LDAs studied.

(P) induced by spin exchange collisions with the rubidium vapor which is given by

$$P = \frac{P_{Rb}\ \gamma_{se}}{\gamma_{se} + 1/\mathrm{T}_1} \tag{1}$$

where T_1 is the polarization lifetime of the noble gas set by interactions with cell walls, etc., and γ_{se} is the rubidium–noble gas spin–exchange rate which is proportional to n_{Rb}. Drifts in both the resonant and nonresonant LDA power can thus lead to significant changes in the noble gas polarization. This polarization drift will also change the net magnetic field created by the noble gas spin ensemble, thereby affecting their Larmor frequency (for non–spherical cell geometries), as well as the Larmor frequency of other species that are nearby or intermingled. To reduce these systematics in the dual noble gas maser (DNGM) [3, 10] – a precision measurement device containing intermingled ^{3}He and ^{129}Xe – we developed a two–loop feedback technique to stabilize both the total output power of the LDA and the power on the Rb resonance. Minor modification of the Opto Power LDA was required to enable remote electronic adjustment of the current and temperature setpoints [11]. This technique can be generally applied to stabilize the Rb magnetization in any cell being optically pumped by a temperature– and current–tunable LDA (see Fig. 6).

The first feedback loop (Fig. 6a) monitors the total power from the LDA with a chopper and a photodetector sampling a small fraction of the light using a beam splitter. A diffuser in the light path between the chopper and photodetector reduces the sensitivity of the measured LDA power to beam steering drifts. The current injected into the LDA is adjusted to maintain constant power on the photo-diode. By this technique we control the total emission power of the LDA to a fractional stability of a few parts in 10^4, roughly an order of magnitude more stable than in free-running operation. This maintains a constant heat load on the Rb/noble gas sample cell due to illumination by the LDA, reducing fluctuations in the cell temperature and thus the Rb density.

A second feedback loop directly controls the Rb magnetization. With a slight sacrifice in total Rb magnetization, this loop stabilizes the Rb magnetization by adjusting the temperature of the LDA. First, the temperature of the LDA is adjusted to detune the LDA light slightly away from its optimal value so that a change in temperature will vary the LDA light intensity resonant with the Rb atoms. Then, a weak transverse oscillating magnetic field is applied to the Rb/noble gas cell at the Zeeman frequency of the Rb atoms ($\nu = 687$ kHz in our experiment at 1.0 Gauss) and modulated at a slow rate (a few hundred hertz). The resonant field reduces the Rb spin polarization slightly ($\sim 5\%$ is sufficient), thereby increasing the absorption of the LDA optical pumping light in proportion to the magnetization of the Rb atoms in the cell. The LDA light transmitted through the cell passes through a diffuser (Fig. 6a) and is then incident upon a photodetector. The diffuser both reduces the beam intensity (to prevent potential saturation of the photodetector) and performs a spatial average over the light from various fibers of the LDA and over refractive distortions introduced by the glass cell. Lock–in detection at the Zeeman modulation

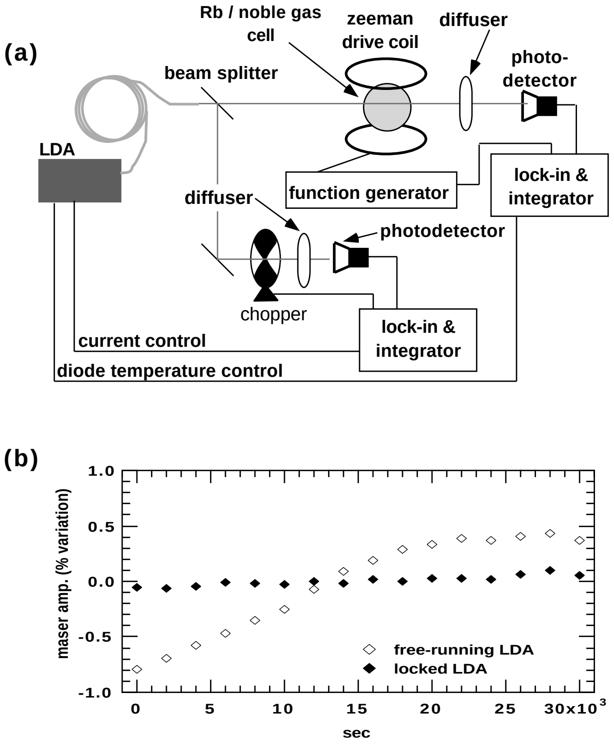

Figure 6: (a) LDA stabilization scheme. Two feedback loops maintain constant total LDA power and Rb magnetization. (b) When both loops are locked, noble gas maser amplitude is an order of magnitude more stable than with a free running LDA.

frequency is used to determine a signal proportional to the Rb magnetization. This magnetization signal allows the temperature of the LDA to be adjusted to maintain a constant average Rb magnetization.

The two–loop feedback technique produces a fractional stability of the Rb magnetization between $0.8 - 2.0 \cdot 10^{-3}$ as measured by the output signal from the feedback loop. This is an improvement in Rb magnetization stability of roughly a factor of 10 over the free running LDA. Independent confirmation of stable Rb magnetization is provided by the improved amplitude stability of the dual noble gas maser (DNGM). Maser amplitude depends sensitively on noble gas (and thus Rb) polarization. Figure 6b shows the typical observed improvement in maser amplitude stability of more than an order of magnitude when the LDA stabilization technique is employed. In the DNGM, LDA stabilization has contributed to significant improvements in maser frequency stability [10].

5 Conclusions

High power fiber–coupled LDAs manufactured by Opto Power, Inc. are widely used sources of light for optical pumping of Rb in spin–exchange applications. We have characterized the spectra and performance of an ensemble of 11 such LDAs, and found them to vary considerably in output power, spectral width, and other important characteristics, in a manner not correlated with age, operating lifetime or information supplied by the manufacturer. We observed spectral widths for different LDAs that varied from 1.3 nm to 4.6 nm, with an average of 1.9 nm. We also measured the maximum power from different LDAs to range from 9 to 15 W with an average of 12.8 W. The performance of the LDAs for Rb optical pumping applications can be improved using two–loop active feedback, including a probe of the Rb magnetization, to stabilize the total LDA power and the power resonant with the Rb atoms. Finally, we note that we are developing injection–locking techniques [12] that may reduce the LDA linewidth to be less than the Rb absorption linewidth [13].

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