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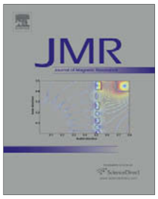

Communication

Generation of laser-polarized xenon using fiber-coupled laser-diode arrays narrowed with integrated volume holographic gratings

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ABSTRACT

Volume holographic gratings (VHGs) can be exploited to narrow the spectral output of high-power laser-diode arrays (LDAs) by nearly an order of magnitude, permitting more efficient generation of laser-polarized noble gases for various applications. A ~3-fold improvement in ^{129}Xe nuclear spin polarization, $\boldsymbol{P}_{\mathrm{Xe}}$, (compared to a conventional LDA) was achieved with the VHG-LDA's center wavelength tuned to a wing of the Rb D_1 line. Additionally, an anomalous dependence of $\boldsymbol{P}_{\mathrm{Xe}}$ on the xenon density within the OP cell is reported—including high $\boldsymbol{P}_{\mathrm{Xe}}$ values (>10%) at high xenon partial pressures (~1000 torr).

1. Introduction

Alkali-metal spin exchange optical pumping (AMSE OP)[3] can generate high nuclear spin polarization in noble gases [1] for a variety of NMR/MRI [2,3] and fundamental physics [4] applications. While different types of light sources have been used to prepare spin-polarized gases via AMSE OP (e.g., Refs. [1–12]), laser-diode arrays (LDAs) have become increasingly dominant because of their high photon flux, low costs, and operational simplicity. However, a key drawback of conventional LDAs is the poor quality of the emitted light—particularly the breadth of their spectral output (~2–3 nm) compared to atomic lines. The resulting low absorption efficiency can necessitate high incident powers (up to hundreds of Watts), presenting thermal-management problems. Moreover, while this low absorption efficiency can be mitigated by pressure-broadening the alkali spectral line [7,13], this practice brings on its own complications. To combat these problems, two methods have been developed to constrict the LDA wavelength range: external cavity narrowing [14–16], and more recently—volume holographic grating (VHG) narrowing [17].

Here we report our preliminary investigations of the use of VHG-narrowed LDAs to prepare laser-polarized xenon. Two fiber-coupled LDAs with integrated VHGs provided dramatically narrowed spectral output with high power efficiencies and low costs—allowing more efficient absorption under relatively mild in-cell conditions. Optimal OP (corresponding to a ~3-fold improvement in ^{129}Xe nuclear spin polarization, $\boldsymbol{P}_{\mathrm{Xe}}$) was achieved with the VHG-LDA's center tuned to the wing of the Rb D_1 line rather than the center [18,19]. Additionally, changes in the transmitted laser intensity were observed upon magnetic field cycling—enabling an *in situ* estimate of the Rb electronic spin polarization ($\boldsymbol{P}_{\mathrm{Rb}}$) [8]. Finally, we report an anomalous dependence of $\boldsymbol{P}_{\mathrm{Xe}}$ on the Xe density within the OP cell ($[\mathrm{Xe}]_{\mathrm{cell}}$)—including unexpectedly high $\boldsymbol{P}_{\mathrm{Xe}}$ values (>10%) at high Xe partial pressures (~1000 torr). These results demonstrate the utility of VHG-narrowed sources for both fundamental AMSE OP studies and hyperpolarized gas applications.

2. VHG-LDAs: background and experimental details

External cavity narrowing [14–16] employs planar dispersive gratings to provide feedback to the individual LDA elements; however the optical alignment is critical to maintain feedback to all the elements to ensure acceptable spectral quality and energy effi-

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[3] *Non-NMR Abbreviations:* AMSE OP, alkali metal spin-exchange optical pumping; $\boldsymbol{P}_{\mathrm{Xe}}$, xenon nuclear spin polarization; $\boldsymbol{P}_{\mathrm{Rb}}$, rubidium electron spin polarization; $[\mathrm{Xe}]_{\mathrm{cell}}$, xenon in-cell density; VHG, volume holographic grating; LDA, laser diode array; **VL1**, VHG-narrowed LDA '1'; **VL2**, VHG-narrowed LDA '2'; VBG, volume Bragg grating; ECDL, external cavity diode laser; FWHM, full width at half maximum; TEC, thermoelectric cooler; FAP-B, fiber array packaged bars; CP, circular polarizer; SAC, slow-axis collimation; FAC, fast-axis collimation; LP, laser polarized; HC, Helmholtz coil pair.

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ciency (typically ∼40–66% [15,16]), and whether the gratings can withstand sufficiently high intensities is questionable [15]. Alternatively, VHGs (a.k.a. volume Bragg gratings (VBGs)) can achieve LDA spectral narrowing with efficiencies exceeding 90% [20]. VHGs are bulk slabs of photosensitive glass [21] containing Bragg planes of varying index of refraction; in a VHG-based external-cavity diode laser array (VHG-ECDL, Fig. 1(a)) [22], the VHG retro-reflects a narrow band of the laser emission into the LDA elements, forcing them to lase at the injected wavelength. Barlow et al. recently reported a 120 W VHG-ECDL with output near the Rb D_1 (794.76 nm) and with a FWHM of 0.24 nm [17].

Details concerning the LDA light sources utilized here are provided immediately below (other experimental aspects are summarized in Section 5). Both VHG-LDAs used in the present work are engineering prototypes from Spectra-Physics/Newport ('**VL1**' is a "Comet" VHG-LDA module, and '**VL2**' is an "Integra" turn-key laser system). **VL1** was mounted to the same TEC / heat sink used by our original 40 W 'standard' LDA (Coherent FAP-B), is driven with the same 65 A diode and TEC-drivers (Newport), and fiber-couples to the same circular-polarizer (CP) optics box (Coherent). **VL1** employs additional slow-axis collimation (SAC) and achromatic lenses after the VHG (thickness: 1.5 mm[21]) to focus the 19 frequency-locked laser elements into a single-core 200 μm silica-clad fiber; **VL1**'s spectral profile is narrowed by nearly an order of magnitude compared to that of our previous LDA (Fig 1(b)), while providing nearly the same power.

VL2 combines two VHG-LDA modules (each similar to **VL1)** but with simplified optical arrangements: Instead of using FAC or SAC lenses, individual optical fibers (400 μm) are brought within ∼600 μm of each laser element (giving 19 fibers/module). The close proximity ensures that each diverging fast-axis beam is launched into its fiber, but requires each module's VHG (placed between the LDA elements and the fibers) to be thin (500 μm)—yielding somewhat reduced spectral narrowing and lineshape quality (Fig. 1(b)). Obtaining the optimal spectral output from **VL2** required overdriving the current (∼104%), giving nearly twice the power of **VL1**—albeit with nearly twice the spectral width.

The 1 m optical fibers used with **VL1** and the standard LDA maintain much of their original linear polarization; this 'memory' of the LDAs' polarizations affects the power ratio of the two side-by-side circularly-polarized beams emitted from the CP box—causing the ratio of the beam intensities to be sensitive to the strain on the fiber. For the 'standard' LDA, **VL1**, and **VL2**, the nominal beam intensity ratios (straight vs. angled) were ∼72:28, ∼80:20, and ∼55:45, respectively (because of its design, **VL2**'s beam ratio is much closer to unity and less amenable to variation by fiber straining).

Whereas tuning of conventional LDAs may be achieved by varying the LDA temperature (∼0.3 nm/°C), the nature of the VHG feedback makes tuning VHG-narrowed LDAs a non-trivial function of LDA temperature and VHG temperature (itself primarily determined by the laser power). A change in the VHG temperature induces a slight change in the element spacing within the VHG, altering the laser's spectral profile. For example, increased driving current for **VL1** (Fig. 2(a)) provides greater laser flux in addition to red-shifting of the centroid towards the Rb D_1 center (∼0.1 nm/amp, with operational range of ∼0.3 nm); the linewidth also increases. As with **VL1**, the output for **VL2** red-shifts with increased current, but at a reduced rate (∼0.006 nm/amp, as a consequence of its design differences); at 94 A (i.e., 47 A/diode, 100% current, 51.6 W at cell) the centroid is ∼(−)0.18 nm from the Rb D_1 ('blue' side) with a diode temperature of 25 °C, and ∼0.09 nm from D_1 at

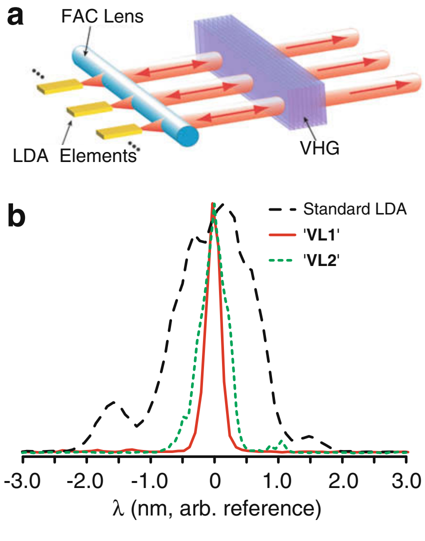

Fig. 1. (a) Key components of VHG-narrowed LDAs. (b) Normalized output of a standard fiber-coupled LDA (Coherent FAP-B; black, dashed), **VL1** (red, solid), and **VL2** (green, dotted). Conditions: standard LDA: ∼32 W (at 47 A), $\Delta\lambda_{FWHM} \approx 2$ nm, $\lambda_{max} \approx 795$ nm; **VL1**: ∼26 W (at 50 A), $\Delta\lambda_{FWHM} = 0.27$ nm, $\lambda_{max} = 794.62$ nm; **VL2**: ∼55 W (at 96 A), $\Delta\lambda_{FWHM} = 0.49$ nm, $\lambda_{max} = 794.65$ nm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

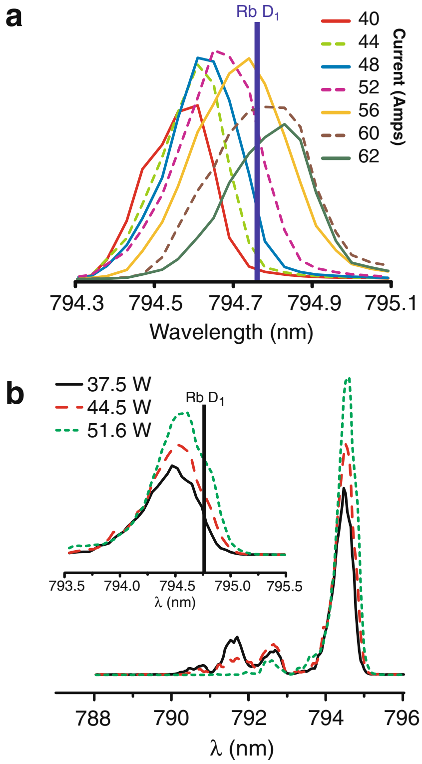

Fig. 2. (a) Spectral output of **VL1** as a function of laser diode driving current, showing the lineshape broadening and red-shifting ($\Delta\lambda \sim 0.3$ nm) of the centroid as the laser power increases. FWHM examples: at 40 A: ∼0.24 nm; 52 A: ∼0.27 nm; 62 A: ∼0.33 nm. Position of Rb D_1 at 794.76 nm (air referenced) is included for comparison. (b). Spectral output of **VL2** as a function of laser diode driving current (37.5 W: black; 44.5 W: red; 51.6 W: green). Overall lineshape improves with increasing driving current up to its maximum value, and is slightly red-shifted. *Inset:* Close-up view of **VL2** laser output near the Rb D_1 line. The less-efficient implementation of the VHG into the design of **VL2** (due in part to the requirement of using thinner VHGs) results in reduced lineshape quality at lower driving currents, particularly regarding the presence of additional features some distance from the main line—indicative of incomplete VHG locking. Such features were not minimized until **VL2** was driven at 104% current (96 A, 54.5 W at cell; not shown). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)