Spectrally narrowed external-cavity high-power stack of laser diode arrays

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We describe an effective external cavity for narrowing the spectral linewidth of a multiarray stack of laser diode arrays. For a commercially available 279-W free-running five-array laser diode array operating at 60 A, we narrow the spectral linewidth to 0.40 nm at FWHM with 115 W of cw power output. This technique leads to the possibility of higher-efficiency, lower-cost production of hyperpolarized noble gases for magnetic resonance imaging. © 2005 Optical Society of America

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A low-cost, high-power laser diode array (LDA) can produce powers up to 100 W by integrating many individual laser diode emitters into a single array. Recent developments in production of large volume hyperpolarized xenon for magnetic resonance imaging[1] (MRI) through spin-exchange optical pumping[2] (SEOP) increasingly call for high-power and narrow-bandwidth laser light. The large spectral width, typically approximately 2–4 nm, of the LDA limits the power that can be absorbed by the alkali atoms during SEOP. The traditional method of increasing the amount of power absorbed by the alkali atoms in ^{3}He SEOP is to increase the pressure in the pumping cell and thereby broaden the Lorentzian-shaped atomic absorption lines. Difficulties arise for a new generation of xenon polarizers to produce large volumes of hyperpolarized xenon with the xenon flowing through a polarization column with pressure typically below 1 atm.

Recently, it was demonstrated that appropriately designed external cavities can be used to frequency narrow a single high-power LDA.[3] The technique increases the density of the spectral power (power contained within spectral FWHM) at the wavelength at which the SEOP takes place. With much higher power available from a multiarray stack of laser diode arrays, typically in the kilowatt regime, it is clearly of interest to narrow the output spectral linewidth of the LDA stack and further increase the effectiveness of the SEOP process.

In this Letter we describe an external-cavity technique that can be used to frequency narrow a multiarray LDA stack for SEOP of hyperpolarized xenon. A typical high-power LDA stack, such as Nuvonyx PA-332,[4] consists of five approximately parallel LDAs with a 2.2-mm array pitch distance. Each array consists of 49 optically independent emitters. The emitters are 100 μm wide on a 200-μm center, spaced in an approximately straight line across a 1-cm-wide array. The deviation from the linearity of the emitter arrangement is referred to as array smile. The LDA stack is capable of delivering a full power of 279 W at a current of 60 A. The compactness and astigmatism of the laser diode emitter result in large beam divergence,[5] typically with diffraction-limited divergence angles of 38° perpendicular to the array (fast axis) and 10° parallel to the array (slow axis). A 0.91-mm focal-length cylindrical microlens is used to collimate the rapidly diverging light along the fast axis and reduce its divergence angle to below 0.10°. The slow-axis divergence remains uncollimated. At full power the beam from the LDAs has a polarization parallel to its laser junction with an extinction ratio of better than 20 dB.

The principle used in an external cavity to frequency narrow a LDA stack is that light from each emitter needs to be approximately collimated, reflected off a diffraction grating at a uniform angle, and imaged back onto the emitter with high efficiency. The laser output is taken from the specular reflection or zeroth-order diffraction off the grating. Because of the beam divergence in the slow axis, array smiles, and the lack of parallelism of the arrays along the fast axis, it is necessary to use an afocal magnifying lens combination or telescope to reduce the angular spread. It has been shown[3] that the contributions to the linewidth from the smiles and the divergence are inversely proportional to the telescope magnification and the square of the magnification, respectively.

Our LDA stack external-cavity arrangement is shown in Fig. 1. We constructed a telescope with a magnification of 2 from a 250-mm focal-length achromat and a 500-mm focal-length plano–convex lens. A 75 mm by 140 mm copper substrated Richardson holographic diffraction grating with 1800 lines/mm provided the optical feedback to the LDAs. The grating has a first-order diffraction Littrow angle of 45.7° at the 794.7-nm wavelength, corresponding to the $D1$ absorption line of the rubidium used for SEOP. The grating has groove orientations parallel to the slow axis of the LDAs. The temperature of the grating is controlled by a thermoelectric cooling module. An orientation-variable half-wave plate located inside the external cavity allows the rotation of the beam polarization and is used to maximize the power output.

We tested two innovations with this external-cavity arrangement. We implemented a rectangular collimator in the intermediate focal point of the external cavity on the slow axis to reduce divergence and increase brightness so that more laser power was

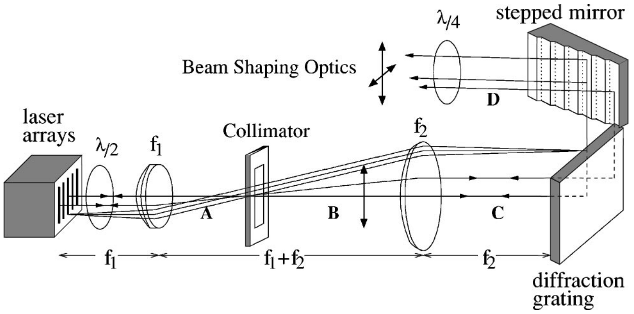

Fig. 1. Schematic of the LDA stack external-cavity arrangement with selected rays.

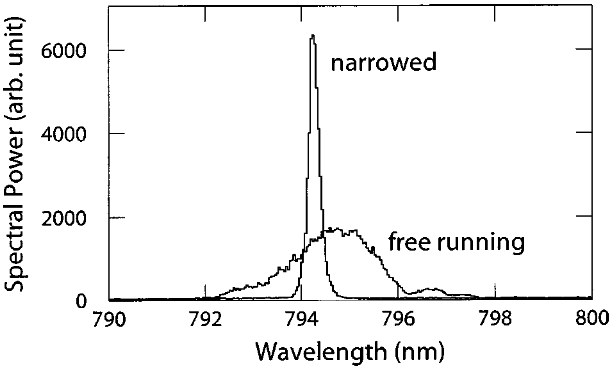

Fig. 2. Comparison between free-running and spectrally narrowed LDA stack external-cavity laser linewidths.

concentrated into spatial modes that passed through the collimator. No additional fast-axis collimation was needed. The size of the collimator aperture, 0.5 cm along the fast axis and 3.5 cm along the slow axis, was determined by the slow-axis beam divergence and the fraction of the power that it blocks. The slow axis beam divergence was significantly reduced by the collimator, but only approximately 10% of the laser power in the cavity was blocked. We then developed and fabricated a gold-plated stepped mirror for increased intensity and beam uniformity. The stepped mirror provides individual reflective elements for each of the LDAs such that the dark areas caused by array pitch distance are substantially removed with minimum loss of laser power. The step width and step height were determined by the light and dark bandwidth of the incident beam measured at the location of the stepped mirror, the direction of the incident and reflected beams, and the uniformity requirement of the reflected beam. The step width is fixed once the mirror is sliced, but the step height can be finely adjusted through a custom-designed mirror mount.

The spectral output of the external-cavity laser is measured by an Ocean Optics 2000 high-resolution miniature fiber-optic spectrometer with a spectral resolution of 0.07 nm. The output laser beam is analyzed for each individual array and for all five arrays combined after being focused onto a glass diffuser. Figure 2 shows a comparison between the free-running and the external-cavity narrowed laser spectra at 20 A. The linewidth for all five arrays combined is 0.31 nm FWHM. The spectral power of the narrowed laser is approximately 3.5 times that of the free-running laser. The linewidth of the narrowed light for each individual array is typically from 0.22 to 0.47 nm FWHM, as shown in Fig. 3. The linewidth of all five arrays combined increases to 0.40 nm FWHM at 60 A. The LDA stack is not selected by the manufacturer for strict requirement on array smiles and the parallelism of the five LDAs along the fast axis. Figure 3 indicates that the linewidth varies significantly from array to array with the middle LDA (Array 3) having the largest linewidth. We measured the smiles by using a 15-cm focal-length cylindrical lens to image the slow axis onto a screen at a distance of 76 cm from the LDAs. The image captured on a digital camera for a low current of 10 A is shown in Fig. 4. It confirms that the middle LDA has the largest smile. The parallelism of the five collimated beams is adequate, so the contribution to the linewidth of all five arrays combined is insignificant. The grating depth of field, defined as the difference in path length for arrays imaged at the near edge and arrays imaged at the far edge of the grating, for our LDA stack is 19.4 mm. Our results indicate that the depth of field had an insignificant contribution to the linewidth of all five arrays combined.

The external-cavity laser power output is measured by a water-cooled Molectron PM150-50C laser powermeter. The grating S-plane (electric vector perpendicular to the grooves) efficiency is typically much higher than that of the P plane (perpendicular to the S plane)[6]; therefore the maximum output power occurs when the specular reflection from the grating is linearly polarized in the P plane. A maximum of 115 W of linearly polarized light is coupled out of the external cavity at a current of 60 A when a Richardson high-modulation (43% modulation depth) grating is used. Approximately 10% of the power is absorbed by the grating. The Melcor thermoelectric cooling

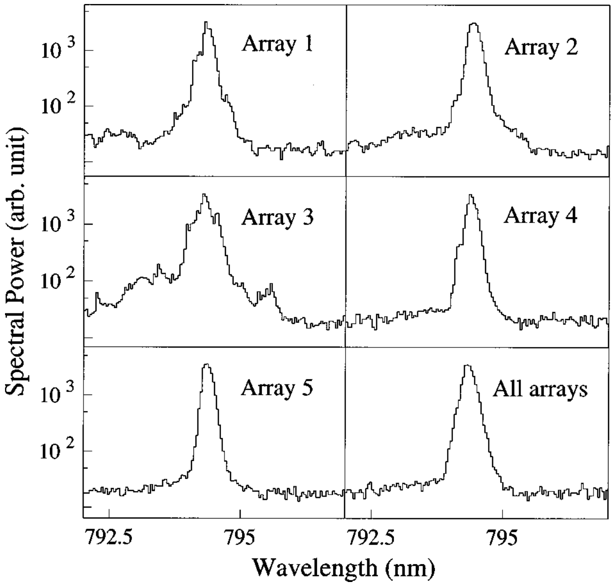

Fig. 3. Spectral linewidth for each LDA and all five LDAs combined.

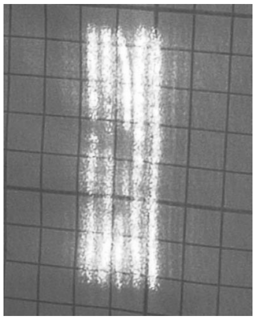

Fig. 4. Photograph showing smiles of PA-332 LDA stack arrays 1–5, left to right, on a 0.5-cm grid graph paper.

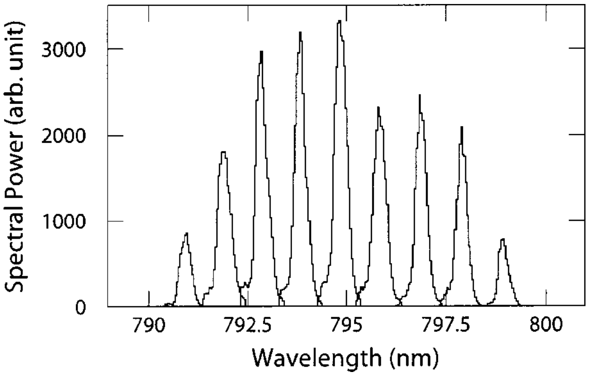

Fig. 5. External-cavity tuning range and the spectral power of the narrowed laser beam.

module along with a CPU fan are capable of maintaining the grating at a constant operating temperature. The external-cavity power output increases to 132 W at 60 A when an Edmund low-modulation (12% modulation depth) grating is used. Both gratings have adequate power feedback to effectively narrow the linewidth; however, beam heating over an extended period of time causes the inexpensive Edmund grating to shatter at currents above 30 A.

The higher the grating *P*-plane efficiency, the lower the cavity power output efficiency. To determine the *P*-plane efficiency of the high- and low-modulation gratings, the power output and feedback within the external cavity at various locations (represented by A, B, C, and D in Fig. 1) is measured with a powermeter in conjunction with a beam sampler. The beam sampler reflection coefficient is carefully calibrated, and the powers coupled out of the laser and feedback from the grating are determined by measuring the reflected power from the beam sampler. The measured *P*-plane efficiencies are 22.8% and 7.1% for high- and low-modulation gratings, respectively.

The Nuvonyx PA-332 LDA stack has a free-running central wavelength of 795 nm with a FWHM of approximately 2.5 nm at 25 °C. The free-running central wavelength increases with the laser operating temperature at 0.25 nm/°C. One of the most attractive features of external-cavity lasers is their wavelength tunability and locking. The external cavity allows a large tunability on the wavelength by diffracting beams back to the laser with a slightly different first-order Littrow angle within the laser tuning range. The external cavity in our application allows as much as 10-nm tuning. As the laser is detuned from its free-running central wavelength, the narrowed spectral power decreases, as shown in Fig. 5.

The external-cavity spectrally narrowed LDA stack is used to polarize xenon for MRI at the University of New Hampshire Center for Hyperpolarized Gas Studies. The skew light caused by the slow-axis beam divergence from the external cavity can reduce the efficiency of the SEOP process[7] and makes using the spectrally narrowed light inefficient. A set of beam-shaping optical elements is designed to control the beam size and divergence. Beam divergence is determined by measuring the beam size at various locations within 3 m downstream. The measured divergence angle is 2° in the slow axis with the collimator in place. A convex–concave lens combination is constructed for both slow and fast axes. The focal lengths are chosen by beam envelope calculations. With the beam-shaping optics the slow-axis beam divergence angle is reduced to 0.2°. The laser beams are completely homogenized with an additional 0.25° holographic diffuser to be uniformly distributed across the xenon polarization column for SEOP. With such a powerful narrowed laser the polarizer is capable of producing hyperpolarized xenon gas at a rate of typically 1.2 l/h with polarization in excess of 45%.[1] This result is comparable with that of using a much more expensive fiber-coupled broad diode laser with nearly twice the amount of power.

In conclusion, we have demonstrated for the first time to our knowledge a low-cost, high-efficiency spectrally narrowed multiarray stack of LDAs and their first applications in hyperpolarizing xenon for MRI. This development can substantially increase the utilization of laser power, particularly for SEOP at low pressure.

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