Development of stable, narrow spectral line-width, fiber delivered laser source for spin exchange optical pumping

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We developed a stable, narrow spectral line-width, fiber delivered laser source for spin exchange optical pumping (SEOP). An optimized external cavity equipped with an off-the-shelf volume holographic grating (VHG) narrowed the spectral line-width of a 100 watt high power diode laser and stabilized the laser spectrum. The laser spectrum showed a high side mode suppression ratio (SMSR) of >30 dB and good long term stability (center wavelength drifting within ±0.01 nm during 220 hours operation). Our laser is delivered by a multi-mode fiber with power ~70 Watts, center wavelength 794.77 nm, and spectral bandwidth of ~0.13 nm.

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1. Introduction

High power laser diodes have been developed for applications including solid-state laser pumping, fiber laser pumping, and material processing. The spectral bandwidth of high power diodes typically spread over the range of 3–5 nm. A narrower emission spectrum in the range of 0.1–0.5 nm and a smaller wavelength tolerance can be extremely beneficial for special applications such as the spin exchange optical pumping (SEOP) [1], which is of great importance in the field of nuclear physics [2], atomic physics [3], laser cooling [4] and neutron scattering [5].

A variety of external cavity techniques have been developed to narrow the spectral line-width of high power diode lasers. Two types of gratings are used to form the external cavity. The diffraction grating external cavity provides a large tunable range of the center wavelength ~10 nm [6-9]. Meanwhile the volume holographic grating (VHG) external cavity has a smaller footprint with a limited tunable center wavelength range of <0.5 nm [10-13]. The resonant wavelength of a VHG can be precisely tuned with temperature control. Using a thick VHG (14-18 mm) one can narrow the spectral line-width down to a few GHz (7-10 GHz) with output power exceeding tens of watts [12, 13]. Lei *et al.* used a 25% reflectivity VHG to control the laser beam collimated in both fast-axis and slow-axis to achieve a narrow spectral line-width around 0.013 nm with SMSR ~20 dB [12]. Gourevitch *et al.* used a higher reflectivity (70%) and larger acceptance angle (1°) VHG to control the laser beam collimated along fast-axis and achieved a narrow spectral line-width of ~0.02 nm with SMSR >30 dB [13]. Due to the low beam quality of high power broad-area laser diodes, it is difficult to effectively couple the laser power into a multi-mode fiber without special beam shaping treatment [12].

High power, narrow spectral line-width diode lasers are useful for optical pumping of alkali metal vapors, typically rubidium. One of the applications is to polarize ^{3}He atoms using SEOP. In SEOP, rubidium outer shell electrons are first polarized via laser, and then the polarization of rubidium is transferred to ^{3}He via hyperfine interaction. A device containing polarized ^{3}He gas can be used as a neutron spin filter (NSF) which is an essential component in polarized neutron scattering experiments. High power, spectral narrowed lasers with good stability are the key to the success of SEOP. In the *in situ* optically pumped NSF demonstrated at the Spallation Neutron Source at Oak Ridge National Laboratory [14], free-space delivered 500 Watts laser diode arrays with 0.6 nm spectral bandwidth were used to perform the optical pumping. However, such laser diode arrays are not the best choice for the high efficiency optical pumping applications. We used a narrower bandwidth (~0.35 nm) and lower powered laser (~200 W) in our recent experiment [15].

In order to achieve highly efficiency optical pumping, the spectral band-width of high power lasers is required to match the pressure-broadened D1 absorption line of rubidium vapor. When the spectral bandwidth of a laser exactly matches the absorption line-width of rubidium vapor, a tiny (10% of spectral line-width) drift of the center wavelength will greatly reduce the efficiency of the laser. The long term stability of the line-width matched laser is crucial for high efficiency *in situ* NSFs based on SEOP. At the same time, a fiber delivered laser is also highly desired for easy integration into an *in situ* SEOP system. The perfect laser for *in situ* SEOP will have specifications listed below: center wavelength precisely aligned to the rubidium D1 absorption line, spectral bandwidth matched with the pressure-broadened rubidium D1 absorption line, long term stability (center wavelength drifting <±0.02 nm in a week), and high power laser delivered using a single optical fiber.

In this paper, we report the design and implementation of a stable, high power, narrow spectral band-width, and fiber delivered diode laser system for SEOP. An off-the-shelf VHG was used to provide the external cavity feedback and narrow the spectral line-width of the diode laser to 0.13 nm. The resonant wavelength of the VHG was aligned to the absorption of rubidium with fine temperature tuning. We modeled and optimized the external cavity with the commercial available ray-tracing software Zemax. The optimal external cavity diode laser has the features of superior efficiency (~95% of total power), high spectrum purity (high SMSR >30 dB), and good long term stability compared to the conventional design. The laser drifting (long term ~220 hour) was around ±0.01 nm. 70 Watts of laser power was delivered by a fiber with core diameter 800 μm, NA=0.22. The entire system was designed as a turnkey system. In the future upgrade, we plan to combine the output of two modules into one optical fiber with polarization beam combining schematic design. The total optical power will reach ~140 W in 0.15 nm spectral bandwidth.

2. Simulation and experiment

Wang *et al.* proposed and implemented a schematic design to narrow the spectral line-width of a high power laser diode array with good beam quality [16]. The beam of laser diodes was collimated by fast-axis collimation (FAC) lens. The laser beam of each diode was rotated by a beam twister followed by a FAC lens [17]. A VHG was posted right after the beam twister to narrow the laser spectral line-width. The collimated laser beam was delivered to pump cesium vapor. This schematic design was adapted to alkali laser pumping [18]. Following the approach of Limo Optics [17], the beam shaping lens pair was added to couple the laser into a multi-mode fiber effectively. Since this design is well-known, we will cite it as the conventional design [12]. Following the procedure of Ref. [15], we were able to simulate the laser beam shaping and the coupling of an optical fiber with Zemax ray-tracing software in the non-sequential mode. The 100 watts water-cooled, laser diode bar with the center wavelength around 797 nm was manufactured by LaserTel. There are 25 laser diodes on one laser bar. The emitter size of each laser diode is 200 μm x 1 μm and the pitch of diodes is 400 μm. Each laser diode object has a spatial power distribution $F(x,y)$ given by $F(x,y)=F(0,0)Exp\left(-2\left[(x/w_x)^{2H_x}+(y/w_y)^{2H_y}\right]\right)$, where x and y are the horizontal and vertical position, respectively; w_x (200 μm) and w_y (1 μm) are the emitter size along x, y direction, respectively; H_x (10) and H_y (1) are the spatial-Gaussian factors. The beam twister manufactured by Limo Optics consists of two parts, an FAC and a 45° tilted cylindrical lenses array [17]. Three cylindrical lenses shape the laser beam and couple it into a multi-mode fiber with a core diameter of 800 μm and with NA=0.22. The parameters of collimation and beam shaping lenses in simulation are similar to the product from Limo Optics. The Zemax simulated schematic design is shown in Fig. 1(a). The laser beam of each individual diode is rotated 90° by the beam twister. The laser beam of each diode is well collimated along the slow-axis (former fast-axis). The divergence of the laser beam along the fast-axis (Y-axis in Fig. 1(b)) remains ~120 mrads and this is confirmed by Zemax simulation. The output of the fiber with a core diameter of 800 μm is shown in Fig. 1(c). We used an off-the-shelf VHG with geometry 15 mm x 5 mm x 1.5 mm manufactured by Ondax, Inc. The VHG is located directly after the beam twister. The center wavelength of the VHG is 794.7 nm with a spectral bandwidth of 0.13 nm and diffraction efficiency of 15%. The temperature of the copper VHG holder is controlled by a temperature electronic controller. The 4% of the output laser from the fiber was sampled by a beam sampler and focused on a diffuser with a 20° diffraction angle. The laser beam passing through the diffuser was refocused and coupled into a multi-mode fiber connected with an Optical Spectrum Analyzer (Agilent 86146B) with a spectral bandwidth 0.07 nm. The spectrum of the laser is shown is Fig. 2. The full-width at half-maximum (FWHM) of the laser spectral line-width is around 0.13 nm. The center wavelength of the laser is 794.77 nm when the temperature of the VHG holder is tuned to 15°C. The output power delivered by a 5-meter long 800 μm core NA 0.22 fiber is 72.2 Watts. Compared with the free running power 72.9 Watts, the optical efficiency of the laser system is ~99%. However, the SMSR is ~9 dB. The acceptance angle of the off-the-shelf VHG is small, around 5 mards [20]. The low SMSR, ~9 dB of the spectrum, is due to the acceptance angle of the off-the-shelf VHG that is not matched with the 120 mrads divergence angle of the laser beam along the fast-axis. Only a small portion of 15% is fed back to lock the spectrum of the laser. The feedback of the VHG is not strong enough to suppress all side modes, especially because the center of gain profile is 2 nm away from the resonant center wavelength 794.77 nm. One possible way to increase SMSR is by replacing the VHG with one with high diffraction efficiency of ~70% and a large acceptance angle of ~30 mrads [13]. The other way is shaping the laser beam to fit the off-the-shelf VHG. We use the latter approach.

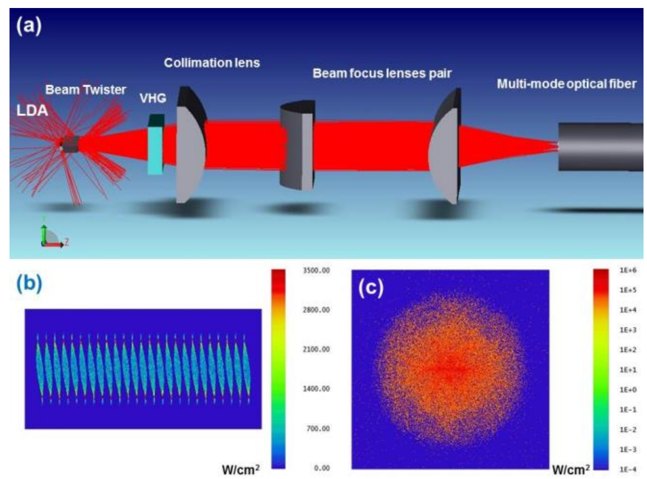

Fig. 1. (Color online) (a) Conventional design for the optical fiber delivered, narrow spectral bandwidth, high power laser diode system. LDA is a linear array of 25 high power diodes. FAC is fast axis collimator. Beam twister is an array of 45° tilted cylindrical lenses used to rotate the laser beam 90°. VHG stands for volume holographic grating. The collimation lens collimates the laser beam along the fast axis. Beam focusing lenses focus the laser beam in both fast and slow axis and couple the laser beam into a multi-mode optical fiber. (b) Image of the laser beam on the surface of the VHG. (c) Output of the optical fiber with efficiency up to 82%, core diameter 800 μm, and NA=0.22.

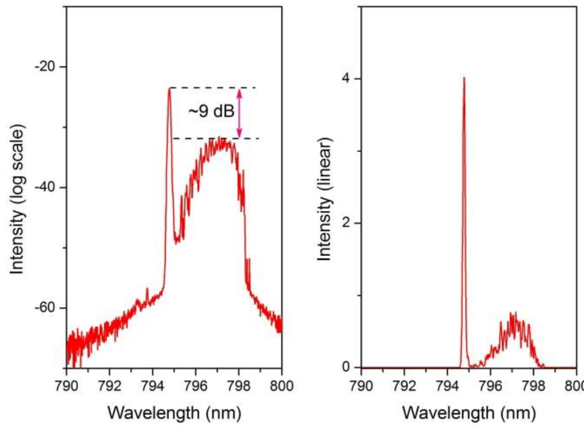

Fig. 2 (Color online) Spectrum of the conventional design for optical fiber delivered, narrow spectral bandwidth, high power laser diode system. VHG with a diffraction efficiency of 15% and bandwidth of ~0.13 nm is used to narrow the spectral line-width of the laser diode array. (a) spectrum of laser diodes (log scale); (b) spectrum of laser diodes (linear scale). The SMSR of the spectrum is ~ 9 dB.

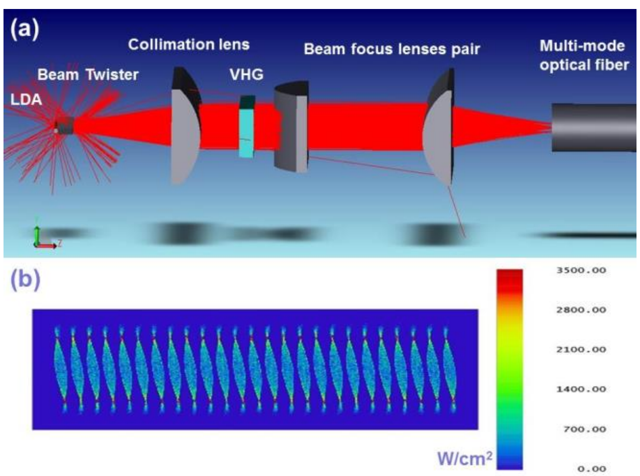

Fig. 3. (Color online) (a) An optimized optical design was simulated by Zemax in non-sequential mode. (b) Image of the laser beam on VHG surface. Laser beam divergence angle along the fast-axis (beam twisted from slow-axis) was reduced to 5 mrads by a collimated lens. This laser beam is well suited to the off-the-shelf VHG.

Based on the simulation of Zemax, the collimation lens collimates the laser beam along the y-axis (fast-axis for the laser diode) and reduces the divergence angle of the laser beam along y-axis to 5 mrads such that the divergence angle of the laser beam matches the acceptance angle of the VHG. Therefore, the VHG provides effective control of the laser diodes. The optimized optical design of the external cavity is shown in Fig. 3. The spectrum of the laser with the optimized external cavity is shown in Fig. 4. The SMSR is significantly increased from 9 dB to more than 30 dB. The side mode is almost invisible in Fig. 4(b) since the intensity ratio of the peak to the side mode is more than 1000. The output power from the optical fiber is 69.5 Watts. Compared with the free running power of 72.9 Watts, more than 95% total power is located in the narrow bandwidth of 0.13 nm. The optimized external cavity effectively locks the center wavelength of the laser with the off-the-shelf VHG.

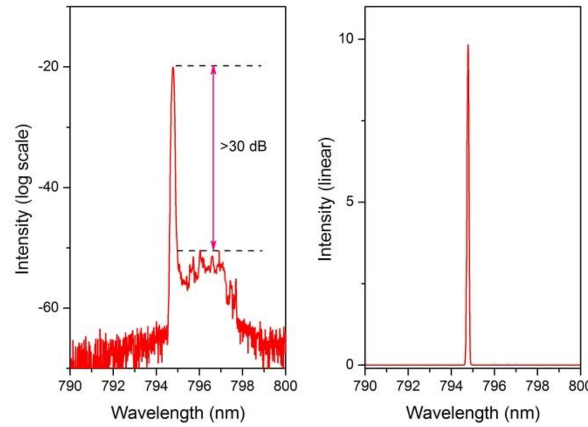

Fig. 4. (Color online) Spectrum of the optimal external cavity laser. (a) log scale; (b) linear scale. The SMSR of the spectrum is >30 dB.

In order to check the tunable range of laser diode system, we tuned the temperature of the VHG holder from 10˚C to 40˚C. The center wavelength was smoothly tuned from 794.714 nm at 10˚C to 794.940 nm at 40˚C. The center wavelength vs the temperature of the VHG holder is shown in Fig. 5. The average tuning rate is 0.0075 nm/K.

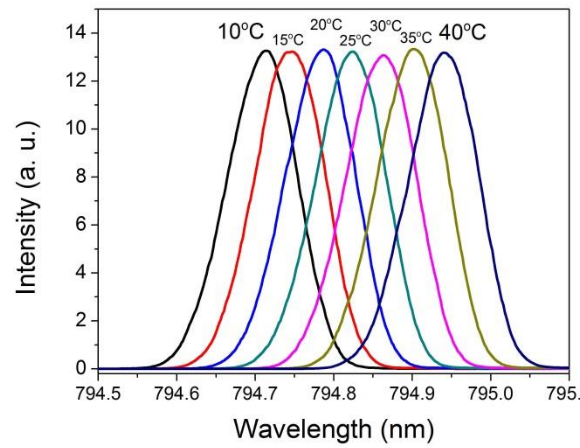

Fig. 5. (Color online) Center wavelength tuning by changing the temperature of the VHG holder. The average tuning rate is 0.0075 nm/K.

In figure 6, the long term stability of the spectrum is shown. We measured the spectrum every hour during a 220 hour test. The laser was turned off every evening and was turned back on every morning. The first data point was taken after the laser had run for one hour. The center wavelength drifting of the laser diode was ~±0.01 nm during our long term stability testing. There are several factors that caused the center wavelength fluctuation: (a) the fluctuation of the laser diode current; (b) the fluctuation of the laser diode temperature; (c) the fluctuation of the VHG temperature; (d) the misalignment of the external cavity and the cavity length due to alignment change with the temperature change. The current fluctuation is less than ±0.1 A based on the display of our current driver. The drifting rate of the locked center wavelength is around 0.01 nm/A [11]. The center wavelength drift due to current fluctuation is less than ±0.001 nm. Since the temperature of our water chiller fluctuates ±0.1K around the set temperature, our water-cooled laser diodes have a temperature fluctuation around this range. Within VHG locking, the center wavelength fluctuation with diode temperature is 0.02 nm/K [11]. The center wavelength of the laser varies ±0.002 nm due to the temperature fluctuation of the cooling water. Our VHG holder is located in open space. The temperature fluctuation is estimated to be ±0.5 K and the temperature tune rate of the VHG was measured as 0.0075 nm/K. So the wavelength drifting due to the VHG temperature is estimated around ±0.003 nm. We could not estimate the center wavelength drifting due to the external cavity misalignment and the cavity length change in our current setup. The total center wavelength drift is estimated to be around ±0.006 nm. Enclosing the laser system reduces the air flow and in turn reduces the wavelength drift of spectrum. Using a more stable water chiller with a larger water reservoir may also help reduce the diode temperature fluctuation.

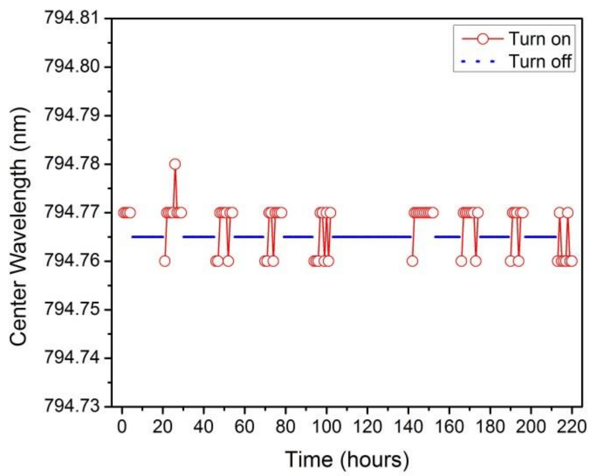

Fig. 6 (Color online) Center wavelength fluctuates with time. Good long term stability with an optimized optical design laser system is shown for up to 220 hours. We measured the spectrum every hour.

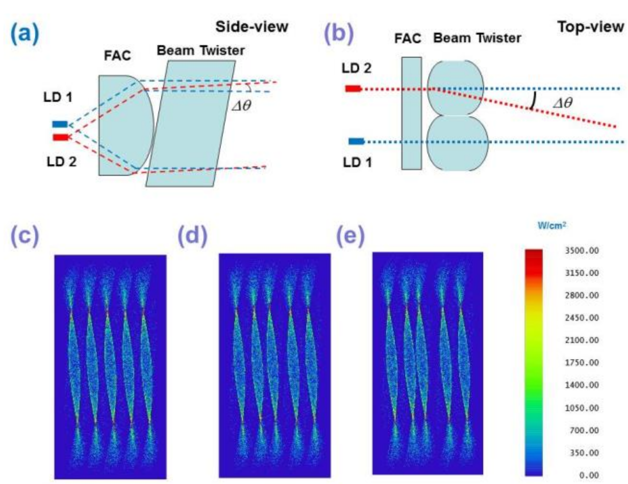

Fig. 7. (Color online) Smile effect of diodes generates the point deviation of laser beams. Collimation of two laser diodes (exaggerated drawing): (a) side view; (b) top view. Image of 5 diode lasers at VBG position with optimized external cavity (Fig. 3). The center one diode with smile: (c) 0 μm; (d) 1 μm; (e) 2 μm. The vertical point error is transferred into the horizontal point error.

The smile effect of laser diodes with a telescope external cavity was explained clearly [6, 8]. However, the smile effect of laser diodes with a beam twister has not been discussed. Generally speaking, the smile of a laser diode array (vertical position error of laser diodes) is transferred into the vertical point error by the FAC lens. The vertical point error is then transferred into the horizontal point error by the beam twister. This process is shown in Fig. 7 (a) and (b). We simulated the smile effect of an array of laser diodes with Zemax. The image of five laser diodes on a VHG (after beam twister) are shown in Fig. 7 (c), (d), and (e). Figure 7 (c), (d), and (e) show the center diode having a smile (vertical position error) 0 μm, 1 μm, and 2 μm, respectively. A vertical point error generated by a smile is transferred into a horizontal point error by the beam twister. From our simulation, one micron smile generates 3.0 mrads deviation for the beam point along horizontal direction. It is bigger than half of the acceptance angle of the off-the-shelf VHG (2.5 mrads). Basically diodes with smile size around 1 micron will not lock to the VHG effectively. As a result, the unlocked side mode will show up and the SMSR will drop. The stability of a diode laser system will be significantly affected by a low SMSR (Higher SMSR indicating that the diode laser system has higher stability). Only half of power of the laser diode with two micron smile will be coupled into 800 μm core fiber. A small smile laser diode array is important for a high efficiency laser system. The smile of laser diode array could be corrected by the technology in Ref. [21].

3. Conclusion

We designed an optimized external cavity using Zemax simulation. An off-the-shelf VHG and a water-cooled high power diode array were used to implement our optimized external cavity design. We achieved 70 Watts fiber delivered laser power with the center wavelength at 794.77 nm and the spectral bandwidth of 0.13 nm. The spectrum shows a high SMSR of > 30 dB and good long term stability with center wavelength drifting ±0.01 nm during the 220 hour operation period. Comparied with the free running power, we achieved 95% of the total power in the 0.13 nm bandwidth with fiber delivery. The stable, fiber delivered, narrow spectral line-width high power laser source is suitable for SEOP and other applications. In the future, we plan to combine two modules with a polarization beam splitter to couple the two laser beams into single fiber with optical power ~140 Watts in 0.15 nm bandwidth with a similar alignment procedure as shown in [22]. It will be a very useful pumping source for various research fields.

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