Injection locking of a fiber-coupled laser diode array

M.A. Humphrey, J.E. Massey, D.F. Phillips, and R.L. Walsworth

Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138

(Submitted to Applied Optics: Lasers, Photonics, and Environmental Optics)

Abstract

The spectral output of a high power, fiber-coupled laser diode array was significantly narrowed by injection locking. Up to 72% of the 1 THz spectrum was narrowed into a line less than 20 GHz wide. However, master laser power loss mechanisms intrinsic to the fiber-coupling of the slave laser reduced the injection-locked gain to less than unity: (slave laser power out)/(master laser power in) < 1. Gain reduction mechanisms inherent to the fiber-coupling were investigated through comparison with injection locking of an identical laser diode array without the optical fiber, for which injection locking gains of 35 were routinely achieved.

OCIS codes: 140.3520, 140.3510, 140.2010

1. Introduction

High power near-infrared (795 nm) light is commonly used for optical pumping of the D1 line of Rb to achieve nuclear spin polarization of high density ^{3}He and ^{129}Xe gas through spin-exchange collisions with Rb vapor [1]. Polarized noble gases have found numerous applications in physics [2], materials science [3], and biomedicine [4]. To provide optical pumping light, many researchers now use fiber-coupled Opto Power multistripe laser diode arrays (LDAs) capable of producing tens of watts of light. However, these lasers suffer from very broad spectral widths of 1-2 THz. Since the Rb absorption line is about 50 GHz (when pressure broadened with several atmospheres of He, Xe, or N_2) less than 10% of the LDA light is suitable for optical pumping, and the remaining light only increases the heat load on the system. Narrowing the spectral profile of these lasers would increase the resonant power without increasing the heat load, and thus could significantly increase noble gas polarization in a practical manner.

Several techniques have been demonstrated for narrowing the spectral output of high power*, non-fiber-coupled* diode lasers. Optical feedback may be employed [5], and we note that recently Nelson et. al. have used this method to narrow the spectrum of high power LDAs suitable for optically pumping Rb vapor to polarize noble gas atoms [6]. Spectral narrowing may also be obtained through injection locking [7], in which a low power, narrowband light source (the master laser, ML) is directed into a higher power, broadband source (the slave laser, SL). If the wavelength of the master laser lies within the gain profile of the slave laser, it can stimulate a collapse of the SL output into the narrow bandwidth of the ML. This paper describes injection locking of a high power LDA *through a multimode optical fiber*. Unfortunately, the observed injection locking performance is inadequate for a practical system to improve the production of spin-polarized noble gas.

2. Experimental setup and results

The slave laser (SL), Opto Power model OPC-A015-FCPS, consisted of 24 individual laser diode arrays each coupled through a microlens into a separate, 5 meter long, multimode optical fiber. The 24 fibers were bundled together and held within a flexible stainless steel cladding. Up to 600 mW of 795 nm light was emitted from each fiber, for a total of 15 watts. (We will refer to each fiber/LDA pair as simply a "single fiber"). The master laser (ML) was an argon-ion pumped Ti:Sapphire laser, operated just over threshold to produce tens to hundreds of mW of power. While this laser could produce much more power than needed to injection lock, it was readily available in our lab and it provided spectrally pure, tunable light with an easily varied output power. The spectral linewidth of the ML was less than 15 GHz.

The experimental setup is shown in Figure 1. The ML light was first passed through a pair of optical isolators to prevent reverse feedback from the SL. The SL and ML beams were then combined using a 50/50 beamsplitter, which directed half the ML light into the SL and half the SL light into a Fabry-Perot cavity spectral analyzer [8]. The remaining half of the ML light was directed into a power meter as a monitor of ML power. A pair of lenses focused the ML beam onto the output facet of a single fiber. Approximately 30% of the ML light was lost to reflection from either the front end of the fiber or the microlens at the LDA end of the fiber. This reflected light was independently measured and subtracted from the SL spectra.

For a single fiber, injection locking collapsed up to 72% of the SL output power into a peak less that 20 GHz wide (Fig. 2). The observed fraction of narrow-line SL output was linear in the ML power up to 72%, above which the narrowing was limited by the ML power allowed by the isolators. While significant spectral narrowing was routinely achieved with this injection locking technique, it required very high ML powers, typically as high as 400 mW. The best gain, defined as the ratio of narrow-line SL output power to ML power incident on the fiber core, was 0.5. A number of factors were found to contribute to this low gain, including power lost by reflections in the fiber/microlens system (> 30% power loss), power lost by attenuation in the fiber (< .2 dB/m, for a power loss up to 20%), ML depolarization by the multimode fiber (50% power loss), and inefficient steering and focusing of the ML beam onto the SL LDA element. If only the reflection, attenuation, and depolarization losses are considered, the gain is increased by a factor of 3.6 to 1.8. It is assumed, however, that the bulk of the ML power loss occurred due to poor focusing of the ML beam onto the LDA. (The LDA/fiber coupling through the microlens was sealed by the manufacturer, eliminating our ability to change the incident angle or focus onto the LDA). An investigation of all these gain limiting mechanisms is presented in section 3 below.

The single fiber injection locking exhibited strong ML frequency dependence. Optimal narrowing occurred with the ML frequency tuned to a longitudinal mode at the low end of the single fiber's free-running spectrum. Detuning the ML by 25 GHz from such a longitudinal mode reduced the injection locked SL power by 60%. Injection at the low frequency end of the free-running single fiber spectrum typically provided 20% more narrow-line power than injecting at the high frequency end.

3. Gain limitation

To confirm that the optical fiber was limiting the injection locking gain, studies were performed on a separate Opto Power LDA with no optical fiber (referred to as the "bare-LDA" or "bare-SL"). In addition to reducing power lost by reflection and attenuation, the lack of an optical fiber allowed control of the polarization, incident angle, and spot size of the injected ML beam onto the SL.

The ML beam was directly focused onto a single bare-LDA element. Injection locking gains of 35 were routinely observed using 1 mW of ML light. This gain improvement of ~70 relative to the fiber-coupled LDA indicates that power losses due to the fiber such as reflections, attenuation, and inefficient focusing of the ML beam, severely limit the practicality of injection locking with the fiber-coupled LDA. More efficient injection locking was also observed by injecting the ML beam at a small angle relative to the normal of the bare-SL surface. With the bare-SL the gain increased by ~10% at an angle of 2˚ relative to normal incidence. No injection locking was achieved at angles greater than 5˚. Finally, the reduction of injection locking gain due to ML polarization loss in the multimode fiber was investigated. With the bare-LDA, insertion of a circular polarizer into the ML path reduced the gain by 50%. This implies a minimum gain reduction of 50% when injecting through a multimode fiber, since the fiber scrambles the polarization state of the ML beam.

Practical use of injection locking requires the narrowed SL output power to be stable. The recorded SL spectra described in this Letter were snapshots of a fluctuating signal that varied in power by factors of ~ 2 over tenths of seconds. This effect may be caused by intensity beats [9], a result of the interaction of the locked and unlocked SL modes. Another factor that contributed to injection locking instability over longer timescales was temperature control of the LDA. An improved temperature control system would be needed to keep the LDA injection locked for periods of hours.

4. Conclusion

Up to 72% of the power from a fiber-coupled Opto Power laser diode array (of 1-2 THz free running spectral width) was narrowed into a peak less than 20 GHz wide by injecting narrowband light into the output of the multimode optical fiber. Since this slave laser was fiber-coupled, a significant fraction of the master laser power was wasted by reflections off the fiber and/or the LDA/fiber-coupling microlens, by attenuation in the fiber, by poor steering and focusing onto the LDA, and by destruction of master laser polarization. As a result, the observed injection locking is inefficient, with best gains that did not exceed unity.

In contrast, by injection locking an identical LDA with no fiber-coupling, average gains of 35 in the narrow-line output were routinely observed.

We thank Glenn Wong for a number of useful discussions and contributions to this work. We gratefully acknowledge funding for this project by the National Science Foundation, NASA, the Office of Naval Research, and the Smithsonian Institution's Scholarly Studies Program.

5. References

1. T.G. Walker and W. Happer, "Spin-exchange optical pumping of noble-gas nuclei," Rev. Mod. Phys. **69**, 629-642 (1997).

2. P.L. Anthony et. al, "Determination of the neutron spin structure function," Phys. Rev. Lett. **71**, 959-962 (1993); M. Wagshul and T. Chupp, "Laser optical pumping of high-density Rb in polarized ^{3}He targets," Phys. Rev. A **49**, 3854-3869 (1994); R. Stoner, M. Rosenberry, J. Wright, T. Chupp, E. Oteiza, and R. Walsworth, "Demonstration of a two-species noble gas maser," Phys. Rev. Lett. **77**, 3971-3974 (1996).

3. E. Brunner, M. Haake, A. Pines, J. Reimer, and R. Seydoux, "Enhancement of ^{13}C NMR signals in solid C_{60} and C_{70} using laser-polarized xenon," Chem. Phys. Lett. **290**, 112-116 (1998); R.W. Mair, G.P. Wong, D. Hoffmann, M.D. Hurlimann, S. Patz, L.M. Schwartz, and R.L. Walsworth, "Probing porous media with gas diffusion NMR," Phys. Rev. Lett. **83**, 3324-3327 (1999).

4. M. Albert, G. Cates, B. Driehuys, W. Happer, B. Saam, C. Springer Jr., and A. Wishnia, "Biological magnetic resonance imaging using laser-polarized ^{129}Xe," Nature **370**, 199-201 (1994); H.U. Kauczor, R. Surkau, and T. Roberts, "MRI using hyperpolarized noble gases," Euro. Radiology. **8**, 820-827 (1998).

5. W. Nagengast and K. Rith, "High-power single-mode emission from a broad-area semiconductor laser with a pseudoexternal cavity and a Fabry-Perot etalon," Opt. Lett. **22**, 1250-1252 (1997).

6. I. Nelson, B. Chann, and T.G. Walker, "Spin-exchange optical pumping using a frequency-narrowed high power diode laser," submitted for publication.

7. S.Q. Shang and H.J. Metcalf, "Narrowband, high power light from diode lasers," App. Opt. **28**, 1618-1623 (1989); R. Lang, "Injection locking properties of a semiconductor laser," IEEE J. Quant. Elect. **QE-18**, 976-983 (1982).

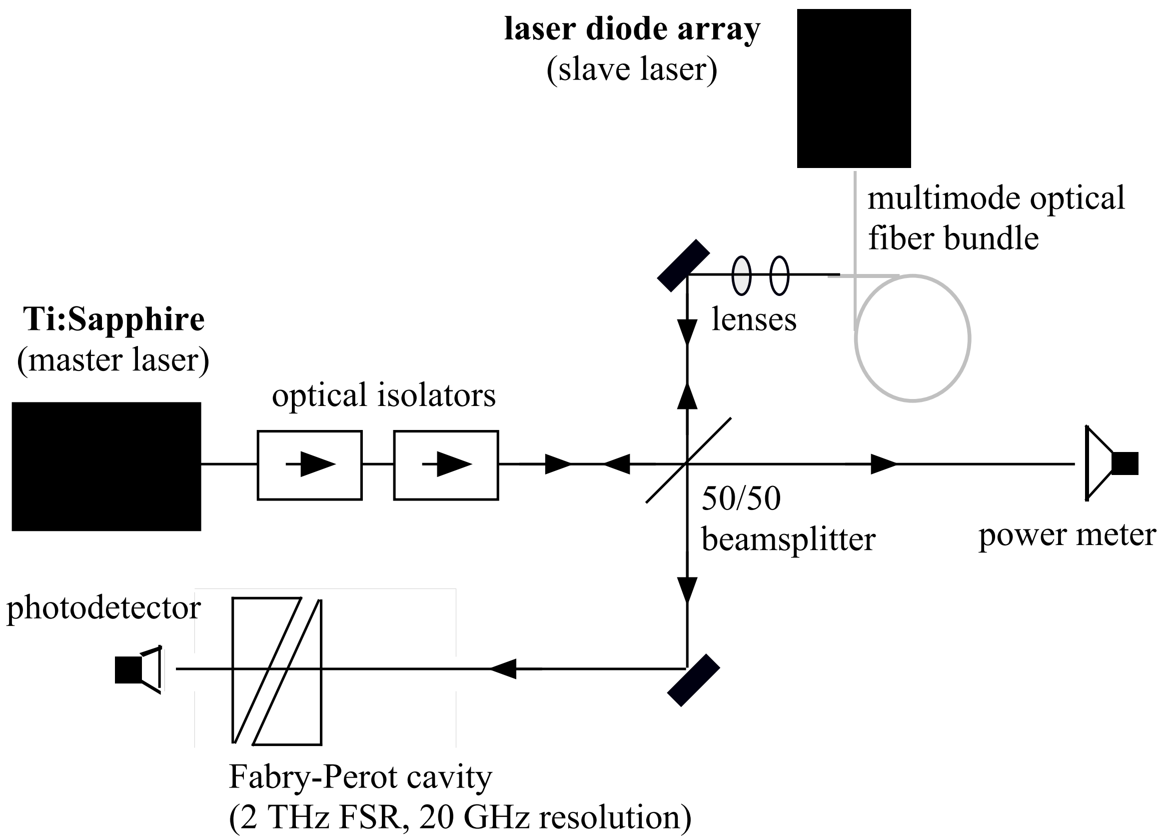
8. The Fabry-Perot cavity (Burleigh Instruments model RC-140) had a free spectral range of 2 THz and a finesse of 100, for a resolution of 20 GHz.

9. K. Otsuka and S. Tarucha, "Theoretical studies on injection locking and injection-induced modulation of laser diodes," IEEE J. Quant. Elect. **QE-17**, 1515-1521 (1981).

6. Figure Captions

Figure 1. Experimental setup for injection locking of the fiber-coupled laser diode array.

Figure 2. Injection locked spectrum for a single fiber in the fiber-coupled laser diode array. The dashed trace is a typical free-running single fiber LDA spectrum (~1 THz wide at these settings, $I \sim 2.5I_{th}$). The solid trace depicts the injection locked spectrum, containing 72% of the total LDA power from the single fiber in a peak less than 20 GHz wide.



laser diode array
(slave laser)
multimode optical
fiber bundle
lenses
Ti:Sapphire
(master laser)
optical isolators
50/50
beamsplitter
power meter
photodetector
Fabry-Perot cavity
(2 THz FSR, 20 GHz resolution)

Figure 1

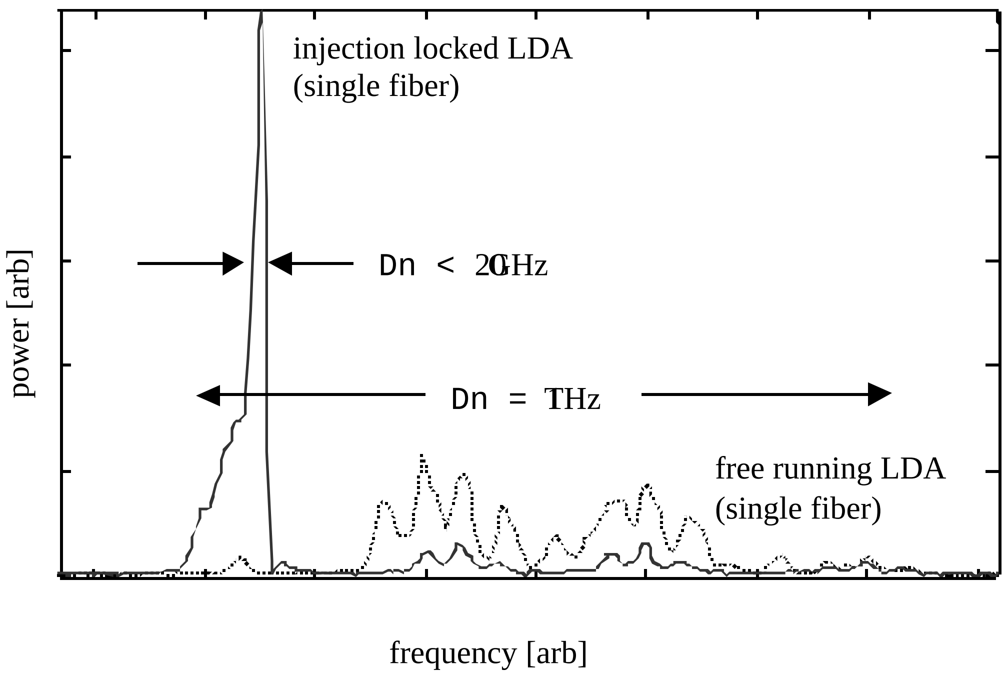

injection locked LDA
(single fiber)
Dn < 2GHz
Dn = THz
free running LDA
(single fiber)
power [arb]
frequency [arb]

Figure 2