Injection Locking of New Focus Lasers for 100+ mW of Power at 461 nm

1. Introduction

The GaN blue light-emitting diode, first demonstrated by Akasaki, Amano, and independently by Nakamura earned them the Nobel Prize in Physics in 2014 and has revolutionized modern lighting technology. This led to many new developments, one of which was the blue laser diode which has similarly transformed the way researchers obtain laser light at blue wavelengths. The blue laser diode has also greatly reduced the cost and level of complexity involved with such experiments.

The blue laser diode can be integrated into an external cavity with wavelength-selective optics to make a tunable external cavity diode laser (ECDL). One example of this is the New Focus TLB-6802 Vortex™ Plus tunable laser which adopts a Littman-Metcalf configuration to give continuously tunable output in the blue in a single longitudinal mode and boasts an output power greater than 40 mW. And in the world of atomic physics, several neutral atoms and ions of alkaline earth metals have electronic transitions in the blue and can therefore be studied using the Vortex Plus. For example, neutral strontium's $^1S_0$-$^1P_1$ main cooling transition is resonant with 461 nm light. Figure 1 shows fluorescence from a cloud of Sr atoms captured in a magneto-optical trap (MOT) utilizing light from a Vortex Plus laser.

For some strontium experiments at 461 nm, which often require over 100 mW of power for laser cooling and trapping of an atomic beam, see Ref. [2] the output power of an ECDL may not be sufficient. To obtain such optical power many researchers resort to resonantly frequency doubling the output of a CW ring Ti:sapphire laser. However, injection locking techniques, which can be used to obtain higher power at 461 nm from an ECDL laser, are now available with the advent of the blue laser diode.

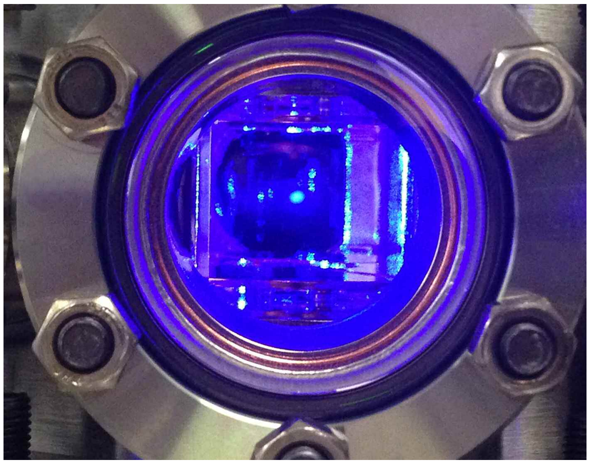

Figure 1. *Fluorescence emitted by strontium atoms (blue dot in center of viewport) trapped in a MOT. Number density is estimated at 10^{11} cm^{-3}. Image courtesy of Francisco Camarga, Tom Killian Lab, Rice University.*

In injection locking of lasers, a small fraction of the output of a "master" laser is injected into the gain region of a free-running, higher-powered "slave" laser. By doing so, the slave laser inherits many of the optical properties of master laser including single-mode output, narrow linewidth, and frequency stability. The aim of this Application Note is to illustrate the injection locking technique in the blue using two New Focus lasers: a TLB-6802-IJ module slave laser will be locked to a small fraction of the output of a TLB-6802 Vortex™ Plus tunable laser to give over 100 mW of light at 461 nm. This Application Note is offered as a starting point to laser injection locking of New Focus lasers rather than a rigorous examination of the technique. We begin with a concise introduction to some general theory behind laser injection locking.

2. Some Theory Behind Laser Injection Locking

In laser injection locking, a weak monochromatic signal from a master laser is injected into the resonant cavity of a second self-sustained slave laser, at a frequency within a narrow locking range around the free-running frequency of the slave. The injected signal from the master can then capture or "lock" the subsequent oscillatory behavior of the free-running slave laser, so that in the end the slave's output is controlled by the injected signal.

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Following the derivation of Ref. [1], it can be shown that the single-pass gain in amplitude of the injected signal from the master at wavelength λ_1 as it approaches the wavelength of oscillation of the free-running slave laser, λ_0, can be approximated according to

$$g(\lambda_1) = \frac{1-R}{i4\pi L}\frac{\lambda_1\lambda_0}{\lambda_1-\lambda_0}.$$

Here, R is the effective reflectivity of the two mirrors bounding the cavity of the slave laser which are separated by a distance L. Therefore, after injecting a signal of intensity I_1, the amplified intensity at λ_1 is

$$I(\lambda_1) = |g(\lambda_1)|^2 I_1 = \left(\frac{1-R}{4\pi L}\right)^2 \left(\frac{\lambda_1\lambda_0}{\lambda_1-\lambda_0}\right)^2 I_1$$

When the injected signal is tuned to exactly the oscillation frequency (i.e., as $\lambda_1 \rightarrow \lambda_0$) the first term representing intracavity losses, is “overtaken” by the second representing the overall regenerative gain. In effect, within a narrow wavelength range all of the intensity at λ_0 will be contributed to or “locked” onto that at λ_1 from the master laser, and both lasers will operate at the exact same wavelength.

3. Injection Locking at 461 nm: The New Focus TLB-6802-IJ Module

Figure 2 shows a schematic diagram of the injection-locking setup at New Focus. For simplicity, only one slave TLB-6802-IJ module is shown being locked although this approach can be scaled up for simultaneous injection locking of multiple slave lasers. Precise current and temperature control of both lasers is crucial to achieve efficient injection locking; therefore each laser is separately controlled by a New Focus TLB-6800-LN controller. The alignment of the injection beam into the slave laser is critical for stable injection-locking and is readily accomplished by using a steering mirror and glass wedge, for instance. A Faraday optical isolator is used in front of the master laser to avoid undesirable optical feedback, including feedback originating from the slave laser. Greater than 60 dB of optical isolation is recommended and this can be achieved by employing two Newport Faraday optical isolators in series (Model ISO-04-461-MP, λ_{center} = 461 nm). A half-wave plate is used after the isolators to align the polarization of the injection beam from the master laser, now rotated by 90°, parallel to that of the slave laser thereby maximizing the injection efficiency. In addition, external optics can be used to match the transverse modes of the injected beam to that of the slave laser; however, efficient injection locking can be established without such optics. The output of each laser and the injection locked output are monitored using an optical spectrum analyzer (OSA).

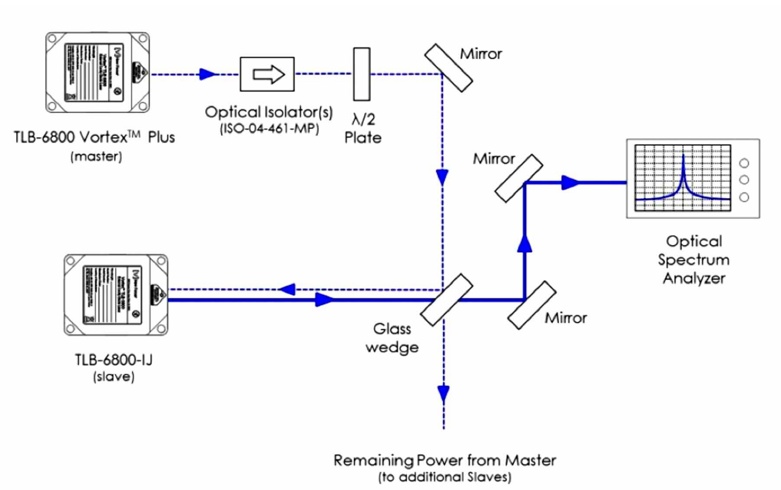

Figure 2. *Injection-locking scheme at 461 nm: Model TLB-6800-IJ is locked to TLB-6802 Vortex™ Plus.*

Injection locking in the blue, at 461 nm for example, is a straightforward process which starts by turning on the power to each controller for the master and slave. The initial injection beam alignment should be done at low laser power, so the master and slave currents are set to values slightly above threshold, and the beams are aligned for maximum spatial overlap along the injection beam path (dotted path in Figure 2). After alignment, the current to the master laser is slowly increased to its recommended operating value and the piezoelectric transducer is set to give the desired wavelength, here λ = 461 nm. After allowing the system to warm up a wavemeter or reference cell can be used to ensure the master is tuned to the target wavelength. As shown in Figure 2, the majority of the master output will be transmitted through glass wedge and can be recombined (not shown) with the slave laser output. A fraction of the remaining master power can also be picked off and used for diagnostics, laser stabilization via a feedback loop using a LB1005 High-Speed Servo Controller, for instance, and to lock any additional TLB-6802-IJ slave lasers depending on the total power requirements of the experiment.

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To achieve the laser light required at 461 nm the spectral overlap between the master and slave laser is achieved by fine-tuning the current to the slave. Temperature tuning the slave laser is always performed by New Focus engineers, so temperature tuning does not usually need to be done by the user. For the present setup, the current to the slave laser is gradually increased and the slave is allowed to "warm up" for 10 minutes. During fine tuning, the evolution of the spectrum of the injection locked output can be followed with an OSA until a single-mode spectrum is observed. When the modes are mismatched, the slave will not lock to the master laser, and the broad frequency peaks on the spectrum analyzer move as the current is adjusted to the slave. However, when mode matching is close enough for injection locking to occur, the frequency of the slave laser will jump to the frequency of the master laser and will remain constant as small changes are made to the slave laser current. Once injection locked, the frequency peak will appear sharp and follow the master Vortex Plus laser even as the laser is scanned over several gigahertz. By following the above procedure, 4 mW of light at 461 nm picked off from the master Vortex Plus laser resulted in an injection-locked power above 100 mW. Figure 3 shows the qualitative evolution of the slave laser spectrum from free running (a), through partially locked (b)-(d), to a fully locked state (e).

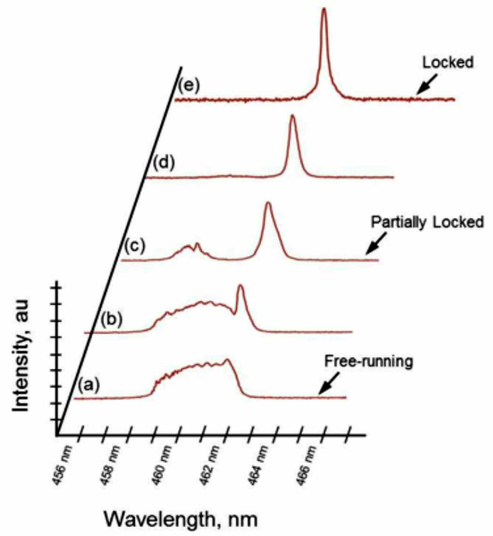

Figure 3. *Evolution of spectrum of TLB-6802-IJ "slave" laser as its current is tuned to optimally locked state as monitored with an optical spectrum analyzer.*

4. Summary

At 461 nm, and for other wavelengths in the blue, injection locking is a cost-effective approach to obtaining over 100 mW of power from an external cavity diode laser. This was illustrated by example: a few milliwatts from the output of a TLB-6802 Vortex Plus were picked off and injected into a TLB-6802-IJ module to obtain over 100 mW. The other commercially available approach involves frequency doubling, via a resonant cavity, the output of a master oscillator power amplifier setup, but this is a more expensive and technically costly solution.

Perhaps the greatest advantage of injection locking is its ability to scale: for additional power the number of injection locked slave lasers can be increased and the output power of each injection locked laser adds in parallel to give an overall greater final power. Indeed, several research groups working on atomic cooling and trapping of beams of strontium atoms, an application often requiring more power than available from a single ECDL, have forgone the difficulties of working with frequency doubling techniques and have shown that injection locking of multiple slave TLB-6802 IJ modules to a Vortex Plus laser is a viable solution to obtaining higher power at 461 nm.

References

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2. B. J. Bloom, Nicholson, T. L., Williams, J. R., Campbell, S. L. , Bishof, M. , Zhang, X. , Zhang, W., Bromley, S. L., and Ye, J. , *An optical lattice clock with accuracy and stability at the* 10^{-18} *level*, Nature 506, pp. 71-75 (2014).