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# Demonstration of injection locking a diode laser using a filtered electro-optic modulator sideband

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**Abstract**

Many experiments in atomic physics require two laser beams with a controllable difference in frequencies. In this paper, we report on realizing this goal using a technique where an electro-optic modulator sideband is filtered through a cavity and injected into a diode laser, in a novel configuration yielding very high feedback isolation without sacrificing access to the output power of the diode laser. The advantages of this approach over alternative techniques for injection locking are discussed. © 2000 Elsevier Science B.V. All rights reserved.

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Many experiments in atomic physics require generation of two laser beams that have an extremely high degree of phase coherence with one another [1–3]. For frequency differences on the order of a few hundred megahertz, an acousto-optic modulator (AOM) can be used to directly produce a frequency shifted beam with high efficiency. However, AOMs that can shift a laser beam by a few gigahertz (e.g. 6.8 GHz for $^{87}$Rb) have efficiencies close to 1% or less, and hence do not produce a frequency shifted beam with power that is adequate for most experiments [4,5].

For example, in order to excite Raman dark resonances [6,7] between the metastable hyperfine states of $^{85}$Rb, one requires two laser beams with frequencies separated by 3 GHz. It is also necessary to have a significant amount of power (of the order of few tens of mW) in each beam. An AOM or an electro-optic modulator (EOM) can be used to produce a 3 GHz shift in frequency, but neither will produce a shifted beam with adequate power. However, one can use injection of external irradiation to lock a diode laser to the shifted beam produced by an AOM or EOM in order to increase the power of the frequency shifted beam. The general concept of injection locking involves the use of a master laser operating at low power and efficiency, but producing a stable single mode output beam which is then injected into the resonant cavity of a high-power slave laser. Injection locking was first demonstrated by Stover and Steier [8], who directly injected a beam from a

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He–Ne laser into another laser. Since that time injection locking has been studied theoretically and experimentally. For a review of this technique see Ref. [9].

One of the drawbacks of using an AOM shifted beam is that the diffracted beam changes direction as the frequency is tuned. As a result, coupling between master and slave lasers is varied so that the frequency range available for stable locking becomes very limited. Since many experiments, including ours [10], require the ability to tune the difference frequency over a broad range, this beam misalignment imposes severe constraints on experimental setup, requiring additional compensation techniques. On the other hand, the sidebands produced by an EOM are always copropagating with the fundamental frequency, so that no misalignment occurs due to frequency tuning. This gives an EOM a clear advantage over an AOM in an injection locking scheme. Furthermore, in general the frequency shift achievable using an EOM is much larger than that achievable using an AOM. Finally, the EOM approach is analogous to yet another approach where the master laser is modulated directly; such an approach will eliminate the need for any external modulator, which is important for miniaturization efforts.

However, the EOM approach (and the direct laser modulation approach) has some obvious potential difficulties. First, the desired modulation sideband needs to be filtered using a cavity with a high enough finesse so that the leakage from the intense fundamental frequency component is negligible. Second, the diode laser output may reflect back to itself from the surface of the cavity mirrors, causing instability [11]. A simple isolation scheme often results in a configuration where only a part of the diode laser output is accessible for use as a single beam [12]. In this paper, we report on our successful demonstration of realizing the EOM approach for locking a diode laser to a 3 GHz shifted sideband of a Ti–sapphire laser using a novel isolation scheme that circumvents these problems.

A schematic of the setup that we used is shown in Fig. 1. A coherent 899 single mode tunable Ti–sapphire ring laser is used as a master laser to produce a fundamental optical frequency. The laser operates near 780.245 nm with frequency jitter estimated to be less than 1 MHz. The laser beam is

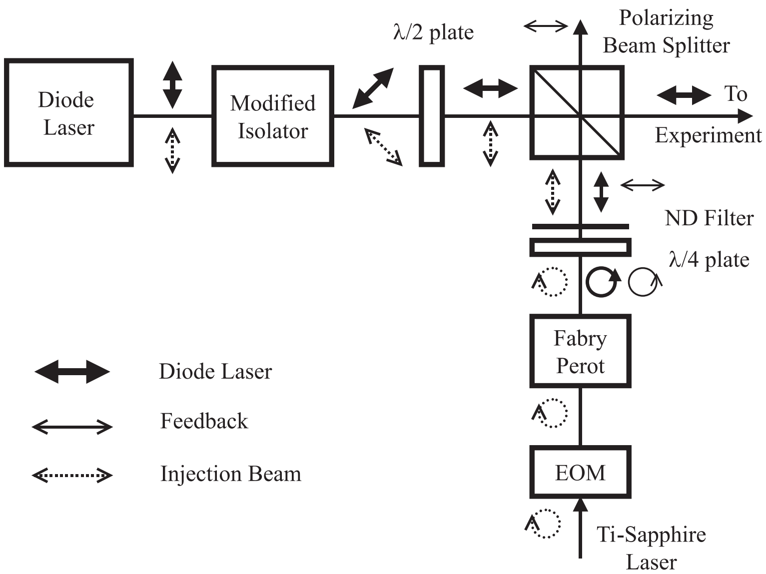


Fig. 1. Experimental setup for injection locking a diode laser. Polarizations of the direct laser beam, feedback, and injection beam are shown.

sent through an EOM (New Focus model 4431) and driven by a 3 GHz high-frequency source that is phase locked to a rubidium atomic clock. The EOM outputs a laser beam with three frequency components, the fundamental frequency and two $\pm 3$ GHz shifted sidebands that are copropagating. The intensity of each sideband is about 4% of the fundamental component intensity. The output beam is then sent through a home-made Fabry Perot cavity with finesse of $\sim 60$ and a free spectral range of about 30 GHz in order to eliminate the fundamental and one of the sidebands components from the injection beam. To implement this, the cavity is first manually tuned to the transmission peak of the desired sideband, and then kept locked to this peak by standard electronics. The resulting output beam, shifted by 3 GHz from the frequency of the Ti–sapphire beam, is then sent into a diode laser after passing through a polarizing broad band cube beam splitter and a modified Faraday isolator. Both the polarizing cube beam splitter and the modified optical isolator play a key role in our experimental setup and will be described below. Finally, the beam is fed into an SDL 5412 diode laser. Coarse longitudinal mode matching is accomplished by controlling the temperature of the laser. Fine tuning is achieved by adjusting the drive current. Transverse mode matching is produced by proper selection of collimating optics. The coupling between the injected field and the diode laser is varied for optimal locking by means of a set of neutral density filters (NDF). The most stable locking was achieved with injection power range of 1.0–0.5 μW. The injection locked diode laser produces a single mode beam, which is 3 GHz shifted relative to the fundamental frequency of Ti–sapphire laser, with more than 100 mW of power.

It is well known that due to the combination of low facet reflectivities, small cavity length, and high gain, feedback has a deleterious effect on semiconductor lasers. A feedback level of $-70$ dB is considered very low and hardly causes any effect in the diode laser behavior. However, a level of $-40$ dB will have a dramatic effect on a system's performance [9]. Optical feedback commonly originates from unwanted reflections coming from lenses and other optical elements. In our system, a strong unavoidable reflection from the cavity is considered to be the major contributor to the optical feedback. It is instructive to point out that even a perfect optical isolator would be unsuitable for our injection locking setup since it would stop all of the injection laser power. Therefore, one of the major challenges in the injection locking system is to block the reflected diode laser light and to allow external optical injection beam to penetrate into the diode laser. We solved this problem by creating a special optical system based on a modified optical isolator and a polarizing cube beam splitter, which utilizes the initial difference in polarization of the diode laser and the external injection beam.

In order to illustrate how the modified isolator works we recall briefly how a regular isolator works [13] and then discuss the modification we made to our isolator. A regular isolator consists of three basic pieces in series: a vertical polarizer, an optically active material that rotates the polarization non-reciprocally by $+45°$, and a linear polarizer oriented at $+45°$. Fig. 2a shows a diagram of a regular isolator with a reflected beam entering from the right and a direct diode laser beam entering from the left. First, consider the direct diode laser beam. The vertically oriented polarizer eliminates the horizontal component of the incoming beam (if it is present) while allowing the vertical component to continue. The beam, now vertically polarized, is then rotated by $+45°$. Finally, the beam passes through a polarizer oriented at $+45°$ without attenuation. The net effect is that the vertical component of the direct laser beam will pass through the isolator, but it will be rotated by $+45°$ at the output. Next, consider the reflected beam. No matter how the beam is initially polarized, after it passes through the first polarizer it encounters, it becomes polarized in the direction of the polarizer, $+45°$. This polarization is then rotated by $+45°$ resulting in a horizontally polarized beam. Since the vertical polarizer and the beam are cross-polarized, the beam cannot penetrate into the diode laser.

Our modified isolator is just like a regular isolator only without the linear polarizer oriented at $+45°$ (see Fig. 2b). We used a standard diode laser isolator from Electro-Optics Technology, Inc.

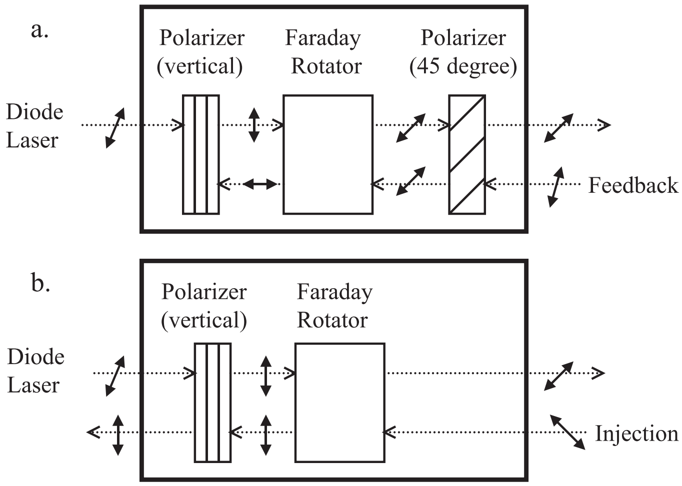


Fig. 2. (a) Schematic illustration of a regular Faraday isolator. (b) Schematic illustration of our modified isolator used to convert polarization of the injected and direct diode laser beams.

According to the manufacturer's specification, this device provided isolation of better than 30 dB. Removal of the polarizer does not affect direct laser beams passing through the isolator. However, an injection beam traveling to the left and polarized at −45° can now pass through the isolator without attenuation. Of course, with its polarization being rotated by +45°, it becomes vertically polarized.

To understand how all of the elements work together we have to consider the transformation of the polarization of the beams as they travel through the experimental setup. Fig. 1 shows the polarization of the injection beam, and the direct and reflected diode laser beams at different points. The Ti–sapphire laser beam is initially circularly polarized. After passing through the EOM and the Fabry Perot cavity, the beam is shifted by 3 GHz and has only about 0.5% of its original power (the cavity transmission is about 13%). The beam then passes through a quarter wave plate that changes the polarization from circular to vertical. After being reflected by the polarizing beam splitter, the shifted beam passes through the half-wave plate and becomes polarized at −45°. The beam continues through the modified isolator to the diode laser. The direct diode laser beam is initially vertically polarized. It passes through the modified isolator with no power loss, but is rotated by +45°. The half-wave plate then rotates the beam by another +45° so that the diode laser beam is horizontally polarized before entering the polarizing beam splitter. Thus, nearly all of the diode laser power continues through the polarizing splitter, which only reflects vertically polarized light, to the experiment. Note that the modified isolator converts counter-propagating beams with parallel polarizations to cross-polarized beams. Without the modification, the polarizations of the diode laser beam and the injection beam would always match at the diode laser (as they must in order for injection locking to work) and hence the beam splitter would not separate the diode laser beam path from the Ti–sapphire beam path.

The quarter wave plate is oriented so that the residual fraction of the direct diode laser beam that is reflected by the polarizing beam splitter becomes circularly polarized after passing through it. The reflected beam passes through the quarter wave plate a second time and is converted from circularly polarized to horizontally polarized. Again, the major part of reflected beam passes straight through the polarizing beam splitter and is prevented from feeding back to the diode laser. In other words, our setup effectively filters the cavity-reflected diode laser beam twice. When the main diode laser beam is sent through the polarizing beam splitter only a small fraction of the beam $\delta$ ($\approx$3%) is reflected. Part of the reflected beam then reflects off of the cavity and returns to the polarizing beam splitter. Again only a small fraction ($\delta$) of this light is reflected back towards the diode laser. In the end a maximum of $\delta^2$ of the diode laser beam feeds back to the diode laser. As a result, this configuration provides feedback attenuation on the level of 30 dB. A set of NDF used to vary intensity of the injected beam is providing an additional feedback isolation up to 20 dB (for an NDF setting of 10 dB) without affecting the useful output intensity of the diode laser. When the NDF is set at a lower value, the feedback suppression is reduced, while the intensity of the injection beam is increased. We observed that under this condition (NDF less than 10 dB), the diode lasers became multimode if the injection beam was blocked, because of the residual feedback. However, when the injection beam was unblocked, the laser became single-mode [14], and locked to the desired EOM sideband. For NDF less than 5 dB, the feedback could no longer be overcome by the injection beam.

In order to test the degree to which the diode laser was phase locked to the sideband of the Ti–sapphire laser, we sampled a part of the injection beam, and shifted it with a 270 MHz AOM. This beam was then combined with a sample from the diode laser output, and the beat note was detected using an APD detector. Fig. 3 shows that the width of this beat note is about 2 kHz, which is essentially the resolution limit of the spectrum analyzer used. Fundamentally, we expect the beat note to be much narrower, limited only by the noise in the servo used to phase lock the 3 GHz high-frequency source to the rubidium clock.

To determine the degree of phase locking more precisely, we also used this injection locking scheme to observe Raman–Ramsey fringes [15]. The 1.2 kHz width of the fringes, shown in Fig. 4, is very close to the transit time limited value. The damping rate of the fringes, caused by the longitudinal velocity spread, is in agreement with the theoretical velocity distribution. The zone separation is 30 cm, and the mean atomic velocity is $\sim$300 m/s, so that the expected transit time width is about 1 kHz. The observed line width here is about 1.2 kHz, where the additional width is attributable to the velocity averaging. Thus, we can conclude that the relative frequency noise between the diode laser and the Ti–sapphire laser is less than 100 Hz. If this experiment were to be performed using trapped

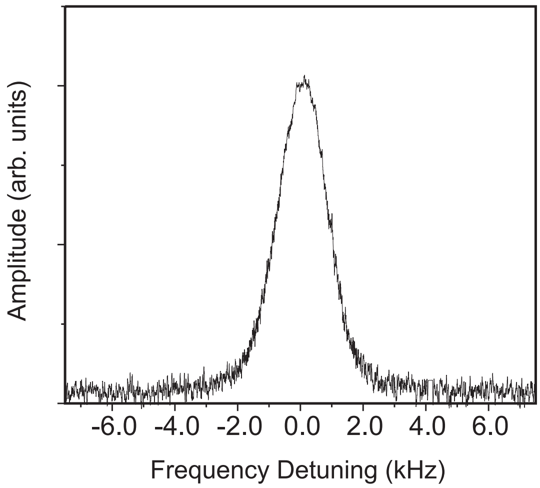


Fig. 3. The beat note generated by mixing the injection locked diode laser with a beam from the Ti–sapphire laser. The beat note is centered near 270 MHz, corresponding to the frequency of the AOM used to shift the injection beam.

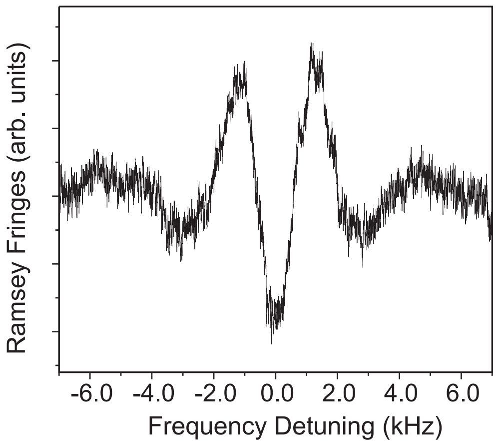


Fig. 4. The transit-time limited Raman–Ramsey fringes obtained for the magnetic field insensitive component of the off-resonant Raman transition in $^{85}$Rb atomic beam. Ti–sapphire laser and injection locked diode laser were used to excite Raman transition.

atoms, which would yield a much narrower (∼1 Hz) transit-time limited line width, one could determine the beat note with even better precision.

In summary, we demonstrated injection locking of a diode laser to a cavity-filtered EOM sideband in a novel configuration yielding very high feedback isolation without sacrificing access to the output power of the diode laser.

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