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Extended tuning of an injection-locked diode laser

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We have investigated the application of an electronic feedback technique recently reported by Repasky *et al.* [Appl. Opt. **45**, 9013 (2006)] to an injection-locked semiconductor diode laser. We find that without electronic feedback, the injection-locked slave laser will only follow the master for less than 1 GHz, but once the electronic feedback is applied, the slave laser is capable of following for more than 20 GHz, corresponding to the full scan range of the master laser. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2906224]

Semiconductor diode lasers are used in both commercial applications and experimental physics as a result of their low cost, high efficiency, and broad wavelength coverage. This has been especially true in atomic and molecular physics experiments.[1,2] Because both precise tunability and frequency stability are often important, it is common to construct an external cavity diode laser (ECDL) by using a frequency-selective optical element such as a diffraction grating in the cavity to control the frequency of the light which is fed back to the laser diode. If the front facet of the laser diode has sufficiently low reflectivity, the laser output frequency is then determined by the external cavity. Tuning is achieved by rotating the grating or a mirror, depending on the cavity design.[3,4] If the laser is to operate at a fixed wavelength, then placement of the tuning element in the cavity is usually not too important; however, if frequency scanning is required—as in spectroscopy experiments, for example—then cavity geometry is critical. If the pivot point of the tuning element in the cavity is not precisely positioned in order to keep the cavity length commensurate with the new wavelength during tuning, the laser will intermittently mode hop or run multimode as it is scanned.[5,6] Correct positioning of the pivot point, however, requires micron level accuracy and is not trivial. Several authors have demonstrated techniques for increasing the scan range of an ECDL by applying feed-forward adjustments to the laser diode current as the external cavity is mechanically adjusted.[7–11] Recently, Repasky *et al.*[12] described an electronic feedback technique to enable very long mode hop-free scans of an ECDL.

In this note, we describe our investigation of the application of the technique in Ref. 12 to an injection-locked diode laser system. In injection locking, light from a "master" laser is sent directly into a "slave" laser causing it to lase with the spectral properties of the master, but usually providing higher power than one would obtain from the master alone. If the laser is to be scanned, it is critical that the slave laser smoothly follow the master during scanning. We have found that an injection-locked diode laser will typically follow the master for only ~500 MHz before it begins to operate multimode, thereby limiting the utility of the long scan capability of the ECDL.

In Ref. 12, a small modulation was placed on the laser current and phase-sensitive detection was used to monitor the laser power. If the laser cavity does not maintain the resonance condition during scanning, sideband suppression is reduced and the amplitude and phase of the modulated power change, thereby providing an "error signal" which can be applied to the laser current in order to bring the cavity back into resonance. Using this approach, Repasky *et al.* were able to extend the mode-hop free tuning of a Littman–Metcalf ECDL, operating at 758 nm, from 1 to more than 65 GHz. We have implemented this technique to an injection-locked diode laser system and find that although the amplitude and phase characteristics of the modulated power of the slave laser differ from those of the ECDL, a suitable error signal—used to send feedback to the slave current and allow the slave laser to stay in resonance with the master laser—is still produced. We have investigated two separate injection-locked laser systems, one with an ECDL in Littman–Metcalf configuration and the second operating in Littrow configuration. In both setups, no attempt was made to correctly position the pivot point of the tuning element. We found the same performance in both setups. Here, we report details of the apparatus using the Littman–Metcalf ECDL.

A schematic of the experimental arrangement is shown in Fig. 1. An 808 nm 150 mW diode laser (Sanyo DL-LS2031) was collimated (Thorlabs L110P-B) and placed in a 7 cm long external cavity containing a 1200 lines/mm diffraction grating (Edmund Scientific K43-848). The laser was tuned by applying a voltage to a piezoelectric transducer (PZT) placed behind the horizontal adjust of the cavity mirror. The PZT (Thorlabs AE0203D08F) has an extension of 6.1 μm at 100 V. The master laser was temperature stabilized to ~10 ppm with a homemade temperature controller and operated at 125 mA with a homemade current controller. At this current, the ECDL output is 26 mW. With no electronic feedback, the laser scans ~1.5 GHz before mode hopping. We monitor the laser output with light reflected off an uncoated glass beam splitter and detected on an external photodiode, as shown in Fig. 1. We modulate our laser current at 8 kHz. Output of the photodiode is directed to a current to voltage converter and then sent to the input of a Princeton Applied Research PAR 120 lock-in amplifier. The lock-in amplifier also provides the reference signal used to modulate the laser current. The lock-in amplifier demodulates the photodiode signal. If the amplitude and/or phase characteristics of the photodiode signal (at the modulation frequency)

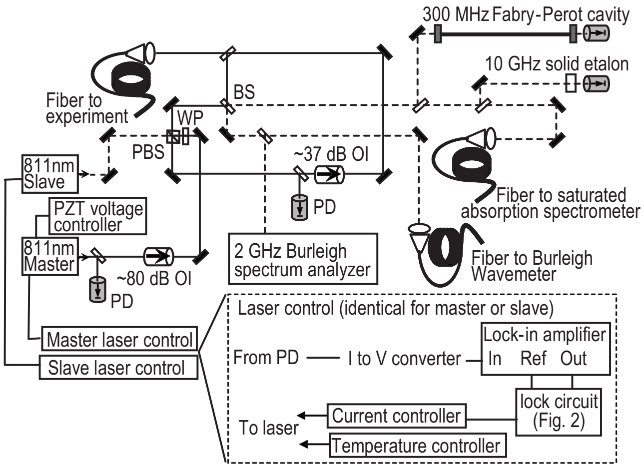

FIG. 1. Schematic of experimental setup. PBS: polarizing beamsplitter cube; BS: beamsplitter; WP: waveplate; OI: optical isolator; PD: photodiode; dashed optical path indicates master and slave laser beam overlap.

change, the voltage output of the lock-in amplifier also changes. This output voltage can be used as an error signal to provide feedback to the diode laser current. We use the time constant setting of the PAR 120 to provide integration and the zero-adjust feature (dc offset) to subtract a fixed voltage from the output and lock the laser to the zero crossing of the output signal. The output of the lock-in amplifier is sent to the simple amplifier circuit shown in Fig. 2 to provide gain and polarity control of the integrated error signal and sum it with the modulation needed for the phase-sensitive detection of the laser power. The output of the lock circuit is then sent to the current controller where it is summed with the set point voltage which controls the laser current. When the feedback technique of Ref. 12 is applied, we are able to scan the ECDL by 23 GHz, limited by the full extension of the PZT element.

Light from the ECDL is injected into a collimated slave laser (Sanyo DL-LS2031, Thorlabs L230P-B). The laser current is 168 mA. Only tens of microwatts of light is required to injection lock the slave when the two polarizations are the same. We find it convenient to direct the ECDL light into the slave via a polarizing beam splitter cube. In this configuration, the injected light has a polarization nearly perpendicular to the slave light and it typically requires a few milliwatts to pull the slave. Though the ECDL is now capable of scanning 23 GHz, the slave laser (without electronic feedback) will only be pulled single mode for a small range of ~600 MHz and will then run multimode before switching to its free-running wavelength as shown in Fig. 3, where the laser frequency (monitored by a Burleigh WA-1000 wavemeter) is plotted versus ECDL PZT voltage. Additional laser diagnostics are provided by a low finesse 300 MHz Fabry–Pérot cavity, a low finesse 10 GHz solid etalon, and a high finesse 2 GHz optical spectrum analyzer. A saturated absorption

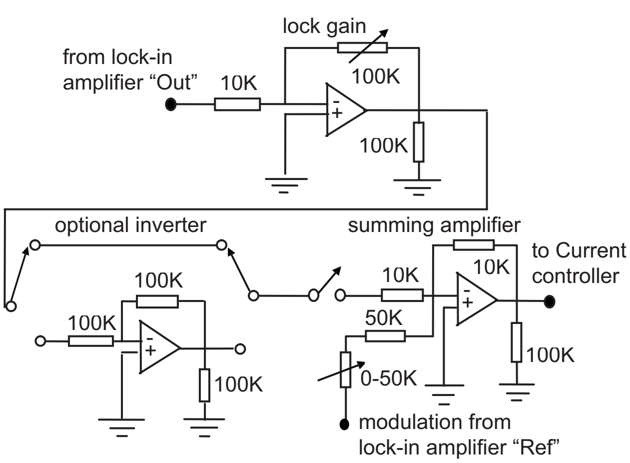

FIG. 2. Amplifier circuit with gain and polarity control for providing combined modulation and error signal to the diode laser current controller. All operational amplifiers are 1/4 TL074.

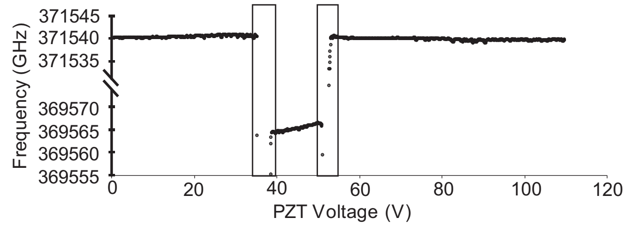

FIG. 3. Output frequency of slave laser without electronic feedback vs master laser PZT voltage (corresponding to master laser frequency). Boxed region indicates multimode behavior.

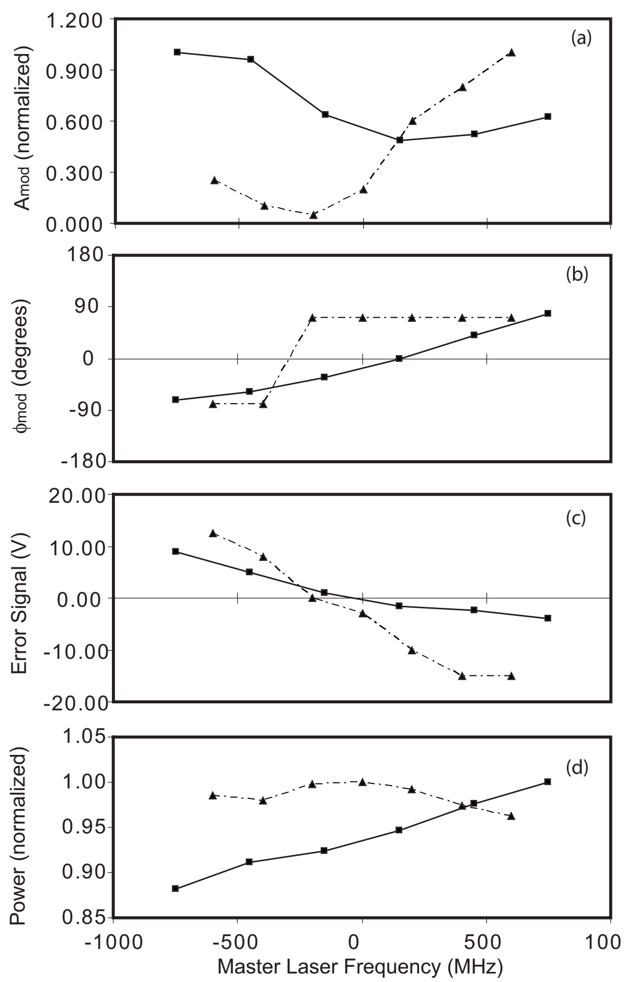

FIG. 4. For master laser (squares) and slave laser (triangles): (a) normalized A_{mod} vs laser frequency, (b) ϕ_{mod} vs laser frequency, (c) output of the lock-in amplifier (used as the error signal) vs laser frequency, and (d) normalized total laser power vs laser frequency.

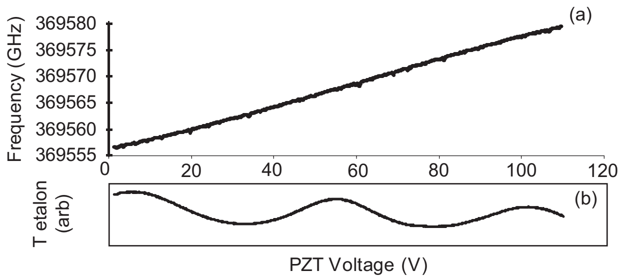

FIG. 5. (a) Output frequency of slave laser with electronic feedback vs master laser PZT voltage (b) Transmission of slave laser light through a 10 GHz solid etalon vs master laser PZT voltage.

spectrometer is used to provide an absolute wavelength reference.

In an attempt to extend the scan range of the slave, we have applied the same technique used on the master laser to the slave laser. Here, the current of the slave laser diode is modulated at 12 kHz (so as to not interfere with the master ECDL lock circuitry) and the modulated power is again monitored on a photodiode. (In an alternate arrangement, we have also used the internal photodiode of the laser diode to monitor the power). As the frequency of the master laser is scanned, the amplitude and phase characteristics of the modulated power of the slave laser change resulting in a change to the output voltage of the lock-in amplifier. The presence of the modulation added to the current can be observed as an ac component of the total output power of the laser, which we will refer to as P_{mod}, having amplitude A_{mod} and phase ϕ_{mod} relative to the reference modulation signal. Figures 4(a) and 4(b) show A_{mod} and ϕ_{mod}, respectively, for both the master and slave laser as the master laser is scanned, with no feedback applied to either laser. A_{mod} is normalized to its maximum value during the scan. Figure 4(c) shows the resulting error signal (with dc offset applied) produced by the lock-in amplifier. As seen in Figs. 4(a) and 4(b), the amplitude and phase characteristics of the modulated power of the slave laser do, in fact, differ from those of the master. What matters for locking the slave laser, however, is that the demodulated signal (the output of the lock-in amplifier) has a form which can be used as an error signal. Indeed, as can be seen in Fig. 4(c), where the output of the lock-in amplifier (with dc offset applied) is shown, a perfectly suitable error signal is produced. Finally, in Fig. 4(d), we show the normalized total output power of each laser as it is scanned without electronic feedback. When the error signal is integrated, sent to the locking circuitry of Fig. 2, and forwarded to the slave laser current controller, the slave laser is now capable of following the master ECDL over the full 23 GHz scan range as shown in Fig. 5, where the wavemeter output and transmission through a 10 GHz solid etalon are displayed.

In conclusion, we have investigated the application of an electronic feedback technique to an injection-locked diode laser. We find that without the electronic feedback, the slave laser will only follow the master ECDL for ~600 MHz, but once locked the slave laser is capable of following the full scan range of the master laser. We expect that the scanning range can be extended even further by application of a piezoelectric element with greater displacement capability.

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