TU1C-5

A CPW PHASE-LOCKED LOOP FOR DIODE-LASER STABILIZATION*

L. D'Evelyn[a], L. Hollberg[a], Z.B. Popovic[b]

[a] National Institute of Standards and Technology
Boulder, Colorado 80303
[b] Department of Electrical and Computer Engineering
University of Colorado
Boulder, Colorado 80309-0425

ABSTRACT

A low-cost, phase-lock circuit for slaving an extended-cavity diode laser to a stabilized reference laser has been developed. Grounded coplanar waveguide and surface mount technology have been used. An internal mixing stage allows continuous tuning of the laser difference frequency between 5 MHz and 1.5 GHz. Absolute phase locks exceeding 8 hours have been demonstrated.

INTRODUCTION

Precise control of the frequency and/or phase of diode lasers opens up a wide variety of scientific and commercial applications. Consequently, several research laboratories have recently demonstrated phase-stabilized diode-laser systems [1-4] similar to the one presented in this paper. The diode-laser phase-lock circuit described below has been developed to address a number of scientific applications at the National Institute for Standards and Technology. These applications require both extreme stability and frequency control of extended cavity lasers and include: high resolution spectroscopy, optical frequency synthesis, and laser cooling and trapping. In combination with new, commercially available extended-cavity lasers [5], our phase-lock servo could also be integrated into numerous commercial applications, such as laser ranging and distance measurements and coherent communications systems. In the future, this circuit may serve as a fundamental building block for a tunable optical synthesizer. A precision optical synthesizer would allow optical heterodyne and RF conversion techniques to be applied to the optical regime.

OPTICAL PHASE-LOCKED LOOP

The phase-lock circuit serves to slave an extended-cavity diode-laser to a highly stable reference laser. Grounded coplanar waveguide (CPW) on a FR4/G10 circuit board and surface mount technology have been employed for all microwave and RF sections to maximize performance while minimizing cost. Only low-cost, commercial-grade parts have been used in the design. Figure 1 shows a photograph of the 11.7 x 14.2 cm (4.6 x 5.6 in) circuit.

The basic operation can be understood as follows (Figure 2). The beat note between the two lasers is detected with a fast photodiode, then input to the microwave mixer. An external synthesized LO source allows continuous tuning of the difference frequency between the two lasers between 5 MHz and 1.5 GHz. The filtered IF signal is first converted to an ECL signal and then detected by a low phase-error ECL phase/frequency detector [6-7]. High speed op-amps perform active loop filtering on the low pass filtered error signal and load compensation for the combined FM response of the current source and extended-cavity laser. The final error signal is fed back to the slave laser via two ports: a wide bandwidth channel (DC to ≈ 1 MHz) to the laser's injection

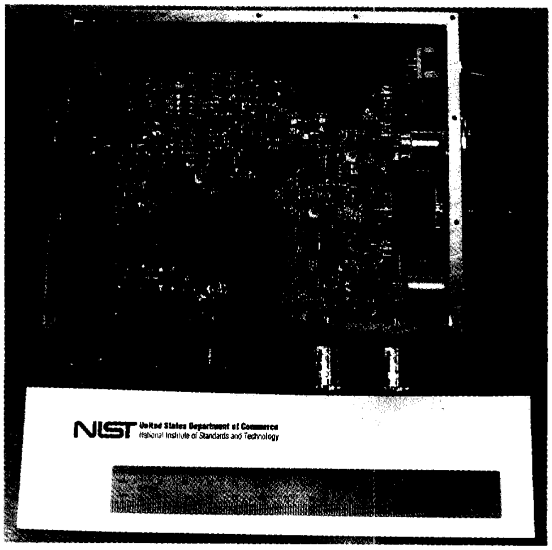

Figure 1: Phase-lock loop for diode-laser stabilization. CPW lines and surface mount technology allow input frequencies to 1.5 GHz.

---

* Contribution of NIST, not subject to copyright

CH3389-4/94/0000-0065$01.00 © 1994 IEEE

current controls fast frequency jitter, while a high dynamic range channel (DC to ≈ 2 kHz) to a piezo-electric transducer (PZT) adjusts the laser's cavity length to compensate for drift.

The design requirements were determined, in part, by our desire to have a simple system that allows offset frequency sweeps from near DC to at least 1.5 GHz with a resolution of ≤ 1 Hz. The 1.5 GHz specification was dictated by our requirement of complete spectral coverage and the 3 GHz free spectral range of the Fabry-Perot reference cavity that we use to lock the master laser. The maximum tuning range is not fundamentally limited, but is rather naturally set by the availability and cost of microwave synthesizers capable of ≤ 1 Hz resolution. The grounded CPW lines on the low-cost FR4/G10 printed circuit board perform adequately to the required 1.5 GHz. Extension of the sweep range beyond 1.5 GHz, however, would require more accurate transmission-line design equations and/or improved circuit board fabrication. Alternatively, external microwave mixing stages can be used to extend the maximum offset frequency. Special Schottky diodes can be used as harmonic mixers, for example, to detect beat notes between near-IR diode lasers to frequencies higher than 600 GHz [8].

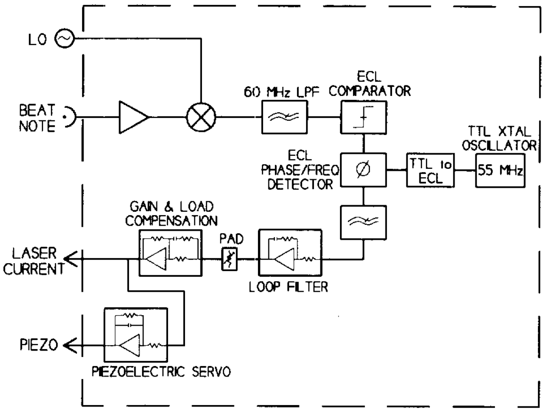

Figure 2: Block diagram for phase-locking extended-cavity diode lasers. The 55 MHz IF signal is detected by an ECL phase/frequency detector. High-speed op-amps provide loop filtering and compensation.

Figure 3 shows the extended-cavity laser [9-10] controlled by the phase-servo circuit. A commercially available diode-laser (with the output facet AR coated) is used together with a high-efficiency holographic diffraction grating [11] in a Littrow geometry. The rear facet of the diode and the grating form an "extended cavity." Cavity lengths ranging from 6 to 50 cm have been used in our experiments. The PZT-adjustable mirror provides a precise adjustment of the optical length of the cavity. Optical feedback of the first-order beam from the grating narrows the linewidth from greater than 30 MHz to about 50 kHz and allows tuning of the laser's wavelength/frequency. The narrowed spectral characteristics of the extended-cavity greatly facilitate locking and control of the slave laser.

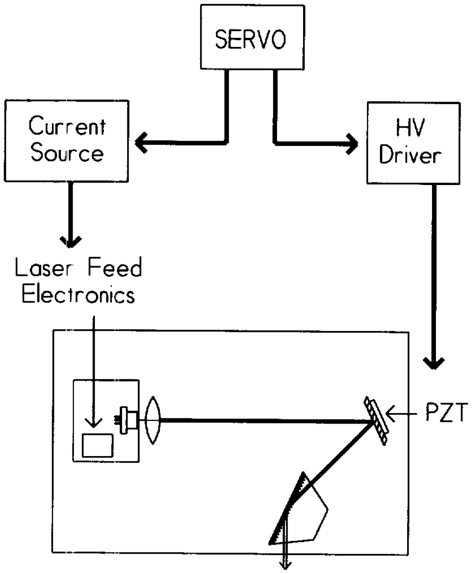

Figure 3: Extended-cavity laser. The rear facet of the laser-diode and the holographic diffraction grating form an "extended cavity." The narrowed spectral characteristics greatly facilitate locking the slave laser.

No additional auto-locking features have been added to the electronics. The PZT provides a 20 GHz continuous tuning range and can easily be used to tune a laser within the -20 to +100 MHz capture range of the electronic circuit. Broader stepwise tuning can be accomplished by mechanical rotation of the grating. Laser mode-hopping remains the greatest impediment to initially locking the long (50 cm) cavity lasers (free spectral range ≈ 300 MHz). An etalon in the extended laser cavity or a clamp on the maximum correction current [3] should solve this complication.

APPLICATIONS

The laser phase-lock circuit is now used in two experiments with different laser setups. In both cases, the servo-loop bandwidth of about 1 MHz results in robust phase-locks. Locking times exceeding 8 hours have been demonstrated. Unfortunately, the sensitive nature of the experimental laser systems preclude longer tests. Both laser systems will be described to illustrate the flexibility of the phase-lock circuit. Plans to include this circuit in a laser cooling and trapping experiment will also be outlined.

The first experiment uses two phase-locked AlGaInP lasers at 657 nm for high resolution spectroscopy of calcium (Figure 4). Phase-locking allows the stability of a nontunable reference laser to be transferred to the offset-tunable slave laser. Extremely narrow laser linewidths are required to observe and lock the laser to narrow saturated-absorption signals. The "master" extended-cavity laser, electronically locked to a stable Fabry-Perot cavity, has a fast linewidth of only 500 Hz and a residual frequency jitter of 5 kHz [12]. Figure 5 shows a spectral plot of the locked beat note between the two lasers. In future experiments the master laser will be referenced to a very high Q ($\approx 10^{10}$), stable Fabry-Perot cavity. Such a laser system locked to the calcium resonance could serve as a high accuracy transfer standard of optical wavelength/frequency.

In the second example, the phase-locked loop (PLL) locks an AlGaAs extended-cavity laser (792 nm) to an Ar^+ laser pumped $Ti:Al_2O_3$ laser. Here, the offset frequency of 47 GHz is established using an external harmonic mixing stage. This system is being used by J.C. Bergquist of NIST for experiments on laser-cooled Hg^+ [13]. Because of the ground-state hyperfine structure splitting, laser cooling of Hg^{199} requires two lasers (at 194 nm) separated by 47 GHz. The 194 nm is generated by summing the 792 nm light with the second harmonic of an Ar^+ laser line (514 nm).

Future plans include incorporating the phase-lock circuit into a laser system for high resolution spectroscopy of laser-cooled, trapped cesium atoms. As demonstrated by Kasevich et al [14], this can lower the effective temperature of the cooled cesium atoms from about 500 μK to less than 1 μK.

CONCLUSION

The CPW phase-lock circuit described in this paper has consistently demonstrated robust locks of several hours duration between diode-lasers. Measured results in two different laser systems illustrate the circuit's potential for advancing many scientific experiements, especially those involving high-resolution spectroscopy and laser cooling and trapping. This low-cost, highly reproducible circuit could also be used in many additional applications. For example, the PLL could be utilized to reduce the number of oscillators required in an optical frequency synthesis system [15-16]. In short, the laser phase-lock circuit promises future viability of coherent optical applications of diode lasers.

ACKNOWLEDGEMENTS

We thank J.L. Hall, J.C. Bergquist, and R.W. Fox for important contributions to the development of this technology. This work was supported in part by the Air Force Office of Scientific Research.

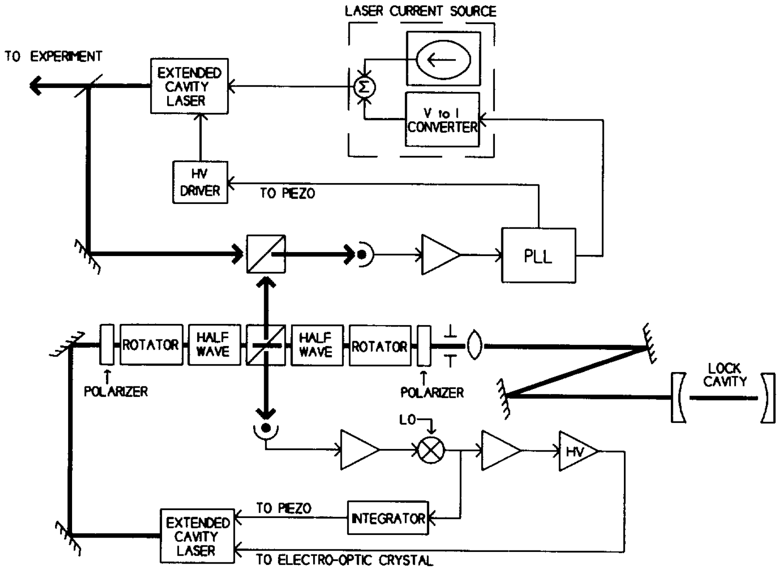

Figure 4: Laser setup for high resolution calcium spectroscopy. Multi-hour phase-locks between two AlGaInP diode-lasers have routinely been demonstrated.

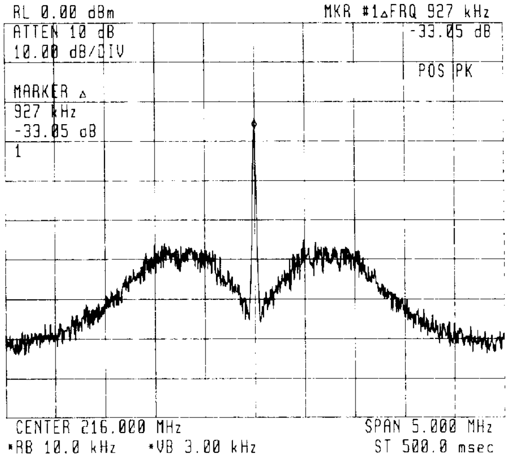

Figure 5: Beat-note between locked diode-lasers. The circuit's loop bandwidth of about 1 MHz results in robust phase-lock

REFERENCES

[1] H.R. Telle, H. Li, "Phase-Locking of Laser Diodes", Electronic Letters, vol. 26, pp. 858-859, 1990.

[2] M. Ohtsu, K. Nakagawa, M. Kourogi, and W. Wang, "Frequency Control of Semiconductor Lasers", J. Appl. Phys., vol. 73, no. 12, pp. R1-R17, June 1993.

[3] G. Santarelli, A. Clairon, S.N. Lea, and G.M. Tino, "Heterodyne Optical Phase-Locking of Extended-Cavity Semiconductor Lasers at 9 GHz", Optics Communications, vol. 104, pp. 339-344, January 1994.

[4] S. Schwartz, J.L. Hall, K. Gibble, D. Weiss, "Robust Phase-Locking of Diode Lasers", submitted to JOSA B 1993.

[5] "NIST, SDL Develop High-Power Laser", Optics & Photonics News, pp. 50, January 1994.

[6] Analog Devices AD9901 Product Data Sheet, Norwood, MA.

[7] W. Egan and E. Clark, "Test Your Charge-Pump Phase Detectors", Electronic Design, vol. 12, pp. 134-137, June 1978.

[8] S. Waltman, A. Romanovsky, J. Wells, R.W. Fox, and L. Hollberg, "Precise Optical Frequency References and Difference Frequency Measurements with Diode Lasers, Proc. Soc. Photo.-Opt. Instrum. Engrs., vol. 1837, pp. 386, 1992. (Note: range now extended to at least 620 GHz)

[9] C. Wieman, L. Hollberg, "Using Laser Diodes for Atomic Physics", Rev. Sci. Instrum., vol. 62, pp. 1-20, January 1991.

[10] M. Ohtsu, Highly Coherent Semiconductor Lasers, Artech House, Norwood MA, 1992.

[11] M.S. Soskin and V.B. Taranenko, "Holographic Total-Internal Reflection Selector for Tunable Lasers", Soviet Journal of Quant. Elect., vol. 7, no. 2, pp. 298-304, 1977.

[12] A.S. Zibrov, R.W. Fox, R. Ellingsen, C.S. Weimer, V.L. Velichansky, G.M. Tino, and L. Hollberg, "High Resolution Diode Laser Spectroscopy of Calcium", submitted to Appl. Phys. B 1993.

[13] J.C. Bergquist, W.M. Itano, D.J. Wineland, "Laser Stabilization to a Single Ion", Proceedings of the International School of Physics <<Enrico Fermi>>, edited by T. Hansch and M. Inguscio, North Holland, Amsterdam, July 1992.

[14] M. Kasevich and S. Chu, "Laser Cooling Below a Photon Recoil with Three-Level Atoms", Physics Review Letters, vol. 69, pp. 1741-1744, 1992.

[15] J. Helmcke, A. Morinaga, J. Ishikawa, and F. Riehle, "Optical Frequency Standards", IEEE Trans. on Instrumentation and Measurement, vol. 83, no. 2, pp. 524-532, April 1989.

[16] K. Nakagawa, M. Kourogi, and M. Ohtsu, "Proposal of a Frequency-Synthesis Chain Between the Microwave and Optical Frequencies of the Ca Intercombination Line at 657 nm Using Diode Lasers", Appl. Phys. B, vol. 57, pp. 435-430, 1993.