Active frequency stabilization, of diode laser pumped, nonplanar ring oscillators

T. Day, E. K. Gustafson, and R. L. Byer

Edward L. Ginzton Laboratories
Stanford University
Stanford CA 94305
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Abstract

We discuss the active frequency stabilization of diode laser pumped, non-planar ring lasers to less than 3 Hz of relative linewidth and describe experiments using these sources in a coherent communication link and to injection lock a 13 W laser.

Frequency stable lasers are required as master oscillators in many applications including coherent communication, high resolution spectroscopy, and gravity wave detection. Helium-neon, dye, and argon-ion lasers have been stabilized for potential use in these fields[1,2,3]. These lasers are typically made from discrete elements (mirrors, etalons, prisms etc.) and have wideband frequency noise requiring complex locking servos. Diode laser pumped Nd:YAG rod lasers have also been stabilized to reference interferometers[4]. However, without a stable reference to compare them to the frequency stability of these lasers is commonly analyzed using the closed loop error signal which can only provide a lower bound on performance. These lasers also require additional elements to force single axial mode operation as well as provide isolation against optical feedback.

The diode-laser pumped nonplanar ring oscillator (NPRO), invented in 1985 by Kane and Byer[5], overcomes many of the difficulties associated with discrete element lasers. Short term free running linewidths of 10kHz have been reported for diode laser pumped Nd:YAG NPRO's [6,7] and spectral densities of frequency noise have been measured to be approximately 100 Hz/$\sqrt{}$Hz at 100 Hz and 16 Hz/$\sqrt{}$Hz at 1 kHz [8]. These impressive frequency properties are attributed to the low noise diode laser pumping together with the monolithic nonplanar ring laser structure. Diode laser pumping avoids frequency noise associated with lamps and the unidirectional oscillation made possible by the nonplanar ring geometry eliminates spatial hole burning forcing single mode operation and providing feedback isolation. Furthermore, the monolithic construction makes the laser less sensitive to ambient acoustic noise.

The lasers we used in our frequency stabilization, and coherent communication studies were modified Lightwave Electronics model 120 NPRO's with 2 mW of output power[9]. The Nd:YAG laser crystals were replaced with Nd:GGG crystals that had been optimized for improved resistance to optical feedback[10] and PZT actuators were bonded directly to the laser to provide fast frequency tuning. The PZT tuning coefficient was 450 kHz/V with a dynamic range of greater than 20 MHz and a tuning bandwidth of 500 kHz. In addition, these lasers could be temperature tuned at 3 GHz/°C with a modulation bandwidth of approximately 1 Hz.

Our locking scheme[11], shown in figure 1, used a frequency discriminant technique known as FM or Pound-Drever locking [12].

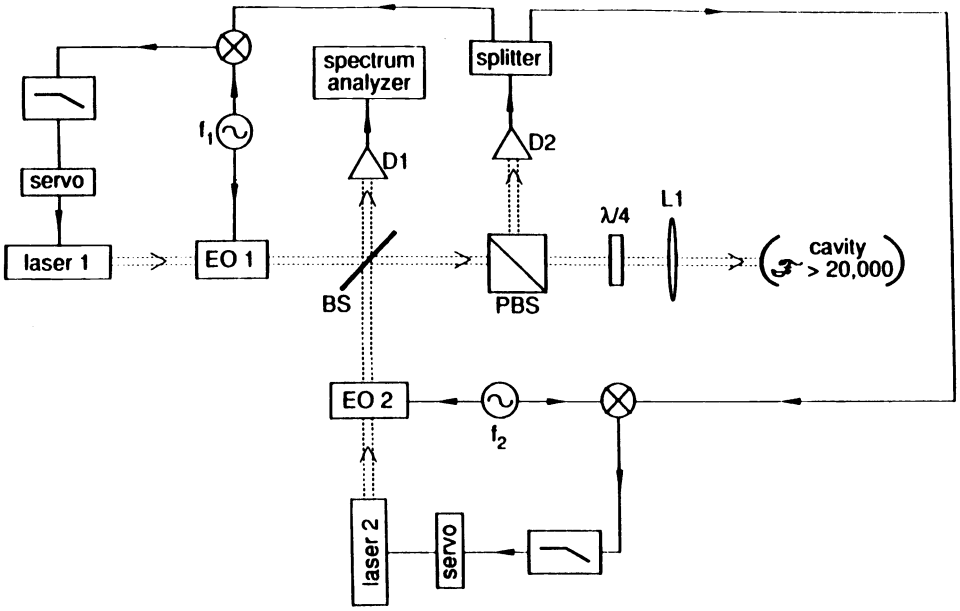

Figure 1: FM locking of two diode laser pumped nonplanar ring oscillators to adjacent axial modes of a high finesse interferometer

Laser 1 was phase modulated at a frequency of 10.9 MHz and laser 2 was modulated at 20.3 MHz. The two laser beams were mode matched into a high finesse interferometer (Newport Reasearch Corp. model SR-150 SuperCavity). The interferometer had a free spectral range of 6.327 GHz and a finesse of greater than 22,000. The interferometer transmission bandwidth was therefore less than 288 kHz. The phase modulation sidebands of each laser were well outside the interferometer passband and were therefore completely reflected with essentially no relative phase shift. The polarizing beam splitter and quarter-wave plate served to provide additional resistance to optical feedback.

On resonance 60% of each carrier is reflected from the cavity. Near resonance the carrier experiences a strongly dispersive phase shift[13]. The phase shifted carriers beat with their respective sidebands at detector D2 and the components at frequencies f_1 and f_2 are detected at the output of the two mixers. The amplitude of these signals is proportional to the frequency offset from the cavity resonance and serves as an error signal used in the locking loop. The error signals were amplified by high gain servos and fed back to the PZT actuators bonded to the laser crystals. The controller had a DC loop gain of 125 dB with a unity gain point of 100 kHz.

Although the two lasers were independently locked to adjacent axial modes of the same interferometer the large interferometer free spectral range eliminated the possibility of the lasers phase locking. By locking the two lasers to the same interferometer limited common mode rejection against cavity fluctuations was obtained. Detector D1 served as a diagnostic port, outside the control loop, enabling direct measurements of the lasers relative stability via the heterodyne beat note.

Figure 2 shows a spectrum analyzer trace of the heterodyne beat note signal detected by D1. The 6.327 GHz signal was mixed down to 20 kHz with a precision RF oscillator and analyzed with a dynamic signal analyzer (Hewlett Packard model 3561A). We measured a 2.9 Hz heterodyne beat note linewidth. Figure 2 shows sideband structure on the signal. This sideband structure is due to the short length of the reference interferometer as well as to electrical pickup (note the 60 Hz sidebands). This arises because the amount of common mode rejection that can be achieved is proportional to the length of the reference interferometer. With our cavity a 0.1 nm length fluctuation corresponds to a 24.9 Hz shift in the free spectral range and hence the beatnote.

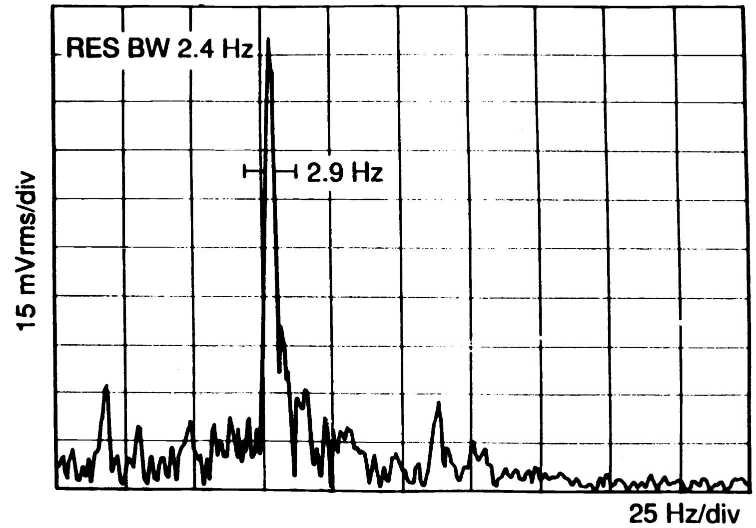

Figure 2: The heterodyne beatnote between two lasers independently locked to adjacent axial modes of a high finesse interferometer.

The beat note linewidth is detemined by system noise[3]. Shot noise on the laser beam together with amplifier noise are interpreted by the servos as frequency fluctuations and are therefore imposed directly by the servos upon the lasers output frequency. This spectral density of voltage fluctuations is converted into frequency fluctuations with a conversion factor given by the inverse slope of the frequency discriminant [3]. We measured this to be 2.5 MHz/V. On resonance the optical power at detector D2 was approximately 77 mW. This corresponded to a photo current of 38.4 μA and therefore a shot noise current density of 3.5 pA/$\sqrt{}$Hz. The amplifier noise current was 14.5 pA/$\sqrt{}$Hz. The voltage gain of the discriminant was 15,810 V/A and therefore the system noise was determined to be 0.33 μV/$\sqrt{}$Hz. This corresponds to an imposed spectral density of frequency fluctuations of 0.834 Hz/$\sqrt{}$Hz. In the regime where the size of the frequency fluctuations is small compared to their bandwidth the resultant linewidth of an oscillator is related to its spectral density (Δ) by[14] $\Delta\upsilon_{laser} = \pi\Delta^2$. Thus each laser had a theoretical, noise limited linewidth, of approximately 2.2 Hz; in good agreement with experiment.

To reduce the relative linewidths to a shot noise limited level the discriminant slope must be increased. The discriminant slope increases proportionally with optical power while the shot noise is proportional only to the square root of power. With only 77 mW of optical power at the detector the amplifier noise dominates the system performance and prevents shot noise limited linewidths. In the absence of amplifier noise the shot noise limited linewidth is approximately 150 mHz.

These low power lasers have also been used to injection lock a higher power oscillator[15]. In this technique a higher power (30 mW) Nd:YAG NPRO master laser was injected into and regeneratively amplified by a high power, CW, lamp pumped slave laser. The slave was a Coherent Antaries laser modified to operate as a ring laser. The slave laser in free running operation was capable of 20 W of multimode output power. When the slave laser cavity was locked to the master laser using RF locking by feeding back the error signal to the slave laser cavity lengthactuator, single mode, frequency stable operation was obtained. Output powers as high as 13 W have be achieved with no significant degradation in the phase noise below that of the master.

The low phase noise of diode laser pumped NPRO's and their demonstrated ability to be easily stabilized as well as used to injection lock high power oscillators make them ideal candidates for use in coherent communication. To demonstrate this potential we built an optical phase locked loop (OPLL) for use in a coherent homodyne reciever. The local oscillator and transmitter were the same Lightwave Electronics model 120 nonplanar ring oscillators described above. Our locking circuitry can be described as a type II third order PLL, which offers the advantages of very high gain at low frequencies together with a small equivalent noise bandwidth. The OPLL achieved tight locking for several hours with transmitter powers of less than -34 dBm on the phase detector. The spectral density of closed loop phase noise was measured by spectrally analyzing the voltage fluctuations at the phase detector output on a Hewlett Packard model 3561A dynamic signal analyzer. The measured noise spectral density corresponded to an rms phase error of 11.6 mrad (0.69°).

The minimum phase error in an optical phase lock-loop was derived by Kazovsky in 1986[16]. In his analysis, he assumed that $\Delta\nu$, the lasers Lorentzian linewidth, is the dominant term in the laser's spectral density of frequency noise. While this is true for diode lasers, it is not the case for our diode-laser-pumped solid state lasers which have very small Lorentzian linewidths and are primarily flicker noise dominated. In order to compare our experimentally determined phase error to that predicted by Kazovsky's theory, we measured the equivalent noise bandwidth of our loop filter and the free running noise spectral density of our lasers. We found a value of 31.5 kHz for the equivalent noise bandwidth of the loop filter. Previous measurements had determined that the spectral density of noise was flicker noise dominated with (in Kazovsky's notation) k_a of 6.5×10^3 Hz^2 and an equivalent $\Delta\nu$ of 0.33 Hz. At the power levels of these experiments, shot noise is negligible, and the theoretically predicted minimum phase error is 9.0 mrad. This agrees well with our experimentally observed phase error of 11.6 mrad.

Monolithic diode laser pumped solid state lasers are extremely rugged and highly efficiency. Diode laser pumped solid state lasers have now been able to achieve less than 3 Hz of relative linewidth in active stabilization experiments, less than 1° of closed loop rms phase noise in an optical phase locked loop, and up to 13 W of CW, frequency stable output in an injection locked laser. These results demonstrate that solid state lasers should provide an attractive alternative for applications requiring high efficiency, easy locking to an optical cavity, injection locking or phase locking.

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