Active frequency stabilization of a 1.062-μm, Nd:GGG, diode-laser-pumped nonplanar ring oscillator to less than 3 Hz of relative linewidth

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

Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

We present results on the frequency stabilization of two diode-laser-pumped ring lasers that are independently locked to the same high-finesse interferometer. We measure the relative frequency stability by locking the lasers one free spectral range apart and observing the heterodyne beat note. The resultant beat note width of 2.9 Hz is consistent with the theoretical system noise-limited linewidth and is appoximately 20 times that expected for shot-noise-limited performance.

Frequency-stable lasers are required as master oscillators in a variety of applications, including coherent communication, high-resolution spectroscopy, and gravity-wave detection. Helium–neon, dye, and argon-ion lasers have been successfully stabilized for potential use in these fields.[1-3] These lasers are typically discrete-element systems that have wideband frequency noise and require complex locking servos. Diode-laser-pumped Nd:YAG lasers have also been stabilized to reference interferometers.[4] However, without a reference oscillator 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 external elements to force single-axial-mode operation and to provide isolation against optical feedback. In this Letter we report on the reduction in relative linewidth to less than 3 Hz and the further characterization by means of time-domain analysis of our diode-laser-pumped, Nd:GGG, nonplanar ring oscillators (NPRO's) previously stabilized to 30 Hz.[5]

Short-term free-running linewidths of 3–10 kHz 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/$\sqrt{\text{Hz}}$ at 100 Hz and 16 Hz/$\sqrt{\text{Hz}}$ at 1 kHz.[8] These impressive frequency properties can be attributed to the diode laser's pumping together with the monolithic nonplanar ring geometry. Diode-laser pumping avoids the frequency noise associated with flash lamps, and the unidirectional oscillation made possible by the nonplanar ring geometry provides feedback isolation that eliminates spatial hole burning and therefore forces single-mode operation. Furthermore, the monolithic construction requires no external elements and is therefore less sensitive to ambient acoustics.

The lasers used in these 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 optimized for improved resistance to optical feedback,[10] and piezoelectric (PZT) actuators were bonded directly to the gain medium to provide fast frequency tuning. The PZT tuning coefficient was 450 kHz/V, with a tuning bandwidth of 500 kHz and a dynamic range of greater than 20 MHz. In addition, these lasers could be temperature tuned at 3 GHz/°C with a modulation bandwidth of approximately 1 Hz.

Our locking scheme (shown in Fig. 1) used a frequency-discriminant technique known as frequency-modulation or Pound–Drever locking.[11] 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 Research Corporation Model SR-150 SuperCavity). The interferometer had a free spectral range of 6.327 GHz and a finesse of greater than 22,000; these values were measured by phase modulating the laser at a known frequency and determining the transmission width as a fraction of the sideband spacing. The interferometer transmission bandwidth
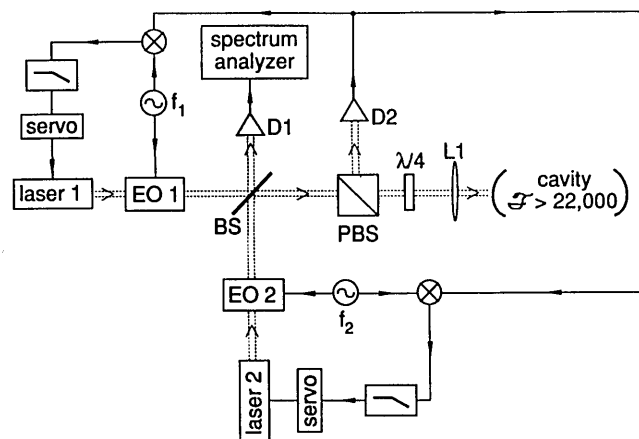

Fig. 1. Schematic of the dual-laser locking system. Both lasers are independently locked, using the frequency-modulation locking technique, to the high-finesse interferometer. They are locked in reflection one free spectral range apart (6.327 GHz). BS, beam splitter; EO's, electro-optic modulators; L1, lens.

was therefore less than 288 kHz. Typically no more than two higher-order transverse modes were measurably excited. The amplitudes of these modes were reduced by greater than 14 dB relative to the fundamental, and their frequencies were offset from the axial mode by 0.811 and 1.62 GHz. The phase-modulation sidebands of each laser lie well outside the interferometer passband and were therefore completely reflected with essentially no relative phase shift. The polarizing beam splitter (PBS) and quarter-wave plate ($\lambda/4$) served to isolate the reflected and incident beams and to provide additional resistance to optical feedback.

On resonance approximately 60% of each carrier is reflected from the cavity. However, near resonance the carrier experiences a strongly dispersive phase shift.[12] 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 normalized output voltage from each mixer serves as the error signal and is given by

$$V_{\text{nor}} = 16F(L/c)J_0(\beta)J_1(\beta)\left[\frac{\text{sinc}(x_N/\sqrt{G})}{1 + G\sin^2(x_N/\sqrt{G})}\right]^{1/2}\Delta\nu,$$
(1)

where $\Delta\nu$ is the amplitude of the laser frequency fluctuations, L is the length of the interferometer, c is the speed of light, β is the phase-modulation index, x_N is the Fourier frequency of the laser frequency fluctuation normalized to the interferometer transmission half-bandwidth, F is the finesse, and $G = (4/\pi^2)F^2$. In this analysis we have assumed optical impedance matching into the interferometer. In addition, $\Delta\nu$ is assumed to be small compared to the interferometer passband, and higher-order terms in the Bessel-function expansion are assumed to be negligible. The phase shift ϕ associated with the error signals is given by

$$\tan(\phi) = -\sqrt{G}\tan\left(\frac{x_N}{\sqrt{G}}\right).$$
(2)

For low Fourier frequencies the error signal follows the frequency noise and the system behaves as a frequency discriminator. However, for higher frequencies there is a 90° phase shift accompanied by a reduced amplitude in the output voltage (inversely proportional to frequency). In this regime the system behaves as a phase discriminator. The transition between the two regimes occurs at a Fourier frequency of half the interferometer bandwidth for large-finesse cavities. Similar expressions for both the phase and amplitude response of the error signals have also been discussed elsewhere.[4,11]

The error signals were amplified by high-gain servos that fed back to the PZT actuators bonded directly to the laser crystals. The loop response of the system had a dc gain of 125 dB with a unity gain frequency of 100 kHz. The servos are cascaded integrators with a lag–lead stage to provide high dc gain as well as the proper slope at the unity gain point. This relatively low gain–bandwidth product was a direct result of the

low spectral density of frequency noise associated with these lasers.

The two lasers were locked to adjacent axial modes of the interferometer and, owing to the large free spectral range, could not phase lock. Locking of the two lasers to the same interferometer also provides limited common-mode rejection against cavity fluctuations. Detector D1 served as a diagnostic port, outside the control loop, that permits direct measurements of the lasers' relative stability through the heterodyne beat note.

Figure 2 shows a spectrum analyzer trace of the heterodyne beat note signal detected at this port. The 6.327-GHz signal was mixed down to 20 kHz with a precision rf oscillator and analyzed with an audio spectrum analyzer (Hewlett Packard Model 3561A). We measured a 2.9-Hz heterodyne beat note linewidth. It is clear from Fig. 2 that there is 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.

The stability that can be achieved in the beat note linewidth is determined by system noise.[3] Shot noise on the laser beam and amplifier noise are interpreted by the servos as frequency fluctuations and are therefore imposed directly on the laser's 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 μW. This corresponded to a photocurrent of 38.4 μA and therefore to a shot-noise current density of 3.5 pA/$\sqrt{\text{Hz}}$. The amplifier noise current was 14.5 pA/$\sqrt{\text{Hz}}$. The voltage gain of the discriminant was 15,810 V/A, and therefore the system noise was determined to be 0.33 μV/$\sqrt{\text{Hz}}$. This corre-
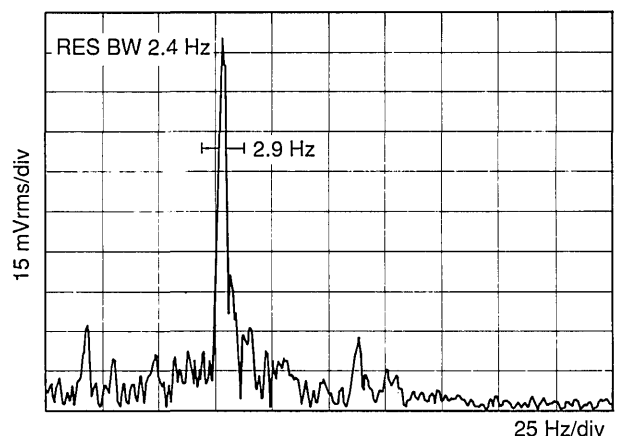

Fig. 2. Heterodyne beat note between two independently stabilized lasers. The lasers are locked to the same interferometer, and the resultant beat note linewidth is 2.9 Hz. The resolution bandwidth (RES BW) was 2.4 Hz for a sampling time of 1.6 sec.
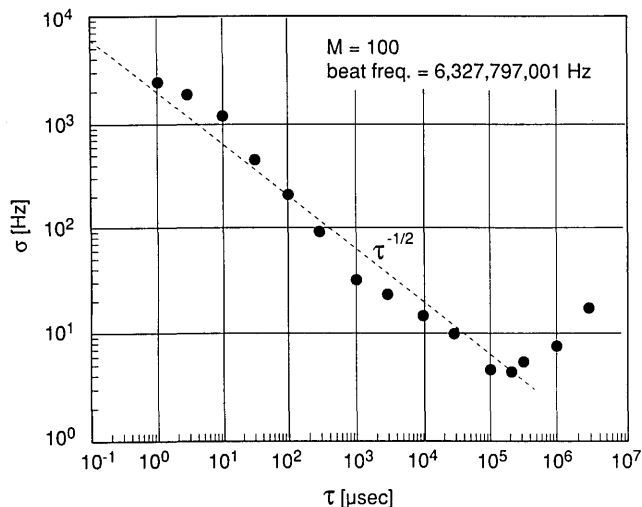
Fig. 3. Two-sample root variance of the frequency of the heterodyne beat note as a function of the sample delay. The minimum root variance is 4.3 Hz and occurs for a sample delay time of 0.2 sec. For sample delay times of less than 0.5 sec the data have a strong white frequency noise behavior $(\tau^{-1/2})$.

sponds to an imposed spectral density of frequency fluctuations of 0.834 Hz/$\sqrt{\text{Hz}}$. In the regime where the size of the frequency fluctuations is small compared with their bandwidth the resultant linewidth of an oscillator is related to its spectral density Δ by[13]

$$\Delta\nu_{\text{laser}} = \pi\Delta^2. \qquad (3)$$

Thus each laser had a theoretical, noise-limited linewidth of approximately 2.2 Hz, which is in good agreement with experiment.

To reduce the relative linewidths to the subhertz level the discriminator 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 μW 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.

We also analyzed the stability of the lasers in the time domain. Figure 3 shows the two-sample root variance in the frequency of the beat note as a function of the sampling interval (τ). These data were obtained by mixing the 6.327-GHz beat note down to 21.4 MHz with a precision oscillator and analyzing the resultant intermediate-frequency signal with a time- and frequency-interval analyzer (Hewlett Packard Model 5371A). The two-sample variance is defined by[14]

$$\sigma^2(\tau) = \frac{1}{2(M-1)} \sum_{i=1}^{M-1} (y_{i+1} - y_i)^2, \qquad (4)$$

where y_i is the ith heterodyne frequency measurement, M is the number of successive measurements, and τ is the time between successive measurements.

The two-sample variance can be equated to the Allan variance through a simple division by the optical frequency (assuming that the interferometer is sufficiently stabilized).[14] We see from Fig. 3 that for small sample delays the root variance is roughly proportional to $\tau^{-1/2}$, whereas for longer times the effects of cavity instabilities become apparent. This behavior is indicative of a white frequency noise source for short time scales (<0.5 sec) together with longer-term drift.[14] The minimum root variance of 4.3 Hz occurs for sample times of 0.2 sec. If the reference cavity could be adequately stabilized over these time scales this would correspond to a root Allan variance of 1.5 × 10^{-14}. This time-domain value is in good agreement with the 2.9-Hz heterodyne beat note linewidth and serves as a separate confirmation of our results.

We have demonstrated that an all-solid-state, diode-laser-pumped nonplanar ring laser can be stabilized to the system noise limit of 2.9 Hz, which is 20 times above the shot-noise limit. We are currently constructing a 25-cm high-finesse interferometer to reduce the optical reference cavity linewidth, increase the common-mode rejection, and decrease the beat note frequency. In this way we expect to reduce the 2.9-Hz heterodyne beat note linewidth to within a factor of 2 of the shot-noise limit.

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