Long-term stability of two diode-laser-pumped nonplanar ring lasers independently stabilized to two Fabry–Perot interferometers

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We have locked two 1064-nm diode-laser-pumped Nd:YAG lasers to two ultralow-expansion glass-ceramic Fabry–Perot interferometers by using the Pound–Drever discriminator technique. The interferometers have finesse of approximately 200,000 and 5-kHz linewidths and are housed in separate temperature-stabilized vacuum vessels. Allan variance measurements of the beat note between the two lasers are as low as 10^{-14} for delay times between 0.5 and 2 s and increase with the time interval for times longer than 2 s, an improvement of 4 orders of magnitude over the free-running performance. Daily variations of the beat-note frequency are less than 1 MHz, which corresponds to a relative temperature change of approximately 100 mK between the interferometers.

Laser frequency stabilization is important in high-resolution spectroscopy, metrology, coherent communications, and gravitational-wave detection. In addition, several space missions, including the microarcsecond astrometry experiment, POINTS, and gravitational-wave experiments such as LAGOS, will require frequency-stabilized lasers.

Commercial diode-laser-pumped solid-state lasers in a nonplanar ring oscillator geometry, such as Nd:YAG and Nd:GGG, are relatively easy to frequency stabilize because of their low free-running frequency noise (free-running linewidths less than 5 kHz compared with 1 MHz for He–Ne lasers), which is a consequence of their diode-laser pumping and their fast frequency actuation (piezotuning with 100-kHz bandwidth).

Day et al. demonstrated the potential of these lasers by locking two of them to adjacent longitudinal modes of a single Fabry–Perot interferometer and, by using a simple single-path feedback servo to control the piezoelectric frequency tuning of each laser, achieved a subhertz relative beat-note linewidth. In a stabilization experiment, in which two lasers are locked to adjacent longitudinal modes of a single Fabry–Perot interferometer, changes in the interferometer length affect the absolute frequencies of both laser frequencies nearly identically while suppressing the noise in their beat note by the factor \( N \), the longitudinal order of the cavity (for Day et al. \( N \approx 44,500 \)). A beat-note measurement with two independent cavities has no intrinsic common-mode rejection, and therefore a beat-note measurement between the two independently locked lasers provides a measure of the absolute stability of both cavities. There may remain some level of extrinsic common-mode noise rejection, however. For example, both interferometer spacers may experience similar temperature changes or mirror spacer creep.

Hall et al. compared a cavity-stabilized He–Ne laser with an iodine-stabilized He–Ne laser and measured a cavity drift rate of 100 kHz/day and a predictability of approximately 100 Hz over a one-day period.

The experimental setup for the measurement of the relative frequency noise of two independently frequency-stabilized Nd:YAG lasers is shown in Fig. 1. Each laser system consists of a 1064-nm nonplanar ring oscillator (Lightwave Electronics Model 120), frequency control and optical isolation components, and a temperature-stabilized evacuated high-finesse Fabry–Perot interferometer. Optical isolation is provided by an acousto-optic modulator.

![Fig. 1. Experimental setup of two identical cavity-stabilized lasers.](image-url)
The measured temperature sensitivity of one cavity is approximately 11 MHz/°C at a nominal temperature of 23°C. This sensitivity corresponds to a thermal expansion coefficient of approximately 4 × 10⁻⁸, which is twice that specified for ultralow expansion by the manufacturer. The characteristic time for the cavity to respond to changes in the housing temperature is approximately 10⁴ s.

The heterodyne beat note between the two lasers is detected with a 1-GHz-bandwidth photodetector. That rf signal is mixed down to lower frequency (typically less than 1 MHz) where the resolution of the frequency and time interval analyzer (Hewlett-Packard 5371A) is greatest.

The frequency stability of oscillators and stabilized lasers is well characterized by the Allan variance. Figure 2 shows two Allan variance measurements. The lower sequence of points represents a series of Allan variance measurements between the two cavity-stabilized lasers, whereas the upper sequence corresponds to measurements of the beat note between two free-running lasers. The variance of the cavity-stabilized lasers has a minimum at approximately 3 Hz for delay times between 0.4 and 2 s. For time intervals shorter than 0.1 s, the noise decreases approximately as the square root of the delay time, indicating a white-noise floor. Excess noise in the region from 1 to 100 ms is attributed to vibrations from the backing pump. This white-noise region is within a factor of 3 of that reported by Day et al. for two lasers locked to a single cavity and indicates that the laser linewidths are of the order of 10 Hz when the noise is assumed white. For integration periods longer than 2 s, the Allan variance increases with the delay time and is largely due to the drift of the spacers resulting from their daily temperature variations.

The time dependence of the frequency drift between the two cavity-stabilized lasers is shown in Fig. 3(a) for a measurement over an eight-day period. These data were normally taken at 20-s intervals and integrated for 8 s. Data collection began when the system was initially evacuated. The cavities were temperature stabilized at a nominal temperature of 27°C. We believe that the initial transient is due
variations resulting from laboratory temperature changes are less than 1 MHz. (b) Residual beat-note frequency fluctuations after subtraction of the linear drift. Random fluctuations of the order of 1 kHz are typical over a 1-h period.

to the stress relief within the spacers. The 5-MHz transient halfway through the second day is a result of closing the Plexiglas housing that encloses the laser table. The beat note over the next four-day period was stable to approximately 1 MHz and shows a daily thermal cycle, indicative of cavity temperature variations of 0.1°C. This cycle is correlated with the temperature changes of the laboratory, which is not air conditioned. The 2-MHz transient at the end of the seventh day resulted from the addition of an 8-cm-thick layer of insulating foam to the laser table. The beat note over the next four-day period was less than 1 MHz, which corresponds to a relative temperature variation of 100 mK.

In conclusion, we have demonstrated the frequency stabilization of two Nd:YAG nonplanar ring oscillators to two independent Fabry–Perot interferometers. This frequency stabilization provided an Allan variance of 10^{-14} for time intervals from 0.5 to 2 s, representing an improvement of as much as 4 orders of magnitude over the stability of the free-running laser. Over a four-day period the frequency drift was less than 1 MHz, which corresponds to a relative temperature variation of 100 mK.

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References