N91-13316

NOISE IN LASER OSCILLATOR SYSTEMS

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The aim of the SUNLITE program is to demonstrate the performance of ultra-stable laser systems in the environment of space. The program uses Non-Planar-Ring-Oscillators (NPRO) which have shown great promise for time and frequency standards with unprecedented resolution and stability. An immediate goal is to test NPRO oscillators in orbital "free fall" by 1994. During the past year there has been remarkable progress in the design and pre-flight testing of the SUNLITE test package. Current theoretical studies are investigating the possible effects of various noise sources on the linewidth and linecenter frequency stability of servo-controlled NPRO lasers. This work reviews the frequency control system and considers the potential impact on frequency stability of noise sources in the control system and in the environment.

The schematic diagram shows the optical system and electronic feecback control circuit for the SUNLITE test package. The frequency of the output laser beam is controlled as follows. The laser diode, Item 1, provides the pump radiation for the NPRO laser, item 2. The electro-optic modulator, item 4, FM modulates the part of the laser beam that is fed to the external reference cavity, item 7. The return signal is FM demodulated and a frequency error signal is generated by items 10, 11, 12, and 13. The error signal is fed to the piezoelectric crystal, item 3, which changes the size of the NPRO cavity and continuously adjusts the laser frequency to lock it onto a resonance frequency of the external cavity.

As can be seen in the diagram, there are numerous optical and electronic interfaces. Each interface provides a potential source of variability or noise in the laser frequency. The purpose of the theoretical work currently underway is to model the entire control system and thereby identify the sensitivities and major contributors to frequency fluctuations in the output beam.

If the laser frequency could be locked perfectly onto the external cavity, the output beam would contain only the frequency noise imposed on the reference cavity by the environment. To test the control system and check for reference cavity noise, two NPRO lasers with separate reference cavities will be compared. The goal of the '94 test is to demonstrate a linewidth $\Delta f \approx 1$ Hz, or a linewidth to linecenter ratio $\Delta f/f_0 \approx 3X10^{-15}$, where $f_0 \approx 3X10^{14}$ Hz, the frequency of the Nd:YAG in the NPRO laser. This goal represents an improvement by a factor of about 1000 over previous surface lab tests. Such a small linewidth ratio can be realized because of the relatively low noise expected in the microgravity environment of space.

When a physical quantity is measured repeatedly, there always will be some variation in the measured quantity. Uncontrolled changes in the frequency of a laser are caused by frequency noise. For measurement times T less than $\approx$ 1 sec, white phase noise contributes to the linewidth, while for measurement times T greater than $\approx$ 1 sec, flicker frequency noise contributes to linecenter drift.

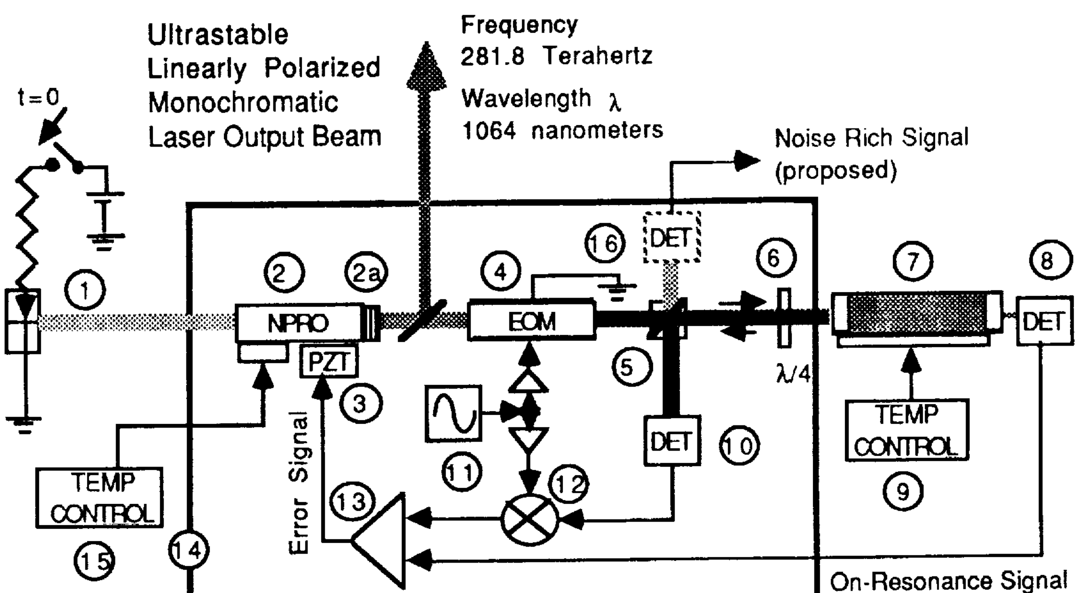
There is a theoretical relationship between the minimum observable Δf, the linecenter frequency f_0, and measurement time T. Suppose an electromagnetic wave is observed at a fixed point in space for a sample or averaging time τ, where τ is determined by a local "perfect" clock. If during the time τ, n_1 periods of the wave pass by and are counted, we say that the "sample" mean frequency $f_1(\tau) = n_1/\tau$. If this experiment is repeated successively N times for a total measurement time $T = \tau N$, the result would be a sequence of N values $\{f_1,...,f_i,...,f_N\}$. By definition from statistics, the mean frequency $f_0 = \Sigma f_i/N$; the variance $\Delta f^2 \approx \Sigma(f_0 - f_i)^2/N$; and the standard deviation $\Delta f = (\Delta f^2)^{1/2}$. If f_0 is constant over the measurement time T, any nonzero variance Δf^2 is said to be due to "phase noise", and the linewidth ratio would decrease in inverse proportion to the square root of τ, according to the equation:

$\Delta f/f_0 \approx [(\Sigma(f_0-f_i)^2)^{1/2}/\Sigma f_i](T/\tau)^{1/2}$. Thus, if there is only zero-mean phase noise on a wave, there are no fluctuations in the mean frequency f_0, and the observed linewidth Δf decreases in inverse proportion to the square root of the averaging time. In this region a log-log graph of the "Root Allan Variance" shows a steady decrease with slope -1/2.

A graph of the Root Allan Variance also indicates the time over which f_0 is constant, which is called the "coherence time", τ_0. If the wave moves with the speed of light, c, the mean wavelength and mean frequency are related by $f_0\lambda_0=c$, and the coherence length $L=c\tau_0$. The point on a graph of the Root Allan Variance where the slope changes from -1/2 to zero or a positive slope is an indication that f_0 is no longer constant beyond the corresponding averaging time. This point gives a measure of the coherence time. Thus, the minimum observable linewidth Δf is related approximately to the coherence time τ_0 by $\Delta f \approx 1/\tau_0$.

If the linewidth of the SUNLITE laser is approximately 1 Hz, the coherence time would be $\tau_0 \approx 1$ sec, and the coherence length would be $\approx$ 1 light-second $\approx$ 186,000 miles $\approx$ 300 million meters. Such a coherence length would be very useful in long-baseline interferometry, inter-satellite communications, laser ranging to the Moon, and gravity wave antennas. We anxiously look to the future when the coherence time mignt be eventually increased to 1000 sec and the coherence length to 300 billion meters.

SUNLITE LASER OSCILLATOR SYSTEM



1 Laser Diode Pump Source
2 Nonplanar Ring Oscillator
2a Polarizer
3 Piezoelectric Crystal
4 Electro-optic Modulator
5 Polarization Sensitive Beamsplitter
6 Polarization Quarterwave Plate
7 Ultrastable Fabry-Perot Cavity
8 On-Resonance Photodiode Detector
9 Temperature Controller
10 Return-beam Photodiode Detector
11 10MHz RF Oscillator
12 FM Demodulator
13 Servocontroller Feedback Error Signal Amplifier
14 Laser Frequency Control Servosystem
15 NPRO Heat/Cool Temperature Controller
16 Noise Signal Photodiode Detector