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Prestabilized NPRO: Frequency Sensing and Shifting

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Abstract

The optical and control system lay-out for a frequency prestabilized 700 mW Nd:YAG nonplanar ring oscillator is presented and one particular set of pertinent technical specifications is given.

1. Introduction

Switching the LIGO laser wavelength from 514.5 nm to 1064 nm requires the new laser to be integrated with a frequency stabilization system in a Prestabilized Laser Subsystem (PSL). The Nd:YAG laser for LIGO will consist of a 700 mW nonplanar ring oscillator (NPRO), the output of which will be either amplified or used to injection-seed a higher power laser. Initially, the PSL will consist only of the NPRO and its frequency control arrangement, with the high power stage to be added later. Design of a new PSL creates the opportunity to achieve better frequency stability at the prestabilized laser stage. A frequency sensing and frequency shifting arrangement for an NPRO prestabilized to 10^{-3} Hz/Hz$^{1/2}$ above 100 Hz is laid out and some requirements on its parts are presented.

2. Prestabilized NPRO Lay-Out

The frequency stabilization arrangement for the NPRO is shown in the diagram on page 2. The arrangement consists of the NPRO itself, a reference cavity, assorted components needed for a conventional Pound-Drever stabilization scheme, and a double-passed acousto-optic modulator (AOM) which is employed as a frequency shifter.[1] A frequency increase due to the AOM will result in the frequency of the main beam being decreased by an equal amount through control system action, in order to keep the light in resonance with the reference cavity. The frequency of the main beam can thus be shifted without the need to change the length of the reference cavity with PZT disks, which seem to introduce cavity length fluctuations and thus limit the degree to which the laser frequency can be stabilized. Placing the AOM in a side beam paths avoids adding beam jitter associated with tuning the AOM to the main beam.

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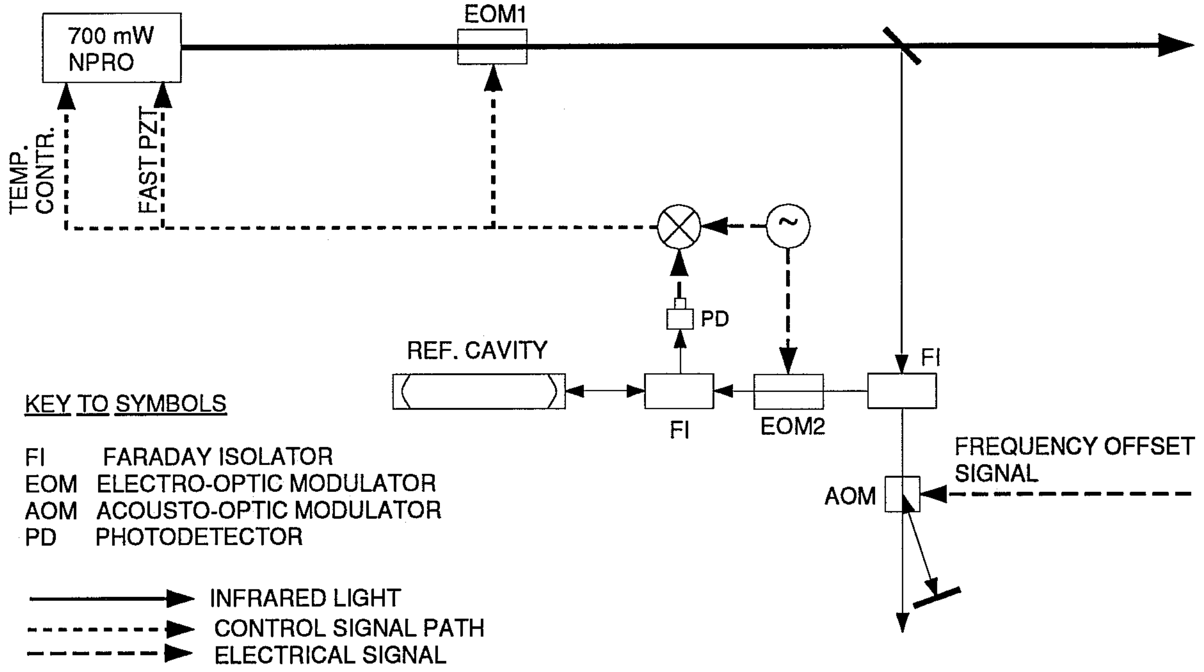
[1] This AOM arrangement has been first used with the Glasgow 10 m interferometer.

PROPOSED CONFIGURATION FOR 700 mW PRESTABILIZED NPRO



3. Selected Technical Specifications

Assuming that the noise contributed by control system electronics is negligible, the following contributions to frequency noise need to be considered:

1. Photon shot noise. The shot noise limited frequency fluctuations depend on:
    - The amount of light incident on the reference cavity P
    - The RF modulation depth β
    - The storage time of the reference cavity τ_e
    - The quality of the mode matching between the light and the cavity and the RF modulation level, described by the modulation function M
2. Fluctuations in reference cavity length L
3. Frequency noise in the frequency offset signal which drives the AOM.

3.1. Shot Noise

When the frequency of a laser beam is locked to the resonance of an optical cavity, shot noise limited frequency noise is described by:[1]

$$\nu(f) = \frac{1}{2\sqrt{2}\pi\tau_e}\sqrt{\frac{3}{8}}\sqrt{M}\left[\frac{h\nu}{P}\left(1 + [f/f_k]^2\right)\right]^{1/2}$$

where $\nu(f)$ is the amplitude spectral density of frequency noise, f_k is the "knee frequency" (half the cavity resonance bandwidth), and the modulation function M is:

$$M = \frac{1}{3}\left[\frac{K^{-1} + A^2 J_0^2 - 2AJ_0^2 + 2AJ_0J_2}{KA^2 J_0^2 J_1^2}\right]$$

where K is the mode matching fraction in the absence of modulation and mirror coupling mismatches, $J_i = J_i(\beta)$ are Bessel functions calculated at the value β of the modulation depth, and $A = 2/[1 + (L_1 + L_2 + T_2)/T_1]$, with T_i, L_i the transmissions and losses of the cavity mirrors, respectively.

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[1] S. Whitcomb, Shot Noise in the Caltech Gravitational Wave Detector - the Mid-1984 Configuration, 1984, unpublished.

3.2. Fluctuations in the Reference Cavity Length

Since the laser frequency is tightly locked to a resonance of the reference cavity, the ability to suppress frequency noise is only as good as the stability of cavity length at the frequencies of interest. Experiments with cavities consisting of mirrors optically contacted to an ultra-low expansion glass spacer[1] have demonstrated frequency stability better than 1 mHz/Hz1/2 above 6 kHz. The higher noise level measured at lower frequencies in the VIRGO stabilization experiment is believed to be caused by insufficient seismic isolation of the reference cavity, marginal stability of the frequency control system, and by the crude nature of their test set-up. It seems thus that a cavity consisting of mirrors attached to a rigid ULE spacer by optical contacting would be an adequate design choice for the Nd:YAG PSL.

3.3. Frequency Noise in the AOM Drive

When the AOM is driven with a signal of frequency ν_a, the frequency of the light is change by $2\nu_a$, if the AOM is double-passed. Thus, the frequency noise in the drive signal needs to be less than $0.5x10^{-3}$ Hz/Hz$^{1/2}$ above 100 Hz 10^{-3}, for laser frequency noise no higher than 10^{-3} Hz/Hz$^{1/2}$ above 100 Hz. This corresponds to phase noise on the drive signal no higher than -109 dBc/Hz at 100 Hz, and decreasing by 20 dB/decade. This requirement is rather stringent, as it needs to be applied to a signal source with tuning range of ~10 MHz.[2]

3.4. Summary of Specifications

A particular choice of parameters that allows for 10^{-3} Hz/Hz$^{1/2}$ above 100 Hz is shown in the table below. While the parameter values shown in the table appear to be reasonable, they can be changed, using the shot noise formula above. Examples of possible trade-offs are:

- Lower modulation index, longer storage time or more power
- Lower visibility, longer storage time or more power
- Overcoupled/undercoupled cavity, by using non-identical mirrors
- Higher mirror transmission, longer cavity.

It is possible that the most difficult requirement on the AOM drive signal phase noise will prove the most difficult to meet, because of the combination of low noise and wide tuning range. The tuning range requirement results from the level of seismic disturbance prevailing on the Caltech campus and the specifics of the seismic isolation stacks and mirror suspensions currently in use with the 12 m mode cleaner and the 40 m interferometer. With lower seismic noise and better

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[1] conducted be the VIRGO group

[2] A tuning range of 10 MHz is needed to keep the laser frequency resonant with either the 12 m mode cleaner or the average length of the 40 m arms. This requirement is based on measured frequency corrections in both locations, and includes a safety factor 10. Any measure which reduces suspended cavity mirror motion will result in reduced tuning range and thus make it easier to meet the phase noise requirement.

stacks/suspensions, it is quite likely that the AOM tuning range requirement at the LIGO sites will be less than 10 MHz, thus making it easier to meet the phase noise requirement.

Cavity design	Linear cavity, sturdy hollow ULE spacer, optically contacted mirrors
Cavity isolation	In vacuum, suspended from 2 or 3-layer stack, eddie-current damping
Cavity length	15 cm
Mirror transmission/loss	300 ppm/30 ppm
Mirror curvature range	25-35 cm
Light level at ref. cav. input	1 mW
Visibility (no modulation)	>90%
Modulation level (SSB/Carrier)	$\beta = 0.68$ (10%)
Frequency shifting for locking to cavity downstream	Double-passed acousto-optic modulator (AOM)
AOM center frequency	TBD, ~100 MHz
AOM tuning range	~10 Mhz
AOM driver phase noise	<-109 dBc/Hz@100 Hz, -20 dB/decade for higher frequencies

Table 1. One possible choice of parameter values for components of the Nd:YAG PSL frequency sensing/shifting arrangement.