

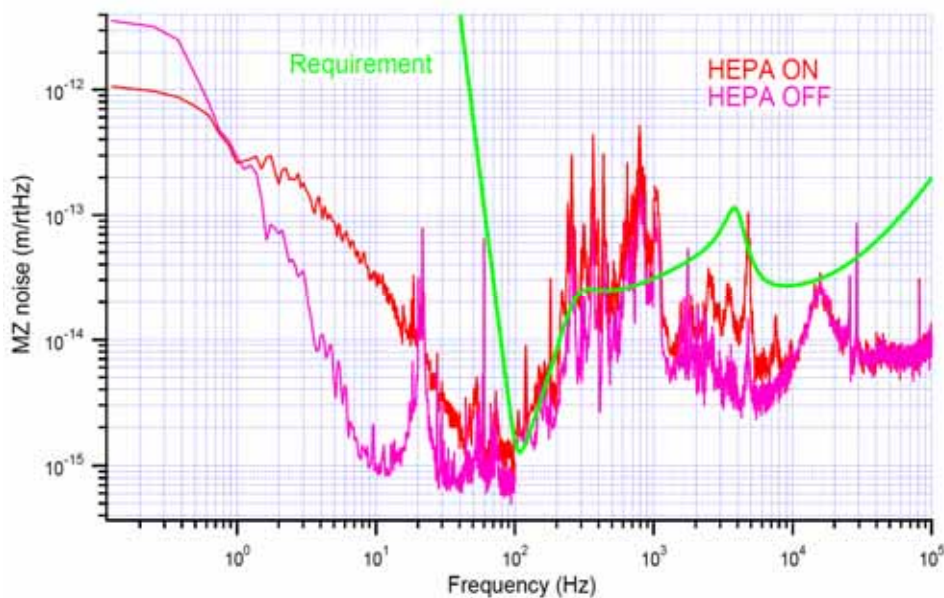
40m Report

Kentaro Somiya

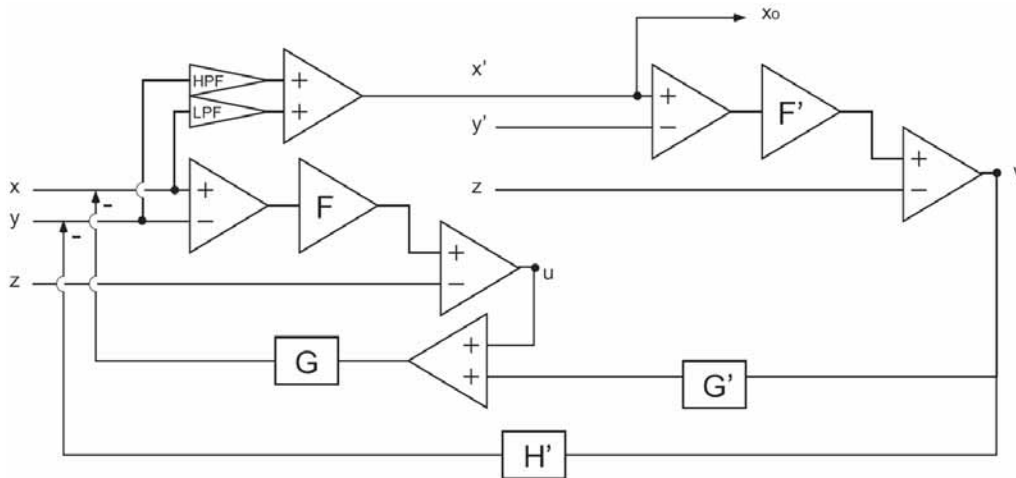
This is a brief report of the measurements I have done in these 2 months.

Mach-Zehnder

- MZ noise spectrum is measured in various conditions.
- HEPA filter enhances the noise level at the low frequencies and at around 2-5kHz.



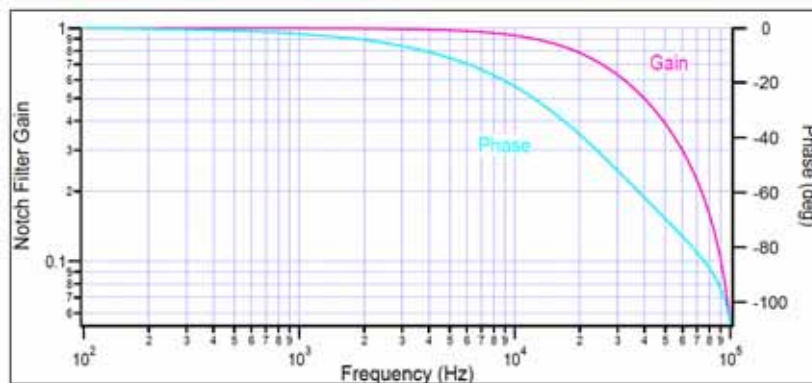
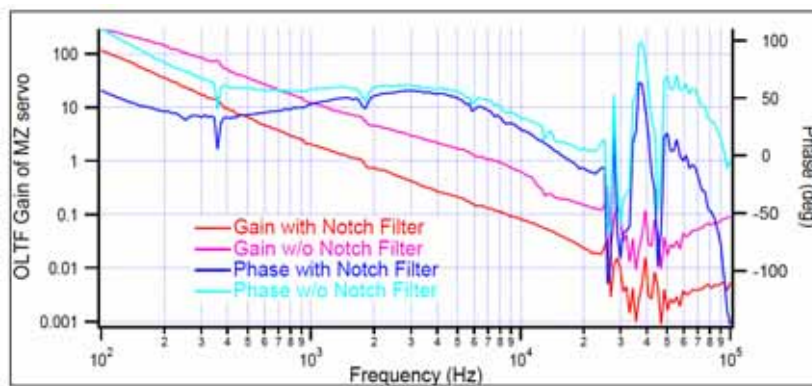
- There is no difference between the data with MC locked and unlocked.
- There is no difference between the data with ISS ON and OFF.
- However the noise level is reduced at around 200Hz-1kHz compared with the previous result measured by Osamu. Maybe it is just that I measured under quieter circumstance in the night time.
- The requirement (green curve) is calculated with the frequency noise requirement of the 40m [T040180], using the FSS of TAMA for an example.



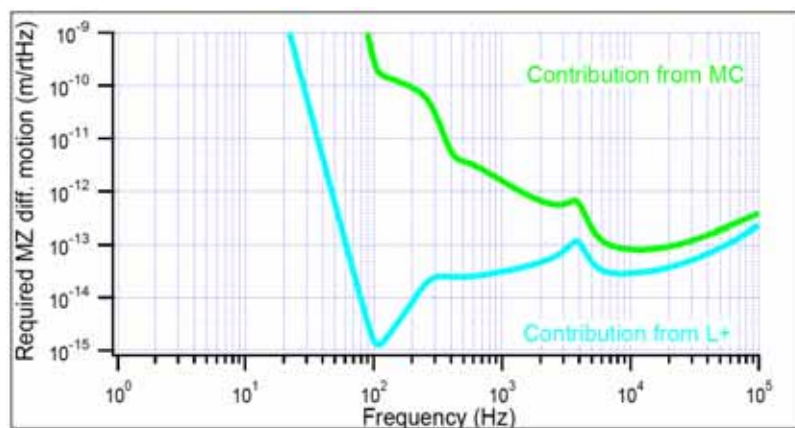
Feed-around frequency stabilization system (used in TAMA).

x: laser freq noise, y: MC mirror motion, z: MZ differential motion

- With the servo gain turned up, 110kHz oscillation starts before 20kHz oscillation begins, so a notch filter is installed just after the servo to avoid the 110kHz oscillation, but somehow the DC gain decreases by factor of 10 and cannot be compensated. Needs investigation.

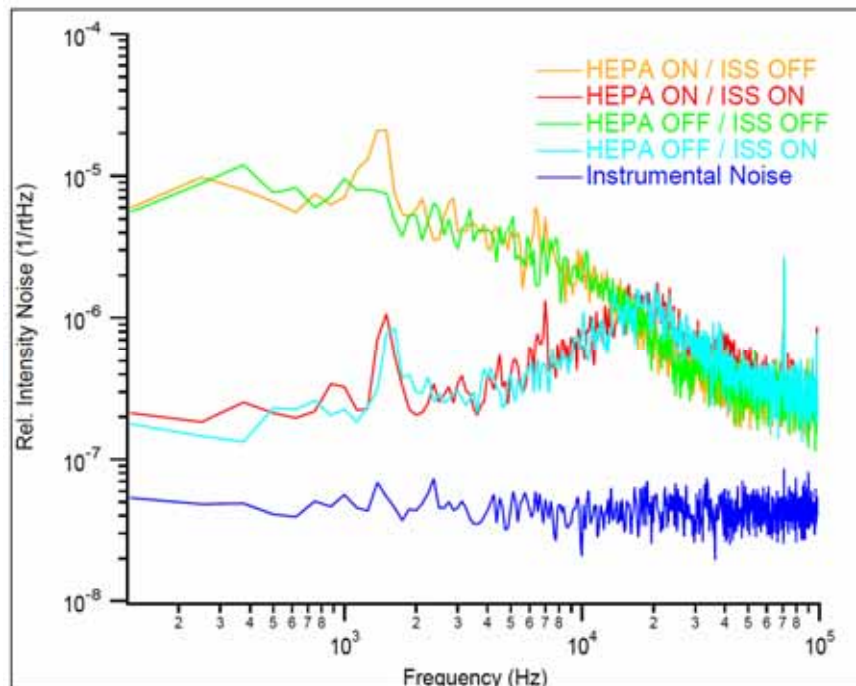


- As MZ noise does not meet the requirement, phase-correcting pockels cell is necessary, or an alternative could be the virtual MZ suggested by P. Beyersdorf [see Appendix A].
- If we put the 29MHz EOM, used to lock the MC, out of the MZ, the contribution of MZ noise to frequency noise via the MC would be removed, but since the contribution via the L+ is larger and cannot be removed in that way it does not change the situation.



ISS

- ISS has been changed and the noise spectrum is measured.



- The gain is too small. The UGF should be above 100kHz.

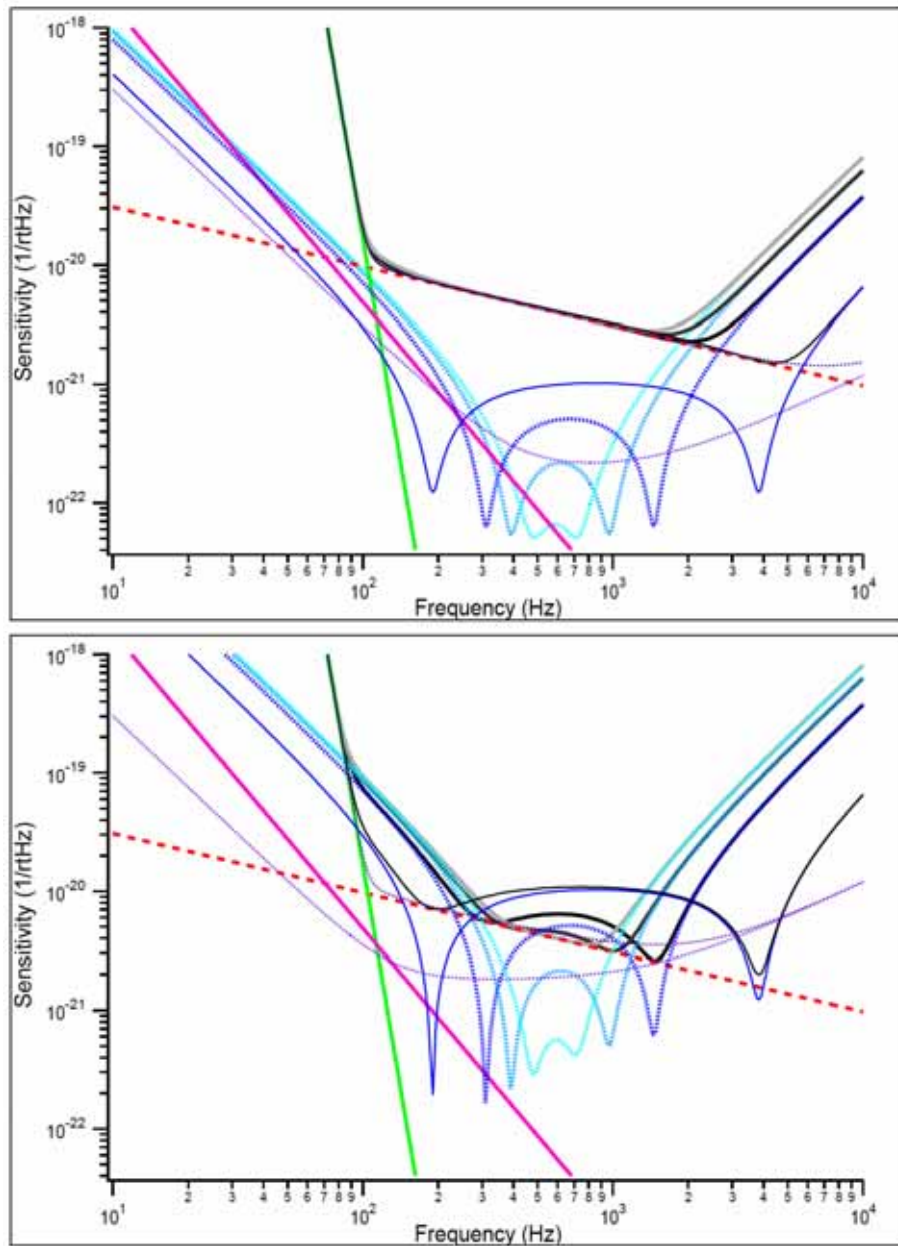
- The gain slider is set to $\sim 0\text{dB}$ for the above data. Turning it up to 6dB makes the UGF $\sim 35\text{kHz}$, which is yet too low. Turning up the gain higher than 10dB causes the saturation of the servo. Maybe the optical gain should be raised, i.e. more light to the ISS(INSENS) photodetector.
- So far, we cannot see the difference between the data of the INSENS PD, whose electronic noise is suppressed, and the data of the MON PD, whose electronic noise is not suppressed.
- ISS shows an intermittent saturation about once in one minute, which turns out to be the 76.8mVpk oscillation at 8.5kHz . It lasts for about 1 second and disappears. Needs investigation.

MC

- If the MZ is not properly locked to the bright fringe, an offset voltage appears on the error signal of the MC. Sweeping the MZ and Looking the MC error signal, one can see the offset amount changes with the MZ fringe. This happens because the orthogonality of the carrier light and the RF SB is disturbed at the MZ with imbalance [T040166].
- MC sensitivity should be measured with and without the MZ in order to prove the noise contribution from the MZ noise to frequency noise [see Appendix B].

Misc. Calculation

- The estimated total sensitivity of the 40m is recalculated and the possibility of the direct measurement of the optical spring is implied [T040174].
- Frequency noise budget via various contribution paths, which shows the expected difference of DC readout and RF readout, is derived and the requirement frequency noise level is given [T040180].
- Quantum noise spectra with various detune phases are calculated and the result is as follows.



QN spectra with the highest power (6WxPRG16) of the 40m (top),
 QN spectra with the pickoff mirror at the dark port (bottom).
 Detune phases are 21, 45, 55, 60 deg from broadband RSE,
 and the broad one is FPMI spectrum without the SR mirror.
 Green: Seismic, Pink: Suspension Thermal, Red: Mirror Thermal.

Appendix A

The following is the document written by P. Beyersdorf.

Virtual Mach-Zehnder based on polarization separation for generating multiple sets of non-cascaded sidebands

Peter Beyersdorf

August 23, 2004

It's well known that light passing through a series of phase modulators, each driven at a unique frequency generates a spectrum that has not only the sidebands directly imposed by each modulator, but also sidebands of sidebands imposed by the modulators further downstream. It is also well known that an array of modulators in parallel, i.e. in opposite arms of a Mach-Zehnder only impose sidebands on the carrier without introducing sidebands of sidebands. At the LSC meeting in August 2004, Kentaro Somiya discussed the optical layout used to generate the desired input field for the 40m interferometer at CalTech. A Mach-Zehnder interferometer is used to allow sidebands at both modulation frequencies to be generated without sidebands of sidebands that would obscure control signals generated through double-demodulation. He also discussed a concern about differential phase noise of the Mach-Zehnder being problematic. What is described below is a "virtual Mach-Zehnder" based on polarization separation that is suitable for generating sidebands at two unique modulation frequencies but is immune to differential phase noise.

Consider the actual Mach-Zehnder configuration for generating the appropriate input light spectrum

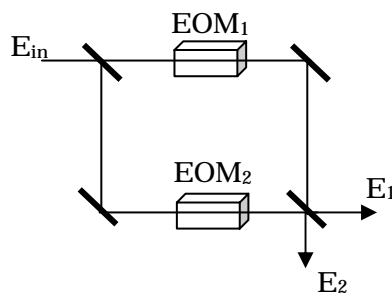


Figure 1 A real Mach-Zehnder interferometer with an EOMs in each arm

The output E_1 is

$$E_1 = \frac{i}{2} \left(e^{ikn(t)L_1 + \phi_1} + e^{ikn'(t)L_2 + \phi_2} \right) E_{in} = e^{i(\phi_1 + \phi_2)/2} e^{i(n(t)L_1 + n'(t)L_2)/2} \cos \left(\frac{(n(t)L_1 - n'(t)L_2) + (\phi_1 - \phi_2)}{2} \right) E_{in}$$

Where $n(t)$ and L_1 are the index of refraction and length of EOM1 respectively, $n'(t)$ and L_2 are the index of refraction and length of EOM2 respectively, and ϕ_1 and ϕ_2 are the static phases accumulated during propagation in each arm. $n(t)$ and $n'(t)$ are responsible for the RF modulation, and the control scheme fixes ϕ_1 and ϕ_2 by feeding back to one of the mirror positions to set $\phi_1 - \phi_2 = 0$ so that the field E_1 is bright and the modulated is purely phase modulation.

Consider the optical layout shown below

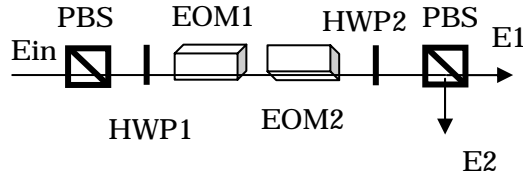


Figure 2. A virtual Mach-Zehnder with an EOM for each polarization.

The Jones matrix for the optical path is

$$M = -\frac{1}{2} \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} -1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} e^{ikn'_e(t)L_1} & 0 \\ 0 & e^{ikn'_oL_1} \end{bmatrix} \begin{bmatrix} e^{ikn_oL_2} & 0 \\ 0 & e^{ikn_e(t)L_2} \end{bmatrix} \begin{bmatrix} -1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

Where the phase modulation is only on the extraordinary ray, not the ordinary ray in the phase modulators. The output E_1 is given by

$$\vec{E}_1 = M \begin{bmatrix} E_{in,p} \\ E_{in,s} \end{bmatrix} = -\frac{1}{2} \left(e^{ikn'_e(t)L_1 + ikn_oL_2} + e^{ikn_e(t)L_2 + ikn'_oL_1} \right) E_{in,s}$$

Which is identical to that of the real Mach-Zehnder interferometer when the static phases are related by

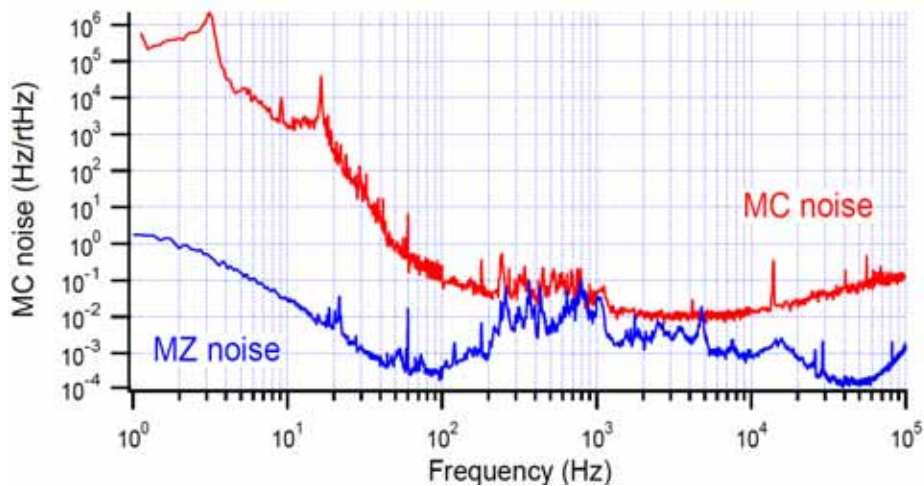
$$\begin{aligned}kn_o L_2 &\rightarrow \phi_1 \\kn'_o L_1 &\rightarrow \phi_2\end{aligned}$$

This phase difference cannot be adjusted by moving a mirror, but rather, if necessary can be adjusted by inserting a waveplate with the proper birefringence into the path. If, however, the length and crystal material of the two modulators is identical, this shouldn't be necessary. Note that because the differential phase shift cannot be adjusted by moving a mirror, differential phase noise cannot be introduced by moving a mirror either. The analogy between the real and the virtual Mach-Zehnder interferometers is easy to understand physically: In the real Mach-Zehnder of Figure 1 a beam splitter separates a beam into paths each path contains a beam of equal amplitude. An EOM in each arm modulates the light in that arm and the two paths are recombined by a second beamsplitter. The static length difference between the arms must be set to an integer number of wavelengths to keep the output on the bright fringe. In the virtual Mach-Zehnder of Figure 2, a half-waveplate separates a linearly polarized beam into two polarization components of equal amplitude. A vertical EOM and a horizontal EOM each modulate one of the polarization components and the two components are recombined by another half-waveplate and a polarizing beamsplitter. The static birefringence between the arms must be set to an integer number of wavelengths to keep the output on the bright fringe.

Clearly the virtual Mach-Zehnder and the real Mach-Zehnder are analogous. Differential phase noise in the real Mach-Zehnder is relatively easy to excite because it only requires the differential motion of the mirrors to modulate the path length difference. In the virtual Mach-Zehnder, however, differential phase noise is hard to excite because it requires differential changes in the birefringence, but there is no mechanism to generate this.

Appendix B

I measured the transfer function from MZ noise to MC noise on the last day.



The MC noise spectrum is measured for the reflected light of the MC so that this does not show the frequency noise spectrum of the transmitted light, and it has been turned out that the contribution of MZ noise would be larger on the transmitted light than reflected light. Moreover, MZ noise spectrum on this results should be multiplied by CLTF, i.e. $G/(1+G)$, where G is the OLTF of the VCO control. The CLTF is, according to the previous measurement by Osamu, flat unity from about 1kHz to 10kHz.

Here is a brief explanation about the difference between noise of the reflected light, or the feedback signal, and noise of the transmitted light:

Feedback signal is

$$\frac{1}{1+GF-HF} [Fx - Fy - z]$$

Transmitted noise is

$$\frac{1}{1+GF-HF} [(LPF - HF)_x + (HPF - GF)_y + (LPF \times G + HPF \times H)_z]$$

Here G , H , F , LPF , HPF are the gain of VCO, gain of MLC, MC finesse, cavity pole low-pass-filter, and high-pass-filter, respectively. These two equations cannot be regarded as the same in any frequency.