Mode Cleaner for TAMA300

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Excess noise which is associated with transmission of phase modulation side-bands through a mode cleaner has been successfully reduced. It is necessary that phase modulation side-bands for an interferometer pass through a mode cleaner since a phase modulator should be placed before the mode cleaner. It can be realized by adjusting the modulation frequency to the Free Spectral Range (FSR) of the mode cleaner. However, it was reported that excess noise exists in the intensity of the light coming out of the mode cleaner around the modulation frequency. The mechanism of the excess noise has been found to be convolution between deviation of the laser frequency from resonant frequency of the mode cleaner and that of the modulation frequency from the FSR. It has been verified in experiment and the excess noise has been reduced successfully.

1 Introduction

TAMA300 is a laser interferometer gravitational wave detector with a baseline of 300 m in length, and is located on the campus of National Astronomical Observatory (NAO). The interferometer is a Fabry-Perot Michelson interferometer with power recycling. The laser is an injection-locked laser whose maximum output power is 10 W. The mode cleaner which is placed between the laser and the interferometer is a triangle cavity. The half round trip of the cavity is about 9.8 m in length and the finesse is about 1700. The mirrors which compose the mode cleaner are suspended in vacuum chambers in the same manner as the mirrors for the interferometer. There are two vacuum chambers for the mode cleaner. One of them contains two mirrors which are independently suspended with a distance of 0.2 m. This vacuum chamber is connected to the other vacuum chamber for the mode cleaner and also to the vacuum chamber for the recycling mirror with vacuum pipes.

The functions of a mode cleaner are cleaning of the wavefront and reduction of beam jitter noise, due to its selectivity of the transverse electric field mode[1]. The mode cleaner is also used for a stabilization of the laser frequency. One of additional requirements for a mode cleaner is transmission of phase modulation sidebands. The phase modulator for the interferometer should be placed before the mode cleaner to avoid additional mode distortion.

2 Sidebands Transmission

2.1 Control of the Cavity

The signal to operate the mode cleaner is taken by the Pound-Drever Method[2]. The incident light is modulated by a phase modulator, the reflected light from the mode cleaner cavity is detected by a photo detector and the signal from the photo detector is demodulated by the modulation signal. The demodulated signal is the error signal which represents the difference between the laser frequency and the resonant frequency of the mode cleaner cavity. The error signal is fed back to the laser frequency control actuator (or to the cavity length control actuator in the preliminary experiment) with suitable electric filters. Since the Recycled Fabry-Perot Michelson interferometer is to be controlled using the similar the Pound-Drever Method. Two phase modulators are required to operate both the mode cleaner and the interferometer.

2.2 Sidebands Transmission

The sidebands produced by phase modulation cannot pass through the mode cleaner, if the modulation frequency is much higher than the cavity band width. However if the phase modulation frequency is exactly equal to the Free Spectral Range of the mode cleaner, the modulation sidebands can pass through the mode cleaner cavity. The carrier and the sidebands pass through at different resonant peaks. The FSR is denoted by the following equation,

$$\nu_{\mathrm{FSR}} = \frac{c}{2\ell}, \tag{1}$$

where c is the speed of light and ℓ is the half round trip length of the cavity.

2.3 Excess Noise associated with Transmission Sidebands

We did an experiment of transmission sidebands in the mode cleaner of the 20 m prototype detector [3] located also on the same NAO campus. The mode cleaner of the 20 m prototype detector is 3.75 m in length so that the phase modulation at the frequency of 40 MHz can pass through the mode cleaner. We found that the transmitted light coming out of the mode cleaner had extra intensity noise at the modulation frequency, although the incident light to the mode cleaner had no intensity noise there. The transmitted light was detected by the photo detector and the signal from the photo detector is demodulated by the modulation signal. The demodulated signal was analyzed in Fourier spectrum. In the same way, the demodulated signal for the incident light to the mode cleaner was analyzed. Two spectra were different. The demodulated signal was limited by the shot noise above 1 kHz, whereas that for the transmitted light had intensity noise which was bigger than the expected shot noise level. The intensity noise level for the transmitted light was found to depend on the modulation frequency. This intensity noise level was reduced by optimizing the modulation frequency. However, even the best signal level for the transmitted light was more than 10 dB bigger than that for the incident light up to 10 kHz.

3 Mechanism of Excess Noise

3.1 FM Deviation and FSR Deviation

We believe that the excess noise for the transmitted light is produced by conversion of the phase modulation the amplitude modulation when both the FM deviation and the FSR deviation exist: the FM deviation is deviation of the laser frequency from the resonant frequency of the mode cleaner cavity, and the FSR deviation is deviation of the modulation frequency from the FSR of the cavity.

If only the FM deviation exists, namely the frequency of the phase modulation is exactly equal to the FSR of the mode cleaner cavity, the phase modulation for the transmitted light is not converted to amplitude modulation, given in front of the mode cleaner is perfectly as same as that given behind the mode cleaner, because the carrier and the modulation sidebands are changed in its amplitude and phase exactly in the same way.

If there is only the FSR deviation without the FM deviation, the amplitude modulation is not generated, because the upper and lower sidebands are still symmetric with respect to the carrier.

But if there are both the FM deviation and the FSR deviation, the amplitude modulation is generated by the following reason. The carrier is given only the FM deviation. The upper sideband is given the sum of the two deviations, FM + FSR, whereas the lower sideband is given the difference of the two deviations, FM − FSR. As the carrier, upper sidebands, and lower sidebands are given the different effect, the amplitude modulation is generated from the transmission sidebands.

3.2 Convolution between FM Deviation and FSR Deviation

When both deviations exist, the intensity noise for the transmitted light is given for the inphase and quadrature-phase signal, respectively as follows:

$$\text{Inphase} \quad : \quad -16\, m\mathcal{F}^3 \frac{\Delta\nu_{\rm FM}}{\nu_{\rm FSR}} \left(\frac{\Delta\nu_{\rm FSR}}{\nu_{\rm FSR}}\right)^2, \tag{2}$$

$$\text{Quadrature} - \text{phase} \quad : \quad -4m\mathcal{F}^2 \frac{\Delta\nu_{\rm FM}}{\nu_{\rm FSR}} \frac{\Delta\nu_{\rm FSR}}{\nu_{\rm FSR}}, \tag{3}$$

$$\frac{\Delta\nu_{\rm FM}}{\nu_{\rm FSR}} \ll 1 \quad \text{and} \quad \frac{\Delta\nu_{\rm FSR}}{\nu_{\rm FSR}} \ll 1, \tag{4}$$

where $\mathcal{F}$ is the finesse of the mode cleaner cavity, m is the modulation index, $\nu_{\rm FM}$ is the FM deviation, $\Delta\nu_{\rm FSR}$ is the FSR deviation, and $\nu_{\rm FSR}$ is the FSR of the cavity. The equation of quadrature-phase demodulation will make a convolution between $\Delta\nu_{\rm FM}$ and $\Delta\nu_{\rm FSR}$ when the formula is converted into the Fourier-frequency domain. Since both $\Delta\nu_{\rm FM}$ and $\Delta\nu_{\rm FSR}$ have dominant DC-components in practice and negligible higher-frequency components, it is safe to say that there are two noise components at frequency f in the quadrature-phase demodulated signal:

$$\left(\Delta\nu_{\rm FM}\right)_{\rm DC} \times \delta\left(\Delta\nu_{\rm FSR}\right)_f + \delta\left(\Delta\nu_{\rm FM}\right)_f \times \left(\Delta\nu_{\rm FSR}\right)_{\rm DC} \quad , \tag{5}$$

where $(\ )_{\rm DC}$ denotes a DC component, and $\delta(\ )_f$ a Fourier component at frequency f.

3.3 Reduction of Excess Noise

According to Equation (5), there are four components to be reduced in order to remove the excess noise for the transmitted light. $\delta\left(\Delta\nu_{\rm FM}\right)_f$ can be suppressed by having a higher servo

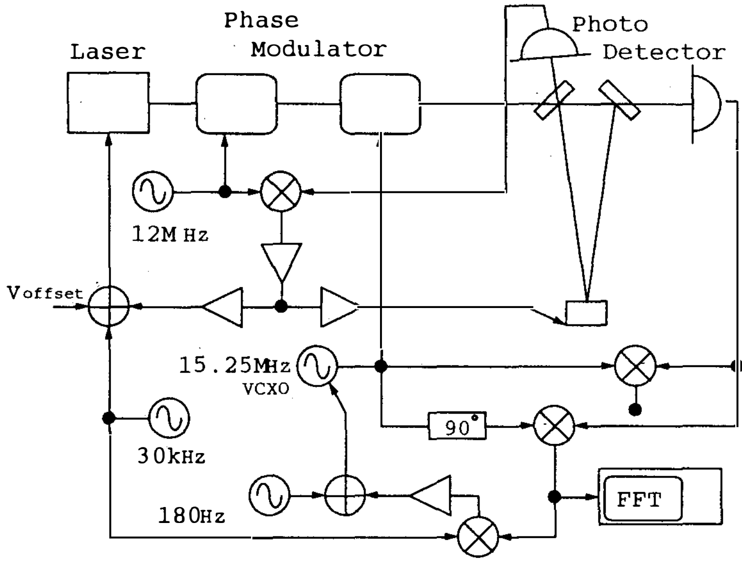

Figure 1: Experimental Setup for Sidebands Transmission.

gain of the mode cleaner locking loop. $\delta\left(\Delta\nu_{\mathrm{FSR}}\right)_f$ can be small with a very stable oscillator. Here we explain how we reduced $\left(\Delta\nu_{\mathrm{FM}}\right)_{\mathrm{DC}} and \left(\Delta\nu_{\mathrm{FSR}}\right)_{\mathrm{DC}}$.

When the FM modulation at the frequency f_0 is applied intentionally, the quadrature-phase demodulated signal has the corresponding component at the frequency f_0 whose amplitude is liner to the magnitude of $\left(\Delta\nu_{\mathrm{FSR}}\right)_{\mathrm{DC}}$ Therefore, the FSR-DC can be adjusted by minimizing the component at the frequency f_0.

The FM-DC can be controlled in the same manner using the intentional modulation on the modulation frequency and minimizing the corresponding signal on the demodulated signal.

4 Experiment of Reducing Excess Noise

4.1 *Experimental Setup*

Figure 1 shows the experimental setup of the reduction of the intensity noise for the transmitted light of the mode cleaner for TAMA300. There are two phase modulators. One generates 12 MHz phase modulation sidebands which is used to resonate the laser to the mode cleaner cavity. The other generates 15.25 MHz phase modulation sidebands which pass through the mode cleaner and is used to lock the interferometer. In order to control $\left(\Delta\nu_{\mathrm{FSR}}\right)_{\mathrm{DC}}$, the laser frequency is modulated at 30 kHz. The transmitted light is detected and demodulated by the phase modulation signal (15.25 MHz). The quadrature-phase demodulated signal is again demodulated by the 30 kHz modulation signal. The signal is fed back to the Voltage Control X'tal Oscillator (VCXO) which generates 15.25 MHz. The phase modulation frequency (15.25 MHz) is also modulated 180 Hz. The quadrature-phase (15.25 MHz) demodulation signal for the transmitted light is analyzed in spectrum and the DC-offset of the feed back signal to the laser frequency is controlled manually so that the 180 Hz component appearing in the demodulated signal for the transmitted light is minimized.

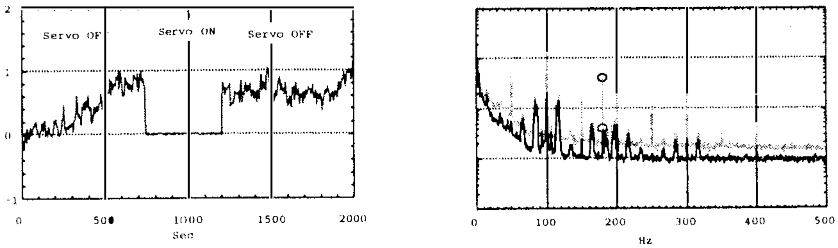

Figure 2: The FSR deviation when the modulation frequency servo is on and off (Left). Noise spectra of the quadrature-phase demodulated signal when the FM DC deviation is optimized and not optimized (Right).

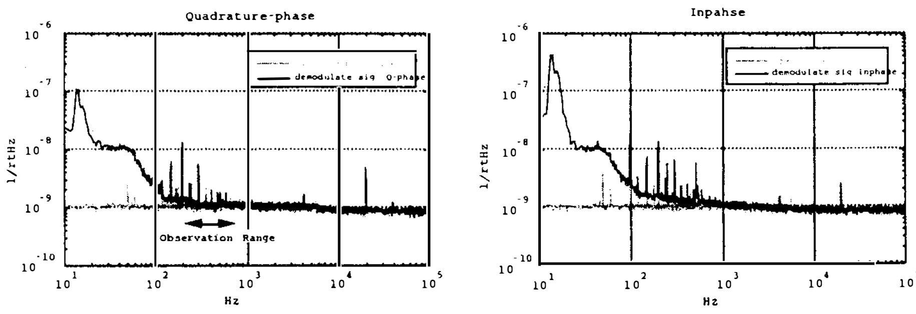

Figure 3: Noise spectra of the quadrature-phase and the inphase demodulated signal for the transmitted light.

4.2 Reduction of FSR-DC-Deviation and FM-DC-Deviation

Figure 2 Left shows the deviation between the modulation frequency and the FSR of the mode cleaner when the modulation frequency servo is switched on and off. There is a drift in the FSR deviation when the modulation frequency servo is off. With the modulation frequency servo on, the modulation frequency is kept to be equal to the FSR.

Figure 2 Right shows the spectra when the 180 Hz signal in the demodulation signal was minimized and not minimized. When the 180 Hz signal in the demodulation signal was minimized manually, the spectrum of the demodulated signal was minimized all over the frequency.

4.3 Results

The noise spectra of the demodulated signal for the transmitted light with the two above-mentioned remedies are shown in Figure 3. The noise is limited by the shot noise above a few hundred Hz. This is considered to be satisfactory for the goal sensitivity of TAMA300. Below one hundred Hz, there is excess noise which is caused by the vibration between the transmitted beam and the photo detector.

5 Discussion

To see the cause of the FSR deviation, we measured the modulation frequency by a frequency counter and compared it with the error signal of 30 kHz demodulation. When the oscillator (VCXO) is not controlled, the oscillator, the FSR of the cavity and the frequency counter should have independent time-variation behavior. As shown in Figure 4 Left, the modulation frequency measured by the frequency counter (line-A) shows much smaller drift than the FSR

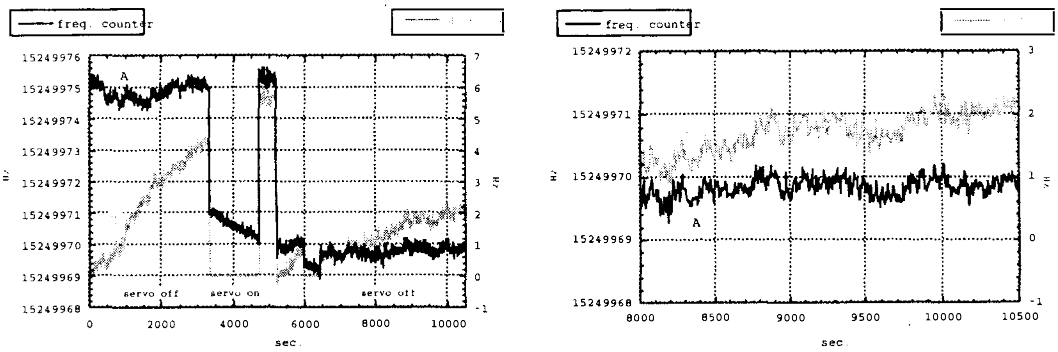

Figure 4: The modulation frequency (A) and $\Delta\nu_{\rm FSR}$ (B).

deviation measured in the error signal of the modulation frequency control system (line-B), when the oscillator is not controlled. Almost constant behavior of (line-A) indicates that no significant drift in both the oscillator and the counter and that the drift of the FSR is dominant. The FSR is determined by the cavity length. On the other hand the cavity length is controlled as the reference of the laser-frequency at low frequencies ($<$ 30 Hz). Hence, the drift of the FSR is caused by the drift of the laser-frequency.

Figure 4 Right is the magnification of Figure 4 Left in the time axis. The short-term behavior of the modulation frequency measured by the frequency counter is similar to that of the FSR deviation. Because only the oscillator is common noise source in both signals, it indicates that variation in the frequency of the oscillator is dominant with the short time scale.

By this measurement, it can be concluded that the FSR is drifting by several Hz per hour, which is mainly caused by the drift of the laser-frequency, and that the frequency of the oscillator (VCXO) vaies by sub-Hz in a few minutes.

6 Conclusions

We have developed the mode cleaner for TAMA300. The phase modulation, which is necessary to lock an interferometer, was successfully transmitted through the mode cleaner. The demodulated signal of the light coming out of the mode cleaner, which originally showed excess noise, have been made shot-noise-limited above a few hundred Hz by carefully controlling the frequency of the carrier and sidebands. The resultant spectrum is satisfactory for the goal sensitivity of TAMA300. In order to make TAMA300 more sensitive at lower frequencies, further reduction of the excess noise at low frequencies is required.

References

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