Sensing and controls for power-recycling of TAMA300

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Abstract. Power recycling will soon be implemented on TAMA300. This article gives motivation for the TAMA recycling experiment, discusses the planned length sensing/control system and considerations for the lock acquisition process.

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1. Power recycling for TAMA300

The TAMA project has been developing the TAMA300 interferometric gravitational wave detector since 1995, having performed several scientific observations since September 1999. After a successful 1000-hour observation run in summer of 2001 [1], power recycling of TAMA300 will be implemented in autumn of 2001.

As a result of the TAMA300 development, which was carried out without power recycling so far, the performance of TAMA300 and techniques for its operation are well matured. Various technical noise sources were identified and reduced by more than two order of magnitude during these two and a half years, resulting in realizing the best strain sensitivity of $5 \times 10^{-20}/\sqrt{\mathrm{Hz}}$ at around 700Hz. All of the components for the stability was installed to TAMA300 in order to achieve the operation through the day and night. Data acquired during the several observation runs has been being analyzed for the search of gravitational waves. The outcomes of the TAMA300 observations were reported in the several papers [2, 3]. As an accomplishment of these efforts, the 1000-hour run was successfully carried out.

Power recycling is now going to be installed with both scientific and technical motivations. The scientific motivation is that power recycling of TAMA300 is expected to improve the actual sensitivity of TAMA300; high frequency part of the current sensitivity is limited by optical read-out noises. Even with the current level of technical noises which limit the sensitivity and should be removed eventually, we can expect

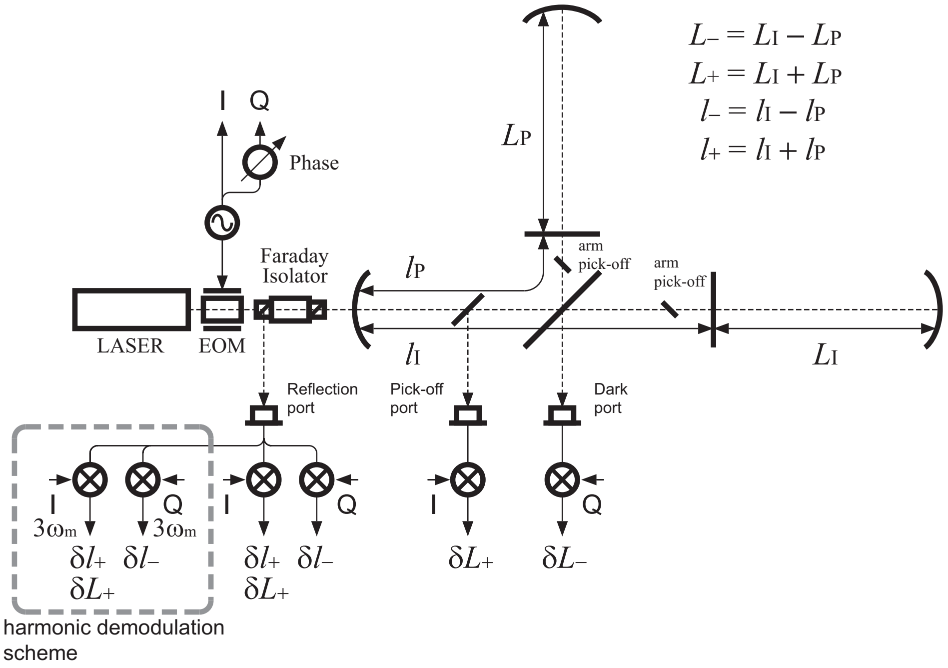

Figure 1. Signal extraction system for the TAMA recycling experiment. Note that a mode cleaner cavity was omitted.

an improvement of the signal-to-noise ratio for relatively light ($\sim 5M_\odot$) binary star coalescences.

There is also technical motivation. All of the results from our R&D programs of power recycling will be integrated into TAMA300. The TAMA project performed the power recycling experiments with 3-m and 20-m suspended prototype interferometers. Since power recycling with cavity-arms and all-suspended mirrors was first demonstrated with the 3-m interferometer, signal sensing and control schemes have been investigated, and a power-recycling gain of up to 5.4 was eventually realized [4, 5, 6]. With the 20-m interferometer, the realistic optics were examined, and a power-recycling gain of 12 was attained [7]. The intended recycling gain of TAMA300 (described later) is within the range of levels achieved in the prototype interferometers. Additionally, most of the techniques we have developed for the non-recycled operation can be applied to the operation of the interferometer without large modification as the two modes of operation are very similar. For instance, the length/alignment sensing and control systems with frontal modulation for non-recycled operation are subsets of those for power recycling. Also, the calibration technique presently employed [8] is directly applicable to power-recycled interferometers. Furthermore, there is a large interest in behaviour of the TAMA interferometer with power recycling. The information, obtained by diagnosing the detector with existing techniques and using the current data quality evaluation procedure, with and without recycling will be fed back to guide the detector development. The technical knowledge achieved by recycling of TAMA300 will be inherited by advanced interferometers such as LCGT.

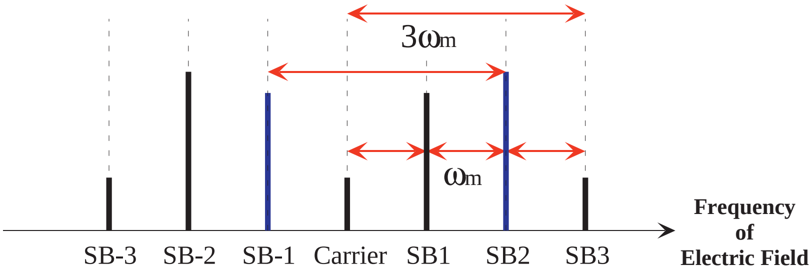

Figure 2. Schematic figure of modulation sidebands at the reflection port.

The introduction of power recycling is carried out with two phases, called Recycling1 and Recycling2. Recycling1 uses a recycling mirror with reflectance ($R_{\rm RM}$) of 48%. We expect a power-recycling gain (G) of 4.6. This rather low gain will allow us to quickly attain full operation and observation with improved sensitivity. Once the full operation is achieved, investigation on the optimization of lock acquisition and control systems will become easier. The information obtained from this phase is utilized for Recycling2. Recycling2 uses a recycling mirror with $R_{\rm RM} \approx 90\%$. The expected gain will be around 10. The goal of this phase is ultimate sensitivity and stability of TAMA300, realizing optimized power coupling and optimal sensing/control systems.

2. Length sensing scheme

In order to achieve stable operation of the interferometer, it is indispensable to obtain signals for feedback control of the longitudinal mirror positions that fluctuate because of seismic motion. Even though the frontal modulation scheme [9, 10] is useful for signal extraction of power-recycled Michelson interferometers, it is thought difficult with the conventional frontal modulation scheme to sense the motion of the recycling mirror independently from the arm cavity motion. To overcome this problem, the planned length sensing scheme for TAMA300 recycling employs frontal modulation with a harmonic demodulation scheme (Figure. 1) [11]. With this scheme, the signals corresponding to common (δl_+) and differential (δl_-) optical path-length fluctuation within the power-recycling cavity are extracted at the reflection port by demodulating the photocurrent at the third-harmonic of the modulation frequency $\omega_{\rm m}$. The local oscillator at $3\omega_{\rm m}$ for demodulation is generated from the modulation oscillator at $\omega_{\rm m}$ using frequency triplers.

The signal extraction with harmonic demodulation naturally involves not only the carrier and the first-order sidebands but also the second- and third- order sidebands (Figure. 2). Each sideband generated by the phase modulation, applied in front of

Port	f_{demod}	Phase	δL_-	δL_+	δl_-	δl_+
Dark	ω_{m}	Q	**1**	3.0×10^{-4}	3.0×10^{-3}	1.0×10^{-6}
Pick-off	ω_{m}	I	1.5×10^{-4}	**1**	2.4×10^{-7}	5.0×10^{-5}
Reflection	$3\omega_{\mathrm{m}}$	Q	1.0×10^{-2}	2.3×10^{-2}	**1**	3.6×10^{-2}
Reflection	ω_{m}	Q	1.5×10^{-2}	6.2×10^{-1}	**1**	1.6×10^{-3}
Reflection	$3\omega_{\mathrm{m}}$	I	1.5×10^{-4}	6.5×10^{-2}	1.2×10^{-3}	**1**

Table 1. Signal sensing matrix with the configuration for TAMA300 Recycling1 phase. f_{demod} is the demodulation frequency. The letters I and Q show which of the two orthogonal local oscillator phases is used for demodulation. The numbers show the sensitivity at each ports to each degree of freedom (δL_-, δL_+, δl_-, or δl_+) normalized by the sensitivity of the dominant signal. It is found that each d.o.f. is represented by the dominant signal in at least one port.

the interferometer, is reflected with a different reflectance by the interferometer. The detected photocurrent is intensity modulated at $2\omega_{\mathrm{m}}$, $3\omega_{\mathrm{m}}$, $4\omega_{\mathrm{m}}$, $\cdots$ as well as at ω_{m}. The photocurrent at $3\omega_{\mathrm{m}}$ is mainly produced by the beating of the first- and second-order sidebands, and by the beating of the carrier and third-order sidebands.

The error signals for $\delta l_\pm$ can be detected by demodulating the photocurrent at ω_{m} to generate a signal primarily due to the phase difference of the first-order sidebands and the carrier, or by demodulating the photocurrent at $3\omega_{\mathrm{m}}$ to generate a signal primarily due to the phase difference between the first- and second-order sidebands. Since the second-order sidebands are usually not resonant in the recycling cavity, an almost constant amount of the second-order sidebands are reflected to the reflection port, independent from the optical parameters and the resonant conditions of the interferometer; this robust reflection of the second-order sidebands results in the robust extraction of the $\delta l_\pm$ signals.

The extracted δl_+ signal inherently has good separation from arm cavity common motion (δL_+). Furthermore, an additional adjustment of the Schnupp asymmetry completely eliminates the residual contribution of δL_+. Table. 1 shows the sensitivity of each port to each degree of freedom (δL_-, δL_+, δl_-, or δl_+) with the configuration for Recycling1. These numbers are normalized by the sensitivity to the dominant signal. It is found that each d.o.f. is represented by the dominant signal in at least one port. The contribution of δL_+ to the $3\omega_{\mathrm{m}}$-demodulated signals at the reflection port are effectively removed by the inherent insensitivity of the first- and second-order sidebands to δL_+ and by adjusting the Schnupp asymmetry to 0.822 m so as to make the reflectance of the interferometer to the third-order sidebands as small as possible.

What we must consider here is the shot-noise level of the δl_- signal. Since the demodulation signal at the dark port intrinsically has sensitivity to δl_- fluctuation, control of δl_- with low S/N signal causes noise coupling to the gravitational wave signal. In order to realize the designed noise level of $5.2 \times 10^{-20}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ for δL_-, $2.9 \times 10^{-16}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at the lower edge of the observation band (150 Hz) is required for the noise level of the δl_- signal, based on the δl_- loop gain measurement with TAMA300. With the current modulation depth of TAMA300 (0.35rad), the shot-noise level is estimated to be $1.4 \times 10^{-14}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ and $2.0 \times 10^{-16}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ for the δl_- signals at the reflection port with harmonic demodulation and conventional demodulation respectively. Since the δl_- signal with conventional demodulation is not suitable for lock acquisition, as described later, the harmonic-demodulated δl_- signal is used for acquiring lock, while the conventionally-demodulated δl_- signal is used for low noise operation.

The control topology with power recycling inherits that of the non-recycled case with small modifications; the only new part is the control of the recycling mirror. The arm cavity differential motion (δL_-) at the dark port, which contains possible gravitational wave signals, is fed back to the two front mirrors differentially. The low frequency part ($<$ 0.1Hz) of the feedback signal is used for the control of the active isolators placed at the end in order to eliminate slow drift of the δL_- feedback signal. The δL_+ signal taken from the pick-off port is fed back to two places; the length of the mode cleaner is controlled by the frequency component of this signal below 1kHz, leading to indirect control of the laser frequency, while the high frequency part (1kHz $\sim$ 30kHz) is directly injected to the frequency stabilization loop, allowing us to have large control gain at low frequency. The δl_- and δl_+ signals are fed back to the beamsplitter and the recycling mirror, respectively. The l_- loop is to have a control bandwidth of around 20Hz to avoid coupling the δl_- control noise to the δL_- gravitational wave signal in the observation band (150Hz$\sim$450Hz).

3. Lock acquisition

One of the most difficult steps to achieve stable operation of the power-recycled interferometer is lock acquisition. For the signals to measure the arm length deviations correctly, the first-order sidebands must first resonate in the recycling cavity. Thus, the process of the lock acquisition has a specified order. In addition, the carrier in the recycling cavity and the arms drastically increases at the last moment of the process. This increase causes drastic changes of the optical conditions such as optical gains of the interferometer and coupling of the carrier to the recycling cavity. To address these issues, TAMA300 has two features: robust extraction of δl_+ and δl_- during lock acquisition, and the pick-off mirrors inserted in front of the cavity arms.

The δl_+ and δl_- signals obtained by harmonic demodulation are robust under the drastic change of the optical condition during lock acquisition. When only the recycled Michelson part is locked, having unlocked arm cavities, TAMA300 is expected to have a recycling gain of 0.18 for the carrier. In this stage, the carrier is very under-coupled to the recycling cavity. When the lock of the arms are completed, the carrier recycling gain increases to 4.6, and the coupling becomes over-coupled. This change causes the optical gain for δl_+ with usual demodulation to decrease by a factor of 43. Additionally the sign of the δl_+ and δl_- signals changes. These dynamics can cause instability of the control system when the simple feedback loops with fixed signs and gains are used.

On the other hand, the δl_+ and δl_- signals with harmonic demodulation do not have sign reversals. Also, the change of the optical gain for δl_+ and δl_- are estimated to be 0.82 and 0.46, respectively. With only the conventional demodulation scheme, the lock acquisition process requires an adaptive control system that diagnoses the status of the interferometer and dynamically changes the feedback condition. Since we currently don't have such a control system with an adequately fast response, a robust control scheme like harmonic demodulation is indispensable.

The TAMA300 interferometer has two pick-off plates for independent control of each 300-m Fabry-Perot arms ("arm pick-offs" in Figure. 1). Without power recycling, each of these port always provides the Pound-Drever-Hall signals [12] that corresponds to the optical path-length deviation of each arm, however the recycling mirror mixes these signals so that for high recycling gain they are essentially redundant. Therefore we consider these signals only useful with low recycling gains. The ratio of the mixing for the arm pick-off port is defined by the sensitivity to the other arm normalized by the sensitivity to the arm which the pick-off belongs to. The ratio is 50% at most for the Recycling1 phase; the signals from the pick-offs are still independent in some extent. On the other hand, the mixing ratio is 85% at most for Recycling2. Therefore, optimization of the lock acquisition process at Recycling1 is necessary to realize lock at Recycling2 without the arm pick-off signals.

4. Summary

Power recycling is going to be applied to TAMA300 because of scientific motivation, as well as for the pursuit of technical achievement. The planned length sensing system employs a frontal modulation scheme with harmonic demodulation. This scheme enables us to obtain the demodulation signals dominated by the contributions of the desired degrees of freedom. Since the δl_+ and δl_- signals obtained with harmonic demodulation are robust both in amplitude and sign, the lock acquisition process is expected to be significantly simplified. In addition, the use of the pick-off mirrors in front of each arm is considered for lock acquisition with low recycling gain configuration.

Acknowledgments

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References

[1] Ando M and the TAMA collaboration *(in this issue)*

[2] Tagoshi H, Kanda N, Tanaka T, Tatsumi D, Telada S, Ando M, Arai K, Araya A, Asada H, Barton M A, Fujimoto M-K, Fukushima M, Futamase T, Heinzel G, Horikoshi G, Ishizuka H, Kamikubota N, Kawabe K, Kawamura S, Kawashima N, Kojima Y, Kozai Y, Kuroda K, Matsuda N, Matsumura S, Miki S, Mio N, Miyakawa O, Miyama S, Miyoki S, Mizuno E,

Moriwaki S, Musha M, Nagano S, Nakagawa K, Nakamura T, Nakao K, Numata K, Ogawa Y, Ohashi M, Ohishi N, Okutomi A, Oohara K, Otsuka S, Saito Y, Sasaki M, Sato S, Sekiya A, Shibata M, Shirakata K, Somiya K, Suzuki T, Takahashi R, Takamori A, Taniguchi S, Tochikubo K, Tomaru T, Tsubono K, Tsuda N, Uchiyama T, Ueda A, Ueda K, Ueda K, Waseda K, Watanabe Y, Yakura H, Yamamoto K and T Yamazaki 2001 *Phys. Rev.* D **63** 062001

[3] Ando M, Arai K, Takahashi R, Heinzel G, Kawamura S, Tatsumi D, Kanda N, Tagoshi H, Araya A, Asada H, Aso Y, Barton M A, Fujimoto M-K, Fukushima M, Futamase T, Hayama K, Horikoshi G, Ishizuka H, Kamikubota N, Kawabe K, Kawashima N, Kobayashi Y, Kojima Y, Kondo K, Kozai Y, Kuroda K, Matsuda N, Mio N, Miura K, Miyakawa O, Miyama S M, Miyoki S, Moriwaki S, Musha M, Nagano S, Nakagawa K, Nakamura T, Nakao K, Numata K, Ogawa Y, Ohashi M, Ohishi N, Okutomi S, Oohara K, Otsuka S, Saito Y, Sasaki M, Sato S, Sekiya A, Shibata M, Somiya K, Suzuki T, Takamori A, Tanaka T, Taniguchi S, Telada S, Tochikubo K, Tomaru T, Tsubono K, Tsuda N, Uchiyama T, Ueda A, Ueda K, Waseda K, Watanabe Y, Yakura H, Yamamoto K and T Yamazaki 2001 *Phys. Rev. Lett.* **86** 3950

[4] Ando M, Arai K, Kawabe K and Tsubono K 1998 *Phys. Lett.* A **248** 145

[5] Ando M, Arai K, Kawabe K and Tsubono K 2000 *Phys. Lett.* A **268** 268

[6] Arai K, Ando M, Moriwaki S, Kawabe K and Tsubono K 2000 *Gravitational Wave Detection II, Proc. the 2nd TAMA International Workshop on Gravitational Wave Detection (Tokyo)* ed S Kawamura and N Mio (Tokyo: Universal Academy Press) p 157

[7] Sato S, Ohashi M, Fujimoto M-K, Fukushima M, Waseda K, Miyoki S, Mavalvala N, Yamamoto H 2000 *Appl. Opt.* **39** 4616

[8] Telada S, Tatsumi D, Ohashi M, Kanda N and Tagoshi H 2000 *Gravitational Wave Detection II, Proc. the 2nd TAMA International Workshop on Gravitational Wave Detection (Tokyo)* ed S Kawamura and N Mio (Tokyo: Universal Academy Press) p 129

[9] Schnupp L 1988 talk at *European Collaboration Meeting on Interferometric detection of gravitational waves (Sorrent)*

[10] Regehr M W, Raab F J and Whitcomb S E 1995 *Opt. Lett.* **20** 1507

[11] Arai K, Ando M, Moriwaki S, Kawabe K and Tsubono K 2000 *Phys. Lett.* A **273** 15

[12] Drever R W P, Hall J L, Kowalski F V, Hough J, Ford G M, Munley A J and Ward H 1983 *Appl. Phys.* B **31** 97