Design of Coupled Wave Front Sensor for TOrsion-Bar Antenna

Yuka Oshima, Satoru Takano, Ching Pin Ooi, Yuta Michimura, Masaki Ando
Department of Physics, University of Tokyo
Email: yuka.oshima@phys.s.u-tokyo.ac.jp

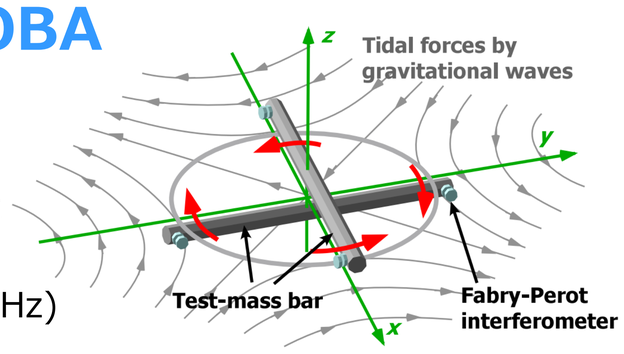
Abstract

TOrsion-Bar Antenna (TOBA) is a ground-based gravitational wave (GW) detector using torsion pendulums. The resonant frequency of torsional motion is ~1 mHz, therefore TOBA has good design sensitivity of 10^{-19} /√Hz in 0.1 – 10 Hz. TOBA can detect intermediate mass black hole binary mergers, etc. A prototype detector Phase-III TOBA with a 35 cm-scale pendulum is under development to demonstrate noise reduction. The target sensitivity is set to 10^{-15} /√Hz at 0.1 Hz. To achieve our target sensitivity, we need to measure the pendulum rotation precisely. We propose a coupled wave front sensor (WFS) as an angular sensor for Phase-III TOBA. In our method, an auxiliary cavity is used to enhance the first-order TEM modes in the main cavity. Here we show the principle and experimental design of a coupled WFS.

1. Introduction of TOBA

TOBA [1]

- Low frequency GW detector
  - Target: 10^{-19}/√Hz in 0.1 - 10 Hz
- Use torsion pendulums
  - Low resonant frequency (~ 1 mHz)
  - Ground-based configuration
- Scientific targets: intermediate mass black hole binary mergers, Newtonian noise, etc.



Development plan [2]

Phase-I (2009)	Phase-II (2015)	Phase-III (Now)	Final (Future)
Principle test		Technical demonstration	GW observation
10^{-8}/√Hz at 0.1 Hz (Established)		10^{-15}/√Hz at 0.1 Hz (Target)	10^{-19}/√Hz at 0.1 Hz (Target)

Developing items for Phase-III TOBA

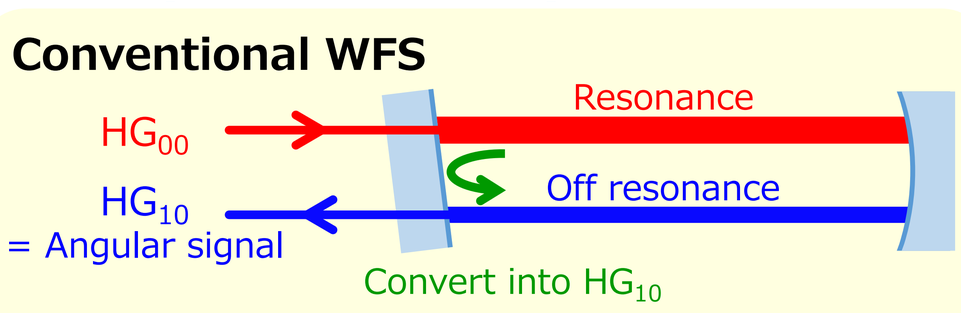
- 35 cm Si torsion pendulums
- Active vibration isolation
- Cooling system
- High-Q suspension wire
- Coupled WFS: a highly sensitive angular sensor to measure the rotation of bars (GW signal)

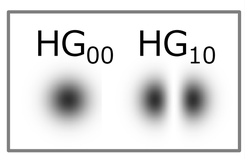
Satoru's talk (ID: 55)
Ching Pin's poster (ID: 66)

[1] M. Ando et al., Phys. Rev. Lett. 105, 161101(2010)
[2] T. Shimoda et al., International Journal of Modern Physics D 29, 1940003 (2020)

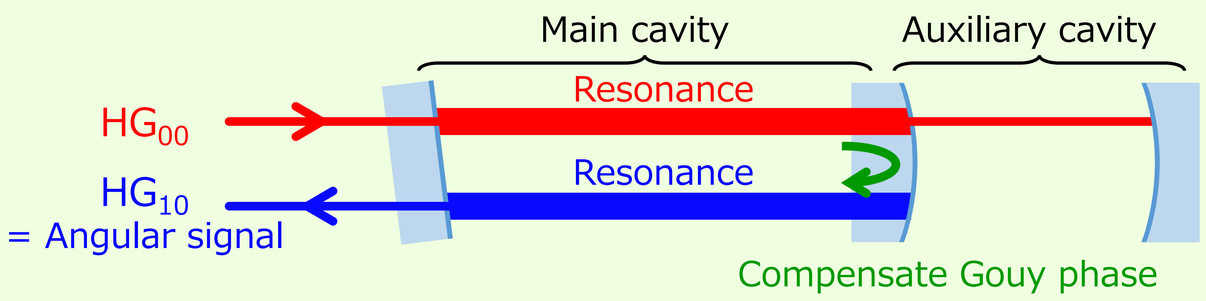
2. Proposal of Coupled WFS

Conventional WFS





Coupled WFS: improved WFS for Phase-III TOBA



→ HG_{10} mode signal can be amplified by finesse of main cavity

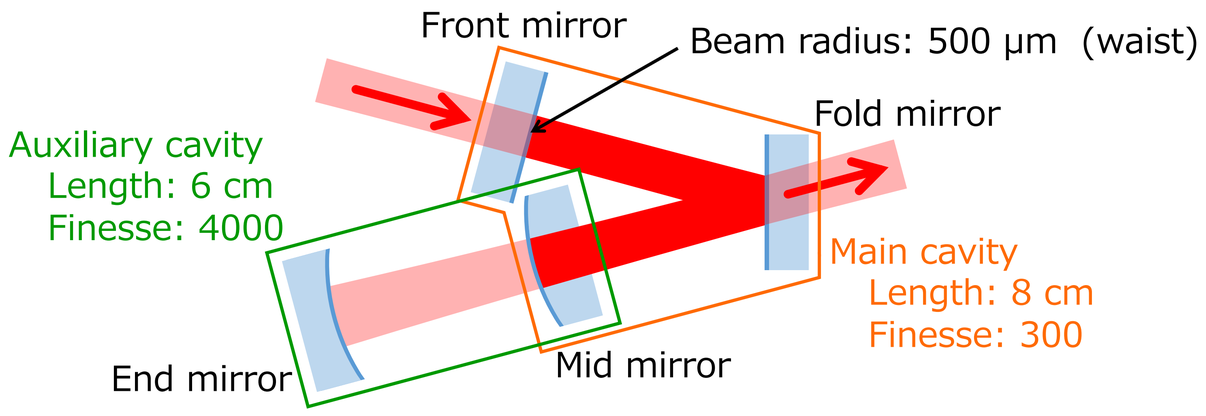
Comparison of angular sensors

	Michelson interferometer	Conventional WFS	Coupled WFS
Shot noise (Phase-III TOBA requirement: 5×10^{-16} rad/√Hz)	✓	✗	✓
Frequency noise	✗	✓	✓
Cross-coupling	✗	✓	✓

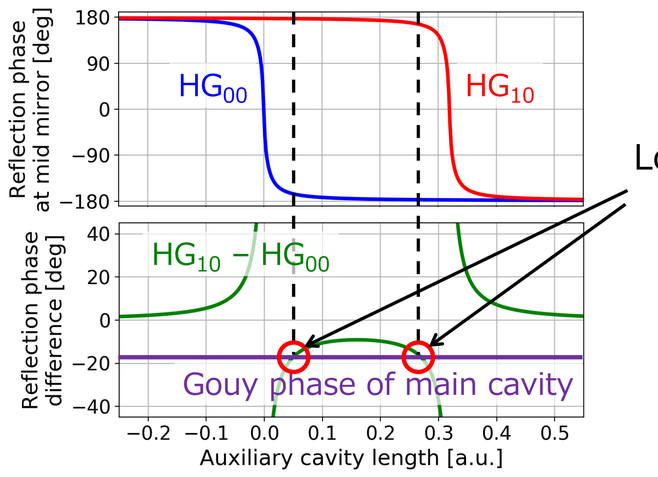
3. Experimental Setup of Coupled WFS

Design of optical cavities

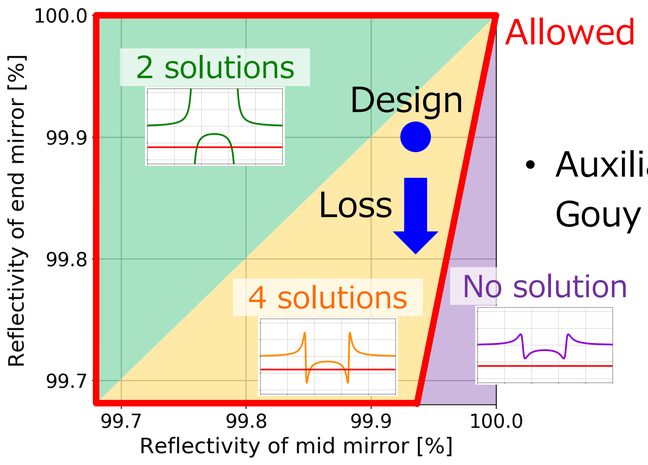
- Fold main cavity to extract signal inside main cavity
- Suspend front mirror by pendulum to look like TOBA's bar
- Build cavities inside vacuum chamber to achieve good sensitivity



Robustness to cavity loss



Lock points of auxiliary cavity
- Detune from resonance
- Some/no solutions exist

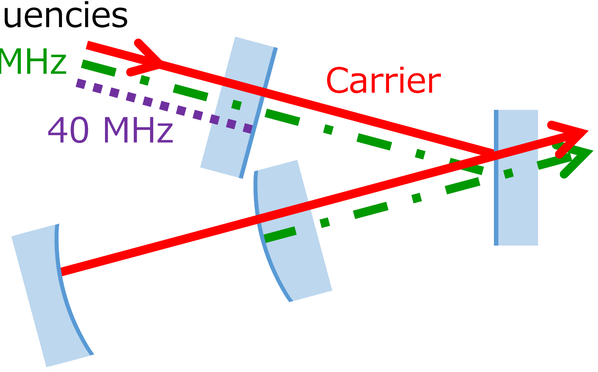


- Auxiliary cavity can compensate Gouy phase even when loss of 0.1 %

Cavity locking scheme

- Lock the length of main and auxiliary cavities with PDH technique
- Use two different modulation frequencies

Cavity	Line width of carrier	Modulation frequency of sidebands
Main	13 MHz	40 MHz
Auxiliary	1.3 MHz	4 MHz



4. Summary & Future Plans

- A prototype GW detector Phase-III TOBA is under development
- We propose a coupled WFS as an angular sensor for Phase-III TOBA
  - HG_{00} and HG_{10} can be resonant simultaneously
  - We design the experimental setup
- We are planning the experimental demonstration to confirm angular signal amplification and locking scheme