Angular Signal Amplification with a Coupled Cavity for Torsion-Bar Antenna

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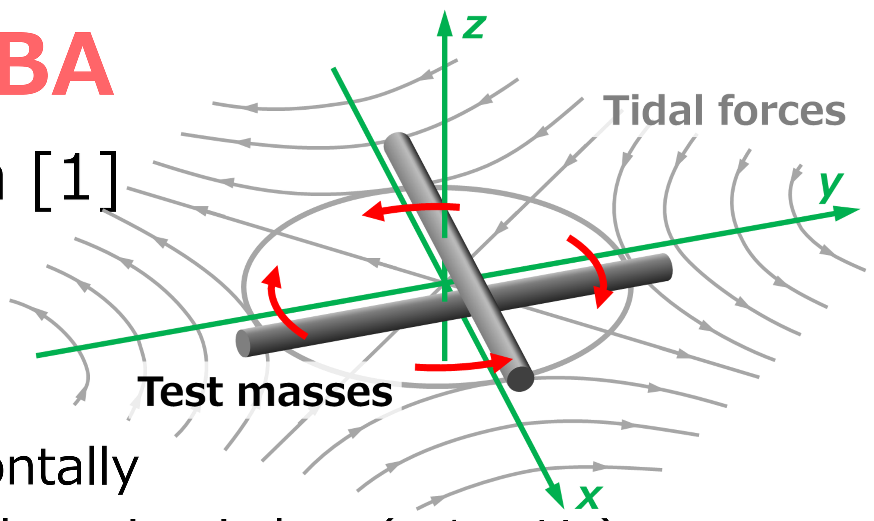
Abstract

Torsion-Bar Antenna (TOBA) is a ground-based GW detector using a torsion pendulum. The resonant frequency of torsional motion is ~1 mHz, therefore TOBA has good design sensitivity in low frequency, specifically 10^{-19} /√Hz at 0.1 Hz. TOBA can detect intermediate-mass black hole binary mergers, Newtonian noise, and so on. 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 wavefront sensor with a coupled cavity (Coupled WFS) as an angular sensor for Phase-III TOBA. In our method, an auxiliary cavity is used to compensate Gouy phase of a main cavity and enhance the first-order TEM modes in the main cavity. The experimental demonstration was successfully performed in 2021. Here we show the principle and demonstration results of a Coupled WFS.

1. Introduction of TOBA

TOBA: Torsion-Bar Antenna [1]



- Ground-based GW detector for low frequency
- Aim to detect the torsional rotation of test masses suspended horizontally
- The resonant frequency of torsional motion is low (~1 mHz)
  → Good sensitivity in low frequency even on the ground
- Scientific targets: intermediate-mass black hole binary mergers, Newtonian noise, Earthquake early warning, 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)
20 cm bars	30 cm bars	10 m bars
Room temp.	Cryo. Temp. (4 K)	Cryo. Temp. (4 K)

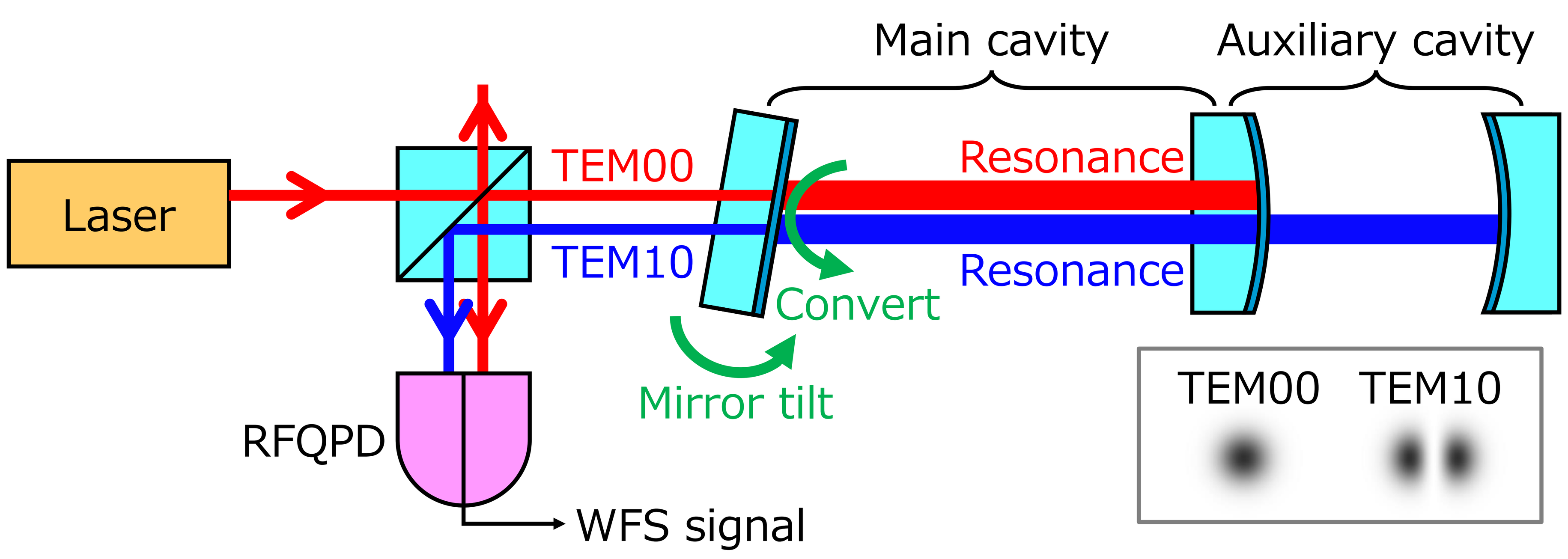
⇒ See **Satoru's poster (#A14)** for more details about TOBA

[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. Principle of Coupled WFS

Coupled WFS: Wavefront sensor with a coupled cavity

- An improved WFS proposed to measure the torsional rotation of TOBA test masses accurately
- An auxiliary cavity can compensate Gouy phase of a main cavity
  → Both TEM00 and TEM10 are resonant in the main cavity
  → Angular signal is amplified by the finesse of the main cavity



Comparison of angular sensors

	Michelson interferometer	WFS	Coupled WFS
Shot noise (Requirement: 5×10^{-16} rad/√Hz)	😊	😞 No signal amplification	😊 Signal amplification
Frequency noise	😞 Asymmetry of two light paths	😊	😊
Beam jitter noise	😞 Non-parallel of two mirrors	😞	😊 No amplification of beam jitter
Thermal noise	😊	😐 Narrow range measurement	😐 Narrow range measurement
Linear range	😊	😊	😞 Trade-off with signal amplification

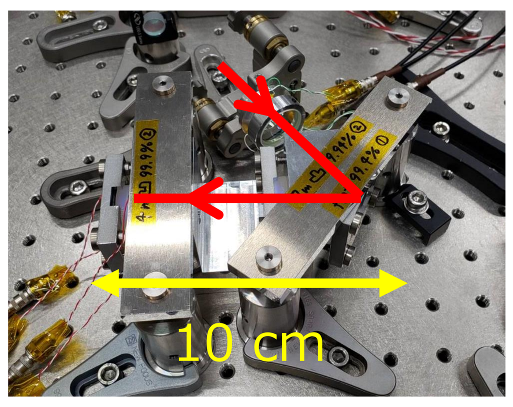
3. Experimental Setup of Coupled WFS

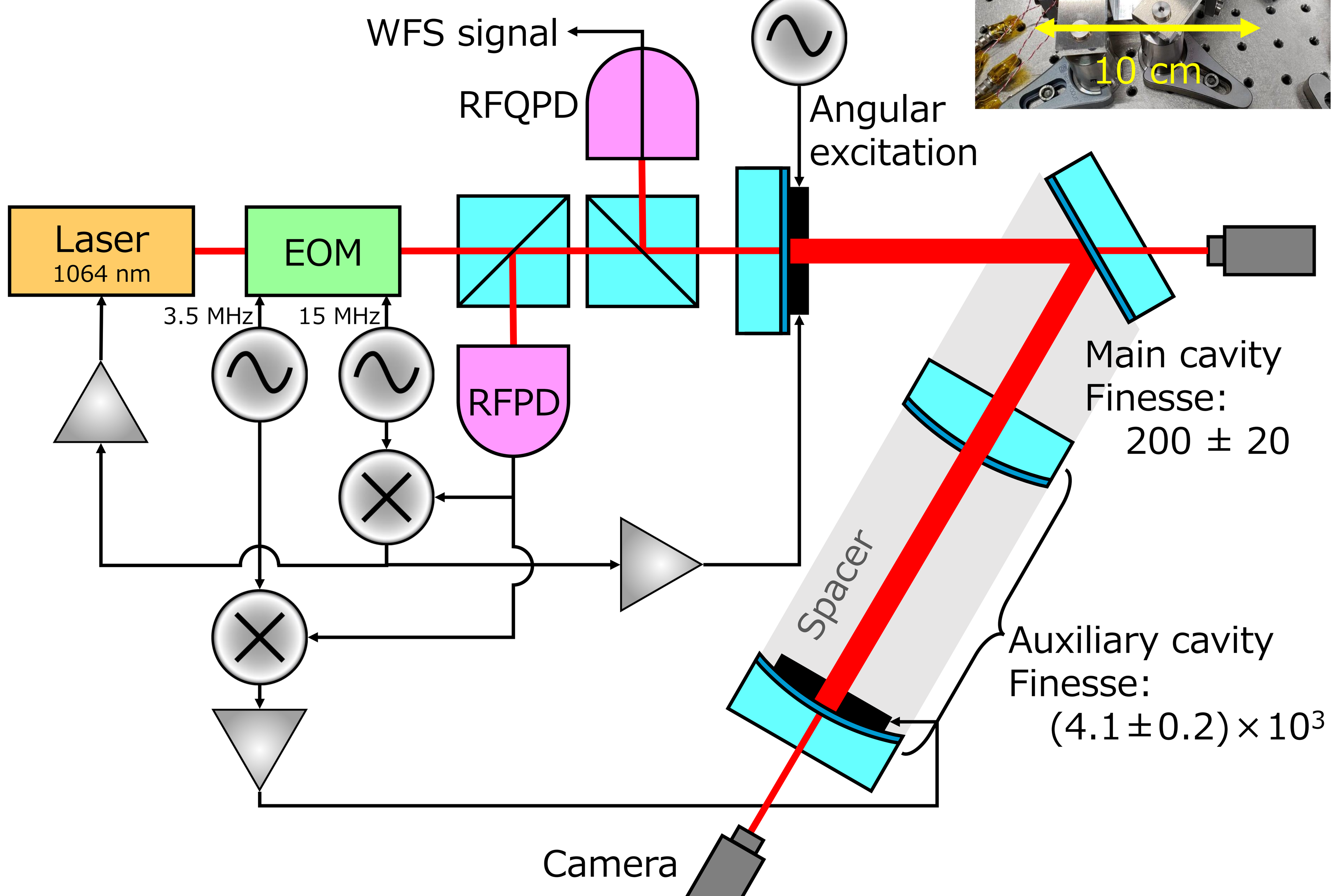
Design of the coupled cavity

- Parameters are designed to allow Gouy phase compensation
- The main cavity is folded to monitor the transmitted light
- Mirrors are fixed to a spacer rigidly to stabilize the alignment

Length control of the coupled cavity

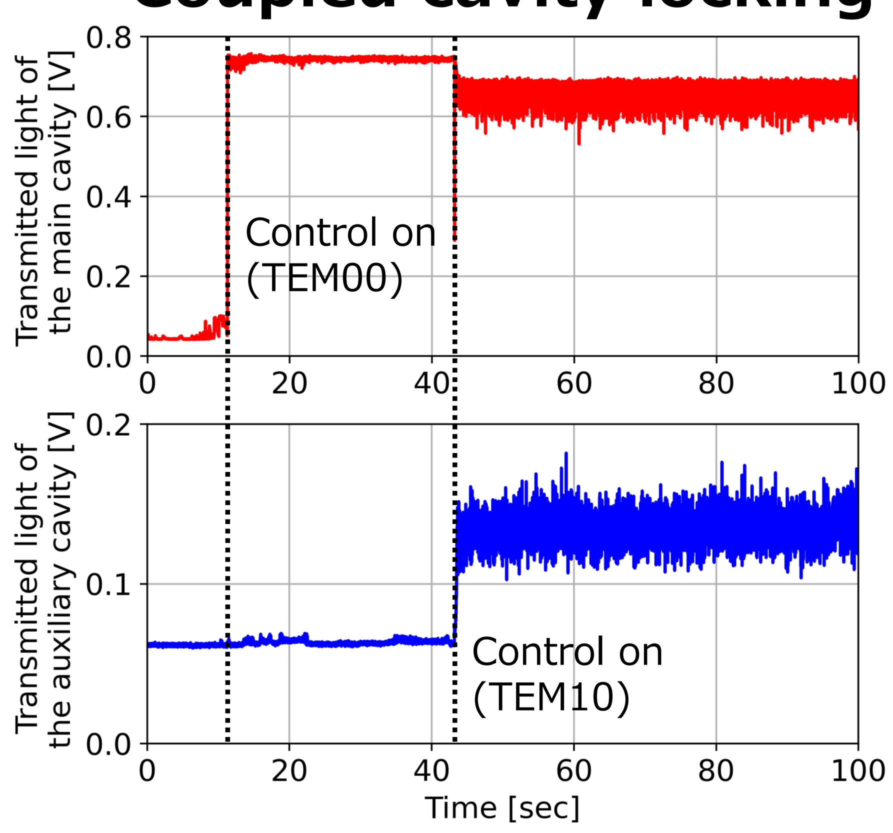
- PDH technique with two modulation frequencies
- Hierarchical control for the main cavity





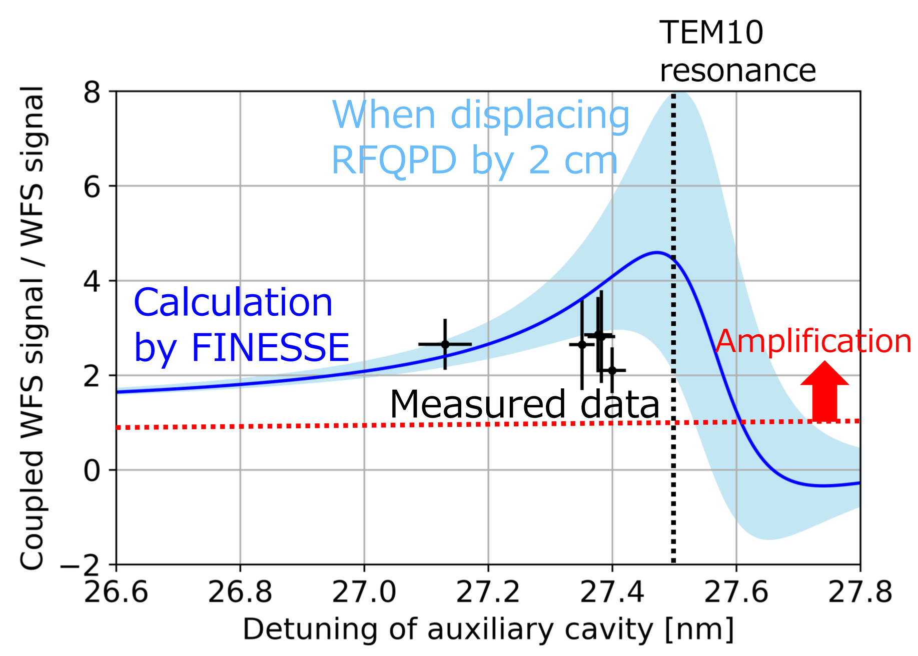
4. Results of Coupled WFS

Coupled cavity locking



- Cavities were successfully locked TEM00 and TEM10 simultaneously

Signal amplification



- Signal amplification was successfully demonstrated by three times

5. Summary & Future plans

- We are developing TOBA to detect GW in low frequency
- We propose Coupled WFS as an angular sensor for TOBA
- We demonstrated angular signal amplification and locking scheme of Coupled WFS
- We plan to suspend the test mass to stabilize the cavity lock

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