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# Parametric signal amplification to create a stiff optical bar

K. Somiya [a,*], Y. Kataoka [a], J. Kato [a], N. Saito [b], K. Yano [a]

[a] Department of Physics, Tokyo Institute of Technology, Japan
[b] Department of Physics, Ochanomizu University, Japan

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ABSTRACT

An optical cavity consisting of optically trapped mirrors makes a resonant bar that can be stiffer than diamond. A limitation of the stiffness arises in the length of the optical bar as a consequence of the finite light speed. High laser power and light mass mirrors are essential for realization of a long and stiff optical bar that can be useful for example in the gravitational-wave detector aiming at the observation of a signal from neutron-star collisions, supernovae, etc. In this letter, we introduce a parametric signal amplification scheme that realizes the long and stiff optical bar with a non-linear crystal inside the signal-recycling cavity.

## 1. Overview

A Fabry–Perot cavity forms a standing wave optical resonator for light waves. With the resonating mode slightly detuned from the input carrier mode, a mirror motion introduces an amplitude modulation on the carrier light to drive the mirrors via radiation pressure and creates an optical bar [1–3]. Susceptibility of the cavity to the mirror motion is enhanced at the bar resonance (*optical spring*) and suppressed at frequencies below the resonance (*optical rigidity*). In an interferometric gravitational-wave detector [4], the optical spring is profitable to increase the signal-to-noise ratio for certain astronomical sources. In a cold-damping experiment [5], the optical spring is essential to realize a harmonic oscillator with low thermal fluctuations. For both cases, it is important to increase the spring frequency so that the measurement can be performed at frequencies high enough to be free from environmental disturbances. With the circulating power and the mass of the mirrors being fixed, the stiffness of the bar is limited by the length of the cavity. This is due to the delay of the mirror position information to be delivered by the circulating light. The cavity has to be as long as possible for the gravitational-wave detector where the signal is proportional to the cavity length.

In this letter, we discuss the optical bar stiffness in terms of the cavity length and introduce a parametric signal amplification scheme to increase the spring frequency without increasing the circulating laser power. The stiff optical bar is a hope to improve the sensitivity of the gravitational-wave detector at high frequencies. We will explain possible applications in the end of the letter. It is important first of all to find a way to realize the stiff optical bar in the large-scale gravitational-wave detector.

## 2. Conventional optical spring

Fig. 1 shows a typical configuration of the interferometric gravitational-wave detector. It is based on the Michelson interferometer operated at dark fringe, where all the input light except for some losses and gravitational-wave signals is reflected back toward the laser. The light split at the 50% beamsplitter circulates in each arm cavity to increase the effective power and the signal. The light coming back from the beamsplitter toward the laser is recycled by another mirror located in between. Gravitational waves increase the distance of the two mirrors in one arm and decrease the distance in the other arm. The differential mode signal leaks through the interferometer toward the photo-detector. There is another mirror placed before the photo-detector and a cavity consisting of this mirror and the input mirrors of the arm cavities (signal-recycling cavity) is detuned from the resonance or anti-resonance of the carrier light to create an optical spring. This configuration is superior to a simple detuned Fabry–Perot cavity, which can also create an optical spring but at the same time decreases the circulating power. There is also a squeeze-light injection system depicted in Fig. 1, which will be explained later.

Gravitational waves induce phase modulation on the carrier light. If the signal-recycling cavity is tuned to the resonance or anti-resonance of the carrier, the phase signal reflected back to the

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* Corresponding author.
*E-mail address:* somiya@phys.titech.ac.jp (K. Somiya).

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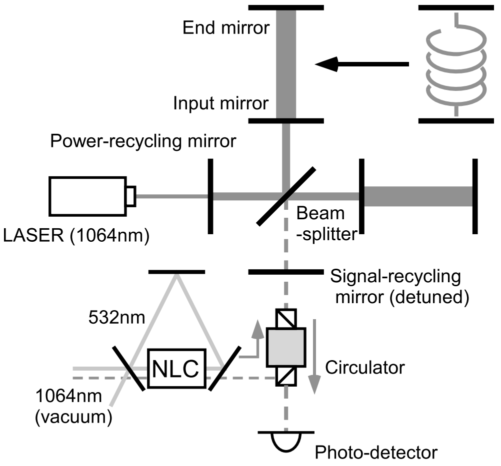

**Fig. 1.** Configuration of a gravitational-wave detector with detuned signal recycling. The test masses in the arm cavities are connected by the optical bar. The vacuum fluctuation entering from the signal port is squeezed by the non-linear crystal (NLC) and a pump beam.

interferometer is still in the phase modulation to the carrier light. With the detuning, the signal is in the mixed modulation and a fraction of the field in the amplitude modulation to the carrier light couples to the input carrier light to produce radiation pressure on the arm cavity mirrors. The mirror motion induces phase modulation and there is a loop of the signal production through the radiation pressure, which creates an optical spring.

The left panel of Fig. 2 shows quantum noise spectra of the gravitational-wave detector with different detune phases. Hereafter, the input power, the power recycling gain, the arm cavity finesse, the signal-recycling mirror power reflectivity, and the detune phase are 75 W, 11, 150, 85%, and $\pi/2$–0.5 rad, respectively, unless noted. The laser power at the beamsplitter and the circulating power in the arm cavities are thus about 0.8 kW and 40 kW unless noted. These values are close to those for KAGRA [4] except for the finesse that is 10 times lower. We have chosen the lower finesse so that the shift of the optical spring frequency appears more clearly. Origin of quantum noise is a vacuum fluctuation that enters the interferometer from the dark port. The noise level is given by the vacuum level divided by the signal strength. Each noise spectrum shows two dips: the dip at a lower frequency (lower dip) is for the optical spring resonance and the dip at a higher frequency (upper dip) is for the optical resonance of the coupled cavity with the detuned signal-recycling and the arm cavities. The two dips approach with the detune phase $\phi$ decreased from $\pi/2$. The highest end of the optical spring is the frequency where the two dips meet in the spectrum. The optical resonance of the coupled cavity is determined by the duration time of the signal field. The optical spring frequency cannot be higher than the optical resonance because it takes more time to deliver the information in the coupled cavity with such long duration time.

The right panel of Fig. 2 shows quantum noise spectra of the gravitational-wave detector with different circulating power. While the upper dip does not move, the lower dip moves upward with the increasing power, approximately by a factor proportional to the square root of the circulating power over the mirror mass until the two dips converge [3,6]. We should note, however, that it is technically challenging to increase the circulating power and to lower the mass.

## 3. Conventional squeezed-vacuum injection technique

The increase of the circulating power is also a challenge in the gravitational-wave detector for the improvement of the sensitivity at high frequencies. One way to overcome the challenge is to use a squeeze-light injection technique. Instead of the coherent vacuum, a vacuum field that is squeezed in the phase quadrature is injected from the dark port of the interferometer so that the signal-to-noise ratio in a non-detuned interferometer can be improved as if the circulating power is increased. The squeezed vacuum can be generated with a non-linear crystal and a pump beam at the doubled frequency of the carrier light. The squeezing technique has been well developed and the squeezing factor is currently as high as 14 dB [7], which means that the quantum phase noise is improved as if the circulating power is made 25 times higher. The squeezing is, however, vulnerable to an optical loss in the interferometer. The optical loss does not only decrease the signal but also introduces a coherent vacuum field that deteriorates the squeezed vacuum.

The squeezing is not equivalent to the increase of the power in a detuned interferometer. The sensitivity improvement in the non-detuned interferometer is due to the reduction of the vacuum fluctuation in the phase quadrature and thus does not affect the opto-mechanical dynamics. Fig. 3 shows the quantum noise spectra with and without the squeezing in a non-detuned interferometer (left panel) and in a detuned interferometer (right panel). The optical spring frequency does not change in the detuned interferometer. Instead, the steepness of the two dips increases with the squeezing in the detuned interferometer. This is due to the squeeze rotation at around the dip frequencies. Such a narrow-band improvement of quantum noise could be realized by simply replacing the signal-recycling mirror by a mirror with higher reflectivity.

## 4. Parametric signal amplification with a non-linear crystal

Now we propose a new way to increase the optical spring frequency without increasing the duration time of the signal field or increasing the circulating power. Fig. 4 shows our setup. A squeezer is placed inside the signal-recycling cavity and is used

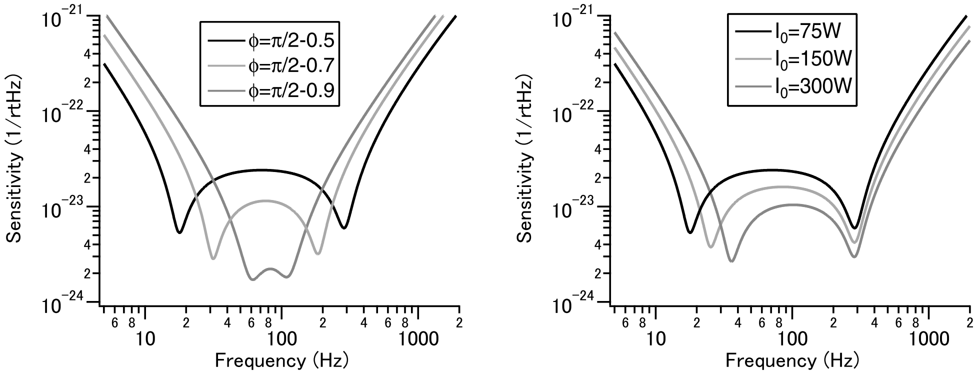

**Fig. 2.** Quantum noise spectra of a detuned interferometer with different detune phases (*left*) and with different power levels (*right*).