Physics Letters A 382 (2018) 2238–2244

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Engineering the optical spring via intra-cavity optical-parametric amplification

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ARTICLE INFO

Article history:
Available online 12 August 2017
Communicated by I. Pinto

Keywords:
Gravitational-wave detectors
Quantum noise
Internal squeezing
Optical spring
Optical bar

ABSTRACT

The 'optical spring' results from dynamical back-action and can be used to improve the sensitivity of cavity-enhanced gravitational-wave detectors. The effect occurs if an oscillation of the cavity length results in an oscillation of the intra-cavity light power having such a phase relation that the light's radiation pressure force amplifies the oscillation of the cavity length. Here, we analyse a Michelson interferometer whose optical-spring cavity includes an additional optical-parametric amplifier with adjustable phase. We find that the phase of the parametric pump field is a versatile parameter for shaping the interferometer's spectral density.

1. Introduction

Electromagnetic dynamical back-action was first observed in radio-frequency systems and its existence predicted for optical Fabry–Perot cavities by Braginsky and his colleagues more that 50 years ago [1,2]. The first proposal of using dynamical back-action to improve the sensitivity of laser-interferometric gravitational-wave detector was made in 1997, again by Braginsky and co-workers [3]. The new scheme was called 'optical bar', since the light's radiation pressure force rigidly connects two far separated mirrors, which are suspended as pendula but quasi-free otherwise. This way, a gravitational-wave signal is transformed into an acceleration of mirrors with respect to the local frame. The interferometric topologies that are considered in [3] as well as in related work [4] are different from the Michelson topology having a balanced beam splitter, and were not experimentally realised so far. Recently, a more practical design was proposed [5].

The second proposal was made in 2002 by Buonanno and Chen [6] and was called 'optical spring'. It targets the sensitivity improvement of Michelson-type gravitational-wave detectors having a signal-recycling (SR) cavity [7,8] or signal-extraction (SE) cavity, also called resonant-sideband extraction (RSE) [9,10]. For the purpose of utilising the optical spring in a Michelson interferometer operated on dark output port, these cavities need to be detuned from carrier light resonance. If the frequency of the carrier light is blue-detuned with respect to the cavity, the lower sidebands of phase modulations that are produced by gravitational waves and that are matching the detuning frequency get optically enhanced while the corresponding upper sidebands are suppressed. Due to energy conservation, the mechanical (pendulum) motion of the suspended mirror is enhanced [11,12]. The overall process corresponds to optomechanical parametric amplification and results in optical heating of the mechanical motion, i.e. the opposite of optical cooling [13]. The radiation pressure of the light not only results in an optomechanical parametric amplification of the pendulum motion but also to an additional (optical) spring constant that increases the pendulum resonance frequency from typically 1 Hz to an opto-mechanical resonance of up to about 100 Hz. Around this frequency the mechanical response of the GW detector is significantly enhanced and its sensitivity improved. The frequency of the opto-mechanical resonance depends on the detuning and the optical power inside the arms of the detector. To further exploit the optical spring, it was proposed to dynamically change the detuning by moving the SR/SE mirror in order to follow expected chirps of GW signals [14,15]. The optical spring was observed in several experiments [16–21,12,22–26]. The gravitational-wave detectors GEO 600 [27], Advanced LIGO [28], Advanced Virgo [29], and KAGRA [30] do use either SR or SE cavities, but so far have not yet employed the optical spring for a sensitivity enhancement due to the requirement of additional control techniques.

The conventional scheme for producing the optical spring does not use any additional parametric amplification of purely optical

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http://dx.doi.org/10.1016/j.physleta.2017.08.008

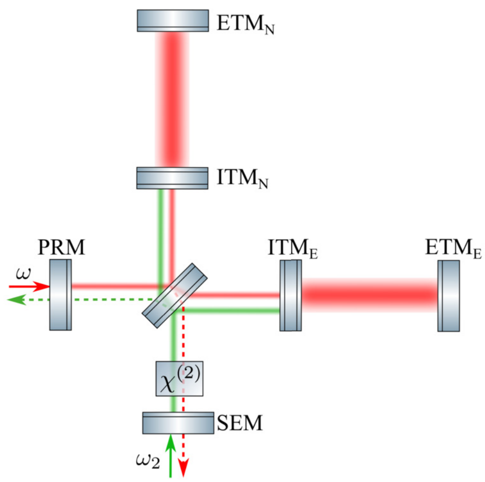

Fig. 1. Schematic diagram of a proposed gravitational-wave detector. On top of the Advanced LIGO topology, consisting of arm resonators, a power-recycling mirror (PRM) and a signal-extraction mirror (SEM), a second-order nonlinear ($\chi^{(2)}$) crystal is placed in the SE cavity. The main carrier light at optical frequency ω is blue-detuned with respect to this cavity, but resonating in the arm cavities as well as in PR cavity. The second-order nonlinear crystal is pumped with a light field at frequency $\omega_2 = 2\omega$ resulting in optical-parametric amplification (OPA) of light at ω, including its quantum uncertainty. The pump field (displaced for better visibility) is also used to measure the differential motion of the ITMs. The two different wavelengths can be separated easily with dichroic beam splitters (not shown). $\mathrm{ITM}_{\mathrm{N,E}}$: input test mass in north and east arm, respectively. $\mathrm{ETM}_{\mathrm{N,E}}$: end test mass.

kind. Recent work, however, proposed complementing the SR/SE cavity with optical-parametric amplification [31] to allow for shifting up further the opto-mechanical resonance frequency without increasing the light power in the arms.

In this work we extend the consideration in [31] and analyse the more general situation, in which not only the parametric gain is varied but also the angle of the amplified quadrature amplitude. The parametric gain relates to the *intensity* of the second-harmonic pump field, whereas the angle relates to its *phase*. In particular the last parameter can be quickly changed providing a new degree of freedom for realising dynamical detuning of the optical spring properties. We consider the internal quantum noise squeezing that is accompanied with the optical-parametric amplification together with the one from the optomechanical parametric amplification and derive spectral densities. Furthermore, we propose utilising the second-harmonic pump field to implement a 'local readout' of the motion of the arm cavity input test masses (ITMs) [32], see Fig. 1. The local readout mitigates the unwanted effect of the optical spring, which is the rigid connection of the ITMs with their respective end test mass (ETM) at frequencies below the optical spring and a corresponding sensitivity loss at these frequencies.

2. The optomechanical system

The effects on the light field of both processes, the optical and the optomechanical parametric amplification, can be described in similar ways. Both result in a consecutive rotation of quadratures (determined by the phase of the pump for optical amplification and by the detuning of the SE cavity for the optomechanical one), squeezing (optical and ponderomotive correspondingly) and rotation again [33,34]. Both types of parametric amplification should thus influence the optical spring also in similar ways. In this section we derive explicitly the optical spring in the case of additional optical-parametric amplification inside the SR/SE cavity and show the effect of the squeeze angle.

We consider the dark port operation, at which all input light is retro-reflected from the interferometer. In this situation, the interferometer output field at the dark port contains the full information about the differential motion of the mirrors, and the output field at the bright port carries the full information about the common motion [35].

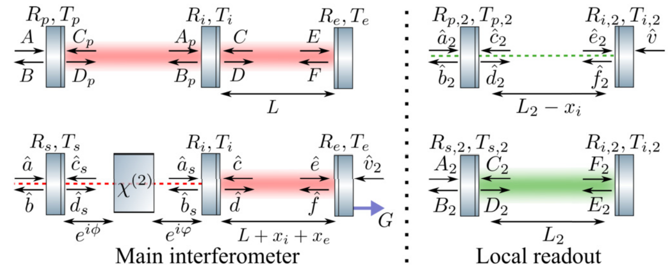

Fig. 2. Notations of the optical fields for the PR cavity together with the common mode of the arm cavities at ω (top left), for the SE cavity together with the differential mode of the arm cavities at ω (bottom left), and respective parts of the interferometer in Fig. 1 at ω_2, which belongs to the local readout (top and bottom right). Operators are annihilation operators and denote complex amplitudes including their uncertainties. Capital letters A to F denote complex amplitudes whose uncertainties are irrelevant. Subscript 's': signal extraction; 'p': power recycling; 'i': input to arm cavity; 'e': end of arm cavity; '2': optical frequency ω_2. R, T: amplitude reflectivity and transmissivity of mirrors. L is the average length of the arm resonators, L_2 is the relevant average length of the local read out, and $x_{i,e}$ represent their dynamical parts due to differential test mass motion. ϕ and φ are additional phases accumulated by the light field inside the SE cavity due to the cavity detuning. The gravitational-wave signal ('G') corresponds to a differential change of the arm length L.

Let us first focus on the main interferometer that includes the arm cavities and is operated at optical frequency ω. This interferometer includes the far mirrors (ETMs) whose differential distance from the rest of the interferometer is directly excited by the gravitational wave. (Depending on the polarisation and direction of propagation of the gravitational wave, also their common distance is changed, however, its measurement is not targeted by a Michelson interferometer.) With this in mind, we use an effective picture, where the interferometer is split into two separate cavity systems, coupled only via the displacement of the test mass mirrors [36]. The first cavity system (Fig. 2, top left) corresponds to the common mode, whose modulation as well as its uncertainty are irrelevant for the signal-to-noise-ratio of a gravitational-wave signal in the differential mode. It is thus fully described by the classical carrier fields at frequency ω. The second one corresponds to the differential mode at ω and requires a quantised description (Fig. 2, bottom left). The other two systems in Fig. 2 (right) describe the short Michelson interferometer in Fig. 1 that uses light at ω_2 for pumping the optical-parametric process and for measuring the differential motion of the ITMs. This part of the interferometer is considered in the section *local readout* further down.

The first mirrors of the main interferometer cavities (Fig. 2, left) are the power recycling (PRM) and signal extraction (SEM) correspondingly, and the middle (input, i) and the end (e) mirrors are combinations of ITM and ETM. Then the differential motion of four mirrors can be defined as the motion of input and end mirrors in the effective cavity picture:

$$\hat{x}_-(\Omega) = \left(x^{(E)}_{\mathrm{ITM}}(\Omega) + x^{(E)}_{\mathrm{ETM}}(\Omega)\right) - \left(x^{(N)}_{\mathrm{ITM}}(\Omega) + x^{(N)}_{\mathrm{ETM}}(\Omega)\right) = x_i(\Omega) + x_e(\Omega)\,. \quad (1)$$

Relative to the beam splitter only the far mirrors are accelerated due to the gravitational wave force G, as the input mirrors are so close to the beam splitter that the effect can be neglected. On top, all mirrors are accelerated by the light's radiation pressure force $F^{ba}_{(i,e,2)}$, which is proportional to the power of the light shining on the mirror and which we call back-action.

$$\hat{x}_i(\Omega) = \chi_i(\Omega)\left[F^{ba}_i - F^{ba}_2\right], \quad (2)$$