I. INTRODUCTION

Sensitivity of the the second generation laser interferometric gravitational-wave (GW) detectors: Advanced LIGO [1, 2], Advanced VIRGO [3, 4], and KAGRA [5, 6], which are under construction now, in major extent will be limited by the quantum noise. Namely, at higher frequencies the shot noise will dominate, originating from the quantum fluctuation of the phase of the optical field inside the interferometer. At lower frequencies, the radiation pressure noise created by the amplitude fluctuations will constitute the significant part of the noise budget. The best sensitivity point, where these two noise sources become equal, is known as the Standard Quantum Limit (SQL).

Two main categories of methods of overcoming the SQL were proposed. The first one includes the so-called quantum noise cancellation schemes, where cross-correlation between the measurement noise and back-action noise is imposed, allowing to reduce the sum quantum noise. Two well-known examples of this approach are the *quantum speedmeter* topologies [7–9] and the *filter cavities* based [10] schemes.

Yet another noise cancellation scheme, based on use of pairs of *antisymmetric* optical carriers (with equal values of optical circulating power, effective bandwidth, squeeze power, and opposite detunings, homodyne angles and squeeze angles) was analyzed in the article [11]. A peculiar feature of this scheme is that its effective (conditional) radiation pressure noise spectral density decreases with the frequency as Ω^2, allowing thus to combine several antisymmetric pairs in the xylophone-like configuration within the same interferometer and to shape flexibly the interferometer quantum noise.

Unfortunately, all schemes of this category share the same major disadvantage, namely vulnerability to the optical losses, which is especially significant in the low-frequency band.

The second group of methods is based on amplification of the detector's response to the GW signal by modifying the test-mass dynamics. This is possible because the force SQL depends on the test-mass dynamics:

$$S_F^{\mathrm{SQL}}(\Omega) = 2\hbar \left|\chi^{-1}(\Omega)\right| , \tag{1}$$

where $\chi^{-1}(\Omega)$ is the test mass mechanical susceptibility. In particular, using the optical spring effect [12, 13], a free mass can be converted into a harmonic oscillator, which has a much stronger response to near-resonance force, and thus a smaller SQL in a narrow frequency band around the resonance frequency.

The broadband sensitivity gain can be obtained by using double optical spring created by two optical carriers [14]. When the power, detuning and bandwidth of the two carriers are chosen appropriately, the effect of the double optical spring can be described as a negative optical inertia, which cancels the positive inertia of the test mass and thus increases its response to the signal force. This allows us to surpass the free-mass Standard Quantum Limit (SQL) over a broad frequency band.

The main disadvantage of this method is that the upper frequency of this band scales only as $I_c^{1/3}$ with the optical power I_c circulating in the interferometer. Estimates show, that for the realistic values of I_c, this frequency can not exceed $\sim 100\,\mathrm{Hz}$.

II. OBJECTIVES AND APPROACH

The main goal of the proposed research is numerical optimization of the multi-carrier configurations of the laser gravitational-wave detectors. We are planning to start with the constrained parameters space by assuming the negative optical inertia regime for the first (low-frequency) pair of carriers, and the antisymmetric carriers regime for other ones. It can be concluded from the aforesaid, that this combination should give the overall sensitivity close to the optimal one. At the same time, the constrained parameters space will significantly reduce the computation time. Depending on the results achieved at this stage, we will try to perform the full unconstrained optimization.

In particular, in our work we are planning to take into account:

- possible injection of the squeezed quantum state in the interferometer
- and the optical losses in the scheme.

As the figure of merit, we will use the following cost function, which is known to give smooth broad-band shape of the quantum noise spectral density $S^h(\Omega)$ [15]:

$$C(\mathbf{p}) = \int_{f_{\min}}^{f_{\max}} \log_{10}[S^h(2\pi f, \mathbf{p})] d(\log_{10} f), \tag{2}$$

$f_{\min}$ and $f_{\max}$ are minimum and maximum frequencies of the GW signal, and $\mathbf{p}$ is the vector of the parameters to be optimized, which includes the values of optical power, effective bandwidth, detuning, homodyne angle, squeezing power, and squeezing angle of all carriers. The total number of carriers will be limited by three pairs, which we consider as a reasonable limitation for both the the practical implementation and the computation time.

All computations will be performed using the computer program, which we are planning to develop using the C language (to achieve the best performance) and the GNU Scientific Library [16].

III. SCHEDULE

Week	Occupation
1	Constrained parameters
2	
3	
4	**First progress report**
5	Unconstrained optimization
6	
7	
8	**Second progress report**
9	
10	**Final Report**

---

[1] `http://www.advancedligo.mit.edu/`.

[2] G.M.Harry (for the LIGO Scientific Collaboration), Classical and Quantum Gravity **27**, 084006 (2010).

[3] `http://wwwcascina.virgo.infn.it/advirgo/`.

[4] F.Acernese et al, J. Phys.: Conf. Ser. **32**, s223 (2006).

[5] `http://gwcenter.icrr.u-tokyo.ac.jp/en/`.

[6] Y. Aso et al., Phys. Rev. D **88**, 043007 (2013).

[7] V. B. Braginsky, F. Ya. Khalili, Physics Letters A **147**, 251 (1990).

[8] P. Purdue and Y. Chen, Phys. Rev. D **66**, 122004 (2002).

[9] Y.Chen, Physical Review D **67**, 122004 (2003).

[10] H.J.Kimble, Yu.Levin, A.B.Matsko, K.S.Thorne and S.P.Vyatchanin, Physical Review D **65**, 022002 (2001).

[11] M. Korobko, N. Voronchev, H. Miao, and F. Y. Khalili, Phys. Rev. D **91**, 042004 (2015).

[12] V.B.Braginsky, F.Ya.Khalili, Physics Letters A **257**, 241 (1999).

[13] A.Buonanno, Y.Chen, Physical Review D **65**, 042001 (2002).

[14] F. Khalili et al., Phys. Rev. D **83**, 062003 (2011).

[15] H. Miao, H. Yang, R. X. Adhikari, and Y. Chen, Classical and Quantum Gravity **31**, 165010 (2014).

[16] GNU scientific library, `http://www.gnu.org/s/gsl/`.