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Study and experiment on the alternative technique of frequency–dependent squeezing generation with EPR entanglement for Virgo

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Abstract. In this paper, we summarize the present state-of-the-art on the proof-of-principle experiment of frequency-dependent squeezing implemented through EPR entanglement for Virgo gravitational-wave detector and we introduce Virgo subsystem proposal for frequency-dependent squeezing, obtained with a compact apparatus and without the costs required by the infrastructure for the filter cavity.

1. Introduction

Current Gravitational-Wave Detectors (GWDs) implement squeezed light injection, as a method for the Quantum Noise (QN) reduction. The sensitivity of present detectors is affected mostly by the high-frequency component of QN as the dominant in the low-frequency region

Radiation Pressure Noise (RPN) is covered by technical noises. This situation fosters Frequency-Independent Squeezing (FIS) technique to be used. On-going work on Virgo detector upgrade will soon lower the technical noises to a level where also RPN becomes a limit. One can obtain a Frequency-Dependent Squeezing (FDS) by applying an external Filter Cavity (FC), which performs squeezing angle rotation, to FIS technique [1]. Another method has been recently proposed [2] to achieve a broadband reduction of quantum noise in GWDs using a pair of squeezed Einstein–Podolsky–Rosen (EPR) entangled beams to produce FDS. This method promises [3] to achieve a frequency-dependent optimization of the injected squeezed light fields without the need for an external FC. FDS with EPR-entanglement offers an attractive solution to this by harnessing the quantum correlations generated between a pair of EPR-entangled beams and effectively exploiting the interferometer itself as a FC, thereby achieving a similar response with minimal additional optical components. For the purposes of this article we will call this technique EPR squeezing.

2. Advantages with respect to the Filter Cavity

Scientific analysis of EPR squeezing brought us to the considerations about its strong and weak points. EPR squeezing has three main disadvantages. It demonstrates intrinsic 3 dB penalty on the sensitivity curve with respect to the same injected squeezing level using a FC. Moreover it makes the detection setup more complicated due to two homodyne detectors and it requires additional output mode cleaner. On the other hand, although suitable filter cavities can be designed, the additional cavity adds further complexity to the interferometer. Requirement of low losses and the rotation at the correct low frequency makes the FC length of the order of tens of metres. FC vacuum tank and towers with mirror suspension needs to provide a high seismic noise attenuation factor. Nevertheless, the main argument which speaks for the EPR squeezing is its flexibility. In contrast to a FC, EPR squeezing produces variable phase rotation for various Signal Recycling Cavity (SRC) configuration, adjustable just with idler detuning. For this reason the described technique should be studied as well as FC for the next generation of GW detectors.

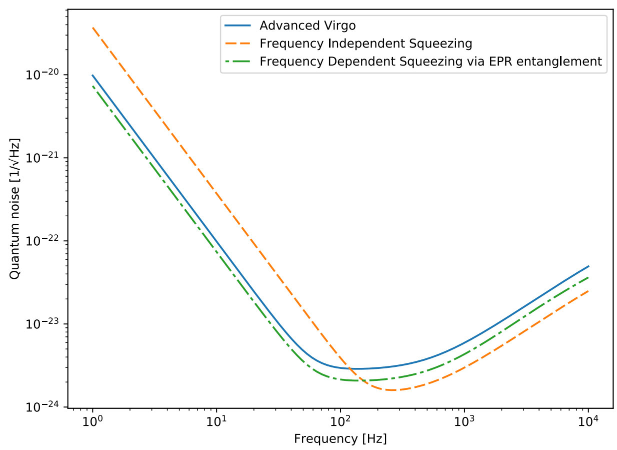

Figure 1. Virgo sensitivity curve comparison: the Advanced Virgo original configuration (solid blue curve), the frequency-independent 12 dB squeezing injection (dashed orange curve) and the expected sensitivity in case of 12 dB injection of frequency-dependent EPR squeezing (dot-dashed green curve).

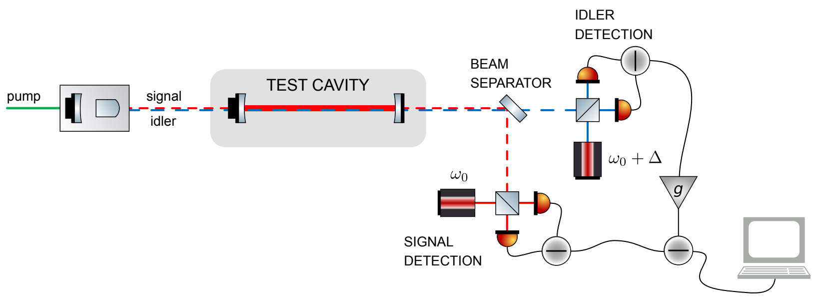

Figure 2. Conceptual scheme of a table-top EPR frequency-dependent squeezing experiment. Green light pumps NOPO what generates pairs of entangled photons. One photon from the pair forms signal beam and the other one idler. Both signal and idler are sent to a test cavity. After the cavity beams are separated by an etalon (Beam Separator) and each beam is independently measured by a corresponding homodyne detector.

3. Implementation in interferometeric GW detectors

In the implementation, a pair of squeezed EPR-entangled optical fields can be generated by means of a Non-degenerate Optical Parametric Oscillator (NOPO). By properly choosing the detuning of the pumping field from the Optical Parametric Oscillator (OPO) resonance, one can generate two entangled photons, named signal and idler [4]. The two entangled vacuum fields are injected into the interferometer; signal field is kept resonant with arm cavities, while idler field is far detuned and experiences a frequency-dependent quadrature rotation, which can be optimized by adjusting it with respect to the lengths of interferometer cavities. In reflection from the interferometer, the two fields are separated and measured by two independent homodyne detectors. Output signals are combined using an optimal filter to retrieve the squeezing of the quantum noise in the signal channel. Accordingly to calculations this leads to the broad-band improvement of the sensitivity curve. The simulated sensitivity curve of Advanced Virgo with 12 dB of FDS injected using EPR scheme is shown in Fig. 1, where it is compared with the sensitivity curve without squeezing and with 12 dB of FIS injection.

4. Proposal for a table-top experiment

A table-top experiment for frequency-dependent squeezing, using EPR entangled beams, is under construction at Virgo site in Cascina. In order to test the squeezed states source we foresee the following steps in the experiment. The first step is shown in Fig. 2, its aim is to obtain the squeezing angle rotation using a Fabry-Pérot Test Cavity (TC) instead of the interferometer. At this point the two entangled beams (signal and idler) will be produced using a NOPO. In the EPR experiment for GW detector quantum noise reduction we need that one of the two beams (signal) has the same frequency of the interferometer laser beam $\omega_s = \omega_0$, while the other beam will have a frequency $\omega_i = \omega_s + \Delta$. In order to obtain this, the main laser of the EPR squeezer will be frequency shifted and its frequency will be $\omega = \omega_s + \Delta/2$. This laser will provide the pump beam for a Second-Harmonic Generation (SHG) cavity. The SHG will in turn provide the pump beam for the NOPO. The two entangled beams will be both injected in the Test Cavity where the signal will be resonant, while the idler, being slightly detuned, will experience the squeezing angle rotation. The two squeezed beams, that have the same polarization, will be separated using an etalon. The squeezing level will be separately measured using homodyne detectors. By opportunely recombine the detector outputs, it is possible to conditionally squeeze the signal beam, in a frequency dependent way, by measuring the squeezing angle rotation experienced by the idler. The local oscillators for the homodyne detections will be provided by two separate

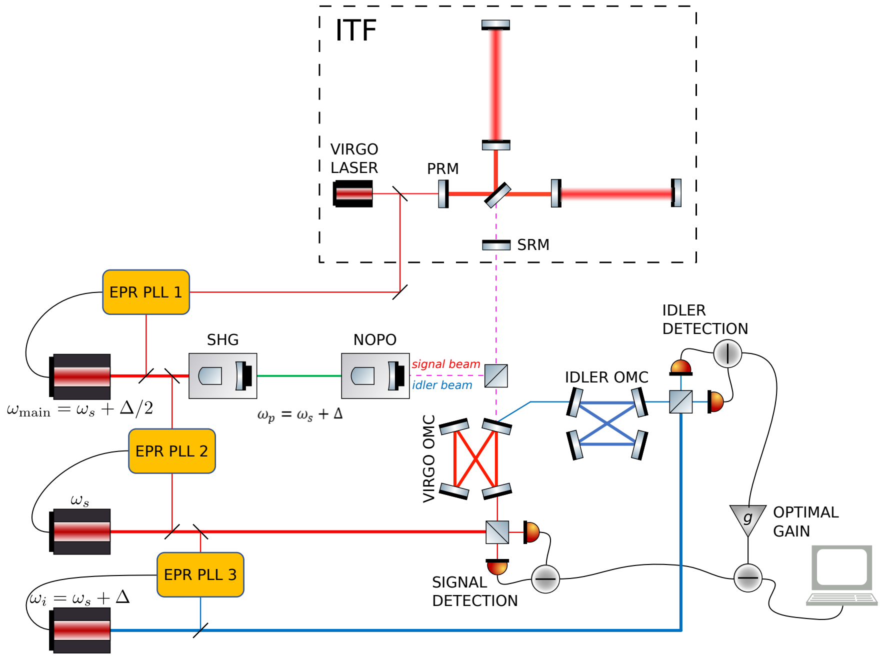

Figure 3. Representation of EPR squeezing preliminary design and its interface to the interferometer. Existing infrastructure on the detector is inside the dashed line (ITF). Another piece of optics which will be reused is Virgo's Output Mode Cleaner (OMC). Three auxiliary lasers are foreseen on the EPR squeezing bench; pump at ω_{main}, signal local oscillator ω_{s} and idler local oscillator ω_{i}. They are lock in cascade to the peak-off of the Virgo main laser.

lasers, phase locked with respect to the main laser using Optical Phase-Locked Loop (OPLL). All the auxiliary beams: NOPO and Test Cavity locking beams and Coherent Control Beams, that have a frequency shift with respect to the signal and idler frequencies will be provided by acousto-optic modulators. Fig. 3 depicts the schematics of the system supplying all the needed beams.

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References
[1] Khalili FY. Optimal configurations of filter cavity in future gravitational-wave detectors. Physical Review D [Internet]. American Physical Society (APS); 2010 Jun 22;81(12). Available from: http://dx.doi.org/10.1103/physrevd.81.122002
[2] Ma Y, Miao H, Pang BH, Evans M, Zhao C, Harms J, et al. Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement. Nature Physics [Internet]. Springer Science and Business Media LLC; 2017 May 15;13(8):776–80. Available from: http://dx.doi.org/10.1038/nphys4118
[3] Gniesmer J, Korobko M, Steinlecher S, Schnabel R. Frequency-dependent squeezed states for gravitational-wave detection through EPR entanglement. Quantum Information and Measurement (QIM) V: Quantum Technologies [Internet]. OSA; 2019; Available from: http://dx.doi.org/10.1364/qim.2019.s2b.4
[4] Zhang J. Einstein-Podolsky-Rosen sideband entanglement in broadband squeezed light. Physical Review A [Internet]. American Physical Society (APS); 2003 May 27;67(5). Available from: http://dx.doi.org/10.1103/physreva.67.054302