An experiment to demonstrate frequency-dependent squeezing with EPR entanglement for gravitational waves detectors

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A key towards better sensitivity of GW detectors is to suppress quantum noise, which arises from the quantum nature of light and is driven by vacuum fluctuations of the optical field entering from the dark port of the interferometer. One way to improve the sensitivity of Advanced Virgo (AdV) with minimal modification to its optical configuration is to inject squeezed vacuum into the dark port. Up to 14 dB of squeezing down to audio sideband frequencies (10 Hz to 10 kHz) has been produced in lab [1]. The impact of squeezing on the quantum noise of a large scale interferometer is limited by optical losses, phase noise and scattered light. GEO600, where squeezing enhancement is routinely employed since 2010, has recently demonstrated almost 6 dB of detected squeezing [2]. Moderate noise reduction by squeezed light injection has been also demonstrated in the large-scale interferometer LIGO, and more recently in Virgo.

On the other hand, squeezed vacuum generated by a nonlinear crystal via optical parametric amplification (OPA) is independent of frequency for audio sidebands: within the gravitational-wave frequency band, one can only 'squeeze' a fixed quadrature, and thus fluctuations in the orthogonal quadrature are amplified by the same factor, as required by the Heisenberg uncertainty principle. The effect of quantum noise on interferometric GW detectors is twofold: shot noise, generating phase fluctuations of the optical field at the output detector, is the main sensitivity limit at high frequencies; radiation pressure noise, generating position fluctuations of the suspended masses, contributes to the noise at low frequencies. In order to fully exploit the quantum noise reduction for GW waves detection, a frequency-dependent quadrature must be squeezed for each sideband frequency. Starting from frequency-independent squeezing (FIS), one should rotate the squeezed quadrature in a frequency-dependent way (FDS). A possible method to achieve such rotation is by filtering the field with two FabryPerot cavities. The narrowness of the bandwidth requires the filter cavity to be long to limit impact from optical losses; the current plan for Advanced LIGO, Advanced Virgo, and Kagra, is to construct an approximately 300-m-long filter cavity, and similar cavities have been studied for the Einstein Telescope.

It has been recently proposed that a broadband reduction of quantum noise in gravitational wave detectors can be achieved using a pair of squeezed EPR-entangled beams to produce frequency-dependent squeezing [3]. This method promises to achieve a frequency-dependent optimisation of the injected squeezed light fields without the need for an external filter cavity. Although suitable filter-cavities can be designed, the additional cavity adds further complexity to the interferometer. EPR-squeezing offers an attractive solution to this by harnessing the quantum correlations generated between a pair of EPR entangled beams and effectively utilising the interferometer itself as a filter cavity, thereby achieving a similar response with minimal additional optical components. Moreover, EPR entanglement would be more flexible versus changes in the optical configuration of the signal-recycled interferometer.

When comparing EPR entanglement and filter cavities for FDS one has to consider that optical losses, which limit the effectiveness of all quantum-noise-reduction techniques, contribute differently in the two cases. I will present preliminary simulations to understand how the sensitivity of AdV with EPR squeezing would be affected by injection and detection losses in the input and output path, or by losses inside the interferometer. I will derive requirements for potential upgrades to reduce the current optical losses to a level that render the implementation of EPR squeezing feasible and an interesting option for broadband quantum noise reduction.

The demonstration of FDS via EPR entanglement, both in the lab and in an active detector, would provide an interesting alternative to the use of filter-cavities currently being planned for detector upgrades and in the design of future detectors. An R&D program is ongoing at the EGO laboratories in Cascina to demonstrate the method. I will present the status of the experiment, and I will discuss the concept for a possible implementation in Virgo.

[1] M. Mehmet and H. Vahlbruch, Class. Quant. Grav. **36** 015014 (2018).
[2] http://www.geo600.org/1888463/new-squeezing-record-at-geo600
[3] Y. Ma et al., Nat. Phys. **13** 776 (2017).

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