A SQUEEZED LIGHT SOURCE FOR THE GRAVITATIONAL WAVE DETECTOR GEO 600

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The sensitivity of large-scale interferometric gravitational wave (GW) detectors is already nowadays limited by quantum noise at frequencies above approximately 1 kHz. Future generations of GW detectors will be limited by quantum noise almost over their entire detection band. An innovative approach to reduce this quantum noise and hence to increase the interferometer sensitivity is given by the application of squeezed states of the light field. The contribution reviews recent proof-of-principle work performed in table-top experiments and presents the status of the squeezed light source for the German-British gravitational wave detector GEO 600.

1. Introduction

The dominant noise source for GW detectors at frequencies in the kHz regime is shot noise which arises from photon number fluctuations.[1] A 'classical' approach to increase the signal-to-noise ratio (SNR) of the detectors is to increase the circulating light power. This will be indeed one of the approaches in the second detector generation. Higher laser powers, however, may lead to a stronger waveform distortion due to light absorption and hence to thermal lensing effects.[2] An alternative, 'non-classical' approach is to improve the SNR by reducing the quantum noise itself, using so-called *squeezed* states of light. The quantum limitation arises from the zero-point fluctuations of the electro-magnetic field which are uniformly distributed in every field quadrature; this *vacuum state* enters the interferometer from the dark signal port, experiences a reflection and interferes with the signal at the photo detector hereby limiting the sensitivity. In a squeezed state, the uncertainty is reduced below the minimum uncertainty value of the vacuum state in *one* of the quadratures. Substituting the vacuum by a squeezed vacuum state directly leads to an improved SNR. In fact, this was proposed by Caves in 1981 in a visionary way before either squeezing or large-scale interferometric detectors were realized for the first time.[3] The first observation of squeezed states followed some years later in 1985.[4] Since then, different techniques for the generation of squeezed light have evolved. Hitherto, below-threshold optical parametric oscillators proved to be most efficient. Up to 11.5 dB of squeezing at the carrier wavelength of present GW detectors (operating at 1064 nm) could be generated using $MgO{:}LiNbO_3$ as nonlinear material.[5] The detection band of earth-bound GW detectors which extends over audio frequencies of about 10 Hz - 10 kHz proved to be a harder challenge for the generation of squeezed light. Only 2004, a first scheme for squeezing generation at frequencies down to 100 kHz could be successfully demonstrated,[6] closely followed by the development of a coherent control scheme for the use in GW detectors.[7] With this, squeezing over the entire GW detection band could be achieved.[8] The following section presents the status of the first squeezed light source designed for continuous operation in a large scale GW detector.

2. A Squeezed Light Source for GEO 600

A simplified sketch of the experimental set-up is shown in Figure 1. The experiment is driven by a monolithic non-planar Nd:YAG ringlaser (NPRO) of 2W single-mode output power at 1064nm. This beam is partially frequency up-converted in a second-harmonic generator which uses a $MgO:LiNbO_3$ nonlinear crystal and generates 180 mW of output power at 532 nm. This second-harmonic frequency is required for pumping the parametric down-conversion process inside the squeezed light source. The latter is set up as an optical parametric amplifier (OPA) which consists of a 9.8 mm long PPKTP crystal placed in a linear hemilithic cavity. This cavity is created by the HR-coated surface of the crystal itself and a coupling mirror with $R = 92\%$ at 1064 nm, while the intra-cavity crystal surface is AR-coated. To ensure the phase-matching condition between the fundamental (squeezed) and the second harmonic (pump) field, the crystal is temperature-stabilized. The generated squeezing is detected in a balanced homodyne detector. For this purpose, a small fraction of the main 1064 nm beam is used as a local oscillator beam.

The generation of squeezed states at audio frequencies of 10 Hz - 10 kHz requires the implementation of a control scheme which avoids the introduction of technical laser noise to the squeezed vacuum state at those frequencies. This control scheme is realized using two additional NPRO laser sources of 200 mW output power each. Both lasers are frequency shifted and phase locked to the main 2 W laser which in turn will be phase locked to the main GEO laser when operating the experiment at the detector site. The first auxiliary laser beam is used to control the OPA cavity length. The second auxiliary laser allows to control the orientation of the squeezing ellipse with respect to the homodyne detector. For application in GEO 600, this beam will also allow to stabilize the phase relation between the squeezed vacuum beam and the interferometer output signal. The coherent control scheme is discussed in more details in Reference.[9] A more detailled description of the over-all set-up can be found in.[10]

In a first stage, the entire squeezed light source is assembled in a class 100 cleanroom of the Albert-Einstein-Institute in Hannover. Such a clean environment is necessary to avoid contamination of the optics by dust particles. Even single particles may lead to the creation of stray light which may introduce technical laser noise to the squeezed vacuum beam. In a second step, after being comissioned, the system will be brought to the GEO 600 site and integrated in the detector. The squeezed light source is assembled on a 1.15 m x 1.35 m large optical breadboard. To allow for a 24h/7days long-term operation, the experiment is interfaced with a real-time UNIX control system (Experimental Physics and Industrial Control System, EPICS). It allows the monitoring of all relevant experimental channels using AD-converters and also a remote control of the entire experiment. Please note that the latter is, however, still controlled by analog electronics to ensure high control bandwidths, while a remote control of this electronics is enabled by the EPICS system.

First measurements at the squeezed light source have shown a non-classical noise reduction with a white spectrum down to a frequency of 500 Hz which was at least 8 dB below the vacuum shot noise level. From the corresponding anti-squeezing level of 12 dB, an optical loss of approximately 10% can be derived. In this value, a loss at the homodyne

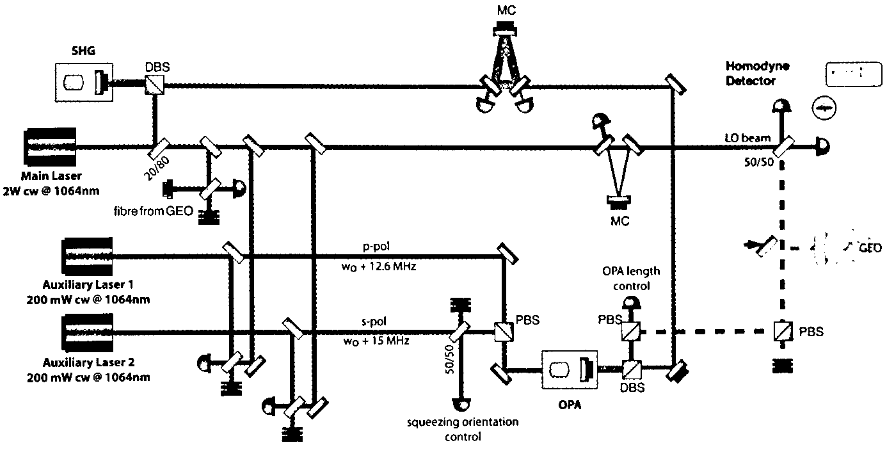

Fig. 1. Simplified experimental set-up. DBS: dichroic beam splitter, PBS: polarizing beam splitter, MC: mode cleaner ring cavity, LO: local oscillator. A detailled description is given in the text.

detector (due to a non-perfect fringe visibility and to photo detector losses) of about 5% is already included. This loss can be subtracted if the squeezed beam is directly guided into the GEO 600 detection port. Integrating the squeezed light source into the GEO 600 detection scheme will therefore reduce the shot noise entering the detector by a value of more than 10 dB. Since the GEO 600 detector will introduce additional loss we expect a final SNR improvement of up to 6 dB.

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