LETTERS
PUBLISHED ONLINE: 11 SEPTEMBER 2011 | DOI: 10.1038/NPHYS2083
nature physics

A gravitational wave observatory operating beyond the quantum shot-noise limit

The LIGO Scientific Collaboration †*

Around the globe several observatories are seeking the first direct detection of gravitational waves (GWs). These waves are predicted by Einstein's general theory of relativity[1] and are generated, for example, by black-hole binary systems[2]. Present GW detectors are Michelson-type kilometre-scale laser interferometers measuring the distance changes between mirrors suspended in vacuum. The sensitivity of these detectors at frequencies above several hundred hertz is limited by the vacuum (zero-point) fluctuations of the electromagnetic field. A quantum technology—the injection of squeezed light[3]—offers a solution to this problem. Here we demonstrate the squeezed-light enhancement of GEO 600, which will be the GW observatory operated by the LIGO Scientific Collaboration in its search for GWs for the next 3–4 years. GEO 600 now operates with its best ever sensitivity, which proves the usefulness of quantum entanglement and the qualification of squeezed light as a key technology for future GW astronomy[4].

Just as electromagnetic radiation is produced by accelerated charges, gravitational waves (GWs) are generated by accelerated mass distributions, such as supernova explosions or neutron star and black hole binary systems spiralling into each other[2]. GWs propagate at the speed of light and reveal themselves as an alternating stretching and compressing of space-time, transverse to their direction of propagation. The direct measurement of GWs is one of the greatest challenges of contemporary physics. Two neutron stars merging at the other side of our galaxy would produce a maximum space strain amplitude h here at the Earth of just $h \approx 10^{-19}$. The strain would be just $h \approx 10^{-22}$ in the case that the same event is located somewhere in the Virgo cluster of galaxies, being about 1,000 times farther away. Michelson-type laser interferometers are suitable observatories to measure gravitational waves[5].

At present, a global network comprising two LIGO observatories in the USA (with an arm length of 4 km (ref. 6), not operational since Nov. 2010 owing to upgrade activity), the Virgo project of the European Gravitational Observatory (with 3 km arms[7]) and the German–British detector GEO 600 (with 600 m arms[8,9]) exists, with further observatories planned or proposed in Japan[10], Australia[11] and Europe[12]. The targeted GW-frequency band extends from below 10 Hz to about a few kHz. An ideal probe for space-time disturbances requires test masses which are free-falling in the direction of the laser beams. Therefore, the interferometer mirrors are suspended as sophisticated multistage pendulums and are situated in ultrahigh-vacuum systems.

To date, no direct detections of gravitational waves have been made. However, upper limits on GW signal strength for certain classes of sources could be derived (see ref. 13 and references therein). To realize gravitational wave astronomy with a daily event rate, a sensitivity improvement by at least one order of magnitude is required, see for example ref. 12, thereby increasing the sensitive sky volume by three orders of magnitude. Science teams all over the world are at present addressing each instrumental noise source for future observatory generations. At lower and intermediate audio-band frequencies the sensitivity is, in practice, limited by seismic noise, suspension thermal noise, and in future interferometers by photon recoil (below several tens of hertz) and mirror thermal noise (in the range of hundreds of hertz). At higher frequencies it is the quantum nature of light that inhibits a more precise measurement, because the counting statistics of the light particles themselves lead to a fluctuating interferometer output (shot noise). This noise is caused by so-called 'vacuum', or 'zero-point' fluctuations of the electromagnetic field[3]. The 'classical' approach to improve the observatory's signal-to-shot-noise ratio is an increase of the circulating light power, as the signals produced by gravitational waves are proportional to the light power, whereas the shot noise is proportional to only the square root of the power. However, a higher light power leads to a thermal deformation of the sensitive interferometer optics and an increasing radiation pressure noise level, resulting in a practical upper limit for the optical light power applicable[12]. Hence, further technologies must be considered to push the sensitivity beyond this limitation[4].

Squeezed states of light[14] provide a way of increasing the sensitivity in the shot-noise-limited region, independently of the circulating light power. Generally, a light field is described by two non-commuting physical quantities, the amplitude and phase quadratures. The minimum product of their uncertainties is limited by Heisenberg's uncertainty relation, which is also valid in the complete absence of photons, that is for a vacuum state. Vacuum states as well as coherent states have noise equally distributed in the field quadratures. Only squeezed states—containing quantum correlated photons—show a noise below the vacuum noise level, however, owing to Heisenberg's uncertainty relation, this is not possible for all quadratures of the state simultaneously. For a Michelson interferometer operated close to a dark output port, squeezed states can be used by injecting them into the observatory's signal output port and spatially overlapping them with the high power laser field at the beam splitter[3]. The squeezed quadrature has to be controlled such that, after being reflected off the interferometer, it is in phase with the readout (amplitude) quadrature of the observatory output light. This scheme produces path entanglement between the high-power light fields in the interferometer arms and reduces the photon counting noise on the photo diode in a way that can be explained only by photon correlations that are stronger than any classical correlation[4].

Since the first observation of squeezed light in 1985 (ref. 15), squeezed-light sources have constantly been improved, recently reaching a factor of almost 13 dB below shot-noise power[16]. At frequencies in the GW detection band, the generation of squeezing remained an unsolved problem for a long time. Only recently, squeezing at Fourier frequencies in the audio band[17,18]

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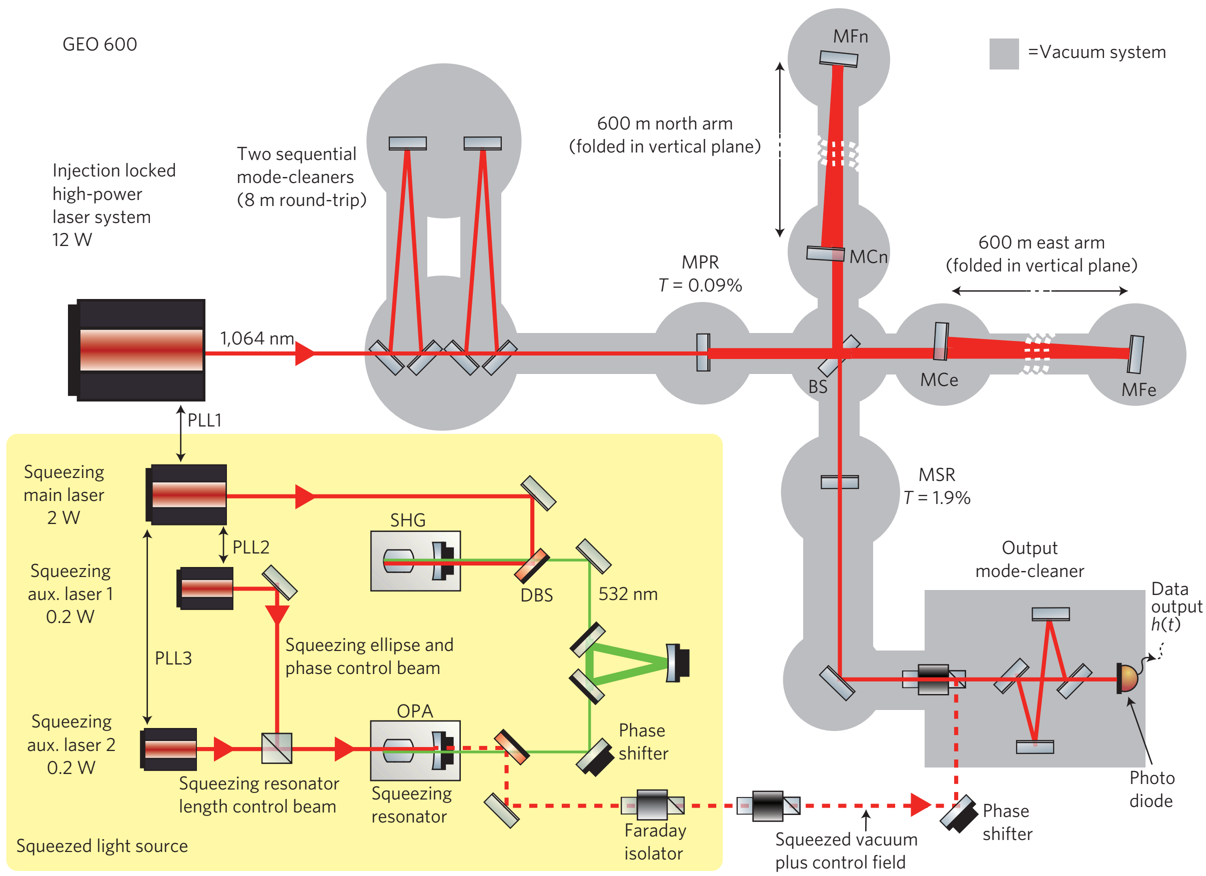

Figure 1 | Simplified optical layout of the squeezed-light enhanced GEO 600 observatory. The observatory consists of the conventional GEO 600 and the additional squeezed-light source (yellow box, see Methods summary for details). The observatory has two singly folded arms with a total optical length of 2,400 m. A GW passing from most directions will shorten one arm, while the length of the perpendicularly orientated arm is increased, and vice versa in the next half-cycle of a passing wave, producing a periodic power change of the output light that is detected by a photo diode. The observatory is operated such that almost all the light is back-reflected towards the 12 W input laser system, by keeping the interferometer output on a dark fringe by means of a control system. A power-recycling mirror (MPR) leads to a resonant enhancement of the circulating light power of 2.7 kW at the beamsplitter. Similar to the power-recycling technique, a partially transmissive signal-recycling mirror (MSR) is installed to further resonantly enhance the GW-induced signal at the interferometer's output. BS: 50/50 beamsplitter, SHG: second harmonic generator, OPA: optical parametric amplifier, DBS: dichroic beamsplitter, PLL: phase locking loop, MFe/MFn: far interferometer end mirrors (east/north), MCe/MCn : central interferometer mirrors, *T*: mirror transmissivity. All interferometer optics are suspended by multi-stage pendulums and situated in a vacuum system.

and a coherent phase control scheme for squeezed vacuum states could be demonstrated[19]. In parallel, proof-of-principle experiments at higher frequencies have shown that small-scale sensitivities of Michelson interferometers can indeed be improved by squeezing[20,21]. Even though squeezed states are an ingredient for a multiplicity of quantum techniques such as quantum teleportation[22], quantum memories[23] and many more, all of them are yet to mature from a proof-of-principle stage into a practical application. The increase of the GEO 600 sensitivity below its shot-noise limit by non-classical means is indeed the first practical application of this quantum technology, with the potential to become an integral part for all future generations of laser-interferometric gravitational wave observatories.

The German–British GEO 600 facility is one of the large-scale Michelson interferometers searching for gravitational wave signals. GEO 600 already uses a number of so-called advanced techniques, which are foreseen to be implemented in future upgrades of LIGO or Virgo[24]. Figure 1 shows a simplified layout of GEO 600. The first steps of the ongoing GEO high-frequency (HF) upgrade program have already been included[25]: GEO 600 is now operated in a tuned (to resonance with the laser carrier) signal-recycling mode with an optical homodyne detection scheme, also called *DC readout*[26,27]. Moreover, the carrier light transmitted by the signal-recycling mirror is filtered with an output mode cleaner cavity (OMC; ref. 26), which suppresses technical modulation sidebands at radiofrequencies, as well as spurious light modes originating from mirror imperfections. Both filter effects assure that the detected beam is not contaminated with additional technical or quantum noise.

The lower left part of Fig. 1 shows a simplified schematic of the squeezed-light source which has been added in this work. The squeezed states of light are produced by parametric down-conversion inside an optical resonator, which contains periodically poled potassium titanyl phosphate (PPKTP) and which is pumped with single-mode continuous-wave light at 532 nm. The squeezed-light beam is phase locked to the 12 W GEO 600 laser and comprises squeezed vacuum states at frequencies from 10 Hz to above 10 kHz and a MHz control field for stabilization of the squeezed quadrature with respect to the GW signal[28]. More details are given in the Methods summary. A view into the GEO 600 central building, showing the squeezed-light source and the parts of the vacuum system, is presented in Fig. 2.

Figure 3 presents the result achieved by this work: the quantum technology enhancement of an operating gravitational wave observatory. The injection of squeezed vacuum states into GEO 600 leads to a broadband noise reduction of up to 3.5 dB (black to red

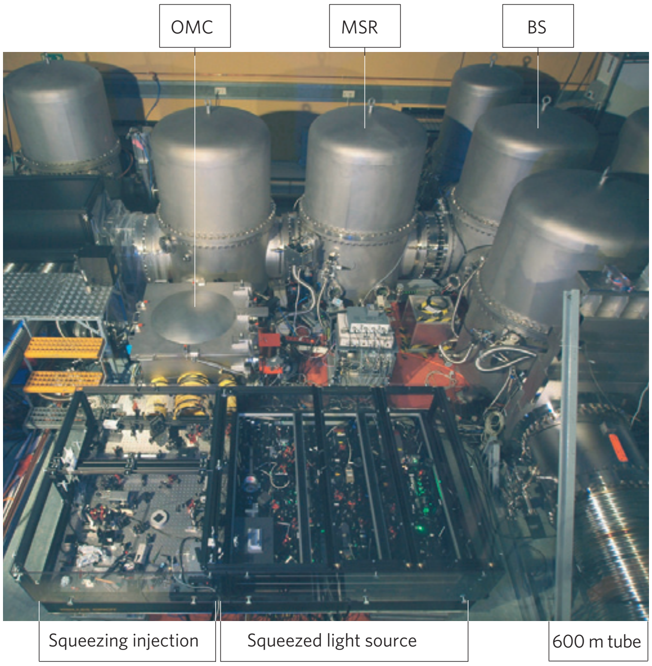

Figure 2 | View into the GEO 600 central building. In the front, the squeezing bench containing the squeezed-light source and the squeezing injection path is shown. The optical table is surrounded by several vacuum chambers containing suspended interferometer optics.

trace) in the shot-noise-limited frequency band (above 700 Hz). The quantum noise at 3 kHz was reduced from 1.0×10^{-21} Hz$^{-1/2}$ down to 6.7×10^{-22} Hz$^{-1/2}$. This corresponds to a factor $1.5^3\approx3.4$ increase in detection rate for isotropically distributed GW sources in that frequency band. The squeezing enhancement has been successfully operated for several consecutive hours just limited by the present performance of the beam alignment. We see no limits in principle to the quasi-continuous application of squeezed light, which is already planned for the next observational run of GEO 600. Owing to the application of squeezed light the GW observatory GEO 600 has now achieved its best ever sensitivity since the implementation of the advanced homodyne detection scheme. As expected, at Fourier frequencies below 700 Hz, squeezed light neither reduces nor increases the present displacement noise level of about 10^{-18} m Hz$^{-1/2}$. This observation makes us confident that a squeezed-light improvement will extend to these frequencies as soon as the present limiting technical noise is reduced. Note, that quantum radiation pressure noise[29] is not expected to be significant at these frequencies at the present sensitivity.

The measured nonclassical quantum noise reduction in GEO 600 presented here is not limited by the squeezed-light laser but by optical loss on the squeezed light during propagation in the interferometer. The 10 dB injected squeezed state is degraded by photon absorption and scattering inside the GEO 600 signal recycling cavity and the output mode-cleaner, both contributing about 10% loss. Furthermore, the non-perfect photo diode quantum-efficiency, the absorption of the Faraday isolators and auxiliary optics, and finally some residual mode mismatch cause a further 20% loss. All losses have been verified by independent measurements and provide an overall optical efficiency of $\eta=0.62$. This leads to an increase of the squeezed noise variance from $V_{sqz}=0.1$ to $\eta V_{sqz}+(1-\eta)=0.44$, and to a corresponding attenuation of the squeezing factor from 10 dB to 3.5 dB, being in excellent agreement with our results shown in Fig. 3. Based on this, we are confident that future optical loss reductions will result in a correspondingly higher

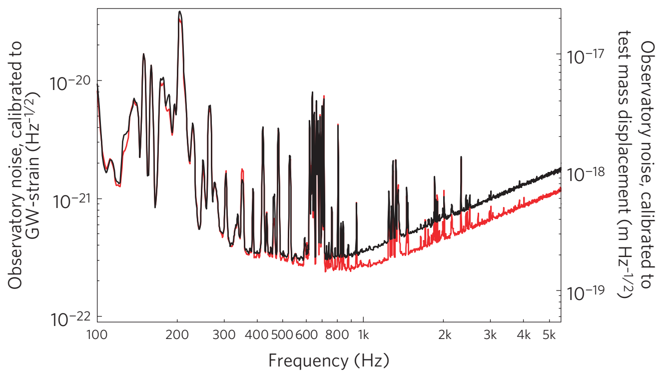

Figure 3 | Nonclassical reduction of the GEO 600 instrumental noise using squeezed vacuum states of light. The noise is calibrated to GW-strain and differential mirror displacement, respectively. In black the observatory noise spectral density is shown without the injection of squeezed light. At frequencies above 700 Hz GEO 600 is limited by shot noise; note that the slope in the kHz-regime is due to the normalization and the frequency-dependent signal enhancement of GEO 600. An injection of squeezed vacuum states into the interferometer leads to a broadband noise reduction of up to 3.5 dB (red trace) in the shot-noise-limited frequency band. The spectral features are caused by excited violin modes of the suspensions (600–700 Hz and harmonics) as well as by calibration (160–2.5 kHz) and OMC alignment control (250–550 Hz) lines. The broad unresolved noise structures from about 120–220 Hz are caused by insufficient seismic isolation of mirrors located between the signal recycling mirror and the output mode cleaner. Both traces shown were averaged over 4 min. The resolution bandwidth is 1 Hz for frequencies below 1 kHz, and 2 Hz at higher frequencies. Note that the noise reduction is independent of the averaging time used, such that the search for all kinds of potential GW sources (short- or long-duration) benefits from the improvement.

squeezing factor. During the GEO-HF upgrade program in 2011 we expect a sensitivity improvement of up to 6 dB to be realized with squeezed-light input. An even stronger impact through the application of squeezed light can be foreseen in future gravitational wave observatories, where state-of-the-art optical technologies will allow for lower optical losses.

The results presented here show that squeezed light can improve operating gravitational wave observatories. We point out that squeezed light is also highly compatible with any future thermal noise reduction by means of cryogenic cooling of observatories[4], as in contrast to increasing the laser power, increasing the squeezing factor does not increase the thermal load on the mirrors. We therefore expect this innovative approach to become a key technology in making gravitational wave astronomy a reality, and we believe that squeezed-light lasers, in addition to high-power lasers, are likely to be integrated into all future gravitational wave observatories.

Method summary

Altogether four different laser frequencies are involved in the generation and coherent control of the squeezed vacuum states, see Fig. 1. The main 2 W laser, which is phase locked to the 12 W GEO 600 laser, drives a second-harmonic generator (SHG). The green light from the SHG is filtered using a ring-resonator to attenuate high-frequency phase noise[30]. The frequency up-converted field is subsequently injected into the squeezing resonator containing a nonlinear medium (PPKTP) placed in a standing-wave half-monolithic cavity. Only 35 mW of the frequency-doubled field are required to generate about 9 dB squeezing down to 10 Hz (ref. 28), via the process of parametric down-conversion (optical parametric amplification). To avoid any contamination of the squeezed light by laser noise in the audio band, two auxiliary lasers, frequency-shifted by several MHz, are employed for coherent control of the squeezed vacuum states[19,28]. Squeezing at Fourier frequencies in the audio band has been shown to be very sensitive to light backscattered into the squeezing resonator (refs 17–19). Therefore, the squeezed beam is guided through two Faraday isolator units before it is injected into the signal port of GEO 600.

Received 11 May 2011; accepted 3 August 2011; published online 11 September 2011

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Acknowledgements

The authors gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory and the Science and Technology Facilities Council of the United Kingdom, the Max Planck Society, the Deutsche Forschungsgemeinschaft, the cluster of excellence QUEST (Centre for Quantum Engineering and Space-Time Research), the BMBF, the Volkswagen Foundation, and the State of Niedersachsen/Germany for support of the construction and operation of the GEO 600 detector. The authors also gratefully acknowledge the support of the research by these agencies and by the International Max Planck Research School (IMPRS), the SFB TR7, the FP7 project Q-ESSENCE, the Australian Research Council, the Council of Scientific and Industrial Research of India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Educación y Ciencia, the Conselleria d'Economia, Hisenda i Innovació of the Govern de les Illes Balears, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, The National Aeronautics and Space Administration, the Carnegie Trust, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the A. P. Sloan Foundation.

Author contributions

The activities of the LIGO Scientific Collaboration (LSC) cover modelling astrophysical sources of gravitational waves, setting sensitivity requirements of observatories, designing, building and running observatories and researching new techniques to increase the sensitivity of these observatories, and performing searches for astrophysical signals contained in the data. The principal investigators of the advancement reported here are H.G. and R.S., being responsible for GEO 600 and for the squeezed-light laser during the past 3 years, in which this experiment was prepared and conducted, respectively. In this period a great number of the LSC members contributed directly to the success of this project. H.V. and H.G. supervised the integration of the squeezed-light laser into GEO 600. Together with A.K., they took and analysed the data shown. The initial manuscript was written by a team involving those mentioned above together with R.S. The manuscript went into a two-stage LSC-wide review process, which was organized and led by R.F., T.R.C., M.H., and D.Sigg. All authors approved the final version of the manuscript.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturephysics. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.S.