Quantum Enhancement of the Zero-Area Sagnac Interferometer Topology for Gravitational Wave Detection

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Only a few years ago, it was realized that the zero-area Sagnac interferometer topology is able to perform quantum nondemolition measurements of position changes of a mechanical oscillator. Here, we experimentally show that such an interferometer can also be efficiently enhanced by squeezed light. We achieved a nonclassical sensitivity improvement of up to 8.2 dB, limited by optical loss inside our interferometer. Measurements performed directly on our squeezed-light laser output revealed squeezing of 12.7 dB. We show that the sensitivity of a squeezed-light enhanced Sagnac interferometer can surpass the standard quantum limit for a broad spectrum of signal frequencies without the need for filter cavities as required for Michelson interferometers. The Sagnac topology is therefore a powerful option for future gravitational-wave detectors, such as the Einstein Telescope, whose design is currently being studied.

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All currently operating interferometric gravitational-wave (GW) detectors (LIGO [1], VIRGO [2], GEO [3], and TAMA [4]) are Michelson interferometers. Their purpose is to measure the position changes (displacements) of quasi-free-falling mirrors thereby revealing changes of space-time curvature, i.e., gravitational waves. The current detectors are aiming for the first direct observation of gravitational waves. Future detectors will aim for establishing gravitational-wave astronomy which will require a considerable increase of the detectors' displacement sensitivity. The Einstein Telescope [5] is an ongoing European design study project for such a gravitational-wave detector. An important issue for future detectors is a reduction of the quantum measurement noise (photon shot noise) and quantum backaction noise (quantum fluctuations in the radiation pressure acting on the mirrors) for a given laser power. This way, the standard quantum limit (SQL) can eventually be surpassed allowing for quantum-nondemolition displacement measurements. Future detectors will most likely be operated at cryogenic temperatures in order to reduce thermally excited motions of the mirror surfaces, and optical absorption will set an upper limit to the laser power inside the interferometer. For Michelson interferometers a nonclassical reduction (squeezing) of the quantum measurement noise can be achieved by injecting squeezed light [6–9]. Squeezing of backaction noise is also possible but turned out to be experimentally challenging because in Michelson interferometers the backaction noise depends on Fourier frequency. Long-baseline narrow band filter cavities are required to compensate for the frequency dependence [10] which complicates the topology and introduces additional optical loss.

The Sagnac interferometer was originally invented by Sagnac in 1913 [11] and can be used as a rotation sensor. However, the Sagnac interferometer is also sensitive to displacements of its mirrors if the latter are not located at half the round-trip length. By setting the area that is enclosed by the two counterpropagating beams to zero, the interferometer can be made insensitive to rotations though keeping it sensitive for displacements. The first experimental tests of zero-area Sagnac interferometers for gravitational-wave detection were performed in the late 1990s [12,13]. No advantage in comparison with the Michelson interferometer could be found. But in 2003, Chen [14] realized that a zero-area Sagnac interferometer, by its very nature, can suppress the quantum backaction noise for displacement measurements over a broad frequency band. Since then the Sagnac topology for gravitational-wave detection has not been further experimentally investigated. It has also not been theoretically investigated whether or not the Sagnac interferometer's quantum-nondemolition property is compatible with squeezing of its quantum measurement noise.

In this Letter, we experimentally demonstrate that a Sagnac interferometer can be efficiently enhanced by the injection of squeezed light. We achieved, to the best of our knowledge, the strongest squeezing of quantum measurement noise in an interferometric device ever observed. We also present a theoretical analysis of how much the sensitivity of a possible design of the Einstein Telescope can surpass the standard quantum limit when realistic values for the squeezing factor and detection loss apply.

Figure 1 shows the schematic of our experiment. The Sagnac interferometer had a round-trip length of 50 cm and

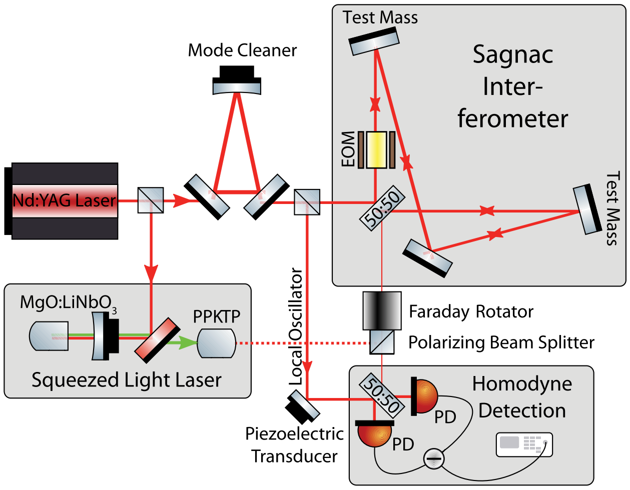

FIG. 1 (color online). Schematic of the experiment. A continuous-wave laser beam at 1064 nm was used to produce squeezed light, operate a zero-area Sagnac interferometer, and perform the interferometer readout with balanced homodyne detection. The squeezed field was injected into the interferometer through its dark port by means of a polarizing beam splitter and a Faraday rotator.

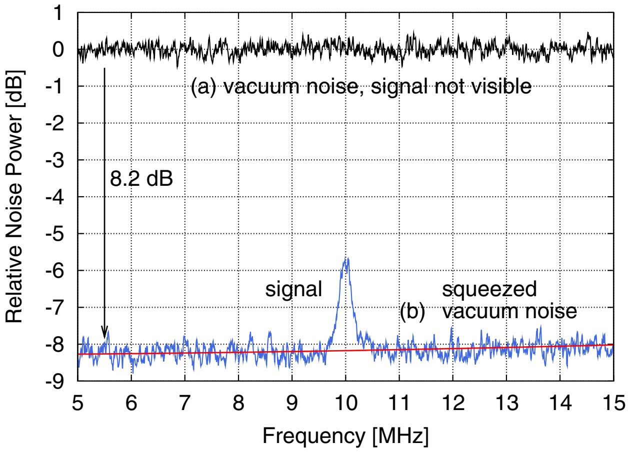

FIG. 2 (color online). 10 MHz phase modulation measured with the Sagnac interferometer without [trace (*a*)] and with [trace (*b*)] squeezed-light input. Trace (*a*) corresponds to the vacuum noise, is normalized to unity, and completely buries the signal. Both traces are averaged twice, each measured with a resolution bandwidth of 300 kHz and a video bandwidth of 300 Hz. The homodyne detector dark noise was 22–25 dB below the vacuum noise and was subtracted from the data. The solid line shows a model for the squeezing strength fitted to the data.

was set up such that it was insensitive to rotations, i.e., with an effective zero area. A continuous-wave laser beam at a wavelength of 1064 nm was used to generate squeezed light, and also provided the carrier field of the Sagnac interferometer and the local oscillator of the balanced homodyne detector. An electro-optical phase modulator (EOM) was placed in one interferometer arm right after the beam splitter in order to generate an optical displacement signal similar to that of a gravitational wave.

Into the second port of the Sagnac interferometer we injected a squeezed mode of light, precisely mode-matched to the interferometer mode. The interferometer signal and the squeezed quantum noise were detected by balanced homodyne detection by means of a pair of high quantum efficiency InGaAs photodiodes. The squeezed light was produced by parametric down-conversion in periodically poled potassium titanyl phosphate (PPKTP). The end faces of the 8.9 mm-long biconvex crystal were dielectrically coated in order to form a monolithic cavity. One surface was highly reflecting for both laser wavelengths involved, the fundamental at 1064 nm and the pump at 532 nm. The second surface had a reflectivity of $R = 90\%$ for the fundamental and $R = 20\%$ for the pump field. To achieve phase matching the crystal was temperature controlled to 37.8 °C. The required pump beam for the parametric process was generated by second-harmonic generation in 7% magnesium-doped lithium niobate.

Figure 2 shows the squeezing of quantum measurement noise in our zero-area Sagnac interferometer. The upper trace (*a*) corresponds to the vacuum fluctuations entering the interferometer through its signal port when the squeezed light was blocked, and was normalized to unity. The lower trace (*b*) shows the noise floor when squeezed light was injected into the interferometer's signal port. The nonclassical noise reduction was 8.2 dB. For both traces a 10 MHz signal was applied using the electro-optical modulator inside the interferometer. In the case of trace (*a*) this signal is not visible; however, it is clearly detected in trace (*b*). The light power circulating in the Sagnac interferometer was 570 μW. The contrast of the interferometer was measured to $\mathcal{C} = 99.7\%$. The visibility at the Sagnac interferometer's beam splitter for the injection of squeezed light was 99.8%, and the visibility at the homodyne detectors' beam splitter was 99.7%. The local oscillator power was 20 mW, and the green pump power was 80 mW.

Figure 3 characterizes the squeezed-light laser output without the optical loss introduced by the Sagnac interferometer. Trace (*a*) shows the vacuum noise measured with the squeezed light blocked. Traces (*b*) and (*c*) represent the noise in the squeezed and antisqueezed quadrature, respectively. We observed 12.7 dB of squeezing and 19.9 dB of antisqueezing. To the best of our knowledge the squeezing factor of 12.7 dB represents the highest value ever observed. Previously, squeezing factors above 10 were observed in Refs. [15,16]. The squeezed (s) and antisqueezed (as) quadrature variances observed in Figs. 2 and 3 can be described by the following equation [17]

$$V_{s,as} = 1 \pm \eta\gamma \frac{4\sqrt{P_{532}/P_{\mathrm{th}}}}{(1 \mp \sqrt{P_{532}/P_{\mathrm{th}}})^2 + 4K(f)^2}, \tag{1}$$

where the total optical loss is described by the detection efficiency η and the nonlinear cavity escape efficiency γ. P_{532} is the parametric pump power, P_{th} the threshold power, and $K(f) = 2\pi f/\kappa$ the ratio between the Fourier frequency f and the cavity decay rate κ. The decay rate is

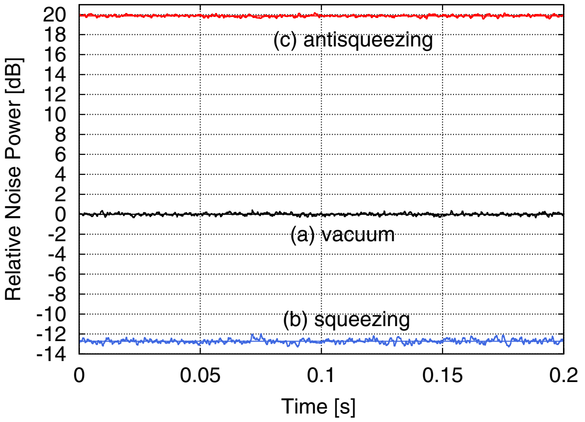

FIG. 3 (color online). Characterization of our squeezed-light laser at a sideband frequency of 5 MHz. All traces are normalized to the vacuum-noise reference of the homodyne detector's local oscillator beam (*a*). Trace (*b*) shows the noise in the squeezed field quadrature; trace (*c*) shows the antisqueezing in the orthogonal quadrature. Detector dark noise is at −25 dB and, here, *not* subtracted from the data.

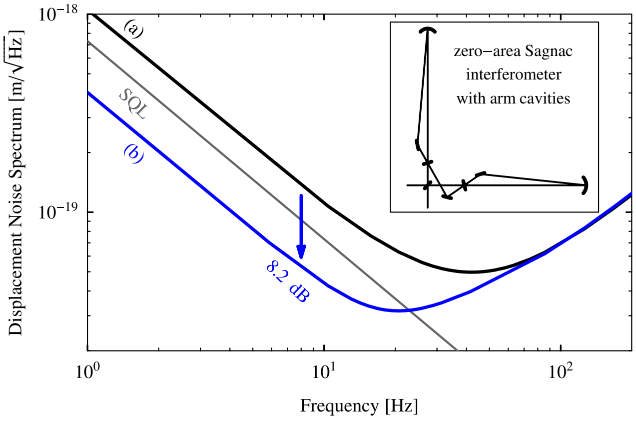

FIG. 4 (color online). Total quantum noise for a displacement measurement of a zero-area Sagnac interferometer with (lower trace) and without (upper trace) squeezed-light injection. Our model assumes optical losses to the squeezed light of 9% in total, keeping 8.2 dB of detected squeezing similar to our experiment. The model is further based upon 40 kg test mass mirrors and arm cavities of 10 km length, 80 Hz linewidth, and 10 kW intracavity power. Dividing the linear noise spectral density on the Y axis by 10 km yields the noise spectral density for a gravitational-wave strain measurement.

defined by $\kappa = (T + L)c/(nl)$ with output coupler transmission $T = 0.1$, the intracavity loss L, the speed of light in vacuum c, the refractive index of PPKTP $n = 1.83$, and the round-trip length $l = 2 \times 8.9$ mm. All the variances observed can consistently be described by setting $P_{532}/P_{\rm th} = 2/3$ and $L = 3.56 \times 10^{-3}$ in Eq. (1). For the measurements in Fig. 2 we deduce a total optical loss of 14% ($\eta\gamma = 0.86$). For the squeezed-light characterization in Fig. 3 we deduce a value of 4.5% ($\eta\gamma = 0.955$) which also accounts for about 1% loss of our nonperfect photodiodes. The loss of about 10% introduced by the Sagnac interferometer was in good agreement with independent loss measurements. First of all, the squeezed light was passed twice through a Faraday rotator (Fig. 1) which introduced optical loss of about 4%. About 1% of the light was transmitted through the Sagnac interferometer because its central beam splitter deviated from its optimum 50:50 splitting ratio. About 1.5% loss was due to the transmission through the EOM crystal and the imperfect antireflection coating of the second beam splitter surface. And finally each of the three interferometer mirrors transmitted about 1% because their high-reflectivity coatings were not optimized for the angles of incidence applied.

Figure 4 presents the calculated quantum noise spectral densities of a 10 km Sagnac GW detector. Traces (*a*) and (*b*) represent the quantum noise without and with squeezed-light enhancement, respectively. The topology of our simulated Sagnac GW detector is almost identical to the one in our experiment and is shown in the inset of Fig. 4. The only difference is that our simulation used two 10 km-long ring resonators. These arm resonators increase the light's storage time and are oriented perpendicular to each other, and thereby optimize the Sagnac interferometer's sensitivity to the frequency band between 1 Hz and about 40 Hz, which is of high astrophysical interest [18]. The squeezing effect at these frequencies is in complete analogy to the one in our experiment. Squeezing down to 1 Hz was demonstrated in [19]. We note that in Fig. 4 the noise spectral density does increase towards lower frequencies not because of remaining backaction noise but due to the decreasing signal transfer function of the Sagnac interferometer at lower frequencies [12]. The topology plotted in the inset slightly differs from the one previously proposed in Ref. [14] in order to keep the effective area of the Sagnac interferometer perfectly zero, thereby avoiding noise couplings from the Sagnac effect [20]. Note that our topology is still rather simple and does not include a signal-recycling resonator [21]. Additionally, a power-recycling resonator [22] is not required if high input powers are readily available from an ultrastable laser source [23]. But most importantly, our squeezed-light enhanced zero-area Sagnac interferometer does not require filter cavities in order to gain a broadband sensitivity improvement.

The quantum noise spectra in Figs. 4(a) and 4(b) are calculated for 40 kg test mass mirrors and a laser power of 90 W at the central beam splitter. The arm resonators have a linewidth of 80 Hz and store a circulating power of 10 kW. For the squeezed-light generation, injection, and detection [trace (*b*)] we assume optical losses similar to those in our experiment, i.e., 3% loss inside the crystal of the squeezed-light laser (an escape efficiency of 97%), 1% loss due to propagation and nonperfect mode-matching, 2% loss per passage through the Faraday rotator, and 1% photodiode inefficiency. We further assume that the loss inside the interferometer is not significant, which should be achievable by optimizing the dielectric coatings of the interferometer mirrors. The total admixture of the vacuum state to the initially pure squeezed state therefore is 9%, and the total optical loss to the signal is 3%. In order to achieve the detected squeezing factor of 8.2 dB, we use an initially pure squeezed state of 12.4 dB, which is actually lower than in our experiment. Consequently, the antisqueezing inside the interferometer is also smaller, just 12.1 dB. For the interferometer readout we used a balanced homodyne detector as in our experiment. The phase angle between interferometer signal field and local oscillator was set to 13.7°. For this detection angle a perfect cancellation of backaction noise inside the arm cavity linewidth is achieved. At higher frequencies backaction is overcompensated. However, our interferometer parameters provide an unchanged noise floor. The SQL in Fig. 4 is not beaten without the injection of squeezed light because of the high linewidths of the arm cavities and the relatively low laser power applied. A low laser power is important in order to ease the cryogenic operation of the mirrors. We note that the quantum noise spectrum in trace (*b*) can be modified on-line, i.e., during the operation of the interferometer. By changing the phase angle of the balanced homodyne detector, the overall quantum enhancement can even be extended to the frequencies above the half-linewidth of the arm cavities; however, in this case the quantum enhancement at low frequencies reduces accordingly.

In conclusion, we have experimentally shown that a nonclassical reduction of quantum measurement noise in a Sagnac interferometer is possible with squeezed-light injection and balanced homodyne readout. The balanced homodyne detector was an essential part of the experiment since it allowed the optimization of the detected quadrature angle. Our theoretical analysis has shown that squeezed-light input and balanced homodyne detection readout is highly compatible with the Sagnac interferometer's intrinsic backaction evading property. Both types of quantum enhancement are essential for future gravitational-wave detectors, in particular, for the detection of signals in the astrophysically interesting band from 1 to 40 Hz covering more than five octaves. We therefore have considered a zero-area Sagnac interferometer with 10 km-long arm cavities targeting this band. We have found that in this signal band a perfect and broadband evasion of backaction noise together with a broadband nonclassical shot-noise reduction is possible if a certain balanced homodyne detection angle is applied. No filter cavities are required. The latter are mandatory in a Michelson interferometer, where not only the backaction noise depends on Fourier frequency, but the antisqueezing of the injected squeezed light also rapidly increases the backaction noise [10]. The factor by which the standard quantum limit is surpassed only depends on the (frequency independent) squeezing factor achieved. Low mass mirrors and low laser powers can be used in order to achieve a quantum noise spectral density of the order of 3×10^{-24} $\mathrm{Hz}^{-1/2}$. Both low masses and low powers are valuable to reduce thermal noise and enable the cryogenic operation of laser interferometers. A quantum-enhanced zero-area Sagnac interferometer is therefore a very suitable candidate for the low-frequency part of a future gravitational-wave observatory.

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[1] B. Abbott *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **517**, 154 (2004).

[2] F. Acernes *et al.*, Classical Quantum Gravity **19**, 1421 (2002).

[3] B. Willke *et al.*, Classical Quantum Gravity **19**, 1377 (2002).

[4] M. Ando *et al.* (TAMA Collaboration), Phys. Rev. Lett. **86**, 3950 (2001).

[5] M. Punturo *et al.*, Classical Quantum Gravity **27**, 084007 (2010); http://www.et-gw.eu.

[6] C. M. Caves, Phys. Rev. D **23**, 1693 (1981).

[7] K. McKenzie, D. A. Shaddock, and D. E. McClelland, Phys. Rev. Lett. **88**, 231102 (2002).

[8] H. Vahlbruch, S. Chelkowski, B. Hage, A. Franzen, K. Danzmann, and R. Schnabel, Phys. Rev. Lett. **95**, 211102 (2005).

[9] K. Goda *et al.*, Nature Phys. **4**, 472 (2008).

[10] H. J. Kimble *et al.*, Phys. Rev. D **65**, 022002 (2001).

[11] G. Sagnac, C.R. Hebd. Seances Acad. Sci. **157**, 708 (1913).

[12] K.-X. Sun, M. M. Fejer, E. Gustafson, and R. L. Byer, Phys. Rev. Lett. **76**, 3053 (1996).

[13] D. A. Shaddock, M. B. Gray, and D. E. McClelland, Appl. Opt. **37**, 7995 (1998).

[14] Y. Chen, Phys. Rev. D **67**, 122004 (2003).

[15] H. Vahlbruch *et al.*, Phys. Rev. Lett. **100**, 033602 (2008).

[16] M. Mehmet, H. Vahlbruch, N. Lastzka, K. Danzmann, and R. Schnabel, Phys. Rev. A **81**, 013814 (2010).

[17] Y. Takeno, M. Yukawa, H. Yonezawa, and A. Furusawa, Opt. Express **15**, 4321 (2007).

[18] K. A. Postnov and L. R. Yungelson, Living Rev. Relativity **9**, 6 (2006).

[19] H. Vahlbruch, S. Chelkowski, K. Danzmann, and R. Schnabel, New J. Phys. **9**, 371 (2007).

[20] A. Freise *et al.*, Classical Quantum Gravity **26**, 085012 (2009).

[21] B. J. Meers, Phys. Rev. D **38**, 2317 (1988).

[22] R. W. P. Drever *et al.*, in *Quantum Optics, Experimental Gravitation, and Measurement Theory*, edited by P. Meystre and M. O. Scully (Plenum, New York, 1983), pp. 503–514.

[23] M. Frede *et al.*, Opt. Express **13**, 7516 (2005).