Quantum-enhanced correlated interferometry for fundamental physics tests

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Improvements in measurement precision have historically led to new scientific discoveries, with gravitational wave detection being a recent prime example. The research field of quantum metrology deals with improving the resolution of instruments that are otherwise limited by quantum shot-noise. Quantum metrology is therefore a promising avenue for enabling scientific breakthroughs. Here we present the first feasibility tests of quantum-enhanced correlated interferometry, which outperforms the sensitivity of a single interferometer in revealing faint stochastic noise by several orders of magnitude. Using quantum-enhanced correlation techniques we detected an injected signal, invisible to the single interferometer, reaching a sensitivity of $3 \times 10^{-17} \text{m}/\sqrt{\text{Hz}}$ (1/20 of the shot-noise) at 13.5 MHz in a few seconds of integration time. By injecting bipartite quantum correlated states into the interferometers we also demonstrated a noise reduction in the subtraction of the interferometer outputs. The experimental techniques employed here could potentially be applied to solve open questions in fundamental physics, such as the detection of the stochastic gravitational wave background or primordial black holes, or to test the predictions of particular Planck scale theories.

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The recent detection of gravitational waves [1, 2] demonstrated that a major improvement of the precision of measuring devices can help unveil fundamental properties of nature. Quantum metrology is a sub-field of quantum physics which deals with improving measurement sensitivity beyond the quantum limit, by exploiting the properties of quantum systems [3–6]. This improvement is generally achieved by making use of quantum correlations, for example from the presence of entanglement.

Quantum metrology has already been used to enhance the performance of interferometers [7–14], improve phase estimation [15] and super-resolution [16–18], surpass the shot-noise limit in imaging [19, 20] and absorption measurements [21, 22]. As a remarkable example, squeezed light has been applied to enhance the sensitivity of large scale interferometers for gravitational wave detection, such as GEO 600 [23] and LIGO [24].

It is indeed of interest for the whole physics community to investigate the advantage that this discipline could produce when applied to the most advanced devices devoted to fundamental research. One of the trends in modern physics is the search and study of omnipresent stochastic sources of noise, like the cosmic microwave background [25] and the hypothetical cosmic neutrino background [26]. Optical interferometers represent the best sensing methodology proposed for a range of predicted fundamental backgrounds, like the gravitational wave background [27, 28] that could reveal information on the first few moments of the universe, or traces of primordial black holes [29, 30]. In particular, these sources of noise can produce correlated phase fluctuations in two separated interferometers increasing the chance of distinguishing them with respect to other noise sources. Indeed, double interferometric setups are currently employed in these ultimate researches [31–33].

A double interferometer configuration is for instance the basis of the Fermilab “holometer” [33–35], a device consisting of two co-located 40 m Michelson interferometers (MIs). The purpose of the holometer is to search for a particular type of correlated background noise, conjectured in some euristic Planck scale theories and dubbed holographic noise [35]. If confirmed, it would provide empirical support to theories attempting to unify quantum mechanics and gravitation. At the moment the holometer is operated with classical light only.

In this letter we present two experiments demonstrating a significant quantum-enhancement of an optical bench interferometric system with the design of the Fermilab holometer. The first experiment uses two independent squeezed vacuum states, injected into the antisymmetric ports of the two MIs. The second experiment uses twin beam-like correlations, obtained by injecting the two modes of the quantum correlated bipartite state into the antisymmetric ports of the two MIs. Previous theoretical analysis [36, 37] has shown that both configurations can provide significant sensitivity improvement in the phase noise comparison between the two interferometers. The first scheme is of simpler implementation and presents advantage even with relatively low detection efficiency. The second approach, in the perspective of reaching very high quantum efficiency and perfect control of the dark
fringe stability, leads in principle to a disruptive advantage. This sensitivity boost has also been demonstrated to be robust against decoherence [38].

The results reported here, demonstrating the quantum advantage in correlated interferometry, represent one of the few quantum-enhanced schemes that can find immediate applications.

The experimental setup

A simplified schematic of the experiment is shown in Fig. 1. A similar configuration is also used in large scale experiments, such as LIGO [24] and the Fermilab holometer [35], however, the latter without the injection of quantum states. Each interferometer consisted of two piezo actuated end mirrors, a balanced beam splitter, and a power recycling mirror. The relative phase of the independent interferometer arms was chosen such that each read-out port was close to the dark fringe and most of the power in the interferometer was recycled [39]. The interferometer fringe position was chosen such that the output power was 500 µW. The √P scaling of the shot-noise power spectral density at 13.5 MHz was verified by increasing the input power in the interferometer (see Methods).

The squeezed-light sources were based on parametric down-conversion in a potassium titanyl phosphate crystal placed in semi-monolithic linear cavities (see Methods). The squeezed light was injected in the two MIs via their antisymmetric (read-out) ports. The read-out signals were separated from the squeezed modes by means of optical isolators. The amount of squeezing before injection into the interferometers was measured on a homodyne detector for both sources to be -6.5 dB relative to the shot noise level (SNL).

The experiment was performed in two different configurations, as shown in Fig. 1.

(i) Independent squeezed states. Two independent squeezed states were injected into the interferometers’ antisymmetric ports.

A faint correlated phase noise source acting in both the MIs can emerge by calculating the cross-correlation of their outputs in the time domain, or the cross-spectrum in the frequency domain, even if in a single interferometer the signal is completely hidden by the shot-noise. The use of quantum light, providing a reduction of the photon noise in each interferometer, also leads to a significant enhancement in the cross-correlation measurement [36, 37].

(ii) Twin beam-like state. A single squeezed state was split on a balanced beamsplitter and the modes were injected into the antisymmetric MI ports.

This scheme produces non-classical correlations along one quadrature direction, as the one present in a proper twin beam or two-mode squeezed state. Exploiting this quantum correlation, we demonstrated a noise reduction below the SNL in the subtracted outputs of the two interferometers. The subtraction is sensitive to signals that are not correlated between the interferometers, and the obtained noise reduction allows detection of signals of smaller amplitude.

We emphasize that genuine twin beam photon-number entanglement can, in principle, offer far superior performance [36, 37], but requires efficiency and stability control yet out of reach in realistic systems.

Results and Discussion

(i) Independent squeezed states

The same stochastic signal was injected by two electro-optical modulators (EOMs) in both interferometers, with an amplitude well below the sensitivity of the single MI, approximately 1/5 of the SNL. Figure 2(a) shows the

FIG. 1: Simplified schematic of the double-interferometer setup. Two Michelson Interferometers (MI, MI2) with arm length L = 0.92 m were co-located, with a distance between the two balanced beam splitters (BSs) of around 10 cm. M: piezo-actuated high-reflectivity (99.9%) end mirrors. PRM: partially reflecting (90%) power recycling mirror, radius of curvature r = 1.5 m. X1(X2): read-out signals. A Faraday isolator in each output port allowed for measuring the read-out signals while either independent squeezed vacuum (i) or twin beam-like states (ii) were injected into the antisymmetric ports. For the (i) case the cross-correlation of the outputs is calculated, while for the (ii) case the output subtraction is the relevant quantity.

Each MI was fed with 1.5 mW of 1064 nm light from a low noise Nd:YAG laser source. The same laser source was used for squeezing generation.
cross-correlation coefficient $\rho(\tau)$ of the read-out signals in the time domain as a function of the number of samples, calculated as

$$\rho(\tau) = \frac{|\text{Cov}(X_1(t)X_2(t+\tau))|}{\sqrt{\text{Var}(X_1(t))\text{Var}(X_2(t))}},$$  \hspace{1cm} (1)

where $X_1(t)$ ($X_2(t)$) is the time series of the read-out signal of the first (second) interferometer.

The sampling rate was 500 ksamples/s and the total acquisition time was 1 s. Figure 2(a) is plotted by calculating $\rho$ for increasing subsets of the total number of samples. The correlated noise peak, which is initially hidden in background noise, is resolved for shorter integration times when squeezing is used (red traces), compared to the classical case of no squeezing (blue traces).

Figure 2(b) shows the signal-to-noise ratio (SNR) of the measurement. Each data point is calculated as the ratio between the cross correlation peak height for $\tau = 0$ and the floor level, averaging over 19 independent data sets similar to the one originating Fig. 2(a). The SNR with squeezing injected is consistently higher, by a factor of 2. Note that the SNR scales as the square root of the number of samples, i.e. with the square root of the acquisition time. Thus, a factor 2 of SNR enhancement corresponds to a reduction of 4 times in the measurement time.

In the spectral domain, correlated signals can be extracted by the cross-linear spectral density (CLSD) of the two interferometers, as shown in Fig. 3. This quantity is obtained by dividing the time series in $N_{\text{spectra}}$ bins. For each bin the cross-power spectral density is calculated as the discrete Fourier transform of the cross-correlation. The average of the $N_{\text{spectra}}$ cross-power spectral density values is then evaluated. Note that in analogy with the cross-correlation, the average reduces the contribution of the uncorrelated signals by a factor $N_{\text{spectra}}^{-1/2}$, while the correlated contribution is unaffected. To obtain the CLSD the square root of the power spectral density is calculated as the discrete Fourier transform of the cross-correlation. The average of the $N_{\text{spectra}}$ cross-power spectral density values is then evaluated. Note that in analogy with the cross-correlation, the average reduces the contribution of the uncorrelated signals by a factor $N_{\text{spectra}}^{-1/2}$, while the correlated contribution is unaffected. To obtain the CLSD the square root of the power spectral density is calculated: therefore the overall scaling of the uncorrelated contribution with the number of spectra is $N_{\text{spectra}}^{-1/4}$. For $N_{\text{spectra}}$ sufficiently high, the CLSD approaches the linear spectral density of the correlated
part of the signals.

Figure 3(a) shows the CLSD in a bandwidth of 100 kHz after down-mixing the detected signal at 13.5 MHz. The acquisition time was 20 s (10 Msamples) and the average was performed over $N_{\text{spectra}} = 1000$. The CLSDs of the solely uncorrelated photon noise are reported as thick solid lines, red with squeezing injection and blue without. They represent the sensitivity level in the detection of correlated noise, calibrated in m/$\sqrt{\text{Hz}}$ (see Methods section). This should be compared with the respective sensitivity of the single interferometer in the two cases (dashed lines). While almost a factor of 5.6 of improvement is gained by the cross-spectra statistical averaging, an additional factor of 1.35 is obtained from the injection of squeezed states.

Injecting a small stochastic signal contribution, the corresponding CLSDs (faint CLSD traces in Figure 3(a)) are almost overlapping the CLSDs of the photon noise in the coherent (classical) case, while the traces are clearly separated from the CLSD of photon noise when squeezing is applied.

Figure 3(b) shows the scaling of the CLSD average with the number of spectra. The CLSDs of the photon noise, independent in the two interferometers, scale as $N_{\text{spectra}}^{-1/4}$ as expected. When a correlated stochastic signal is injected, the CLSD reaches a plateau determined by the amplitude of the signal. The maximum absolute sensitivity achieved with independent squeezed states is measured to be $3 \times 10^{-17}$ m/$\sqrt{\text{Hz}}$, corresponding to 1/20 of the SNL. This number also represents a limit to the magnitude of correlated noise (e.g. holographic noise) in this frequency band.

(ii) Twin beam-like state

With the two modes of an evenly split squeezed beam injected into the MIs antisymmetric ports, the non-classical quadrature correlation is expected to provide a noise reduction in the read-out signal subtraction. Any phase difference between the two MIs produces a change in the relative photo-currents which is detected with sub-shot-noise sensitivity.

Figure 4 shows the variance of $X_1(t) - X_2(t + \tau)$ as a function of delay $\tau$. More specifically, $\text{Var}(X_1(t) - X_2(t + \tau)) = \text{Var}(X_1) + \text{Var}(X_2) - 2 \text{Cov}(X_1(t)X_2(t + \tau))$. For $\tau = 0$ the correlation between the two modes leads to a noise reduction of 2.5 dB with respect to the SNL, represented by a dip in the variance (thick red line). When two uncorrelated stochastic signals are injected in the MIs, the dip reduces by $\sim 1$ dB, as shown by the red faint line. This must be compared with the change between classical coherent trace levels with and without signal injection (blue thick and faint line respectively), which is only $\sim 0.3$ dB. Note that for $\tau \neq 0$, the covariance of $X_1(t)$ and $X_2(t + \tau)$ is zero. Since $\text{Var}(X_1(t) - X_2(t + \tau))$ preserves some sub-shot-noise features (around 1 dB), each of the two modes is a squeezed beam affected by 50% loss induced by the beam splitter: the individual squeezing level is therefore degraded, but still present in the global state.

This enhancement is also observed in the power spectral density of the subtracted interferometer outputs, plotted in Fig. 5. This experimentally demonstrates that the presence of faint uncorrelated noise can be more easily detected by twin beam-like correlations. Conversely, correlated noise is completely suppressed by the subtraction.

Therefore, measuring the read-out signals subtraction for varying distances between the MIs, or the temporal delay, can provide an alternative way to study the coherence properties of the noise sources under investigation.

Figure 6 shows the power spectral density of $X_1(t) - X_2(t)$ for a single frequency tone applied to one of the MIs. Also in this case the quantum-enhancement is clearly visible. The power spectral density enhancements of the individual interferometers are 1.1 and 0.8 dB respectively, resulting in a collective enhancement of 2 dB in the output subtraction, facilitated by the non-classical correlation among the modes. This enhancement might be applied to identify uncorrelated noise sources, such as scattering or unwanted resonances.

Conclusion

In this work we have presented the first realization of a quantum-enhanced double interferometric system. The possible applications of such a system range from measurement of Planck scale effects, over the detection of a conjectured gravitational wave background, to finding traces of primordial black holes.

We have investigated two different approaches to quantum-enhanced interferometry, both realized by injecting quantum states into the antisymmetric ports of
FIG. 5: Power Spectral Density (PSD) of the read-out signals subtraction calculated from the read-out signals down-mixed at 13.5 MHz. Red curves refer to the twin beam-like case (ii) and blue curves to the classical coherent one. Faint lines refer to the addition of an uncorrelated stochastic noise in the two MIs.

spatially close Michelson interferometers. The first approach uses two independent squeezed states, thus being of simpler and immediate application. The latter approach uses the non-classical correlation among two modes of an evenly split squeezed state, opening the perspectives of an extremely high advantage in case of two-mode squeezing (true twin beam entanglement) injection and large detection efficiencies [30, 31]. We demonstrate clear quantum-enhancement using both approaches, though the choice of measured quantity differs. With these two experiments we show that quantum-enhancement can be exploited to improve correlated interferometry potentialities, paving the way to practical applications in fundamental research and quantum sensing.

Methods

Locking Scheme

A detailed schematic of the individual interferometer is shown in Fig. 7. Because of the power recycling mirror (PRM), a change in any individual arm length affects the interferometer power output and the cavity resonance condition at the same time. Therefore two degrees of freedom need to be controlled: rather than considering the individual arm lengths \( L_1 \) and \( L_2 \), we define the common arm length (CARM) as \((L_1 + L_2)/2\) and the differential arm length (DARM) as \(L_1 - L_2\). The CARM controls the cavity resonance, while the DARM controls the interferometer fringe position.

The CARM was locked to the cavity resonance through the Pound-Drever-Hall locking technique (PDH) [42]. A 20 MHz phase modulation was applied to the input beam by an electro optical modulator (EOM). The beam reflected from the PRM was separated from the incoming beam with a Faraday isolator and detected by a photo detector which generated an error signal by demodulating the signal at 20 MHz. This error signal was processed by a proportional-integral (PI) controller, and the output

FIG. 7: Detailed schematic of the individual interferometer. PZT: piezo-electric actuator. EOM: electro-optical modulator. HVA: high-voltage amplifier. LO: local oscillator. PD: photo-diode, InGaAs with high quantum-efficiency photodiodes (99%) and low noise (Noise Equivalent Power \(1.2 \times 10^{-11} \text{ W/}\sqrt{\text{Hz}}\)) are used at the read-out port. Beam-Focusing: set of lenses in order to have Gaussian Optical mode TEM\(_{00}\). \( \delta l_C, \delta l_D \): correction signals from the CARM and DARM lockbox respectively.
was applied to both end mirror actuators with no relative phase lag.

The DARM was locked close to the interferometer dark port using a phase modulated sideband at 7.6 MHz. The read-out signal was demodulated at 7.6 MHz and processed by a PI. The output of this PI controller was applied to the end mirrors actuators differentially (i.e. the two actuators moved exactly out of phase).

The DARM locking sideband at 7.6 MHz was generated by an EOM, positioned in one arm of the interferometer. This EOM was also used to generate single frequency tone and stochastic noise modulation from 12.3 to 13.8 MHz (extending well outside the measurement band). The stochastic noise generator had two channels and allowed producing both uncorrelated and highly correlated noise between them. These modulations acted as artificial signals for testing the system performance.

The intra-cavity power was measured using a spurious reflection from the beamsplitter. This was used to estimate the gain of the cavity, which in typical working conditions varied between 8 and 10.

**Sensitivity calibration**

The sensitivities plotted in Fig. 3 are expressed in m/√Hz. This was obtained by calibrating the strain \( \delta x \) produced by the phase modulator generating the phase noise:

\[
\delta x (m/\sqrt{Hz}) = \frac{\lambda}{2} \frac{V_{\text{rms}}}{V_p} \frac{1}{\sqrt{BW}},
\]

where \( \lambda = 1064 \text{ nm} \), \( BW \) is the measurement bandwidth, and \( V_p \) and \( V_{\text{rms}} \) are, respectively, the half-wave voltage and the input root-mean-square voltage at the phase modulator.

**Squeezing generation**

The schematic of the squeezed-light source is shown in Fig. 8. The source was based on parametric down-conversion in a potassium titanyl phosphate crystal placed in a semi-monolithic linear cavity.

The cavity was seeded with 1064 nm light to lock the cavity length, using a PDH lock, and the crystal was pumped with 70 mW of 532 nm light. The pumping gave rise to a phase dependent amplification of the seed beam. Locking this relative phase between seed and pump to the bottom of the generated gain curve, through a sideband generated error signal, the squeezing was produced in the amplitude quadrature.

**Quantum Noise Locking**

The outputs from the squeezing sources were injected from the antisymmetric port into each interferometer, according to configuration (i) or (ii). The control beams of both squeezing sources entered the interferometers with the squeezed light carrying sidebands at 37.22 MHz (36.7 MHz), see Fig. 7. These sidebands were used to lock the squeezing phase to the bright output beam of the interferometer through a piezo actuated mirror in the squeezed beam path.

**Data Acquisition**

The AC outputs of the photo detectors were demodulated at 13.5 MHz and lowpass filtered at 100 kHz. Both the two DC output signals and the two demodulated AC output signals (dubbed \( X_1 \) and \( X_2 \) in the text) were simultaneously recorded using a data acquisition card. When correlated white noise or twin beam-like light was injected, the phase between the two electrical local oscillators used for demodulation was adjusted to maximize the cross correlations.

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[1] B. P. Abbott et al. Observation of gravitational waves from a binary black hole merger. Physical Review Letters, 116(6):061102, 2016.

[2] B. P. Abbott et al. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. Physical Review Letters, 119(16):161101, 2017.

[3] Vittorio Giovannetti, Seth Lloyd, and Lorenzo Maccone. Advances in quantum metrology. Nature Photonics, 5(4):222–229, 2011.

[4] Vittorio Giovannetti, Seth Lloyd, and Lorenzo Maccone. Quantum-enhanced Measurement: Beating the Standard Quantum Limit. Science, 306:1330–1336, 2004.

[5] Stefano Olivares. High-precision innovative sensing with continuous-variable optical states. Riv. Nuovo Cimento, 41:341, 2018.

[6] Gerardo Adesso, Thomas R. Bromley, and Marco Cianciauro. Measures and applications of quantum correlations. J. Phys. A: Math. Theor., 49:473001, 2016.

[7] Carlton Caves. Quantum-mechanical noise in an interferometer. Physical Review D, 23(8):1693–1708, 1981.

[8] Kirk McKenzie, Daniel A. Shaddock, David E. McClelland, Ben C. Buchler, and Ping Koy Lam. Experimental Demonstration of a Squeezing-Enhanced Power-Recycled Michelson Interferometer for Gravitational Wave Detection. Physical Review Letters, 88(23):231102, 2002.

[9] Géza Tóth and Iagoba Apellaniz. Quantum metrology from a quantum information science perspective. J. Phys. A: Math. Theor., 47(42):424006, 2014.

[10] Rafael Demkowicz-Dobrzański, Marcin Jarzyna, and Jan Kolodyński. Quantum Limits in Optical Interferometry. Progress in Optics, 60:345–435, 2015.

[11] Luca Pezzè and Augusto Smerzi. Quantum theory of phase estimation. Atom Interferometry, 188:691–741, 2014.

[12] Mathieu Manuceau, Gerd Leuchs, Farid Khalili, and Maria V. Chekhova. Detection Loss Tolerant Supersensitive Phase Measurement with an SU(1,1) Interferometer. Physical Review Letters, 119(22):223604, 2017.

[13] Agedi N. Boto, Pieter Kok, Daniel S. Abrams, Samuel L. Braunstein, Colin P. Williams, and Jonathan P. Dowling. Quantum Interferometric Optical Lithography: Exploiting Entanglement to Beat the Diffraction Limit. Physical Review Letters, 85(13):2733–2736, 2000.

[14] S. F. Huelga, C. Macchiavello, T. Pellizzari, A. K. Ekert, M. B. Plenio, and J. I. Cirac. Improvement of frequency standards with quantum-entanglement. Physical Review Letters, 79(20):3865–3868, 1997.

[15] Adrian B. Bern, Tobias Gehring, Bo M. Nielsen, Vitus Händchen, Matteo G.A. Paris, and Ulrik L. Andersen. Ab initio quantum-enhanced optical phase estimation using real-time feedback control. Nature Photonics, 9(9):577–581, 2015.

[16] Milena D’Angelo, Maria V. Chekhova, and Yanhua Shih. Two-photon diffraction and quantum lithography. Physical Review Letters, 87(1):013602, 2001.

[17] S. Oppel, T. Büttner, P. Kok, and J. Von Zanthier. Super-resolving Multiphoton Interferences with Independent Light Sources. Physical Review Letters, 109(23):233603, 2012.

[18] Clemens Schäfermeier, Miroslav Ježek, Lars S. Madsen, Tobias Gehring, and Ulrik L. Andersen. Deterministic phase measurements exhibiting super-sensitivity and super-resolution. Optica, 5(1):60–64, 2018.

[19] G. Brida, Marco Genovese, and I. Ruo Berchera. Experimental realization of sub-shot-noise quantum imaging. Nature Photonics, 4(4):227–230, 2010.

[20] Marco Genovese. Real applications of quantum imaging. Journal of Optics, 18(7):073002, 2016.

[21] J. Sabines-Chesterking, R. Whittaker, S. K. Joshi, P. M. Birchall, P. A. Moreau, A. McMillan, H. V. Cable, J. L. O’Brien, J. G. Rarity, and J. C.F. Matthews. Sub-Shot-Noise Transmission Measurement Enabled by Active Feed-Forward of Heralded Single Photons. Physical Review Applied, 8(1):014016, 2017.

[22] Elena Losero, Ivan Ruo-Berchera, Alice Meda, Alessio Avella, and Marco Genovese. Unbiased estimation of an optical loss at the ultimate quantum limit with twin-beams. Scientific Reports, 8:7431, 2018.

[23] J. Abadie et al. A gravitational wave observatory operating beyond the quantum shot-noise limit. Nature Physics, 7(12):962–965, 2011.

[24] J. Aasi et al. Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light. Nature Photonics, 7(8):613–619, 2013.

[25] Irene Sendra and Tristán L. Smith. Improved limits on short-wavelength gravitational waves from the cosmic microwave background. Physical Review D, 85(12):123002, 2012.

[26] Richard H. Cyburt, Brian D. Fields, Keith A. Olive, and Evan Skillman. New BBN limits on physics beyond the standard model from 4He. Astroparticle Physics, 85(13):2733–2736, 2000.

[27] Joseph D. Romano and Neil J. Cornish. Detection methods for stochastic gravitational-wave backgrounds: A unified treatment. Living Reviews in Relativity, 20(2):1–23, 2017.

[28] Tomotada Akutsu, Seiji Kawamura, Atsushi Nishizawa, Koji Araı̂, Kazuhiro Yamamoto, Daisuke Tamotsu, Shigeo Nagano, Erina Nishida, Takeshi Chiba, Ryouichi Takahashi, Naoshi Sugiyama, Mitsuhiro Fukushima, Toshitaka Yamazaki, and Masa Katsu Fujimoto. Search for a stochastic background of 100-MHz gravitational waves with laser interferometers. Physical Review Letters, 101(10):101101, 2008.

[29] B. J. Carr and S. W. Hawking. Black Holes in the Early Universe. Mon. Not. R. astr. Soc., 168:399–415, 1974.

[30] Aaron S. Chou, Henry Glass, H. Richard Gustafson, Craig J. Hogan, Brittany L. Kamai, Ohkyung Kwon, Robert Lanza, Lee McCuller, Stephan S. Meyer, Jonathan W. Richardson, Chris Stoughton, Ray Tomlin, and Rainer Weiss. Interferometric constraints on quantum geometrical shear noise correlations. Classical and Quantum Gravity, 34:165005, 2017.

[31] Atsushi Nishizawa, Seiji Kawamura, Tomotada Akutsu, Koji Araı̂, Kazuhiro Yamamoto, Daisuke Tamotsu, Erina Nishida, Masa Aki Sakagami, Takeshi Chiba, Ryouichi Takahashi, and Naoshi Sugiyama. Optimal location of two laser-interferometer detectors for gravitational wave backgrounds at 100 MHz. Classical and Quantum Grav-
ity, 25:225011, 2008.

[32] J. Abadie et al. Upper limits on a stochastic gravitational-wave background using LIGO and Virgo interferometers at 6001000 Hz Phys. Rev. D, 85:122001, 2012.

[33] Aaron S. Chou, Richard Gustafson, Craig J. Hogan, Brittany Kamai, Ohkyung Kwon, Robert Lanza, Shane L. Larson, Lee McCuller, Stephan S. Meyer, Jonathan Richardson, Chris Stoughton, Raymond Tomlin, and Rainer Weiss. MHz gravitational wave constraints with decameter Michelson interferometers. Physical Review D, 95(6):063002, 2017.

[34] Craig J. Hogan. Interferometers as probes of Planckian quantum geometry. Physical Review D, 85(6):064007, 2012.

[35] Aaron S. Chou, Richard Gustafson, Craig J. Hogan, Brittany Kamai, Ohkyung Kwon, Robert Lanza, Lee McCuller, Stephan S. Meyer, Jonathan Richardson, Chris Stoughton, Raymond Tomlin, Samuel Waldman, and Rainer Weiss. First Measurements of High Frequency Cross-Spectra from a Pair of Large Michelson Interferometers. Physical Review Letters, 117(11):111102, 2016.

[36] Ivano Ruo Berchera, I. P. Degiovanni, Stefano Olivares, and Marco Genovese. Quantum light in coupled interferometers for quantum gravity tests. Physical Review Letters, 110(21):213601, 2013.

[37] Ivano Ruo-Berchera, I. P. Degiovanni, Stefano Olivares, N. Samantaray, P. Traina, and Marco Genovese. One- and two-mode squeezed light in correlated interferometry. Physical Review A, 92(5):053821, 2015.

[38] F. Benatti, R. Floreanini, S. Olivares, and E. Sindici. Noisy effects in interferometric quantum gravity tests. Int. J. Quant. Inf., 15:1740014, 2017.

[39] P. Meystre and M. O. Scully. Quantum Optics, Experimental Gravity, and Measurement Theory. Springer US, 1983.

[40] A. V. Oppenheim, R. W. Schafer, and J. R. Buck. Discrete-time signal processing. Prentice-Hall, 1999.

[41] Sebastian Steinlechner, Jöran Bauchrowitz, Melanie Meinders, Helge Müller-Ebhardt, Karsten Danzmann, and Roman Schnabel. Quantum-dense metrology. Nature Photonics, 7(8):626–629, 2013.

[42] R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward. Laser phase and frequency stabilization using an optical resonator. Applied Physics B, 31(2):97–105, 1983.

[43] Kirk McKenzie, Eugeni E. Mikhailov, Keisuke Goda, Ping Koy Lam, Nicolai Grosse, Malcolm B. Gray, Nergis Mavalvala, and David E. McClelland. Quantum noise locking. J. Opt. B: Quantum Semiclass. Opt., 7(10):421–428, 2005.