IEEE Transactions on Quantum Engineering

Received 18 June 2022; revised 22 November 2022; accepted 22 November 2022; date of publication 25 November 2022; date of current version 15 December 2022.

Digital Object Identifier 10.1109/TQE.2022.3224686

The "Squeeze Laser"

ROMAN SCHNABEL AND AXEL SCHÖNBECK

Institut für Laserphysik & Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg, Germany

Corresponding author: R. Schnabel (e-mail: roman.schnabel@uni-hamburg.de).

This work was supported in part by the European Research Council (ERC), project MassQ under Grant 339897, in part by the ERC Proof of Concept project QLite under Grant 812763, and in part by the German Federal Ministry of Education and Research (BMBF) project QLaser under Grant 03VP06830.

ABSTRACT The level of quantum noise in measurements is bounded from below by the Heisenberg uncertainty principle, but it can be unequally distributed between two noncommuting observables: it can be "squeezed." Since 2019, all gravitational-wave observatories have been using squeezed light for increasing the astronomical reach. Squeezed laser light is efficiently produced by degenerate parametric down-conversion in a nonlinear crystal located inside an optical resonator. A spontaneously generated initial pair of indistinguishable photons is amplified to a squeezed vacuum state. Overlapped with bright coherent light, the photo-electric measurement shows a sub-Poissonian photon statistics. Squeezed states have ample applications in nonlocal quantum sensing, device-independent quantum key distribution, and quantum computing. Here, we present our continuous-wave 1550-nm "squeeze laser" with a footprint of 80×80 cm. The well-defined output beam has an interference contrast of $\gtrsim 99\%$ with an overlapped 10-mW beam being in an almost perfect TEM00 mode. The interference result shows 13-dB squeezing of the photon shot noise in balanced detection.

INDEX TERMS Quantum computing, quantum sensing, squeezed states, nonlocality.

I. INTRODUCTION

Coherent light is the basis of high-precision measuring devices, such as optical clocks [1], [2], [3] and gravitational-wave observatories [4], [5], [6]. Single-mode ultrastable laser light with frequency widths down to 10 mHz was realized [7], [8]. The reciprocal of the frequency width defines a minimal coherence time Δt, which is given by the Fourier transform. This fact guarantees that an ensemble of short measurements, each of duration $\Delta T \ll \Delta t$, has no classical or technical noise, just quantum noise, unless the measurement device itself adds significant noise. In the case of a conventional laser, the ensemble data correspond to those of a coherent state $|\alpha\rangle$, where α is the expectation value of the dimensionless complex-valued amplitude representing the optical field strength. The expectation value of the coherent state's photon number is well defined and reads $\langle\alpha|\alpha\rangle = \langle\hat{n}\rangle$. The individually measured numbers of photons per short measurement are not all identical, but provide a histogram with a Poisson distribution with a standard deviation of $\Delta\hat{n} = \sqrt{\langle\hat{n}\rangle}$ [9].

Shortly after the theoretical description of the coherent states by Roy Glauber in 1963 [9], the squeezed states of the optical field were theoretically analyzed [10], [11], [12]. The squeezed state can be written as $|\alpha, \beta, \theta\rangle$, where $\beta = e^{2r}$ is the squeeze factor with r the squeeze parameter, and θ is the squeeze angle. The squeeze factor is usually given on the decibel scale $10 \cdot \log_{10}\beta$. As an example, a "3-dB squeezed state" has a squeeze factor of $\beta \approx 2$, and thus, an about 50% smaller variance of the electric field uncertainty compared to a coherent state. For $\theta = 0$ we have an amplitude squeezed state and for $\theta = 90^\circ$ a phase (quadrature) squeezed state. A state with $\alpha = 0$ is called a squeezed vacuum state, whose excitation number is typically just a couple of photon pairs per Fourier-limited mode. A largely displaced amplitude-squeezed state $|\alpha \gg 1, \beta > 1, \theta = 0\rangle$ provides an almost Gaussian photon number histogram with a squeezed standard deviation of $\Delta\hat{n} = \sqrt{\langle\hat{n}\rangle/\beta}$ and is called "sub-Poissonian" [13]. The sub-Poisson statistics of photon numbers per short time window $\Delta T \ll \Delta t$ is remarkable [14], [15]. According to John S. Bell [16], the photon numbers are not defined "locally" — i.e., not per single short time window ΔT — but all of them only jointly and *nonlocally* over Δt. The photon numbers are "quantum correlated." The light of the squeeze laser is therefore referred to as "nonclassical," whereby the term "nonlocal" expresses the special property even more clearly. A conventional laser is unable to produce a squeezed state.

Here, we summarize the properties of laser beams that carry squeezed states and discuss their applications in quantum sensing, quantum key distribution, photometry, and quantum computing. We present a squeeze laser at the telecommunication wavelength of 1550 nm with a footprint of 80 × 80 cm that squeezes the photon counting statistics at sideband frequencies from about 1 kHz to about 100 MHz with a maximal squeeze factor of up to $\beta \approx 20$ (13 dB).

II. QUANTIZED ELECTROMAGNETIC WAVE

The photon view on coherent states and largely displaced amplitude squeezed states is outlined in the introduction. Apart from the photon view, the coherent state can also be described in the phase-space spanned by two normalized field amplitudes of the optical wave with a 90° phase difference. These are the field quadratures $\hat{X}$ and $\hat{Y}$, which obey the commutation relation $[\hat{X}, \hat{Y}] = i/2$ [17], where the normalization is chosen such that the sum of the quantum noise variances equals the zero point occupation number ($\Delta^2\hat{X} + \Delta^2\hat{Y} = 1/2$). The field quadratures are variables with a *continuous* spectrum.

Coherent and squeezed states have Gaussian field uncertainties, which are fully described by the standard deviations $\Delta\hat{X}$ and $\Delta\hat{Y}$ and potential correlations between the two quantities. The product of the standard deviations has a lower bound according to the Heisenberg uncertainty relation [18], which reads $\Delta\hat{X} \cdot \Delta\hat{Y} \geq 1/4$. The phase space representation reflects the wave view of quantum optics.

The general electromagnetic wave is time-dependent and the field quadratures are also time-dependent. A good description is thus given by the measured frequency spectra of time-dependent field quadratures $\hat{X}_{\Omega,\Delta\Omega}(t)$ and $\hat{Y}_{\Omega,\Delta\Omega}(t)$ [19]. In the optical regime, measurement electronics are much slower than the field oscillation at angular frequency ω_0, and $\hat{X}_{\Omega,\Delta\Omega}(t)$ and $\hat{Y}_{\Omega,\Delta\Omega}(t)$ are the time-dependent amplitude modulation depth and phase quadrature modulation depth at the angular modulation frequency Ω with resolution bandwidth $\Delta\Omega$ as they are used in optical communication and measured in optical sensing. The graphical illustration of these field modulations is given in [20, supplement's figure 1]. They are normalized in such a way that at any point in time t they obey the same Heisenberg uncertainty principle as above, i.e.,

$$\Delta\hat{X}_{\Omega,\Delta\Omega} \cdot \Delta\hat{Y}_{\Omega,\Delta\Omega} \geq 1/4 \,. \tag{1}$$

For every angular sideband frequency $\Omega > 0$, the coherent state $|\alpha\rangle_{\Omega,\Delta\Omega}$ is a quantum state of the respective *modulation*. Its phase space representation is the circular Gaussian uncertainty area of the ground state according to $\Delta\hat{X}^{\mathrm{vac}}_{\Omega,\Delta\Omega} = \Delta\hat{Y}^{\mathrm{vac}}_{\Omega,\Delta\Omega} = 1/2$ displaced by $\langle\hat{X}_{\Omega,\Delta\Omega}\rangle$ and $\langle\hat{Y}_{\Omega,\Delta\Omega}\rangle$. The expectation values of the quadratures define the complex-valued amplitude $\alpha = \langle\hat{X}_{\Omega,\Delta\Omega}\rangle + i\langle\hat{Y}_{\Omega,\Delta\Omega}\rangle$. The ground state ($\alpha = 0$, vacuum state) has $\langle\hat{X}^{\mathrm{vac}}_{\Omega,\Delta\Omega}\rangle = \langle\hat{Y}^{\mathrm{vac}}_{\Omega,\Delta\Omega}\rangle = 0$ and is free of any correlations. Fig. 1(a) and (b) show the phase space representations of the ground state and of a displaced coherent state, respectively. The radius of the uncertainty area is normalized to the standard deviation of ideal ensemble measurements, i.e., when every mode serves for a single quadrature measurement. The phase space representation of a modulation's squeezed state $|\alpha, \beta, \theta\rangle_{\Omega,\Delta\Omega}$ is an elliptical Gaussian uncertainty area with the half semiminor axis smaller than the radius of the ground state uncertainty. In full analogy to the coherent states, the uncertainty area might be displaced by $\langle\hat{X}_{\Omega,\Delta\Omega}\rangle$ and $\langle\hat{Y}_{\Omega,\Delta\Omega}\rangle$. Fig. 1(c) shows a squeezed vacuum state, which is defined to have zero displacement. *Squeezed* vacuum states need to be distinguished from the actual vacuum state; their excitation numbers are not zero. For a pure squeezed vacuum state, the excitation number of the modulation at Ω with bandwidth $\Delta\Omega$ is given by $\langle 0, \beta, \theta|\hat{n}_{\Omega,\Delta\Omega}|0, \beta, \theta\rangle = (\beta + 1/\beta)/4 - 0.5$ [19], where $\hat{n}_{\Omega,\Delta\Omega}$ describes the photon number in the two optical frequency ranges $\omega_0 + (\Omega \pm \Delta\Omega)$ and $\omega_0 - (\Omega \pm \Delta\Omega)$.

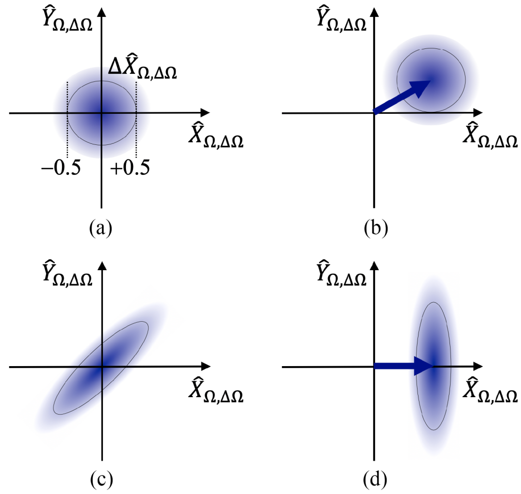

FIGURE 1. **Phase space presentations of pure states of the optical field. (a) Coherent state without displacement (ground state). (b) Coherent state with displacement. (c) Squeezed vacuum state with respect to some arbitrarily chosen phase reference. (d) Amplitude squeezed state. The shaded areas represent Gaussian minimal uncertainty products.**

Fig. 1(d) shows an amplitude squeezed state, which has a nonzero displacement along the semiminor axis of the uncertainty area. The displacement represents a semiclassical excitation of the modulation, which adds the photon number $(\alpha^*\alpha)_{\Omega,\Delta\Omega}$.

All kinds of optical loss, i.e., photons that are not measured, reduce the squeeze factor and increase the quadrature uncertainty product. A pure squeezed state with $\Delta^2\hat{X}^0_{\Omega,\Delta\Omega}\Delta^2\hat{Y}^0_{\Omega,\Delta\Omega} = 1/16$ is converted to a mixed, less squeezed state. The relative energy loss ℓ changes the squeezed and the antisqueezed quadrature variances according to [19]

$$\begin{aligned} \Delta^2\hat{X}^{\ell}_{\Omega,\Delta\Omega} &= \Delta^2\hat{X}^0_{\Omega,\Delta\Omega}(1-\ell) + \ell\,\Delta^2\hat{X}^{\mathrm{vac}}_{\Omega,\Delta\Omega} \\ \Delta^2\hat{Y}^{\ell}_{\Omega,\Delta\Omega} &= \Delta^2\hat{Y}^0_{\Omega,\Delta\Omega}(1-\ell) + \ell\,\Delta^2\hat{Y}^{\mathrm{vac}}_{\Omega,\Delta\Omega} \,. \end{aligned} \tag{2}$$

The measurements of the left-hand sides in the above equations give an uncertainty product that allows the quantification of ℓ, which is a useful feature for applications in quantum photometry and quantum communications, see Section VI.

III. PROPERTIES OF THE SQUEEZE LASER

Devices that emit squeezed light are simply referred to as "squeezed light sources" or "squeezers." What is missing is a name that better expresses the physical properties of these devices. In this article, we introduce the new name "squeeze laser," which we think is well founded. In the following, we compare the squeeze laser with the conventional laser.

The first squeeze lasers were demonstrated in the mid 1980s [21], [22]. Over the decades, the squeeze factor β was increased [23], [24], [25], [26], [27] to the currently highest value of $\beta \approx 32$ (15 dB) [28]. The squeeze factor is not only embodied in the shape of the phase-space uncertainty area but also in the sub-Poissonian photon number statistics, but only in the cases of strongly displaced amplitude squeezed states.

Squeezed light, regardless of whether it is in a squeezed vacuum state or in a displaced squeezed state, is efficiently produced by pumping a crystal inside an optical resonator; the resonator provides optical feedback, introduces an oscillation threshold, and defines Fourier limited transverse spatial modes, i.e., Gaussian beams. All these properties are those of a laser.

An important characteristic of the generic laser is stimulated emission of radiation. Stimulated emission describes the amplification of light through a pumped medium. In the particle view, a mode of light that is excited by at least one photon stimulates quantized energy transfer from the medium [29]. In the wave view, the excitation of a mode of light is amplified through constructive interference with a mode excited by the pumped medium. The latter description of stimulated emission fits well with the parametric amplification that takes place inside the squeeze resonator in the course of parametric downconversion (PDC). Arguably, the contributions of higher order photon pairs to a squeezed vacuum state can be understood as the result of stimulated emission induced by a spontaneous photon pair.

A special property of the conventional laser is its capability of converting *incoherent* pump light, e.g., from a thermal source, into coherent light. This requires the conventional laser to be operated far above oscillation threshold.

A special property of the squeeze laser is the need for *coherent* pump light, which is usually quasi-monochromatic and at twice the frequency of the squeezed field. The coherence of the pump makes the squeeze laser produce coherent light even below oscillation threshold. In the theoretical case of zero optical loss and zero pump depletion, the squeeze factor becomes infinite exactly when the oscillation threshold is reached [19]. Fig. 2 illustrates this theoretical situation. The critical amplitude gain per round trip is given by $g_{\text{crit}} = 1/r_1$, where r_1^2 is the power reflectivity of the resonator's coupling mirror while all other resonator mirrors are perfectly reflective. If the resonator round-trip amplification exceeds the total round-trip loss, the squeeze laser is above threshold and becomes a degenerate optical parametric oscillator (OPO). OPOs are also laser devices. While they have been usually used in the nondegenerate regime to produce laser beams at new wavelengths, the *degenerate* far-above threshold case is also possible, as demonstrated in [30].

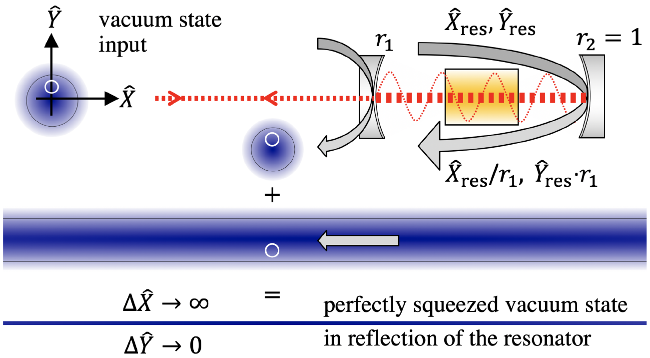

FIGURE 2. Concept of the ideal squeeze-laser resonator. A continuous sequence of well-defined ground-state modes (upper left) is coupled to the squeeze resonator, which contains a pumped parametric gain medium and is assumed here to be free of absorption and scatter loss. Generally, most of the mode is directly reflected by the first mirror with power reflectivity r_1^2. The fraction $(1 - r_1^2)$ is transmitted into the resonator. The field quadratures of the transmitted field at resonance frequency built up to $\hat{X}_{\text{res}}$ and $\hat{Y}_{\text{res}}$ in the course of constructive interference of many round trips. Depending on the pump phase, $\hat{X}_{\text{res}}$ includes a parametric gain while $\hat{Y}_{\text{res}}$ includes parametric damping. If the amplitude gain per round trip reaches $g = 1/r_1$, the oscillation threshold is accomplished. In case of an ideal cavity with $r_2 = 1$, $g = 1/r_1$ is also the condition for an impedance matched cavity for the incoming $\hat{Y}$-quadrature. Due to the superposition indicated, the reflected $\hat{Y}$-quadrature approaches zero, while the reflected $\hat{X}$-quadrature approaches infinity. The result are modes on cavity resonance in a perfectly squeezed state, which propagate to the left [19]. The small circle labels the phase space orientation of the quantum uncertainty which is necessary to illustrate the destructive interference.

Highest squeeze factors can be produced by operating the squeeze laser slightly below threshold [28], [31]. The results are strongly squeezed vacuum states. The typical mode of operation of a squeeze laser is thus different from all conventional lasers. The down-converted field is, nevertheless, fully coherent due to the quasi-monochromatic pump field at frequency $2\omega_0$. The key feature of the squeeze laser is the fact that despite its full coherence the down-converted degenerate field at frequency ω_0 is much less monochromatic than the pump field. In this situation, energy conservation and symmetry enforce correlations in the number of measured photons resulting in the nonlocal property of squeezed light. Elaborating the precise connection between energy conservation, symmetry, and nonlocal properties is beyond the scope of this paper and will be published in upcoming work.

Like any laser, a squeeze laser uses a cavity length where the transverse spatial modes are nondegenerate. Then the TEM00 mode can be chosen to be emitted in a squeezed vacuum state while all others remain in the ground state.

However, squeeze lasers can also be operated to squeeze higher order transverse modes [32], [33].

Squeezed light is most efficiently observed by a balanced homodyne detector (BHD) that uses the overlap of the squeezed field with an optical local oscillator in the same mode on a balanced beamsplitter. The two beam splitter outputs are measured with two photo diodes having close to perfect quantum efficiency. The differential voltage is either analyzed by a spectrum analyzer or sampled by an analog-to-digital converter and then further processed. The actually observed squeeze factor is usually not limited by the PDC, but by the quantum efficiency of the photodiodes and by the interference contrast achieved at the balanced beam splitter.

Finally, we note that the squeeze laser uses the same PDC process as photon pair sources [34], [35], [36]. Photon pair sources, however, usually do not have a resonator for optical feedback, no mode confinement, and no oscillation threshold. In the case of photon pair sources, the induced emission does not play a role and one often speaks of "spontaneous" PDC. The photon pairs of such a source are all spontaneous, but never the less as coherent as the pump field.

IV. SQUEEZED LIGHT FOR ASTRONOMY

Gravitational-wave observatories, such as GEO 600 [37], Kagra [38], LIGO [39], and Virgo [40] target oscillations in spacetime at audio-band frequencies, such as those caused by two merging black holes. The first gravitational wave (GW) was observed by LIGO on September 14, 2015 [4]. GW-observatories are resonator-enhanced Michelson laser interferometers. Properly polarized GWs produce a differential arm length oscillation. The topology of a Michelson interferometer suppresses a large fraction of the classical noise on the laser light due to destructive interference in the signal output port. Nevertheless, GW observatories require highly coherent continuous-wave light to achieve the required sensitivities.

Increasing the light power in the Michelson arms only improves sensitivity if photon shot noise is the dominant measurement noise. Other sources of noise must be reduced by other means. At some point, however, increasing the light output will become more and more challenging for fundamental and practical reasons. In this case, squeezing the quantum noise is a valuable alternative, as proposed in 1981 [41]. Squeezing the variance of the photon shot noise in the signal output port by the factor β improves the sensitivity as does increasing the light power in the arms by the same factor [41]. The first squeezing-enhanced laser interferometers were realized shortly after the first ever observation of squeezed light in the mid 1980 s [46], [47]. The shot-noise was squeezed by factors of up to two (3 dB). But at the end of the last century, the time of the squeeze laser had not yet come, because laser technology and the qualities of optical components were continuously improving, and light powers in interferometer arms could be scaled up by orders of magnitudes. In the first decade of the new century, it

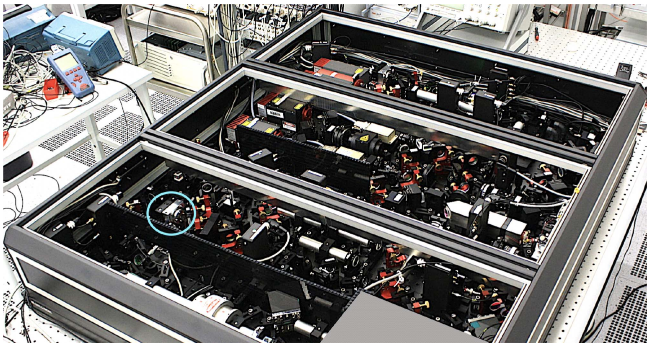

FIGURE 3. Photograph of the first squeeze laser designed and built for continuous operation in gravitational-wave observatories for improving their astronomical reach. It was realized by the group of RS at the Leibniz Universität Hannover in 2010 [42]. Since then it has been used by GEO 600 [43], [44], [45]. The circle highlights the resonator of the squeeze laser. Wavelength: 1064 nm; footprint of the breadboard: 135 × 113 cm; portable.

became apparent that the light powers in all GW observatories could no longer be easily increased and that the design values could not necessarily be achieved. For instance, one issue was thermal lensing in the Michelson beam splitter that could no longer be compensated for. Another problem were parametric instabilities of internal mirror vibrations driven by radiation pressure.

In the same period, the squeeze laser technology for GW observatories was developed, for reviews see [48] and [49], culminating in the first squeeze laser designed and built for continuous operation in gravitational-wave observatories [42], see Fig. 3, which is in operation in GEO 600, since 2010 [43], [44], [45]. It turned out that all GW observatories require squeezed light to come closer to their design sensitivities. Since 2019, all GW observations are improved by squeezing the quantum noise of light [5], [6], [50], [51].

We note that squeezed light can further enhance GW observatories in ways fundamentally beyond what can be achieved by scaling light output. Squeezing allows for the *simultaneous* suppression of photon shot noise (pSN) *and* photon radiation pressure noise (pRPN) [52], [53]. While pSN arises in the context of the photodiode measurement, pRPN arises from the transfer of uncertain momentum from the light to the reflecting interferometer mirrors. After reflection, the uncertain mirror displacement is quantum correlated with the uncertain phase of the reflected light [54], [55]. An appropriately selected measurement phase exploits the quantum correlations to simultaneously suppress pSN and pRPN below the values of conventional laser light having the same power. This further development is already in preparation in all GW observatories [56], [57], [58], see also Section VI-A.

V. OUR 1550-NM SQUEEZE LASER

The optimal laser wavelength for fiber-based communication is 1550 nm, where state-of-the-art glass fibers have very low optical losses. Crystalline silicon also shows low losses

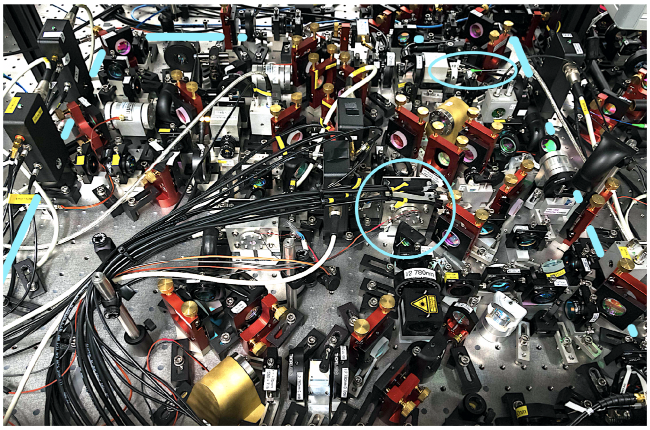

FIGURE 4. Photograph of the currently most compact squeeze laser in the >10 dB range. It was designed and built by AS at the Universität Hamburg. The dashed line shows the 80 × 80 cm breadboard, and thus, the footprint of the squeeze laser. The circle marks the squeeze resonator. The pump light from a fiber laser is coupled to the breadboard via an optical fiber (ellipse). Alternatively, the pump laser can also be placed on the breadboard (free space in front left). Wavelength: 1550 nm; portable.

at this wavelength. 1550 nm laser light thus opens up the possibility of synergies between optical and semiconductor technologies. The wavelength might also enable new optical materials with less Brownian noise from mirror surfaces in the next generations of GW observatories [59], [60], [61].

The first strongly squeezed light at 1550 nm was reported in [62]. Fig. 4 shows a photo of our latest squeeze laser at 1550 nm. It is the first squeeze laser with a footprint of well under one square meter. It is built on a breadboard with the dimensions 80 × 80 cm. A fiber laser, which supplies the pump light at 1550 nm, and our home-made second harmonic generator, which produces the coherent pump field at 775 nm, have space on the breadboard. The power supplies and the servo control electronics are in a separate rack.

Our squeeze laser uses a periodically poled KTP crystal inside a double-resonant cavity for producing 12-mW quasi-monochromatic pump light at 775 nm from 20 mW at 1550 nm. With 12-mW pump power, which accounts for about 87% of the oscillation threshold power, our squeeze laser generates up to 13-dB-squeezed vacuum states ($\beta \approx 20$). We measure the squeeze factor at sideband frequencies $\Omega/(2\pi)$ between 3 and 5 MHz with a home-built balanced homodyne detector (BHD) using a cavity-filtered 1550-nm local oscillator (LO) beam of 12 mW. The interference contrast between LO and squeezed beam was about 99%, attesting to the quality of the latter's transverse mode. Local oscillator power does not affect the observed squeeze factor. We chose 12 mW because it was high enough to achieve a clearance of almost 25 dB between shot noise and dark noise of our BHD electronics, and low enough not to damage the BHD [31]. The breadboard can be covered with a solid case and is portable. It serves as a concept study for high-quality squeeze lasers with an even smaller footprint to make squeeze lasers usable for researchers and developers who are not experts in laser optics. Squeeze lasers have multiple degrees of freedom that must be passively stable and/or actively servo-controlled. That is why all previous setups for generating squeezed light have an area of square meters. First of all, a squeeze laser requires ultrastable laser light at the wavelength of the squeeze laser. Commercial lasers are often suitable. Parts of the light must be frequency doubled to coherently pump the squeeze resonator. Other parts are needed for downstream sensing or communication applications and also for the local oscillator to characterize the squeezed light. The differential path of the squeezed light and the coherent light at the same wavelength must be stable and feedback-controlled. This requires that the second harmonic pump field also be phase stable. The resonator for generating the second harmonic pump light and the squeeze resonator must have feedback-controlled lengths. Our squeeze laser uses double resonant standing wave cavities, the length of which can be adjusted via a piezoelectric element. They are controlled to resonate at 1550 and 775 nm simultaneously, maximizing frequency conversion efficiency. The nonlinear material used in the cavities is periodically poled KTP. The poling period roughly establishes a quasi-phase matching between the two wavelengths. The fine-tuning of the quasi-phase matching is achieved through precise adjustment and feedback-control of the crystal temperature. Tuning the crystal temperature, in turn, changes the resonance conditions for the two wavelengths. The rather stringent double resonance requirement can be achieved by a tradeoff between operating with slightly suboptimal quasi-phase matching. In order to achieve mode overlaps with interference contrasts close to one, mode-cleaning cavities [27] are used, which all have to be controlled to resonance. All components are on a mechanically stable breadboard to ensure that perturbations are low enough for the dynamic ranges of the counteracting piezoelectric elements.

VI. APPLICATIONS

There are several ways that squeezed light can save resources in nonlocal quantum sensing, but also in nonlocal quantum photometry, communication, and optical computation. It is important to note that quantum technologies cannot solve tasks that are in principle impossible with conventional technology, but quantum technologies are able to realize these tasks with fewer resources, e.g., energy. This is crucial for any application and the main motivation for the development of quantum technologies.

A. NONLOCAL QUANTUM SENSING

A sensor using an ensemble of identical quantum systems, for instance identical Fourier-limited modes of light, is a "quantum sensor" in common parlance. It is a sensor whose sensitivity can be further improved by upscaling the number of quanta. According to this, GW observatories were already quantum sensors before squeeze lasers were implemented. It is therefore useful to introduce another term when nonlocal resources enhance the sensing: “nonlocal quantum sensing.” We can distinguish between different regimes.

Sub-Poissonian Sensing is largely covered by Section IV. GW observatories had been limited in their upper signal band by Poissonian photon shot noise (pSN) for many years. At a certain point, exploiting the nonlocal property of the squeezed light turned out to be more cost-effective to improve the signal-to-noise ratio than further upscaling the coherent light power. Squeeze lasers have been used in GW observatories since 2010 [5], [6], [42], [43], [44]. They are *not* just used to demonstrate their potential, but to solve a problem that is not easily solvable without a squeeze laser. In this sense, the sub-Poissonian, nonlocal sensing due to the squeeze laser is already a user application.

Quantum Back-Action Evading Sensing can also be achieved with a squeeze laser. In the optical domain, quantum back-action noise manifests itself in the form of the photon radiation pressure noise (pRPN). Without changing the optical power in the interferometer, the optical input path of the squeezed light must be changed by a quarter wavelength compared to sub-Poissonian sensing. This changes the squeeze angle by 90°. While the photodiode now measures an antisqueezed photon statistic, the photon statistic in the *arms* is squeezed, causing the pRPN to decrease. The latter effect arises from the way any interferometer works, according to which it rotates the phase quadrature into the amplitude quadrature. It is an example of the basic principle according to which more precise monitoring leads to stronger quantum back-action. It is possible, however, to optimize the squeeze angle for every individual signal frequency by reflecting the squeezed light from a detuned filter cavity. Different frequencies then experience different path lengths, thereby producing a frequency-dependent squeeze angle [53], [57], [58], [63]. The pRPN is already limiting current GW observatories at low signal frequencies [54], [64], although they are not yet operated at the high light outputs according to their design values. The reason for this is that no filter cavities are used yet and a squeezed pSN forces an antisqueezed pRPN. In the near future, the pRPN must also be squeezed at frequencies below about 50 Hz, while maintaining the shot noise squeezing at higher frequencies. This can be realised by 300-m long high-quality detuned filter cavities [56]. The installations of these filter cavities are immediate projects at the current GW observatories [57], [58].

Quantum Non-Demolition (QND) Sensing is even more advanced [65]. It concerns the situation, when pSN and pRPN contribute about equally to the overall quantum noise within the same frequency band. In this case, squeezing one or the other noise does not reduce the total quantum noise, and the sum of the balanced uncorrelated pSN and pRPN define the so-called standard quantum limit (SQL). One known QND approach, however, uses squeezed light injection with the purpose of introducing quantum correlations between the pSN and pRPN. This way, it is possible to surpass the standard quantum limit [52], [54], [55]. The filter cavities that are in preparation at current GW observatories can in principle achieve QND sensing to some degree. The challenge is that with pSN and pRPN being of the same magnitude also thermal noise is usually relevant. Thermal noise is due to thermally induced movements of the mirror surfaces, and cryogenic cooling of the mirrors might be required to turn a GW observatory into a deep-QND sensor. A further reduction in optical loss is also required, which could also enforce even longer filter cavities. Einstein–Podolsky–Rosen (EPR) entangled light beams generated from two squeezed light fields [66], [67] could be a more cost-effective approach since the existing cavities of the GW observatory can then be used [68], [69], [70].

Quantum Dense (QD) Sensing is able to simultaneously monitor two noncommuting observables of a signal field with uncertainties below that of the ground state. Here, too, two entangled EPR light beams are required, which are generated from two squeezed beams. QD sensors make it possible to identify parasitic interference from modulated backscattered light [20], [71], [72], [73], [74]. Eventually, conventional techniques to avoid these parasitic disturbances become expensive and QD sensing becomes a cost-effective complement.

B. NONLOCAL QUANTUM PHOTOMETRY

The coherent states remain such even under arbitrarily strong optical loss. They remain pure, i.e., their uncertainty product remains at the lower bound of (1). The uncertainty product of squeezed states, on the other hand, increases with loss, see (2). The possibility of estimating the total loss ℓ on squeezed light from the uncertainty product has an application in photometry. The absolute calibration of the quantum efficiency of a photosensor $\eta_{\rm ph}$ by a calibrated light source (“standard candle”) is difficult, time-consuming, and the error bars are relatively large at short infrared wavelengths between 1.4 and 3 μm and beyond. The resource-saving alternative is to let the photo sensors detect strongly squeezed light [28]. Measuring the squeezed noise as well as the antisqueezed noise quantifies the degree of mixedness and hence the total amount of optical loss ℓ according to (1) and (2).

The photosensor’s imperfect quantum efficiency contributes just the optical loss $(1 - \eta_{\rm ph}) < \ell$. The independent determination of the sum of all other loss contributions, such as absorption in the nonlinear crystal and residual reflection and scattering at surfaces of lenses and mirrors in the propagation path of the squeezed light allows to determine $\eta_{\rm ph}$ from ℓ. A standard candle is not required.

C. NONLOCAL QUANTUM KEY DISTRIBUTION

Quantum key distribution (QKD) [75] builds on the possibility of estimating the upper bound of information loss in distributed light, i.e., its decoherence. QKD primarily secures the quantum channel. Advanced QKD uses nonlocal light to provide additional security for the devices that generate and measure the light [76]. "One-sided device independent QKD" secures the channel as well as the devices at the remote station B ("Bob"). In the implementation in [77], the local station A (Alice) generates two continuous EPR-entangled light beams by superimposing two squeezed beams on a balanced beam splitter, and sends one of them to Bob. Alice and Bob perform a large number of synchronised quadrature measurements, randomly switching between between $\hat{X}_{\Omega,\Delta\Omega}$ and $\hat{Y}_{\Omega,\Delta\Omega}$. After the measurement phase, Bob sends a randomly selected subset of the measured quadrature values to Alice, where the entanglement between the dataset at Alice (superscript A) and Bob (superscript B) is quantified. From the data in which accidentally the same quadrature was measured at the same time t_i, the squeeze factors in the nonlocal observables $\hat{X}^A_{\Omega,\Delta\Omega}(t_i) \pm \hat{X}^B_{\Omega,\Delta\Omega}(t_i)$ and $\hat{Y}^A_{\Omega,\Delta\Omega}(t_j) \mp \hat{Y}^B_{\Omega,\Delta\Omega}(t_j)$ are determined. (The signs have to be chosen such that the variances of the two nonlocal quadratures are squeezed and not antisqueezed.) The maximum loss of the entangled states ℓ is then calculated using (2) and assuming initially perfectly squeezed nonlocal observables. It represents the upper limit of the relative amount of information that an eavesdropper could in principle have gathered. This is because it is impossible to increase the squeeze factor in the nonlocal quadratures if you only have access to the channel and equipment on Bob's side [78], [79].

In principle, devices can also be secured by conventional monitoring. This is for instance required in order to enable QKD that is based on the BB84 protocol [75] in order to defuse side channel attacks [76], [80]. Squeeze lasers can arguably achieve remote device security more effectively and with fewer resources than constantly pushing traditional surveillance to its technical limits to stay one step ahead of potential eavesdroppers.

D. ALL-OPTICAL CONTINUOUS VARIABLE QUANTUM COMPUTATION

Roughly speaking, doubling the number of conventional computers doubles the computational speed. A *quantum* computer doubles its speed when the number of entangled qubits increases from N to $N+1$. Quantum computers, once they are deterministic, scalable, and universal, are thus able to save resources. Quantum computing is always a "nonlocal" approach, since it always requires quantum correlated states. Knill et al. [81] proposed an all optical quantum computer based on superpositions of the optical ground state and the single-photon Fock state as the qubit space. In this discrete variable setting, however, the realization of deterministic gates is rather demanding, see also [82].

In recent years, all optical quantum computing with strongly squeezed vacuum states as a *continuous-variable* nonlocal resource attracted more and more attention, because squeezed states are a *deterministic* quantum resource, and optical multiplexing techniques provide *high scalability* [83], [84]. All-optical continuous-variable quantum computation can also be made *universal*. For this, the easy to implement Gaussian gates, such as the beam splitter, phase shifter, displacement operation, and squeezing operation need to be complemented by a non-Gaussian gate. The latter is difficult to implement. Arguably, the most promising approach is a nonlinear phase gate that encodes a qubit into the light's amplitude and phase quadratures by measuring parts of the squeezed light via number-resolving photon counters [85].

VII. CONCLUSION

Squeeze lasers emit diffraction-limited Gaussian beams with long coherence times. Their central components are laser resonators with nonlinear materials that are pumped with coherent light of the second harmonic frequency with a power close to the oscillation threshold. Due to the high spatial and temporal coherence of squeezed light, we propose to use the name "squeeze laser" instead of the less descriptive term "squeezed light source."

Squeezed light, be it in a squeezed vacuum state or in a displaced one, is nonlocal. Depending on the coherence time Δt, the photon number measured in a first short time window $\Delta T \ll \Delta t$ is quantum correlated with those of all subsequent such time windows. For amplitude-squeezed light, the nonlocal correlation leads to sub-Poissonian photon statistics.

Squeezed light has many uses. We consider it to be the most relevant resource in the fields of nonlocal quantum sensing, nonlocal quantum key distribution, nonlocal photometry, and optical quantum computing.

In the past, squeeze lasers had footprints of more than one square meter. Here we present a squeeze laser that delivers up to 13 dB of squeezing at 1550 nm with a footprint of 0.64 m^2. We consider our setup as a concept study to commercialize the squeeze laser.

REFERENCES

[1] C. Chou, D. Hume, J. Koelemeij, D. Wineland, and T. Rosenband, "Frequency comparison of two high-accuracy Al optical clocks," *Phys. Rev. Lett.*, vol. 104, Feb. 2010, Art. no. 070802, doi: 10.1103/PhysRevLett.104.070802.

[2] B. J. Bloom et al., "An optical lattice clock with accuracy and stability at the 10–18 level," *Nature*, vol. 506, pp. 71–75, Feb. 2014, doi: 10.1038/nature12941.

[3] M. Schioppo et al., "Ultrastable optical clock with two cold-atom ensembles," *Nature Photon.*, vol. 11, pp. 48–52, Jan. 2017, doi: 10.1038/nphoton.2016.231.

[4] B. P. Abbott et al., "Observation of gravitational waves from a binary black hole merger," *Phys. Rev. Lett.*, vol. 116, Feb. 2016, Art. no. 061102, doi: 10.1103/PhysRevLett.116.061102.

[5] M. Tse et al., "Quantum-enhanced advanced LIGO detectors in the era of gravitational-wave astronomy," *Phys. Rev. Lett.*, vol. 123, Dec. 2019, Art. no. 231107, doi: 10.1103/PhysRevLett.123.231107.

[6] F. Acernese et al., "Increasing the astrophysical reach of the advanced Virgo detector via the application of squeezed vacuum states of light," *Phys. Rev. Lett.*, vol. 123, Dec. 2019, Art. no. 231108, doi: 10.1103/PhysRevLett.123.231108.

[7] T. Kessler et al., "A sub-40-mHz-linewidth laser based on a silicon single-crystal optical cavity," *Nature Photon.*, vol. 6, pp. 687–692, Sep. 2012, doi: 10.1038/nphoton.2012.217.

[8] D. G. Matei et al., "1.5 μm lasers with Sub-10 mHz linewidth," *Phys. Rev. Lett.*, vol. 118, Art. no. 263202, Jun. 2017, doi: 10.1103/PhysRevLett.118.263202.

[9] R. J. Glauber, "Coherent and incoherent states of the radiation field," *Phys. Rev.*, vol. 131, pp. 2766–2788, Sep. 1963, doi: 10.1103/PhysRev.131.2766.

[10] D. Stoler, "Equivalence classes of minimum uncertainty packets," *Phys. Rev. D*, vol. 1, pp. 3217–3219, Jun. 1970, doi: 10.1103/PhysRevD.1.3217.

[11] E. Y. C. Lu, "New coherent states of the electromagnetic field," *Lettere Al Nuovo Cimento Ser.*, vol. 2, pp. 1241–1244, Dec. 1971, doi: 10.1007/BF02770161.

[12] H. Yuen, "Two-photon coherent states of the radiation field," *Phys. Rev. A*, vol. 13, pp. 2226–2243, Jun. 1976, doi: 10.1103/PhysRevA.13.2226.

[13] R. Short and L. Mandel, "Observation of sub-Poissonian photon statistics," *Phys. Rev. Lett.*, vol. 51, pp. 384–387, Aug. 1983, doi: 10.1103/PhysRevLett.51.384.

[14] R. Schnabel, "'Quantum weirdness' in exploitation by the international gravitational-wave observatory network," *Annalen der Physik*, vol. 532, Mar. 2020, Art. no. 1900508, doi: 10.1002/andp.201900508.

[15] J. Zander, C. Rembe, and R. Schnabel, "10 dB interferometer enhancement by squeezing of photon shot noise with sub-femtometer resolution and eye-safe optical power," *Quantum Sci. Technol.*, vol. 8, 2023, Art. no. 01LT01, doi: 10.1088/2058-9565/ac9ad5.

[16] J. S. Bell, "On the Einstein Podolsky Rosen Paradox," *Physics*, vol. 1, pp. 195–200, 1964, doi: 10.1103/PhysicsPhysiqueFizika.1.195.

[17] C. C. Gerry and P. L. Knight, *Introductory Quantum Optics*. Cambridge, U.K.: Cambridge Univ. Press, 2005, doi: 10.1017/CBO9780511791239.

[18] H. P. Robertson, "The uncertainty principle," *Phys. Rev.*, vol. 34, pp. 163–164, Jul. 1929, doi: 10.1103/PhysRev.34.163.

[19] R. Schnabel, "Squeezed states of light and their applications in laser interferometers," *Phys. Rep.*, vol. 684, pp. 1–51, Apr. 2017, doi: 10.1016/j.physrep.2017.04.001.

[20] J. Zander and R. Schnabel, "Full monitoring of ensemble trajectories with 10 dB-sub-Heisenberg imprecision," *npj Quantum Inf.*, vol. 7, pp. 1–4, Dec. 2021, doi: 10.1038/s41534-021-00486-z.

[21] R. E. Slusher, L. W. Hollberg, B. Yurke, J. C. Mertz, and J. F. Valley, "Observation of squeezed states generated by four-wave mixing in an optical cavity," *Phys. Rev. Lett.*, vol. 55, pp. 2409–2412, Nov. 1985, doi: 10.1103/PhysRevLett.55.2409.

[22] L.-A. Wu, H. J. Kimble, J. L. Hall, and H. Wu, "Generation of squeezed states by parametric down conversion," *Phys. Rev. Lett.*, vol. 57, pp. 2520–2523, Nov. 1986, doi: 10.1103/PhysRevLett.57.2520.

[23] E. S. Polzik, J. Carri, and H. J. Kimble, "Spectroscopy with squeezed light," *Phys. Rev. Lett.*, vol. 68, 1992, Art. no. 3020, doi: 10.1103/PhysRevLett.68.3020.

[24] G. Breitenbach and S. Schiller, "Homodyne tomography of classical and non-classical light," *J. Mod. Opt.*, vol. 44, Nov. 1997, Art. no. 2207, doi: 10.1080/09500349708231879.

[25] P. K. Lam, T. C. Ralph, B. C. Buchler, D. E. Mcclelland, H.-A. Bachor, and J. Gao, "Optimization and transfer of vacuum squeezing from an optical parametric oscillator," *J. Opt. B: Quantum Semiclassical Opt.*, vol. 1, pp. 469–474, 1999, doi: 10.1088/1464-4266/1/4/319.

[26] Y. Takeno, M. Yukawa, H. Yonezawa, and A. Furusawa, "Observation of -9 dB quadrature squeezing with improvement of phase stability in homodyne measurement," *Opt. Exp.*, vol. 15, pp. 4321–4327, Apr. 2007, doi: 10.1364/OE.15.004321.

[27] H. Vahlbruch et al., "Observation of squeezed light with 10-dB quantum-noise reduction," *Phys. Rev. Lett.*, vol. 100, Jan. 2008, Art. no. 033602, doi: 10.1103/PhysRevLett.100.033602.

[28] H. Vahlbruch, M. Mehmet, K. Danzmann, and R. Schnabel, "Detection of 15 dB squeezed states of light and their application for the absolute calibration of photoelectric quantum efficiency," *Phys. Rev. Lett.*, vol. 117, Sep. 2016, Art. no. 110801, doi: 10.1103/PhysRevLett.117.110801.

[29] A. Einstein, "Zur Quantentheorie der Strahlung," *Physikalische Zeitschrift*, vol. 18, pp. 121–128, 1917, doi: 10.1515/9783112596609-016.

[30] C. Darsow-Fromm, M. Schröder, J. Gurs, R. Schnabel, and S. Steinlechner, "Highly efficient generation of coherent light at 2128 nm via degenerate optical-parametric oscillation," *Opt. Lett.*, vol. 45, Nov. 2020, Art. no. 6194, doi: 10.1364/OL.405396.

[31] A. Schönbeck, F. Thies, and R. Schnabel, "13 dB squeezed vacuum states at 1550 nm from 12 mW external pump power at 775 nm," *Opt. Lett.*, vol. 43, no. 1, pp. 110–113, Jan. 2018, doi: 10.1364/OL.43.000110.

[32] N. Treps, N. Grosse, W. P. Bowen, C. Fabre, and H.-A. Bachor, "A quantum laser pointer," *Science*, vol. 301, pp. 940–943, 2003, doi: 10.1126/science.1086489.

[33] S. Steinlechner, N.-O. N.-O. Rohweder, M. Korobko, D. Töyrä, A. Freise, and R. Schnabel, "Mitigating mode-matching loss in nonclassical laser interferometry," *Phys. Rev. Lett.*, vol. 121, Dec. 2018, Art. no. 263602, doi: 10.1103/PhysRevLett.121.263602.

[34] D. Burnham and D. Weinberg, "Observation of simultaneity in parametric production of optical photon pairs," *Phys. Rev. Lett.*, vol. 25, pp. 84–87, Jul. 1970, doi: 10.1103/PhysRevLett.25.84.

[35] A. Aspect, P. Grangier, and G. Roger, "Experimental tests of realistic local theories via Bell's theorem," *Phys. Rev. Lett.*, vol. 47, 1981, Art. no. 460, doi: 10.1103/PhysRevLett.47.460.

[36] P. G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, and A. V. Sergienko, "New high-intensity source of polarization-entangled photon pairs," *Phys. Rev. Lett.*, vol. 75, 1995, Art. no. 4337, doi: 10.1103/PhysRevLett.75.4337.

[37] K. L. Dooley et al., "Phase control of squeezed vacuum states of light in gravitational wave detectors," *Opt. Exp.*, vol. 23, Apr. 2015, Art. no. 8235, doi: 10.1364/OE.23.008235.

[38] S. Miyoki, "Current status of KAGRA," in *Ground-Based and Airborne Telescopes VIII*, H. K. Marshall, J. Spyromilio, and T. Usuda, Eds., Bellingham, WA, USA: SPIE, 2020, pp. 192–204, doi: 10.1117/12.2560824.

[39] The LIGO Scientific Collaboration, "Advanced LIGO," *Classical Quantum Gravity*, vol. 32, Apr. 2015, Art. no. 074001, doi: 10.1088/0264-9381/32/7/074001.

[40] F. Acernese et al., "Advanced Virgo: A second-generation interferometric gravitational wave detector," *Classical Quantum Gravity*, vol. 32, Jan. 2015, Art. no. 024001, doi: 10.1088/0264-9381/32/2/024001.

[41] C. Caves, "Quantum-mechanical noise in an interferometer," *Phys. Rev. D*, vol. 23, pp. 1693–1708, Apr. 1981, doi: 10.1103/PhysRevD.23.1693.

[42] H. Vahlbruch, A. Khalaidovski, N. Lastzka, C. Gräf, K. Danzmann, and R. Schnabel, "The GEO 600 squeezed light source," *Classical Quantum Gravity*, vol. 27, Apr. 2010, Art. no. 084027, doi: 10.1088/0264-9381/27/8/084027.

[43] J. Abadie et al., "A gravitational wave observatory operating beyond the quantum shot-noise limit," *Nature Phys.*, vol. 7, pp. 962–965, Sep. 2011, doi: 10.1038/nphys2083.

[44] H. Grote, K. Danzmann, K. L. Dooley, R. Schnabel, J. Slutsky, and H. Vahlbruch, "First long-term application of squeezed states of light in a gravitational-wave observatory," *Phys. Rev. Lett.*, vol. 110, May 2013, Art. no. 181101, doi: 10.1103/PhysRevLett.110.181101.

[45] J. Lough et al., "First demonstration of 6 dB quantum noise reduction in a kilometer scale gravitational wave observatory," *Phys. Rev. Lett.*, vol. 126, Jan. 2021, Art. no. 041102, doi: 10.1103/PhysRevLett.126.041102.

[46] M. Xiao, L.-A. Wu, and H. J. Kimble, "Precision measurement beyond the shot-noise limit," *Phys. Rev. Lett.*, vol. 59, 1987, Art. no. 278, doi: 10.1103/PhysRevLett.59.278.

[47] P. Grangier, R. E. Slusher, B. Yurke, and A. LaPorta, "Squeezed-light-enhanced polarization interferometer," *Phys. Rev. Lett.*, vol. 59, 1987, Art. no. 2153, doi: 10.1103/PhysRevLett.59.2153.

[48] R. Schnabel, N. Mavalvala, D. E. McClelland, and P. K. Lam, "Quantum metrology for gravitational wave astronomy," *Nature Commun.*, vol. 1, no. 1, pp. 1–10, Jan. 2010, doi: 10.1038/ncomms1122.

[49] S. E. Dwyer, G. L. Mansell, and L. McCuller, "Squeezing in gravitational wave detectors," *Galaxies*, vol. 10, Mar. 2022, Art. no. 46, doi: 10.3390/galaxies10020046.

[50] M. Mehmet and H. Vahlbruch, "The squeezed light source for the advanced Virgo detector in the observation run O3," *Galaxies*, vol. 8, Nov. 2020, Art. no. 79, doi: 10.3390/galaxies8040079.

[51] R. Abbott et al., "GWTC-2: Compact binary coalescences observed by LIGO and Virgo during the first half of the third observing run," *Phys. Rev. X*, vol. 11, Jun. 2021, Art. no. 021053, doi: 10.1103/PhysRevX.11.021053.

[52] M. T. Jaekel and S. Reynaud, "Quantum limits in interferometric measurements," *Europhysics Lett.*, vol. 13, 1990, Art. no. 301, doi: 10.1209/0295-5075/13/4/003.

[53] H. J. Kimble, Y. Levin, A. B. Matsko, K. S. Thorne, and S. P. Vyatchanin, "Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics," *Phys. Rev. D*, vol. 65, Dec. 2001, Art. no. 022002, doi: 10.1103/PhysRevD.65.022002.

[54] H. Yu et al., "Quantum correlations between light and the kilogram-mass mirrors of LIGO," *Nature*, vol. 583, pp. 43–47, Jul. 2020, doi: 10.1038/s41586-020-2420-8.

[55] R. Schnabel and M. Korobko, "Macroscopic quantum mechanics in gravitational-wave observatories and beyond," *AVS Quantum Sci.*, vol. 4, Mar. 2022, Art. no. 014701, doi: 10.1116/5.0077548.

[56] L. Barsotti, J. Harms, and R. Schnabel, "Squeezed vacuum states of light for gravitational wave detectors," *Rep. Prog. Phys.*, vol. 82, Jan. 2019, Art. no. 016905, doi: 10.1088/1361-6633/aab906.

[57] Y. Zhao et al., "Frequency-dependent squeezed vacuum source for broadband quantum noise reduction in advanced gravitational-wave detectors," *Phys. Rev. Lett.*, vol. 124, Apr. 2020, Art. no. 171101, doi: 10.1103/PhysRevLett.124.171101.

[58] L. McCuller et al., "Frequency-dependent squeezing for advanced LIGO," *Phys. Rev. Lett.*, vol. 124, Apr. 2020, Art. no. 171102, doi: 10.1103/PhysRevLett.124.171102.

[59] M. Punturo et al., "The third generation of gravitational wave observatories and their science reach," *Classical Quantum Gravity*, vol. 27, Apr. 2010, Art. no. 084007, doi: 10.1088/0264-9381/27/8/084007.

[60] R. Schnabel et al., "Building blocks for future detectors: Silicon test masses and 1550 nm laser light," in *Proc. J. Phys.: Conf. Ser.*, vol. 228, IOP Publishing, 2010, Art. no. 12029, doi: 10.1088/1742-6596/228/1/012029.

[61] R. X. Adhikari et al., "A cryogenic silicon interferometer for gravitational-wave detection," *Classical Quantum Gravity*, vol. 37, Aug. 2020, Art. no. 165003, doi: 10.1088/1361-6382/ab9143.

[62] M. Mehmet et al., "Observation of CW squeezed light at 1550 nm," *Opt. Lett.*, vol. 34, pp. 1060–1062, Apr. 2009, doi: 10.1364/OL.34.001060.

[63] S. Chelkowski et al., "Experimental characterization of frequency-dependent squeezed light," *Phys. Rev. A*, vol. 71, Jan. 2005, Art. no. 013806, doi: 10.1103/PhysRevA.71.013806.

[64] F. Acernese et al., "Quantum backaction on kg-scale mirrors: Observation of radiation pressure noise in the advanced virgo detector," *Phys. Rev. Lett.*, vol. 125, Sep. 2020, Art. no. 131101, doi: 10.1103/PhysRevLett.125.131101.

[65] V. B. Braginsky and F. Y. Khalili, "Quantum nondemolition measurements: The route from toys to tools," *Rev. Modern Phys.*, vol. 68, 1996, Art. no. 1, doi: 10.1103/RevModPhys.68.1.

[66] Z. Y. Ou, S. F. Pereira, H. J. Kimble, and K. C. Peng, "Realization of the Einstein-Podolsky-Rosen paradox for continuous variables," *Phys. Rev. Lett.*, vol. 68, pp. 3663–3666, Jun. 1992, doi: 10.1103/PhysRevLett.68.3663.

[67] T. Eberle, V. Händchen, and R. Schnabel, "Stable control of 10 dB two-mode squeezed vacuum states of light," *Opt. Exp.*, vol. 21, no. 9, pp. 11546–11553, 2013, doi: 10.1364/OE.21.011546.

[68] Y. Ma et al., "Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement," *Nature Phys.*, vol. 13, pp. 776–780, May 2017, doi: 10.1038/nphys4118.

[69] J. Südbeck, S. Steinlechner, M. Korobko, and R. Schnabel, "Demonstration of interferometer enhancement through Einstein–Podolsky–Rosen entanglement," *Nature Photon.*, vol. 14, pp. 240–244, Apr. 2020, doi: 10.1038/s41566-019-0583-3.

[70] M. J. Yap et al., "Broadband reduction of quantum radiation pressure noise via squeezed light injection," *Nature Photon.*, vol. 14, pp. 223–226, Jan. 2020, doi: 10.1038/s41566-019-0527-y.

[71] H. Vahlbruch, S. Chelkowski, K. Danzmann, and R. Schnabel, "Quantum engineering of squeezed states for quantum communication and metrology," *New J. Phys.*, vol. 9, pp. 371–371, Oct. 2007, doi: 10.1088/1367-2630/9/10/371.

[72] S. Steinlechner, J. Bauchrowitz, M. Meinders, H. Müller-Ebhardt, K. Danzmann, and R. Schnabel, "Quantum-dense metrology," *Nature Photon.*, vol. 7, pp. 626–630, Jun. 2013, doi: 10.1038/nphoton.2013.150.

[73] M. Meinders and R. Schnabel, "Sensitivity improvement of a laser interferometer limited by inelastic back-scattering, employing dual readout," *Classical Quantum Gravity*, vol. 32, Oct. 2015, Art. no. 195004, doi: 10.1088/0264-9381/32/19/195004.

[74] M. Ast, S. Steinlechner, and R. Schnabel, "Reduction of classical measurement noise via quantum-dense metrology," *Phys. Rev. Lett.*, vol. 117, Oct. 2016, Art. no. 180801, doi: 10.1103/PhysRevLett.117.180801.

[75] C. H. Bennett and G. Brassard, "Quantum cryptography: Public key distribution and coin tossing," *Theor. Comput. Sci.*, vol. 560, no. P1, pp. 7–11, 2014, doi: 10.1016/j.tcs.2014.05.025.

[76] S. Pirandola et al., "Advances in quantum cryptography," *Adv. Opt. Photon.*, vol. 12, Dec. 2020, Art. no. 1012, doi: 10.1364/AOP.361502.

[77] T. Gehring et al., "Implementation of continuous-variable quantum key distribution with composable and one-sided-device-independent security against coherent attacks," *Nature Commun.*, vol. 6, Oct. 2015, Art. no. 8795, doi: 10.1038/ncomms9795.

[78] J. Fiurášek, "Gaussian transformations and distillation of entangled Gaussian states," *Phys. Rev. Lett.*, vol. 89, Sep. 2002, Art. no. 137904, doi: 10.1103/PhysRevLett.89.137904.

[79] G. Giedke, J. Ignacio Cirac, and I. J. Cirac, "Characterization of Gaussian operations and distillation of Gaussian states," *Phys. Rev. A*, vol. 66, Sep. 2002, Art. no. 032316, doi: 10.1103/PhysRevA.66.032316.

[80] L. Lydersen, C. Wiechers, C. Wittmann, D. Elser, J. Skaar, and V. Makarov, "Hacking commercial quantum cryptography systems by tailored bright illumination," *Nature Photon.*, vol. 4, no. 10, pp. 686–689, 2010, doi: 10.1038/NPHOTON.2010.214.

[81] E. Knill, R. Laflamme, and G. J. Milburn, "A scheme for efficient quantum computation with linear optics," *Nature*, vol. 409, pp. 46–52, Jan. 2001, doi: 10.1038/35051009.

[82] P. Kok, W. J. Munro, K. Nemoto, T. C. Ralph, J. P. Dowling, and G. J. Milburn, "Linear optical quantum computing with photonic qubits," *Rev. Modern Phys.*, vol. 79, pp. 135–174, Jan. 2007, doi: 10.1103/RevModPhys.79.135.

[83] M. V. Larsen, X. Guo, C. R. Breum, J. S. Neergaard-Nielsen, and U. L. Andersen, "Deterministic generation of a two-dimensional cluster state," *Science*, vol. 366, pp. 369–372, Oct. 2019, doi: 10.1126/science.aay4354.

[84] K. Fukui and S. Takeda, "Building a large-scale quantum computer with continuous-variable optical technologies," *J. Phys. B: At., Mol. Opt. Phys.*, vol. 55, Jan. 2022, Art. no. 012001, doi: 10.1088/1361-6455/ac489c.

[85] D. Gottesman, A. Kitaev, and J. Preskill, "Encoding a qubit in an oscillator," *Phys. Rev. A. At., Mol., Opt. Phys.*, vol. 64, no. 1, Jun. 2001, Art. no. 012310, doi: 10.1103/PhysRevA.64.012310.

Roman Schnabel received the Ph.D. degree in physics with experimental work in plasma physics and atomic spectroscopy from the Leibniz Universität, Hannover, Germany, in 1999.

From 2000 to 2002, he was a Research Fellow with the Australian National University, Canberra, ACT, Australia, supported by a Feodor Lynen grant from the Alexander von Humboldt Foundation. From 2003 to 2008, he was a Junior Professor, and from 2008 to 2014, a Full Professor (W2) with the Leibniz Universität Hannover. Since 2014, he has been a Full Professor (W3) with the Universität Hamburg, Hamburg, Germany, at the Institut für Laserphysik and the Zentrum für Optische Quantentechnologien. He has authored more than 300 articles. His research interests include in the foundations of quantum physics.

Dr. Schnabel was the recipient of the 2013 Joseph F. Keithley Award from the American Physical Society. He has been member of the GEO 600 Collaboration and the LIGO Scientific Collaboration since 2003 and 2005, respectively, and is a Full Member of the Academy of Sciences and Humanities in Hamburg and the German Physical Society.

Axel Schönbeck received the B.Sc. and M.Sc. degrees in physics from the Leibniz Universität Hannover, Hannover, Germany, in 2010 and 2014. He received the Ph.D. degree in physics from the Universität Hamburg, Hamburg, Germany, in 2018.

During his master studies, he spent two semesters with the University of Queensland, Brisbane, QLD, Australia. Since then, he has worked as a Postdoctoral Researcher with the Institut für Laserphysik, Universität Hamburg. He has authored severa articles in *Optics Letters*. His research interests include laser physics, quantum optics and squeezed states of light. He is focusing on advancing the development of squeeze lasers.