Quantum Up-Conversion of Squeezed Vacuum States from 1550 to 532 nm

Christina E. Vollmer,[1] Christoph Baune,[1] Aiko Samblowski,[1] Tobias Eberle,[1] Vitus Händchen,[1]
Jaromír Fiurášek,[2] and Roman Schnabel[1,*]
[1]*Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut)*
and Institut für Gravitationsphysik der Leibniz Universität Hannover,
Callinstraße 38, 30167 Hannover, Germany
[2]*Department of Optics, Palacký University, 17. listopadu 12, 77146 Olomouc, Czech Republic*

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Squeezed vacuum states constitute a particularly useful resource in quantum information as well as in quantum metrology. The frequency conversion of these states is important to provide the bridge between different wavelengths within a sequence of downstream applications and also to provide a way for squeezed-state generation at so-far inaccessible wavelengths. Here we demonstrate the external quantum up-conversion of carrier-light-free squeezed vacuum states for the first time. Our result proves that nondegenerate sum-frequency generation preserves the coherences that are present between photon pairs and higher-order photon pairs of the squeezed input state.

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Frequency conversion constitutes a standard process for light fields in coherent states and mixtures thereof. Via frequency conversion, laser radiation can be shifted to wavelength regimes that are not directly accessible via state-of-the-art laser media. In particular, frequency up-conversion is of high interest to increase the resolution in imaging and lithography [1] and to increase the sensitivity in phase measurements [2]. For light in nonclassical states, the task of frequency conversion is much more challenging. First, nonlinear processes are the more efficient the higher the light intensities, but the most practical and useful nonclassical states are extremely faint, for instance Fock states, squeezed vacuum states and superpositions of (dim) coherent states. Second, in order to preserve the distinct nonclassical properties of the input states high conversion efficiencies of ideally close to unity are mandatory.

Optical fields in squeezed vacuum states consist of pairs and higher-order pairs of photons. The coherences between them give rise to a squeezed photon counting noise in a balanced homodyne detector. These states have been used for the realization of teleportation [3,4], superpositions of coherent states (Schrödinger kitten states) [5,6], and quantum key distribution [7,8], as well as quantum enhancements of spectroscopy [9], imaging [10,11], and weak-force measurements such as those performed in gravitational-wave detectors [12–15]. The absence of any bright carrier field makes squeezed vacuum states ideal for quantum communication and metrology since photon-phonon scattering from the carrier field (Brillouin scattering) easily spoils the squeezed vacuum states in the audio- and radio-frequency sideband [16,17].

With their pioneering work in 1992, Huang and Kumar demonstrated quantum frequency conversion of a bright beam maintaining its nonclassical intensity correlation with another bright beam via second-harmonic generation (SHG) [18]. SHG, however, cannot be used for faint nonclassical states. In 2004, frequency up-conversion of single photons was achieved via nondegenerate sum-frequency generation [19] and used to increase the detection efficiency in quantum key distribution [20]. In [21] the nonclassical correlation between an up-converted photon and a reference photon was verified. While not yet demonstrated the success of these experiments suggests that sum-frequency generation should allow for the quantum up-conversion of more complex faint nonclassical states.

Here, we report on the first quantum conversion of (carrier-light-free) squeezed vacuum states. A 4 dB squeezed vacuum state at 1550 nm is coupled into an external cavity and converted to a 1.5 dB squeezed vacuum state at 532 nm. The reduction of the squeezing factor can be explained by optical loss. Our scheme for quantum up-conversion uses external-cavity, nondegenerate sum-frequency generation with an intense field at 810 nm and is depicted in Fig. 1.

In a perfect lossless experiment with optimized cavity parameters, sum-frequency generation is able to provide an up-conversion efficiency of 100%, even for arbitrarily faint light fields. It is thus able to transfer the full quantum properties of the input state (described by the annihilation operator $\hat{a}_1$) to a state with higher optical frequency (described by the annihilation operator $\hat{a}_2$). For faint input states such as squeezed vacuum states the intense pump field ($\hat{a}_P$) is not depleted and the Hamilton operator of this process is approximately given by [22,23]

$$\hat{H}_{\text{eff}} = i\hbar(\zeta \hat{a}_1 \hat{a}_2^\dagger - \zeta^* \hat{a}_1^\dagger \hat{a}_2). \tag{1}$$

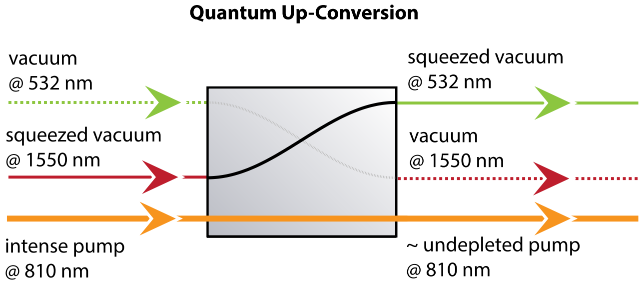

FIG. 1 (color online). Schematic of quantum up-conversion (QUC) of a squeezed vacuum field from 1550 nm to 532 nm. The nondegenerate sum-frequency generator is pumped with a coherent light field at 810 nm being the shortest intense wavelength in this setup. In contrast to a direct squeezing generation at 532 nm via parametric down-conversion (PDC), our scheme does not require an intense pump field at half the squeezing wavelength (here 266 nm). Since absorption and vulnerability for photorefractive damage of typical nonlinear media increases towards shorter wavelengths our approach opens the possibility for so far inaccessible short wavelengths.

Here, $\zeta = |\zeta| e^{i\phi}$ is a complex-valued coupling constant. Its absolute value is proportional to the mean pump amplitude $\langle \hat{a}_{\mathrm{P}} \rangle$ and the second-order susceptibility $\chi^{(2)}$ of the crystal, and ϕ describes the phase difference between the input field and the pump field. The evolution of $\hat{a}_j$ obtained from Heisenberg's equation of motion [22,23],

$$\hat{a}_1(t) = \hat{a}_1(0)\cos(|\zeta| t) - \hat{a}_2(0)\frac{\zeta^*}{|\zeta|}\sin(|\zeta| t),$$
$$\hat{a}_2(t) = \hat{a}_2(0)\cos(|\zeta| t) + \hat{a}_1(0)\frac{\zeta}{|\zeta|}\sin(|\zeta| t), \tag{2}$$

shows that the entire quantum state can be transferred. After the time $t_c = \pi/2\zeta$ the input field $\hat{a}_1$ is converted completely into the output state $\hat{a}_2(t_c) = \hat{a}_1(0)e^{i\phi}$. Equations (2) further show that the phase of the up-converted field reproduces the phase of the pump field $e^{i\phi} = \zeta/|\zeta|$. In summary, changes of the pump field's amplitude result in changes of the up-conversion efficiency. Changes of the pump field's phase result in changes of the up-converted output state's phase. Requirements on the pump field stability are thus identical to those in the generation of squeezed vacuum states via parametric down-conversion.

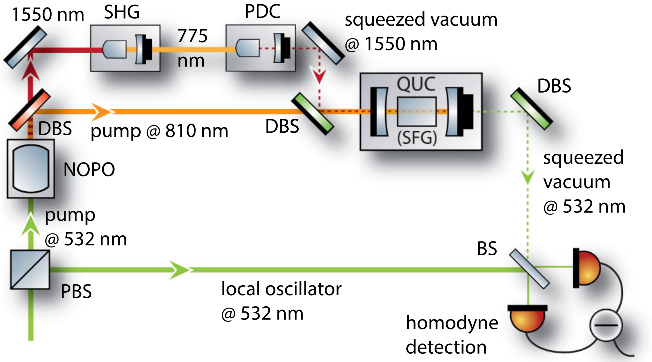

FIG. 2 (color online). Schematic of the experimental setup. The left half shows the (conventional) generation of squeezed vacuum states of light at 1550 nm and the generation of intense radiation at 810 nm based on cavity enhanced parametric down-conversion (PDC) and above-threshold nondegenerated optical parametric oscillation (NOPO), respectively. Both fields are superimposed and mode matched into the sum-frequency generator (SFG) for quantum up-conversion (QUC). Here photon pairs at 1550 nm are converted unconditionally to photon pairs at 532 nm with a measured quantum efficiency of 75%. The coherences between the photon pairs are conserved since balanced homodyne detection proved a squeezed shot noise when overlapping the up-converted squeezed vacuum state with a bright local oscillator at 532 nm. SHG: second-harmonic generation; DBS: dichroic beam splitter for separating different wavelengths; PBS: polarizing beam splitter; BS: balanced beam splitter.

A schematic of our experimental setup is depicted in Fig. 2. A 700 mW continuous-wave light field at 532 nm was used to produce the required pump field at 810 nm via nondegenerate optical parametric oscillation (NOPO) in periodically poled type I potassium titanyl phosphate (PPKTP). The PPKTP crystal was polished and coated to form a monolithic cavity that was doubly resonant at 810 and 1550 nm. Besides bright 810 nm radiation, the cavity also produced a copropagating bright idler field of about 100 mW at 1550 nm. The latter we used for the generation of squeezed vacuum states at 1550 nm in downstream cavities. First, the idler field at 1550 nm was frequency doubled via second-harmonic generation [24]. Second, the new field at 775 nm (18 mW) was then mode matched into another PPKTP cavity for parametric down-conversion (optical parametric amplification below threshold) and for the generation of squeezed vacuum states at 1550 nm. For details see for example [16]. The outgoing wavelengths of the NOPO could be varied in a range of about 15 nm by temperature tuning of the crystal. The squeezed vacuum field at 1550 nm was overlapped with an intense pump field at 810 nm and mode matched into our quantum up-conversion (QUC) cavity. The input coupler had a reflectivity of $(96.5 \pm 0,5)\%$ at both input wavelengths and a high reflectivity of $> 99.9\%$ at 532 nm. The output coupler at the opposite side of the cavity had an antireflection coating at 532 nm, which additionally provided high reflectivities at 810 and 1550 nm. The QUC cavity had an optical length of about 52 mm and contained an antireflection coated KTP crystal with respective periodic poling. The tuning of the crystal's temperature was used to achieve simultaneous resonance for both input wavelengths, and also to approximate the quasi-phase-matching condition for all three wavelengths involved. The quantum up-converted squeezed vacuum states at 532 nm were finally separated from the remaining pump field by a dichroic beam splitter and were characterized with a balanced homodyne detector (BHD). A small fraction of

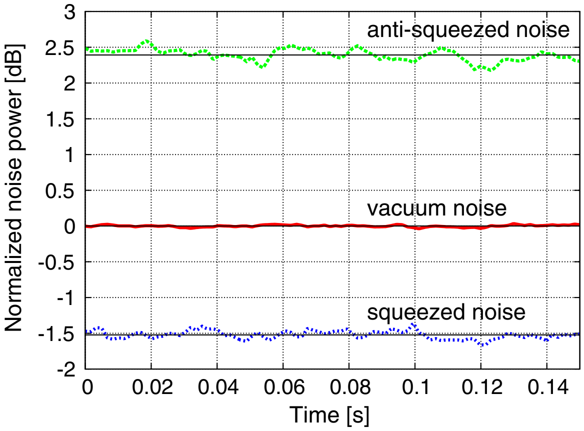

FIG. 3 (color online). Experimental proof of up-converted vacuum squeezing at 532 nm. For this measurement the balanced homodyne detector (BHD) output was bandpass filtered around a Fourier frequency of $f = 8$ MHz. The noise power of the corresponding zero-point fluctuation (vacuum noise) was taken with a blocked signal input port of the BHD and then used to normalize all three traces. Corrections to the data such as dark noise subtraction were not applied. A nonclassical noise reduction of 1.5 dB below the vacuum noise and an antisqueezing of 2.4 dB were measured. These values correspond to an initial 4 dB highly pure squeezed state at 1550 nm, a quantum up-conversion efficiency of 75% and a total detection efficiency of 71% . These values were independently verified.

the initial green pump field served as the BHD's local oscillator. A detailed description of the measurement of the QUC cavity's up-conversion efficiency can be found in [25].

In our setup, neither the SHG cavity nor the PDC cavity were optimized for the low intensities available. Squeezed vacuum states of just 4 dB squeezing and 4 dB antisqueezing were available at 1550 nm for the quantum up-conversion process. The high purity of the squeezed vacuum states was in agreement with the fact that the same PDC cavity could produce up to 12 dB of squeezing for higher pump powers [26,27]. We finally observed a nonclassical noise reduction of 1.5 dB at 532 nm with a respective antisqueezing of 2.4 dB. Subtraction of the BHD's dark noise, which was 10 dB below the shot noise, resulted in values of 1.7 dB squeezing and 2.6 dB antisqueezing. The reduction of the squeezing factor can be explained by a total loss of 47%, which is in excellent agreement with the independently measured efficiencies of our setup. The total propagation efficiency from the PDC cavity to the QUC cavity and from the QUC cavity to the BHD was 97%, the coupling efficiency to the PDC cavity was 99.4%, the efficiency of the quantum up-conversion process was 75%, the mode-matching efficiency at the BHD was 92%, and the quantum efficiency of the photodiodes was 80% (at 532 nm).

Our measurement data are shown in Fig. 3. Data were taken at a sideband frequency of 8 MHz with a resolution bandwidth of $\Delta f = 300$ kHz and a video bandwidth of 30 Hz. The traces are normalized to the measured vacuum noise and were neither corrected for dark noise nor for detection loss. The same squeezing value was measured at lower MHz frequencies. Below the MHz regime squeezing measurements were not performed since limitations were set by the reduced dark-noise clearance of the balanced homodyne detector and also by the expected imperfect input squeezing at low frequencies. The latter aspect is outlined further down in this paragraph. When increasing the measurement frequencies above 8 MHz the squeezing strengths were found to decrease. This is expected from theory and a result of the finite QUC cavity linewidth of 32 MHz. Our result at 8 MHz, however, represents the capability of our up-conversion setup down to the audio band. Due to our model that is described by Eqs. (1) and (2) our QUC cavity should have a quantum up-conversion efficiency as well as a noise performance that are frequency independent for sideband frequencies well within its linewidth. At all sideband frequencies, down to the audio band, any disturbances of the up-converted squeezing spectrum should relate to disturbances that are already present in the input squeezing spectrum. The up-conversion process itself should not add disturbances. Spectral components of the pump's amplitude fluctuations solely result in (small) modulations of the up-conversion efficiency. Phase fluctuations of the pump lead to an averaging effect that can reduce the measured squeezing factor [28]; however, phase fluctuations of the pump field can be minimized by adopting the phase control scheme that was developed for pump field stabilization in audio- band squeezed-light generation via parametric down-conversion [29]. Since white squeezing spectra have already been demonstrated down to a sideband frequency of 1 Hz [16,17,30], we conjecture that our setup is in principle capable of producing a white squeezing spectrum down to the audio band and below. An experimental demonstration of up-converted low-frequency squeezing will be achievable once a control system as used in Refs. [14,16,29] is added to the generation of the input squeezing as well as to the up-conversion process.

The observed squeezing factor of 0.7 (−1.5 dB) in Fig. 3 was mainly limited by the strength of the input squeezing factor of 0.4 (−4 dB), by the total detection efficiency of 71%, as well as by the efficiency of the quantum up-conversion process (75%). The quantum up-conversion efficiency of 75% was lower than the value of 84.4% as was achieved with our setup in [25]. In the work reported here we could not use the input wavelengths for which our QUC cavity had its best efficiency because these wavelengths corresponded to a rather poor efficiency of the SHG cavity. Our experiment thus used a trade-off between a good conversion efficiency of the SFG cavity and a good conversion efficiency of the SHG cavity.

The high coupling efficiency from the squeezing (PDC) cavity to the up-conversion (QUC) cavity of 99.4%

emphasizes the high potential of our setup for an increased quantum up-conversion efficiency. In the following we describe possible improvements of our setup for better performance. First, the SHG process needs to be improved by increasing the intensity of the pump light at 1550 nm inside the SHG cavity, for instance by increasing the reflectivity of the coupling mirror. Second, similar adjustments have to be made for the squeezing (PDC) cavity and the QUC cavity. Without changing the NOPO cavity our setup should then be able to provide a measured value of more than 12 dB of input squeezing at 1550 nm, even if this wavelength is precisely tuned to the optimum conversion efficiency of the up-conversion cavity. Third, numerical simulations of the up-conversion cavity that also include optical absorption predict a quantum conversion efficiency of slightly above 90% for an optimized coupler reflectivity. Fourth, the detection efficiency of the BHD at 532 nm needs to be as high as the one of our BHD at 1550 nm to avoid any additional loss compared to the measured input squeezing value. With such an optimized setup the observation of up-converted squeezing at 532 nm of about 8 dB should be possible.

In conclusion, we have demonstrated that nondegenerate sum-frequency generation is a feasible route for quantum up-conversion of faint nonclassical states of light. Quantum up-conversion of squeezed vacuum states into the visible regime does not require an ultraviolet second-harmonic pump field as is required by the straight forward approach via parametric down-conversion. The high absorption and the photorefractive damage of nonlinear crystals being irradiated with intense ultraviolet light [31] is thus avoided. Squeezed light can in principle also be produced via four-wave mixing [32], but strong squeezing has not been achieved this way so far. Other methods are self-phase modulation [33] and second-harmonic generation [34]. Neither processes, however, can be used to produce carrier-free squeezed vacuum states.

We emphasize that our setup uses an external cavity for quantum up-conversion; i.e., our setup can be applied within a quantum network that requires up-conversion ‘on the fly’, for instance for up-converting squeezed vacuum states at 1550 nm after transmission through a telecommunication fibre.

By having converted 4 dB squeezed vacuum states at 1550 nm to 1.5 dB squeezing at 532 nm, we have proved that the coherences between photon pairs are maintained by the process of sum-frequency generation. We thus go beyond single-photon conversion [19–21]. With appropriate input states our setup is able to up-convert superpositions of coherent states with negative Wigner functions [5,6] as well as Einstein-Podolsky-Rosen entangled states [3,4]. By converting one part of such a two-mode squeezed state we could provide a quantum link between the telecommunication wavelength of 1550 nm and an in principle arbitrary wavelength in the visible or even ultraviolet spectrum.

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*roman.schnabel@aei.mpg.de

[1] The best resolution that can be achieved in classical lithography is $x \approx \lambda/2$, with λ the light’s wavelength.

[2] The (backaction free) quantum-noise linear spectral density of a laser interferometer in $\mathrm{m}/\sqrt{\mathrm{Hz}}$ reads $\sqrt{S} = e^{-r}\sqrt{\hbar c\lambda/(2\pi P)}$, where P is the light power inside the interferometer, r the squeezing parameter, and λ the light’s wavelength.

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