A Source for Mesoscopic Quantum Optics[†]

Georg Harder^{1,*}, Tim J. Bartley^{1,2}, Adriana E. Lita², Sae Woo Nam², Thomas Gerrits², and Christine Silberhorn¹

The nature of quantum decoherence renders the observation of nonclassical properties in large systems increasingly difficult. Optical states are a good canditate to observe nonclassical features since they are less susceptible to environmental effects. Starting with the landmark experiment by Hanbury-Brown and Twiss,¹ the statistical properties of photons have been used in a broad range of contexts, from quantum enhanced metrology² and fundamental tests of local realism³ to quantum information tasks such as Boson sampling⁴

- and quantum key distribution.⁵ However, generating and directly measuring large numbers of photons in well-defined optical modes has proven highly challenging. To date, the largest states demonstrating non-
- ¹⁵ classical distributions with direct photon number measurements consisted of 8 single-photon modes,^{6,7} spanning a Hilbert space of dimension $2^8 = 256$. Here, we show that a nonclassical state in two well-defined modes of dimension $80 \times 80 = 6400$ can be efficiently
- 20 generated and directly measured. It can further be used to herald nonclassical distributions of up to 50 photons in a single mode. This significantly increases the scale at which quantum optical phenomena can be probed. Moreover, the states we generate are mea-
- $_{25}$ sured with >65% efficiency in the telecom wavelength band of 1535 nm, making them ideal for use in existing telecommunication infrastructure, enabling the next generation of quantum-enhanced technology with large quantum optical states.
- In quantum optics, one common technique to generate nonclassical states of light is parametric downconversion (PDC). This occurs in a dielectric medium with a $\chi^{(2)}$ nonlinearity in which high frequency pump photons decay into two low frequency daughter pho-
- ³⁵ tons, called signal and idler. In our case, the signal and idler photons are orthogonally polarized and ideally described by the two-mode squeezed vacuum state:

$$\left|\psi\right\rangle = \sqrt{1 - \lambda^2} \sum_{n} \lambda^n \left|n, n\right\rangle, \qquad (1)$$

where *n* is the photon number in each mode and $\lambda = \tanh(r)$. The squeezing parameter *r* scales lin-¹Applied Physics, University of Paderborn, 33098 Paderborn,



Figure 1: Setup. Transform-limited pulsed light from a Ti:Sapphire laser is spectrally filtered to produce 1 ps pulses and coupled into the periodically poled KTP waveguide. A Long Pass (LP) filter removes the pump after the down-conversion process in the waveguide and a Band Pass (BP) filter suppresses the sinc-sidelobes of the phasematching function. Signal and idler are split at a Polarizing Beam Splitter (PBS), coupled into single-mode fibers and connected to (up to four) Transition Edge Sensors (TES).

early with the pump field amplitude, the nonlinear coefficient $\chi^{(2)}$, the interaction length inside the crystal and the mode overlap of the pump- and PDC modes. Having perfect photon number correlations, the PDC states can be used to herald Fock states - states with well-defined photon number. Using a unit-efficiency photon-number-resolving detector to measure n photons in one mode projects the other mode in an nphoton Fock state. However, generating and measuring a pure state like in eq. 1 is challanging in practice. If the nonlinear process generates correlations in the spatial or spectral degree of freedom and the measurement cannot resolve these degrees of freedom, then the measurement operation projects the state into a classical mixture of PDC states. As current techniques to filter⁸ or resolve⁹ in particular the spectral degree of freedom for pulsed light introduce significant losses,¹⁰ the key to large, strongly nonclassical states is the engineering of PDC sources which do not produce such correlations^{11,12} in the first place and hence generate the states into well-defined, fully accessible modes.

Spectral decorrelation can be achieved by engineering the momentum conservation (phasematching) condition of the nonlinear interaction,¹³ which typically means engineering the nonlinear dielectric medium and pump properties. Spatial correlations can be fully suppressed by using a waveguide,¹² which is single-mode for the signal and idler down-converted modes. Pre60

40

50

55

Germany

 $^{^2\}mathrm{National}$ Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA

 $^{^{\}dagger}\mbox{Contribution of NIST},$ an agency of the US government, not subject to copy right

^{*}e-mail: georg.harder@uni-paderborn.de



Figure 2: (a) Raw photon number correlation matrix of the state $\langle n \rangle = 20$ with exponentially decaying diagonal elements (inset logarithmic scale). (b) Mean photon number in one mode versus pump power measured with a low efficiency APD. The excellent fit with only one fit parameter α indicates that the state stays single-mode up to at least 80 photons. (c) Noise reduction factor (NRF) for different mean photon numbers, showing the nonclassical correlations in the state. Statistical errorbars in (b) and (c) are smaller than the datapoints.

vious approaches to generate single-mode PDC states used bulk crystals. To generate bright states in a bulk
nonlinear medium, the pump must be tightly focussed to achieve a large nonlinear interaction, which can introduce additional spatial and spectral correlations as the pump power is increased. Due to the intrinsic collinear interaction in a single-mode waveguide, such
pump power dependence should not be present in our source. Additionally, a waveguide geometry has the benefit of increasing the process efficiency in a single spatial mode by two orders of magnitude compared to bulk PDC sources due to confinement of the pump

⁸⁰ beam.¹⁴

85

A schematic of our experimental setup is shown in fig. 1. In the single-photon regime, our source has been characterized in detail^{12,15} and showed relatively high single-photon purities above 80 %. The nonlinear medium consists of an 8 mm long periodically poled

KTP waveguide engineered to produce decorrelated and

degenerate signal and idler modes at 1535 nm. We pump the chip with 1 ps optical pulses containing energies of up to 1.5 nJ and producing states with a mean photon number of up to 80 photons. We measure the photon numbers, shot to shot, with transition edge sensors (TES).¹⁶ The TES have a near unity detection efficiency and feature single-photon resolution below 10 photons but can detect up to 100 photons with a fewphoton uncertainty.¹⁷ We analyze the TES response for each event based on trace overlaps with calibration traces from known coherent state inputs (see methods section). We use either one TES on each mode for states with mean photon numbers $\langle n \rangle < 10$ or two TES on each mode for one state with $\langle n \rangle = 20$. Additionally, we use an avalange photo diode (APD) with attenuators to measure mean photon numbers.

100

The measured photon number probabilities, shown in fig. 2(a) for the state $\langle n \rangle = 20$, feature photon number correlations as well as a logarithmic decaying diago-105 nal, as expected from eq. 1. The vacuum component is still the highest element despite measured mean photon numbers of 11 and 9 in each mode. This directly reveals the single-mode character of the state; for a multimode state, the mixture of different thermal distributions 110 would lead towards a Poissonian distribution. To quantify the single modeness, we calculate the second order autocorrelation function¹⁸ $g^{(2)}(0) = \frac{\langle n^2 \rangle - \langle n \rangle}{\langle n \rangle^2}$, where n is the photon number, on the marginal distribution of each mode. For thermal statistics, $g^{(2)}(0) = 2$ and for 115 Poissonian statistics $g^{(2)}(0) = 1$. For the state shown in fig. 2(a) we obtain 1.89(3) and 1.87(3) for signal and idler, respectively. This corresponds to effective mode numbers¹⁹ $K = 1/(g^{(2)}(0) - 1)$ of 1.12(4) and 1.15(4), where 1 would be the ideal case. All uncertainties given 120 in this letter correspond to the 1σ standard deviation. We see no dependence of the effective mode number on pump power. When we use the highest pump powers available to us, the source generates states with a mean photon number of 80, see fig.2(b). (For this single mea-125 surement we use an APD, calibrated using the Klyshko method.²⁰) The datapoints follow the expected singlemode curve up to the highest available powers.

If we had no loss in our system, the maximum mean photon number of 80 would correspond to 25dB of 130 continuous variable squeezing.¹⁸ Currently, the highest value measured to our knowledge is $12.7 dB^{21}$ including losses (20dB corrected for losses), in a cavity system and continuous wave operation. Since we have a pulsed single-pass source, our approach is fun-135 damentally different from cavity-based continuous-wave schemes, which allows us to use direct photon number detection. Such squeezing may be measured using homodyne detection provided one has fast, low-noise photodiodes at our wavelength (1535 nm) and precise 140 control over the mode of the local oscillator.



Figure 3: Heralded $g^{(2)}(0)$ as a nonclassicality measure for a state with $\langle n \rangle = 7$. The shaded green area accounts for worst case systematic errors stemming from the analysis of the TES response. Errorbars are statistical errors. The heralded states stay nonclassical up to around 50 photons.

The nonclassicality of our state can be seen directly in the raw data. Any classical state, by definition, can

150

be written as a mixture of coherent states with a positive probability distribution. Hence, the photon number uncertainty of \sqrt{N} in a pulse with a mean photon number of N imposes a lower bound on the antidiagonal width $n_s - n_i$ in fig. 2(a). To encapsulate this criterion, one figure of merit is the noise reduction factor NRF = $\frac{\operatorname{Var}(n_s - n_i)}{(n_s - n_s)}$, which is necessarily ≥ 1 for classical states. For ideal PDC states undergoing a loss η , the NRF is equal to $1 - \eta$. We measure values below 0.4, see fig. 2(c), in those cases where we use one

TES on each mode, in agreement with the measured efficiencies of around 66%. This corresponds to $4.2\,\mathrm{dB}$ 155 of correlated photon number squeezing not corrected for losses. In the case where we use two TES on each mode the NRF is higher due to slightly lower and more asymmetric efficiencies in that configuration.

The nonclassicality can also be seen in heralded 160 states. For one and three-photon heralded states we see negative parities $\langle (-1)^n \rangle$ of -0.131(1) and -0.013(2) in the raw heralded data, which is a sufficient condition for nonclassicality. For higher heralded states the parity tends to zero and is obscured by statistical errors.

A more robust criterion is the heralded $g^{(2)}(0)$ value, i.e. the $q^{(2)}(0)$ in one mode conditioned on a certain outcome in the other mode. The $q^{(2)}(0)$ is 1 for coherent states and indicates subpoissonian statistics for

- values below 1. Even heralding on a 50-photon event, 170 the states fulfill this nonclassicality criterion, see fig. 3. As the heralded photon number increases, the transition from strongly nonclassical states to classical states becomes apparent. Producing larger nonclassical states
- would require reducing the losses in the heralding mode. 175 At the current efficiencies, the 50 photon event happens about twice a second with a PDC mean photon number



Figure 4: Inferred states before losses. a) High power state $(\langle n \rangle = 20)$ using a parameter fit to the data. b) Low power state ($\langle n \rangle = 1.4$) using full loss inversion without assumptions about the state.

of 7.

To get a glimpse of how the state of fig. $\mathbf{2}$ would look without losses, we perform a weighted 180 least square fit to the data. We restrict ourselves to contributions from a multimode PDC mode, a coherent state mode and a thermal state mode: $\rho_{in} =$ $\rho_{\rm PDC}(n^{\rm PDC}, K) \otimes \rho_{\alpha}(n_{\rm s}^{\alpha}, n_{\rm i}^{\alpha}) \otimes \rho_{\rm th}(n_{\rm s}^{\rm th}, n_{\rm i}^{\rm th}),$ where nare the respective mean photon numbers and K the effective mode number of the PDC mode. This state undergoes losses, modelled by beam splitter matrices L: $\rho_{\text{out}} = (L_{\text{s}}(\eta_{\text{s}}) \otimes L_{\text{i}}(\eta_{\text{i}}))\rho_{\text{in}}$. The best fit of ρ_{out} to the data has the fit parameters ($\eta_{\rm s} = 43.13(3)\%$; $\eta_{\rm i} = 52.12(4)\%$; $n^{\rm PDC} = 20.30(2)$; $K = 1.097(1), n_{\rm s}^{\alpha} =$ 190 $0.14(12); n_i^{\alpha} = 0.38(5); n_s^{\text{th}} = 0.00(12); n_i^{\text{th}} = 0.00(5))$ and is shown in fig. 4. It has a fidelity with the data of 99.98%. The largest contribution by almost two orders of magnitude is the PDC. For low power states, which can be described in a space < 15 photons, we also perform a general loss inversion,²² shown in fig. 4(inset). 195 These states also resemble the expected PDC states.

The excellent agreement with theory indicates that the limiting factor is indeed the loss in our setup. We calculate our system efficiencies by either assuming per-200 fect photon number correlations²³ or by our least square fit. We obtain 60% and 64% for signal and idler, respectively, using the first method and 64% and 68%using the second method with systematic uncertainties around 3%. The efficiencies are slightly higher in the 205 latter case because we allow for Poissonian and thermal noise in the original data stemming either from an optical background or a non-perfect photon number resolution in the detectors. Such noise looks like loss in the first method. For the $\langle n \rangle = 20$ state, the sec-210 ond method gives 43% and 52% for signal and idler.

Here, the efficiencies are lower due to the change of the experimental configuration from two TES to four TES requiring an extra pair of fibre beam splitters.

- Total Efficiencies close to 70% are among the highest 215 in the literature^{3,24,25} and to our knowledge the highest at telecom wavelengths. These high efficiencies are the reason why we see clear nonclassical features in the raw data without loss inversion. For example, negative parity can only be observed above 50% in principle.
- 220

The main loss contributions in our setup come from the coupling to single-mode fibers of around 80% and the linear optical elements with a total transmission of about 90%. With on chip integration of polarizing

- beam splitters and detectors, of which both have been 225 demonstrated.^{26,27} the total efficiencies could go up to above 90%. This would push the size of possible nonclassical states to hundreds of photons. The ultimate goal would be an efficiency around 99% at which fault tolerant quantum computation with CV cluster states
- becomes possible.²⁸

In this letter we have directly measured large quantum states with up to 80 photons per mode and accessed that space with near single-photon resolution.

- This increases the size of photonic quantum states that 235 can be probed by an order of magnitude, entering a new regime of mesoscopic quantum optics. Moreover, this is achieved with world record efficiencies at telecom wavelenghts. The combination of bright single-
- mode states and high-efficiency TES detectors is ideally 240 suited for the generation of large cat states,^{24,29} NOON states³⁰ and CV entangled states. It extends the singlephoton world of current quantum experiments into a mesoscopic, multiphoton regime.
- This work was supported by the Qauntum Informa-245 tion Science Initiative (QISI). TJB acknowledges funding from the Deutscher Akademische Auslandsdienst (DAAD).

References

260

- ¹ Hanbury-Brown, R. & Twiss, R. Correlation between 250 Photons in two Coherent Beams of Light. Nature 177, 27 (1956).
- ²Giovannetti, V., Lloyd, S. & Maccone, L. Quantum-Enhanced Measurements: Beating the Standard Quantum Limit. Science 306, 1330-255 1336 (2004). URL http://www.sciencemag.org/ content/306/5700/1330.
 - ³ Christensen, B. G. et al. Detection-Loophole-Free Test of Quantum Nonlocality, and Applications. Phys. Rev. Lett. 111, 130406 (2013). URL
- http://link.aps.org/doi/10.1103/PhysRevLett. 111.130406.

⁴ Spring, J. B. *et al.* Boson Sampling on a Photonic Chip. Science 339, 798-801 (2013). URL http:// www.sciencemag.org/content/339/6121/798.

265

- ⁵Gisin, N., Ribordy, G., Tittel, W. & Zbinden, H. Quantum cryptography. Rev. Mod. Phys. 74, 145-195 (2002). URL http://link.aps.org/doi/10. 1103/RevModPhys.74.145.
- ⁶ Yao, X.-C. et al. Observation of eight-photon 270 entanglement. Nat Photon 6, 225-228 (2012). URL http://www.nature.com/nphoton/journal/v6/n4/ abs/nphoton.2011.354.html.
- ⁷Huang, Y.-F. et al. Experimental generation of an eight-photon Greenberger-Horne-Zeilinger state. 275 Nature Communications 2, 546 (2011). URL http:// www.nature.com/doifinder/10.1038/ncomms1556.
- ⁸ Pérez, A. M. et al. Bright squeezed-vacuum source with 1.1 spatial mode. Opt. Lett. 39, 2403-2406 (2014). URL http://ol.osa.org/abstract.cfm? 280 URI=01-39-8-2403.
- ⁹ Brecht, B. et al. Demonstration of coherent timefrequency Schmidt mode selection using dispersionengineered frequency conversion. Phys. Rev. A 90, 030302 (2014). URL http://link.aps.org/doi/10. 285 1103/PhysRevA.90.030302.
- ¹⁰ Christ, A., Lupo, C., Reichelt, M., Meier, T. & Silberhorn, C. Theory of filtered type-II parametric down-conversion in the continuous-variable domain: Quantifying the impacts of filtering. Phys. Rev. A 90, 290 023823 (2014). URL http://link.aps.org/doi/10. 1103/PhysRevA.90.023823.
- 11Mosley, P. J. et al. Heralded Generation of Ultrafast Single Photons in Pure Quantum States. Phys. Rev. Lett. 100, 133601 (2008). URL http://link.aps. org/doi/10.1103/PhysRevLett.100.133601.
- ¹² Eckstein, A., Christ, A., Mosley, P. J. & Silberhorn, C. Highly Efficient Single-Pass Source of Pulsed Single-Mode Twin Beams of Light. Phys. Rev. Lett. 106, 013603 (2011). URL http://link.aps.org/ 300 doi/10.1103/PhysRevLett.106.013603.
- ¹³Grice, W. P., U'Ren, A. B. & Walmsley, I. A. Eliminating frequency and space-time correlations in multiphoton states. Phys. Rev. A 64, 063815 (2001). URL http://link.aps.org/doi/10.1103/ PhysRevA.64.063815.
- 14 Fiorentino, M. *et al.* Spontaneous parametric down-conversion in periodically poled KTP waveguides and bulk crystals. Opt. Express 15, 7479-7488 (2007). URL http://www.opticsexpress.org/ 310 abstract.cfm?URI=oe-15-12-7479.

¹⁵ Harder, G. et al. An optimized photon pair source for quantum circuits. Opt. Express 21, 13975-13985 (2013). URL http://www.opticsexpress. org/abstract.cfm?URI=oe-21-12-13975.

315

¹⁶ Lita, A. E., Miller, A. J. & Nam, S. W. Counting near-infrared single-photons with 95% efficiency. Opt. Express 16, 3032-3040 (2008). URL http://www.opticsexpress.org/abstract.cfm? URI=oe-16-5-3032.

320

335

340

345

350

360

 17 Gerrits, T. *et al.* Extending single-photon optimized superconducting transition edge sensors beyond the single-photon counting regime. Opt. Express 20, 23798–23810 (2012). URL http://www.opticsexpress.org/abstract.cfm?

325 URI=oe-20-21-23798.

- ¹⁸Loudon, R. The Quantum Theory of Light (OUP Oxford, 2000).
- ¹⁹ Eberly, J. H. Schmidt analysis of pure-Laser Phys. 16, 921-926 state entanglement. 330 (2006). URL http://link.springer.com/article/ 10.1134/S1054660X06060041.
 - ²⁰ Klyshko, D. N. Use of two-photon light for absolute calibration of photoelectric detectors. Sov. J. Quantum Electron. 10, 1112 (1980). URL http: //iopscience.iop.org/0049-1748/10/9/A09.
 - ²¹ Eberle, T. et al. Quantum Enhancement of the Zero-Area Sagnac Interferometer Topology for Gravitational Wave Detection. Phys. Rev. Lett. 104, 251102 (2010). URL http://link.aps.org/doi/10.1103/
 - PhysRevLett.104.251102.
 - ²² Feito, A. *et al.* Measuring measurement: theory and practice. New J. Phys. 11, 093038 (2009). URL http://iopscience.iop.org/1367-2630/11/ 9/093038.
 - ²³ Worsley, A. P. *et al.* Absolute efficiency estimation of photon-number-resolving detectors us-Opt. Express 17. 4397-4411 ing twin beams. (2009).URL http://www.opticsexpress.org/ abstract.cfm?URI=oe-17-6-4397.
 - $^{24}\,\mathrm{Gerrits},\,\mathrm{T.}$ $et\,al.$ Generation of optical coherent-state superpositions by number-resolved photon subtraction from the squeezed vacuum. Phys. Rev. A 82, 031802 (2010). URL http://link.aps.org/doi/10. 1103/PhysRevA.82.031802.

355

 25 Dixon, P. B. *et al.* Heralding efficiency and correlated-mode coupling of near-IR fiber-coupled photon pairs. Phys. Rev. A 90, 043804 (2014). URL http://link.aps.org/doi/10.1103/ PhysRevA.90.043804.

- ²⁶ Alferness, R. C. & Buhl, L. L. Low-cross-talk waveguide polarization multiplexer/demultiplexer for ? =1.32 ?m. Opt. Lett. 9, 140-142 (1984). URL http: //ol.osa.org/abstract.cfm?URI=ol-9-4-140.
- ²⁷ Calkins, B. et al. High quantum-efficiency photon-365 number-resolving detector for photonic on-chip information processing. Optics Express 21, 22657 URL http://www.opticsinfobase.org/ (2013).abstract.cfm?URI=oe-21-19-22657.
- ²⁸ Menicucci, N. C. Fault-Tolerant Measurement-370 Based Quantum Computing with Continuous-Variable Cluster States. Phys. Rev. Lett. 112, 120504 (2014). URL http://link.aps.org/doi/10.1103/ PhysRevLett.112.120504.
- $^{29}\,\mathrm{Ourjoumtsev},\,\,\mathrm{A.},\,\,\mathrm{Jeong},\,\,\mathrm{H.},\,\,\mathrm{Tualle-Brouri},\,\,\mathrm{R.}\,\,\&$ 375 Grangier, P. Generation of optical 'Schrödinger cats' from photon number states. Nature 448, 784-786 (2007). URL http://www.nature.com/nature/ journal/v448/n7155/abs/nature06054.html.
- ³⁰ Afek, I., Ambar, O. & Silberberg, Y. High-NOON 380 States by Mixing Quantum and Classical Light. Science 328, 879-881 (2010). URL http://www. sciencemag.org/content/328/5980/879.