Efficient conversion of coherent laser light to photon bunching

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Light sources demonstrating photon bunching find practical applications in range finding, imaging, and clock synchronization. However, existing schemes to generate detectable photon bunching subject the source light to high losses, resulting in dim photon bunching light. We present a low-loss scheme to generate ultrabright photon bunching, by transmitting laser light with a finite coherence time through a multi-path interferometer. Using this scheme, we demonstrated a less lossy photon bunching source about 14 orders of magnitude brighter in spectral density than many photon bunching sources from down-conversion in non-linear media.

I. INTRODUCTION

There are a few ways to generate photon bunching with sufficiently long coherence timescales to be detected and timing resolved by single photon avalanche detectors. Popular techniques transmit coherent laser light through random phase dispersion media such as a rotating ground glass, or a liquid suspension of microspheres. However, the random scattering process introduces spatial incoherence that reduces the coupled single-mode bunched light by around 10 orders of magnitude. Photon bunching can also be generated by laser light through spontaneous parametric conversion (SPDC) processes which are similarly inefficient.

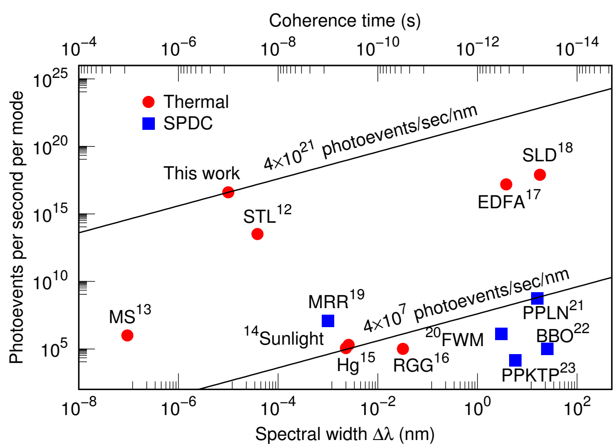

FIG. 1. Spectral densities of stationary light sources with thermal and SPDC correlations: STL [5] – subthreshold laser diode, MS [6] – suspension of microspheres, Sunlight [7] – filtered Sunlight, Hg [8] – Mercury discharge lamp, RGG [9] – rotating ground glass, EDFA [10] – Erbium-doped fiber amplifier, SLD [11] – superluminescent diode, MRR [12] – cavity enhanced via microring resonator, FWM [13] – four-wave mixing, PPLN [14] – periodically poled Lithium Niobate, BBO [15] – Beta-Barium Borate, PPKTP [16] – periodically poled Potassium Titanyl Phosphate.

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We present an efficient photon bunching conversion technique based on sending continuous-wave laser through a multi-path interferometer with path differences significantly longer than the coherence time of the laser light. A photon bunching source at 1 mW output power is demonstrated, with a characteristic photon bunching timescale of about 135 ns which is easily resolvable by readily available photodetectors.

II. THEORY

We present here an analytical description of a scheme that changes the coherent light, from a laser, to light exhibiting photon bunching. In this scheme, coherent light is sent through a multi-path interferometer, formed by a cascade of n number of Mach-Zehnder interferometers. By choosing appropriate propagation delay in each of the Mach-Zehnder interferometer, a resulting light field appears to be a superposition of 2^n coherent light fields which demonstrate some extent of phase-independence between each other. This superposed light field approaches the model for thermal or chaotic light.

The coherent light from the laser can be modelled as an electric field

$$E(t) = E_0 e^{i[2\pi f t + \phi(t)]}, \tag{1}$$

where E_0 is the amplitude of the electric field that is assumed to be constant, f is the frequency of the laser, and $\phi(t)$ is a random phase fluctuation related to the coherence time τ_c of the laser light source via

$$\langle e^{-i\phi(t)}\, e^{i\phi(t+\Delta)} \rangle = e^{-\tau/\tau_c}, \tag{2}$$

where $\langle \ldots \rangle$ is denotes the expectation value of its arguments and we have assumed a Lorentzian spectral lineshape for the laser light.

The laser light is coupled into a fibre beam splitter which the light into two paths. The light in one of the paths travels through a long optical fibre which introduces a propagation delay Δ_1 with respect to the light in the second path. The light from these two paths each enter separate input ports of a second beam splitter which interferes the two light fields, forming an asymmetric

Mach-Zehnder interferometer. The resulting light emerging from the output port A_1, B_1 of the interferometer has an electric field

$$E_{A_1,B_1}(t) = \frac{1}{\sqrt{2}}\left[E(t) \pm E(t-\Delta_1)\right], \quad (3)$$

where the sign difference is the result of a relative π phase-shift added to one of the fields by the beam splitter, here assumed to be on $E(t+\Delta_1)$.

The light from one of the output port, here assumed to be port B_1, is sent through another long optical fibre. This introduces another propagation delay Δ_2 to the light from at output B_1, with respect to the light from output A_1. The light from output port A_1 and the light from output port B_1 delayed by Δ_2 each enters separate input ports of a third beamsplitter, interfering the two light fields. This results in the light emerging from the output ports A_2, B_2 of the third beamsplitter to be

$$E_{A_2,B_2}(t) = \frac{1}{\sqrt{2}}\left[E_{A_1}(t) \pm E_{B_1}(t-\Delta_2)\right], \quad (4)$$

where the sign difference is the result of a relative π phase-shift added to one of the fields by the beam splitter, here assumed to be on $E_{B_1}(t+\Delta_1)$.

The act of sending light from one of the beamsplitter output ports through a long optical fibre, and recombining at another beams splitter may be repeated for a total of n iterations. The resultant electric field emerging from the final beamsplitter in the chain is

$$E_{A_n,B_n}(t) = \frac{1}{\sqrt{2}}\left[E_{A_{n-1}}(t) \pm E_{B_{n-1}}(t-\Delta_n)\right], \quad (5)$$

where we have assumed the light field $E_{B_{n-1}}$ has been sent through the n-th long optical fibre, introducing a propagation delay Δ_n, and have picked up a π-phase at the last beamsplitter.

From Eqn. 3 to 5, it can be shown that the light field $E_{A_n,B_n}(t)$ emerging from the the last beamsplitter generally consists of 2^n electric field terms, which each term being the coherent light field $E(t)$ with a propagation delay formed by different combinations of Δ_1 to Δ_n. Furthermore, we impose the following condition between the propagation delays Δ_i and the coherence time τ_c of the coherent light

$$\Delta_i - \sum_{\alpha=1}^{\alpha=i-1} > \Delta_{\min} \gg \tau_c, \quad (6)$$

where $\Delta_{\min}$ is the smallest difference in propagation delays pairwise between the 2^n electric fields. This results in the difference in propagation delays between any of the 2^n fields to be alwats significantly greater than τ_c. Effectively, any electric field pairs $E_{\alpha,\beta}$ of the 2^n electric fields would appear phase-independent between zero-time difference up to the vicinity of $\Delta_{\min}$ i.e.

$$\langle E^*_\alpha(t)E_\beta(t+\tau)\rangle \approx 0 \text{ for } \|\tau\| \lessapprox \Delta_{\min}. \quad (7)$$

This approximate phase-independence condition results in the output light field to appear like a superposition of 2^n independent coherent emitters, modelled similarly for thermal light. Following the model of an ensemble of indendent emitters, the second-order photon correlation would similarly predict photon bunching for this light source.

III. SETUP

This work shows a near-unity conversion scheme to produce ultrabright, spectrally narrowband, and spatially single-mode photon bunching from a seed laser.

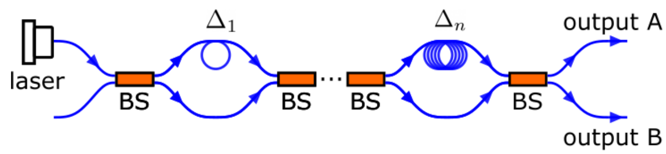

FIG. 2. Multi-path interferometer to generate bunched light. Laser light is sent to an input port of a beamsplitter (BS) and splits into two paths. Light in one of the path is delayed by a propogation delay Δ_1. The delayed light and non-delayed light interferes at second beamsplitter. The act of splitting the light, delaying one of them and recombining is repeated for n times. Photon bunching would be observed from light at any of the two output ports A,B of the final beamsplitter in the chain. The propagation delay Δ is distinct in each Mach-Zehnder interferometer satisfying the condition Eqn. **(to insert later)**. Inset: Details of components between pairs of beamsplitters. In-line polarisation control pedals are used to match the polarisations of light in the delayed and non-delayed paths of the respective Mach-Zehnder interferometer when they recombine at the next beamsplitter.

A distributed feedback laser is used to output 30 mW of linearly polarised coherent laser light at 780 nm. This light is then coupled into a spatial single-mode through a fiber beamsplitter which splits the light into two paths. One of the paths is then transmitted through a delay optical fiber longer than the coherence length of the laser at around 40 m. This is so that the two splitted beams are phase-independent when they mode-overlap and recombine and a second fiber beamsplitter. As such, the two beams are effectively a micro-ensemble of 2 emitters, and exhibit temporal photon bunching behaviour like a thermal light source. A pair of half-wave plate and quarter-wave plate are placed into both beam paths prior to recombination, to match their polarisation modes. The variable attenuator in the undelayed beam path is to compensate for attenuation losses in the delay optical fiber and rebalance both beams before recombining.

IV. CONCLUSION

Recently, photon bunching sources have found applications in range finding, imaging, and clock synchro-

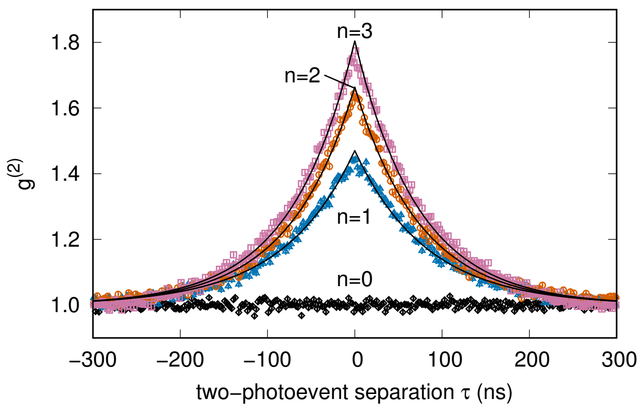

FIG. 3. Tunable photon bunching amplitudes $g^{(2)}(0)$ using different number n of cascaded Mach-Zehnder interferometer, approaching $g^{(2)}(0) = 2$ for thermal light. For n = 0 (diamonds), $g^{(2)}(\tau) = 1$. For n = 1 (triangles), $g^{(2)}(0) = 1.471 \pm 0.003$, coherence timescale of $\tau_c = 135.6 \pm 0.3$ ns. For n = 2 (circles), $g^{(2)}(0) = 1.665 \pm 0.003$ and $\tau_c = 134.8 \pm 0.2$ ns. For n = 3 (squares), $g^{(2)}(0) = 1.805 \pm 0.004$ and $\tau_c = 135.2 \pm 0.2$ ns. The solid lines show the fits to the second-order timing correlation function $g^{(2)}(\tau) = 1 + e^{-2|\tau|/\tau_c}$.

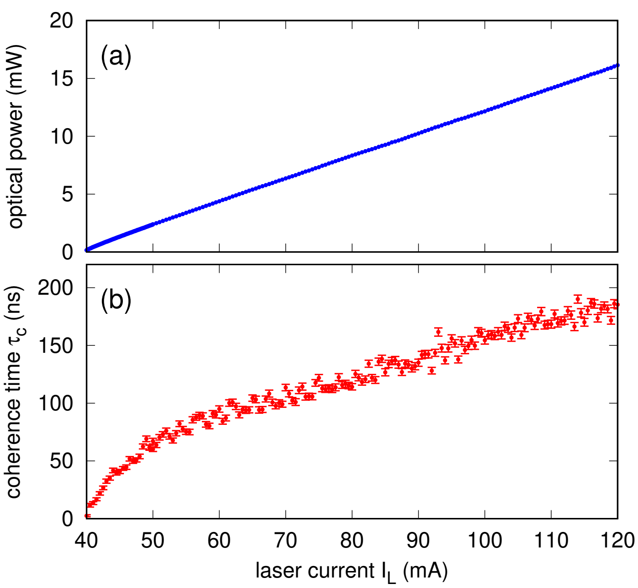

FIG. 4. Tunable (a) output optical power and (b) coherence time τ_c of photon bunching source by adjusting the laser current I_L.

nization. In these applications, the temporal correlations of these sources were used to extract timing information or increase the distinction between signal and noise. Furthermore, in contrast to light sources with timing correlations artificially encoded from external sources, such as randomly pulsed lasers, the photon bunching light sources with timing correlations from natural causes are potentially resilient to vulnerabilities such as optical cross-talk between similar devices or third-party manipulation. This provides motivation for bright photon bunching sources with resolvable characteristic timescales τ_c.

V. ACKNOWLEDGMENTS

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[1] R. Hanbury-Brown, R. C. Jennison, and M. K. D. Gupta, Apparent angular sizes of discrete radio sources, Nature **170**, 1061 (1952).
[2] R. Hanbury-Brown and R. Q. Twiss, A new type of interferometer for use in radio astronomy, Phil. Mag. **45**, 663 (1954).
[3] R. Glauber, The quantum theory of optical coherence, Phys. Rev. **130**, 2529 (1963).
[4] R. Glauber, Coherent and incoherent states of the radiation field, Phys. Rev. **131**, 2766 (1963).
[5] P. K. Tan, X. J. Yeo, A. Z. W. Leow, L. Shen, and C. Kurtsiefer, Practical range sensing with thermal light, Phys. Rev. Appl. **20**,

https://doi.org/10.1103/PhysRevApplied.20.014060 (2023).

[6] D. Dravins, T. Lagadec, and P. D. Nuñez, Optical aperture synthesis with electronically connected telescopes, Nat. Commun. **6**, 6852 (2015).

[7] P. K. Tan, A. H. Chan, and C. Kurtsiefer, Optical intensity interferometry through atmospheric turbulence, MNRAS **457**, 4291 (2016).

[8] P. K. Tan, G. H. Yeo, H. S. Poh, A. H. Chan, and C. Kurtsiefer, Measuring temporal photon bunching in blackbody radiation, ApJL **789**, L10 (2014).

[9] J. Zhu, X. Chen, P. Huang, and G. Zeng, Thermal-light-based ranging using second-order coherence, Appl. Opt. **51**, 4885 (2012).

[10] P. Janassek, A. Herdt, S. Blumenstein, and W. Elsaber, Ghost spectroscopy with classical correlated amplified spontaneous emission photons emitted by an erbium-doped fiber amplifier, Appl. Sci. **8(10)**, 1896 (2018).

[11] A. T. M. A. Rahman and P. F. Barker, Optical levitation using broadband light, Optica **7(8)**, 906 (2020).

[12] T. J. Steiner, J. E. Castro, L. Chang, Q. Dang, W. Xie, J. Norman, J. E. Bowers, and G. Moody, Ultrabright entangled photon pair generation from an algaas on insulator microring resonator, Phys. Rev. X Quantum **2**, 010337 (2021).

[13] D. G. England, B. Balaji, and B. J. Sussman, Quantum-enhanced standoff detection using correlated photon pairs, Phys. Rev. A **99**, https://doi.org/10.1103/PhysRevA.99.023828 (2019).

[14] Z. Zhang, S. Mouradian, F. N. C. Wong, and J. Shapiro, Entanglement enhanced sensing in a lossy and noisy environment, Phys. Rev. Lett. **114**, 110506 (2015).

[15] A. Lohrmann, A. Villar, A. Stolk, and A. Ling, High fidelity yield stop collection for polarization-entangled photon pair sources, Appl. Phys. Lett. **113**, 171109 (2018).

[16] Y.-C. Jeong, K.-H. Hong, and Y.-H. Kim, Bright source of polarization-entangled photons using a ppktp pumped by a broadband multi-mode diode laser, Opt. Express **24(2)**, 1165 (2016).

[17] X. J. Yeo, E. Ernst, A. Leow, J. Hwang, L. Shen, C. Kurtsiefer, and P. K. Tan, Direct measurement of the coherent light proportion from a practical laser source, Phys. Rev. A **109**, https://doi.org/10.1103/PhysRevA.109.013706 (2024).

[18] R. Hanbury-Brown and R. Q. Twiss, Correlation between photons in two coherent beams of light, Nature **177**, 27 (1956).

[19] M. Fox, *Quantum Optics: An Introduction* (Oxford University Press, UK, 2006).