Ultrabright Thermal Photon Bunching Source for Practical Quantum Sensing

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Photonic quantum sensing techniques [1, 2], such as ghost imaging and quantum illumination, aim to improve physical measurements against their classical counterparts by exploiting quantum phenomena like entanglement [3–5]. Many of these sensing schemes are based in correlated photon pairs generated by spontaneous parametric down conversion (SPDC)[6]. Although the output photon pairs may be entangled, it is often only the photon timing correlations that are implemented for actual measurements [7]. Popular schemes include range finding [8, 9] and clock synchronization [10, 11] configurations that exploit the stationary behaviour of SPDC light sources to extract timing correlation information without distinct temporal structures that can be subjected to vulnerabilities through optical crosstalk or third-party manipulation. However, the output brightness of SPDC-based photon bunching sources are limited to the single-photon regime , i.e. hundreds of picowatts, which significantly constraints its viability for practical sensing applications in real-world use cases and non-cooperative targets with high return losses and signal attenuation. In this work, we propose the use of thermal photon bunching as an alternative quantum resource of stationary timing correlated photons. We successfully demonstrate a novel scheme to generate an ultrabright source of thermal photon bunching at 1 mW output within a very narrow spectral passband of 10 fm, which is about 14 orders of magnitude brighter in spectral density than many SPDC light sources.

I. PHOTONIC SENSING SOURCE

Conventional photonic sensing techniques implement modulated light sources to produce timing correlations between a signal probe with the modulation pattern. The corresponding quantum sensing schemes extract the intrinsic timing correlations in the stationary photon pairs generated by spontaneous parametric down conversion (SPDC) processes. These timing correlated photons manifest in second-order timing correlation functions $g^{(2)}(\tau)$ with singly peaked temporal structures such that $g^{(2)}(\tau < \tau_c) > 1$ of coherence timescale τ_c, whereby τ describes the timing separation between two photodetection events.

External sources of intensity modulation to light sources for producing timing correlations, e.g. laser pulsing, may allow for optical crosstalk by third-party light sources with similar modulation patterns, and thus introduce unwanted accessibility to the sensing information. This results in potential security vulnerabilities.

II. STATIONARY CORRELATED LIGHT

Quantum light sources such as SPDC sources circumvent this vulnerability by being stationary, i.e. not modulated. Stationary light sources are not cross-correlated, even if they are of similar physical design and construct, therefore allowing for some degree of anti-spoofing property. However, quantum light sources can be complex and fragile to build and operate, with relatively faint outputs.

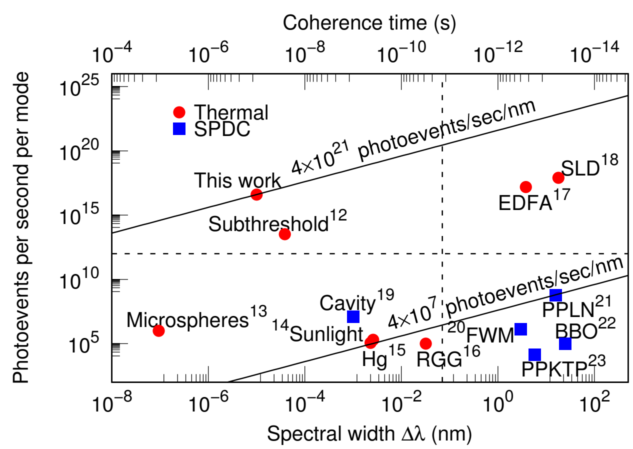

FIG. 1. Spectral densities of stationary light sources with thermal and SPDC correlations: Subthreshold [12] – subthreshold laser diode, Microspheres [13] – suspension of microspheres, Sunlight [14] – filtered Sunlight, Hg [15] – Mercury discharge lamp, RGG [16] – rotating ground glass, EDFA [17] – Erbium-doped fiber amplifier, SLD [18] – superluminescent diode, Cavity [19] – cavity enhanced via microring resonator, FWM [20] – four-wave mixing, PPLN [21] – periodically poled Lithium Niobate, BBO [22] – Beta-Barium Borate, PPKTP [23] – periodically poled Potassium Titanyl Phosphate.

A practical consideration for photonic sensing applications is the output luminosity of the correlated light source. The comparison in Fig. 1 shows that SPDC light sources generate power outputs below a nanowatt, or in the range of 10^4 to 10^9 photoevents per second. This restricts the use of SPDC light-based sensing in environ-

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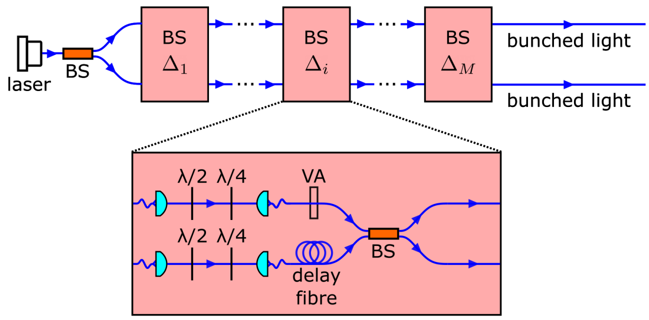

FIG. 2. Setup for an ultrabright thermal light source. BS: Beamsplitter, VA: variable attenuator, $\lambda/2$: half-wave plate, $\lambda/4$: quarter-wave plate.

ments with high return loss or realistic signal attenuation.

In order to detect the timing correlations to use in sensing implementations, the size or the coherence timescale of the photon bunching first must be resolvable by the photodetectors. Readily available detectors such as passively quenched Silicon single-photon avalanche detectors have timing uncertainties around a nanosecond, while research-grade superconducting nanowire detectors may reach tens of picoseconds in precision. The detector timing resolution thus requires the spectral bandwidth of the thermal light source to be less than 1 GHz, and so eliminates superluminscent diodes, erbium-doped fiber amplifiers, and Sunlight as functional sources of stationary timing correlations despite high brightness outputs in the milliwatts, as their photon bunching signatures are 4 to 5 orders too short to be timing resolved.

There are a few ways to generate thermal light with sufficiently long coherence timescale for their photon bunching signals to be detected and resolved. Popular techniques make use of coherent laser light being transmitted through random phase dispersion media such as a rotating ground glass, or a liquid suspension of microspheres. However, the scattering process introduces spatial incoherence which reduces the coupled single-mode light that is usable for sensing applications, by around 10 orders of magnitude.

We propose thermal light as a simpler source of stationary correlated photons. Bright, narrowband, and single-mode thermal light has been generated in our previous works, by operating a laser diode below threshold [24], and implemented in a time-of-flight measurement [12].

III. ULTRABRIGHT SOURCE GENERATION

We develop an experimental setup to produce a micro-ensemble of 2 phase-independent light emitters to generate a temporal photon bunching source that is ultrabright, spectrally narrowband, and spatially single-mode. A distributed feedback laser is used to output 30 mW of linearly polarised coherent laser light at 780 nm. This light is then coupled in spatial single-mode through a fiber beamsplitter into two beams. One of the beams 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. THERMAL PHOTON BUNCHING

Thermal light, such as spontaneous emission and blackbody radiation, exhibits a characteristic temporal photon bunching behavior [25, 26], also known as the Hanbury-Brown–Twiss effect [27]. This can be described by the second-order timing correlation function,

$$g^{(2)}(\tau) = 1 + e^{-2|\tau|/\tau_c}\,, \tag{1}$$

whereby the thermal photons have a tendency to propagate closer together, hence photon bunching, than described by random Poissonian timing statistics.

The coherence timescale τ_c of the thermal photon bunching effect is inversely proportional to the spectral width $\Delta\lambda$ of the thermal light source, such that $\tau_c = 1/\Delta\lambda$ for single-line Gaussian spectrum, which can be generalised to the Fourier transform of the source power spectrum [28] for other spectral distributions.

V. ACKNOWLEDGMENTS

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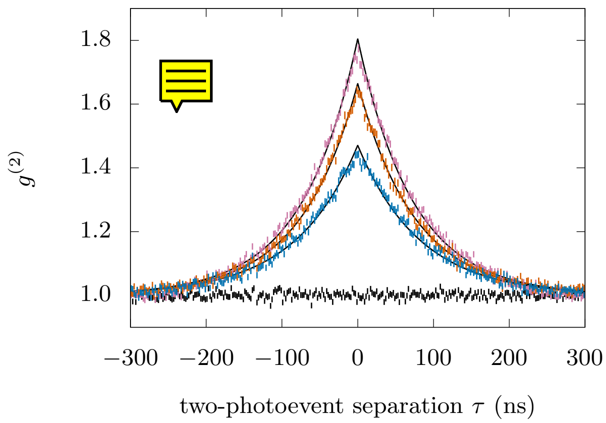

FIG. 3. Second-order photon correlations for different number of loops. For 0-loop (black), $g^{(2)}(\tau) = 1$. For 1-loop (blue), $g^{(2)}(\tau = 0) = 1.471 \pm 0.003$, coherence timescale of $\tau_c = 135.6 \pm 0.3\,\text{ns}$. For 2-loops (orange), $g^{(2)}(\tau = 0) = 1.665 \pm 0.003$ and $\tau_c = 134.8 \pm 0.2\,\text{ns}$. For 3-loops (pink), $g^{(2)}(\tau = 0) = 1.805 \pm 0.004$ and $\tau_c = 135.2 \pm 0.2\,\text{ns}$. The black solid curve shows the fitted curves to Eqn. 1.

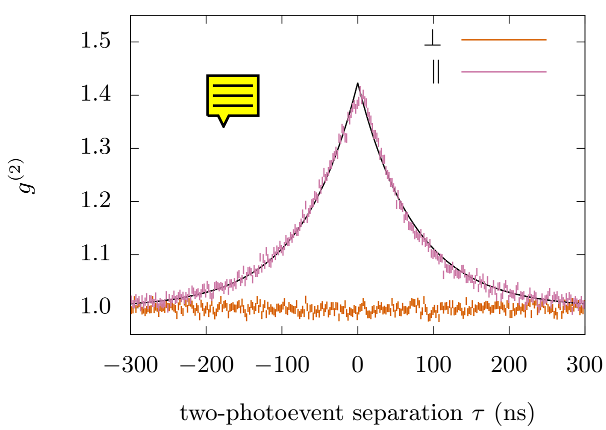

FIG. 4. Second-order photon correlations for parallel polarisation (pink) and orthogonal polarisation (orange) between the two modes.

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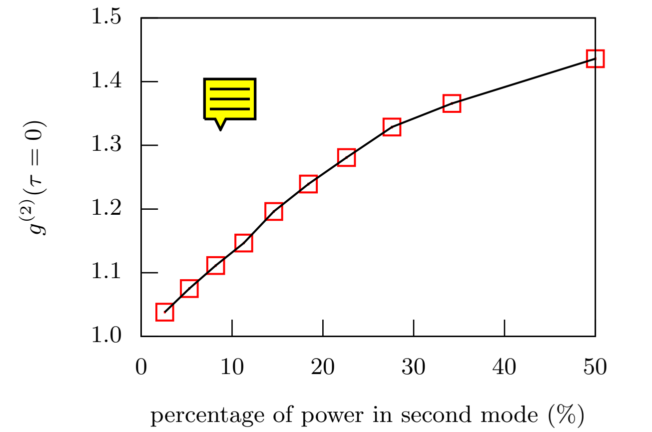

FIG. 5. Peak photon bunching $g^{(2)}(\tau = 0)$ of the bunched light source through an asymmetric interferometer with one loop, as a function of percentage of power in the second mode (with respect to the total output power). In this configuration, the input light travels through two distinct paths before superposing. In one of the paths, the light is attenuated over a range, from complete attenuation (0 % power in second mode), to a balanced power between the two paths (50 % power in second mode).

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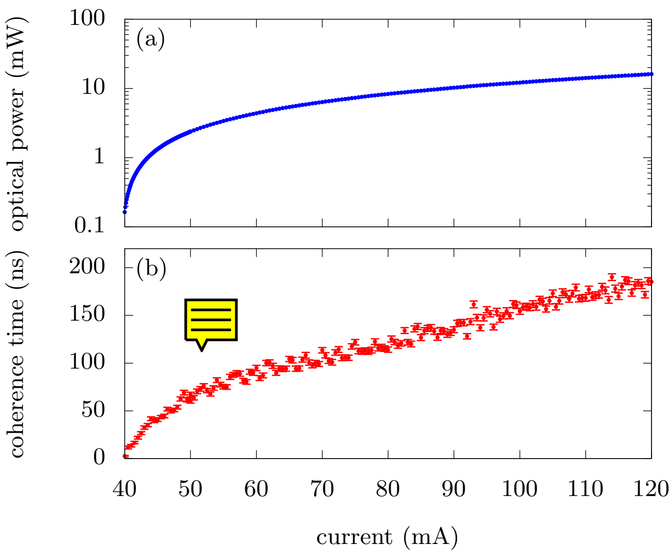

FIG. 6. (a) The optical power coupled from the laser diode into a single mode fibre at different operating currents, above the lasing threshold at around 40 mA. (b) The characteristic timescale τ_c extracted from second-order photon correlation measurements $g^{(2)}(\tau)$ at different operating currents.

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