Direct ~~measurement of Siegert relation using interferometric photon correlations~~test to identify a pseudothermal light source

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The first-order field correlation $g^{(1)}(\tau)$ and second-order photon correlations $g^{(2)}(\tau)$ of thermal light ~~, can be connected via the~~ are related via the equation $g^{(2)}(\tau) = 1 + |g^{(1)}(\tau)|^2$, commonly referred to as the Siegert relation. However, the Siegert relation may not hold for a pseudothermal light source. We present a technique to ~~directly test for Siegert relation violation using interferometric photon correlations ; correlations~~ identify a pseudothermal light source, by measuring timing correlations between photoevents detected at the output ports of an asymmetric Mach-Zehnder interferometer. From these correlations, we directly extract the difference between the second-order intensity correlation and interferometric visibility-square of the light source. For thermal light, this difference is equal to one, according to the Siegert relation. In contrast, we identify a pseudothermal light source when this difference is not equal to one, although the light source exhibits photon bunching. We perform this ~~technique on two bunched light sources~~ difference measurment on two light sources exhibiting photon bunching: laser light scattering off a rotating ground glass, and light from a mercury vapor lamp. ~~Using this method, we~~ Our measurements show that laser light scattering off a rotating ground glass ~~violates the Siegert relation, and hence cannot be classified as thermal light . In contrast, we observe that light from a~~ emits pseudothermal light and suggest that the mercury vapor lamp ~~is shown to obey the Siegert relation, suggesting~~ emits thermal light.

I. SECOND-ORDER PHOTON CORRELATIONS: AN INCONCLUSIVE TEST FOR THERMAL LIGHT

Second-order photon correlations $g^{(2)}(\tau)$, a modern approach to intensity interferometry by Hanbury-Brown and Twiss [1, 2], is a common technique to distinguish between light sources of different photon statistics [3–5]. ~~The different photon statistics include sub-Poissonian, Poissonian and super-Poissonian photon statistics, with super-Poissonian photon statistics commonly associated with thermal light [3].~~

A light source with super-Poissonian photon statistics exhibits photon bunching, i.e. $g^{(2)}(0) > 1$ [3]. Examples of these light sources include ~~sunlight~~blackbody radiation [6, 7] discharge lamps ~~[8? , 9]~~ [8–10] lasers undergoing amplitude modulations [11], and light scattered off a collection of scatterers such as rotating ground glass diffusers [12–14], or particles undergoing Brownian motion suspended in a medium [15–18].

Amongst these light sources, a subset classified as thermal light is of fundamental interest. Thermal light originates from spontaneous emission by an ensemble of light emitters in thermal equilibrium. These emitters would radiate stationary light at different frequencies with no fixed phase relationship [19].

Apart from exhibiting photon bunching, thermal light also satisfies the Siegert relation $g^{(2)}(\tau) = 1 + |g^{(1)}(\tau)|^2$, where $|g^{(1)}|$ is the interferometric visibility [20, 21]. In contrast, there exists light sources that exhibits photon bunching, yet violates the Siegert relation are also referred to as pseudothermal light such as lasers undergoing amplitude modulations [11, 22]. The test for whether Siegert relation is obeyed is therefore a more stringent ~~criteria~~ criterion for qualifying a light source as emitting thermal light, as compared to only depending on the fact that the light sources exhibit photon bunching.

The test for Siegert relation ~~violation~~ typically requires two separate measurements to obtain $g^{(2)}(\tau)$ and $|g^{(1)}|$. To obtain $|g^{(1)}|$, a scanning Michelson or Mach-Zehnder type interferometer may be used [5]. The interferometer scans through a path difference on the order of the coherence length of the light, which is the coherence time multiplied by the speed of light in the interferometer medium. However, the construction of a scanning interferometer may be tedious when the coherence length of the light source exceeds the size of laboratory. In the context of testing for Siegert relation ~~violation~~, this motivates for methods that allow testing for Siegert relation ~~violation~~ that eliminates the need for scanning interferometer.

We present a method to ~~test for~~ identify a pseudothermal light source via testing whether the Siegert relation ~~violation without a need for a scanning interferometer,~~ holds using interferometric photon correlations, a correlation of photoevents detected at the output ports of an asymmetric Mach-Zehnder interferometer. Furthermore, this method directly tests the Siegert relation in a single measurement, rather than obtaining $g^{(2)}(\tau)$ and $|g^{(1)}|$ separately. This method was originally used to differentiate chaotic light and a laser undergoing

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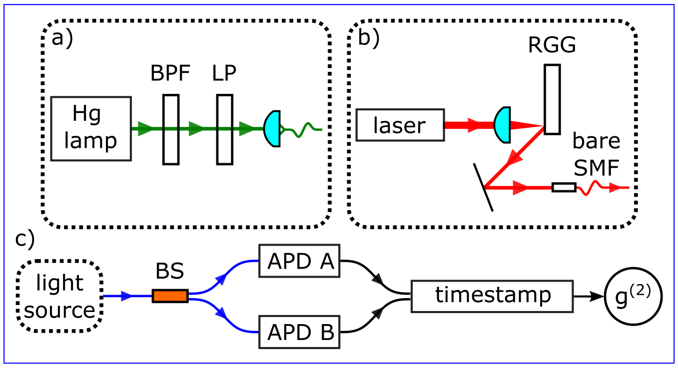

FIG. 1. Experimental set up for a) the thermal light source with mercury vapor lamp, b) the pseudothermal light source with laser light scattered off the rotating ground glass, c) the Hanbury-Brown Twiss type interferometer to observe photon bunching in a second-order photon correlations $g^{(2)}(\tau)$. (BPF: bandpass filter, LP: linear polariser, RGG: rotating ground glass BS: fibre-based beamsplitter, APD: Single photon avalanche photodetectors)

amplitude fluctuations [11, 22]. Here, we use it to test for a violation of Siegert relation on two commonly used light sources exhibiting photon bunching: a mercury vapor lamp filtered with a 546 nm optical bandpass, and scattered light from a rotating ground glass illuminated by a 780 nm laser light focused on the ground glass. We observe a violation of Siegert relation for light scattered off the rotating ground glass. Conversely, light emission from the mercury vapor lamp obeys Siegert relation, suggesting thermal light. This method is also an improvement over a previous technique that tests the Siegert relation directly [23]. as it removes the need to interfere the light source with an external local oscillator, but instead interferes the light source with a delayed copy of itself.

II. PHOTON BUNCHING IN THERMAL AND PSEUDOTHERMAL LIGHT

III. PHOTON BUNCHING OBSERVED IN BOTH LIGHT SOURCES

In our experiment, we prepare two light sources that exhibit photon bunching: light from a mercury vapor lamp, and light scattered off a rotating ground glass diffuser.

For the first light source, we prepare light from a mercury vapor lamp as shown in Fig.**In our experiment, a mercury vapor lamp is used as a thermal light source, prepared as shown in Fig. 1a.** Light from the lamp is filtered with a 546 ± 3 1a. We filter the light from the lamp with a linear polariser and 546 nm optical bandpass and a linear polariser. The filtered light is collected into a multimode fibre, before projecting into a single spatial mode with a single mode fibre. The $g^{(2)}(\tau)$ of light from the mercury vapor lamp can be modelled using a double exponential decay function [10]

$$g^{(2)}(\tau) = 1 + \beta_{\mathrm{Hg}} \cdot \exp\left[-\left|\frac{2\tau}{\tau_{\mathrm{Hg}}}\right|\right],$$

where β_{Hg} is the amplitude of the bunching peak, and τ_{Hg} is the characteristic timescale of this bunching feature. **The emission profile from the filtered mercury vapor lamp is expected to follow a Lorentzian lineshape [24]. The corresponding second-order correlation $g^{(2)}(\tau)$ of a Lorentzian lineshape light source is a double exponential decay function due to the Wiener-Khintchine theorem [25, 26],**

$$g^{(2)}(\tau) = 1 + \beta_{\mathbf{Hg}} \cdot \exp\left[-\left|\frac{2\tau}{\tau_{\mathbf{Hg}}}\right|\right], \tag{1}$$

where $\beta_{\mathbf{Hg}}$ is the amplitude of the bunching peak, and $\tau_{\mathbf{Hg}}$ is the characteristic timescale of this bunching feature.

Insets: Experimental setup for light sources a) laser light scattered off the rotating ground glass, b) mercury vapor lamp. Bottom: Hanbury-Brown Twiss type interferometer to measure second-order photon correlations $g^{(2)}(\tau)$. (SMF: Single-mode fibre, MMF: Multimode fibre, BPF: Bandpass filter, BS: Beamsplitter, APD: Single photon avalanche photodetectors)

For the second source, **For the pseudothermal light source,** we prepare laser light scattered off the rotating ground glass diffuser as shown in Fig. 1b. Light from a 780 nm distributed feedback laser is focused on a reflective ground glass difffuser of grit 1500. We estimate the diameter of the beam on the ground glass W to be about 4 μm, and at a radial distance of about 1 R of about 10 cm mm from the rotation axis of the motor. The motor rotates the ground glass with a period T_0 of about 4 ms. A single mode fibre for 780 nm was placed 19 cm away from the illuminated spot on the ground glass, to sample the light scattered off the rotating ground glass.

The $g^{(2)}(\tau)$ of light scattered off the rotating ground glass can be modelled using a Gaussian function [14, 27–29] **Theoretical models of laser light scattered from a rotating ground glass predict a $g^{(2)}(\tau)$ with a Gaussian profile at a point of detection [14, 27–29]**

$$g^{(2)}(\tau) = 1 + \beta_{\mathrm{RGG}} \cdot \exp\left[-\left(\frac{\tau}{\tau_{\mathrm{RGG}}}\right)^2\right], \tag{2}$$

where β_{RGG} is the amplitude of the bunching peak, and τ_{RGG} is the characteristic timescale of this bunching feature. In our experiment, as the ground glass is placed at the focus of the lens, and the scattered light is collected at a distance significantly larger than the spot size, the value of ~~τ_c~~ τ_{RGG} can be approximated using [14, 27–29]

$$\tau_{\text{c}\,\text{RGG}} \approx \frac{W}{v}, \frac{WT_0}{2\pi R}. \quad (3)$$

~~where v is the linear speed of the ground glass at the beam. Using~~ From a substitution of our experimental settings ~~, we estimate $\tau_c \approx 200$~~ to Eq. 3, we predict $\tau_{RGG} \approx 200$ ns.

~~Second-order photon correlations $g^{(2)}(\tau)$ for mercury vapor lamp (top,green), laser light scattered off a rotating ground glass (bottom, red). The solid lines are best-fit curves to their respective $g^{(2)}(\tau)$ models, from Eqn. 2 and 1. For mercury vapor lamp, $\beta_{Hg} = 0.41 \pm 0.03$, $\tau_{Hg} = 0.17 \pm 0.01$ ns, and a reduced $\chi^2 = 1.98$. For laser light scattered off a rotating ground glass, $\beta_{RGG} = 0.869 \pm 0.009$, $\tau_{RGG} = 164 \pm 1$ ns, and a reduced $\chi^2 = 2.00$.~~

~~Experimental setup for measuring interferometric photon correlations $g^{(2X)}$. The propagation delay in the interferometer introduced about 2.22 μs , for testing laser light scattered off the rotating ground glass, and about 10 ns propagation delay for testing light from the meeury vapor lamp. (BS: Beamsplitter, APD: Single photon avalanche photodetectors)~~

~~To measure the second-order photon correlation $g^{(2)}(\tau)$ of both light sources, we construct a Hanbury-Brown Twiss type interferometer (Fig. 1 bottom).~~ **To observe photon bunching, we measure the second-order photon correlation $g^{(2)}(\tau)$, using a Hanbury-Brown Twiss type interferometer, shown Fig. 1c.** Light from the source under test is sent to a beamsplitter. Photoevents at each output port of the beamsplitter were detected using actively quenched silicon single photon avalanche diodes (APD). The photoevents were timestamped over an integration time T. The time differences τ between timestamped photoevents across the two APDs were measured, and the number of coincidences N for each τ is ~~collated~~ sorted into a histogram. As the counting of N returns a mean value from a Poisson distribution, error bars of magnitude $\sqrt{N}$ were assigned for each bin of the histogram. ~~The histogram is then normalised by T divided by the product of photoevents detected at each APD, to obtain $g^{(2)}(\tau)$, shown in Fig. 2. We fit the $g^{(2)}(\tau)$ to Eqn. 2 and 1, to extract $\beta_{Hg,RGG}$ and $\tau_{Hg,RGG}$ from the fit. Using these fitted parameters, we predict the respective interferometric photon correlation, with the assumption that Siegert relation holds.~~ **The histogram is then normalised by the product of single events rates at each detector, to obtain $g^{(2)}(\tau)$, shown in Fig. 2. The $g^{(2)}(\tau)$ histograms for each light source were also fitted to their respective theoretical models in Eq. 1-2.**

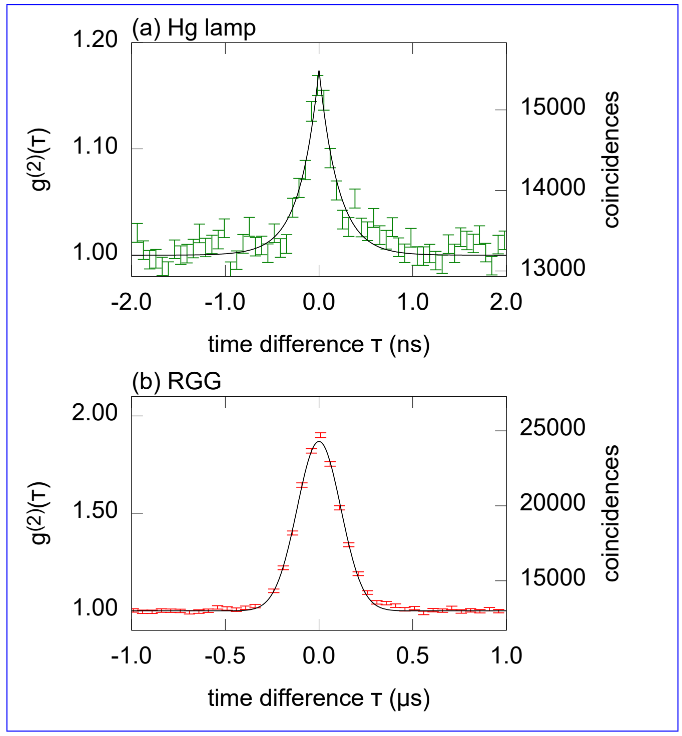

FIG. 2. Second-order photon correlations $g^{(2)}(\tau)$ for (a) mercury vapor lamp, (b) laser light scattered off a rotating ground glass. The solid lines are best-fit curves to their respective $g^{(2)}(\tau)$ models, from Eqn. 2 and 1. For the mercury vapor lamp, $\beta_{Hg} = 0.17 \pm 0.01$, $\tau_{Hg} = 0.41 \pm 0.03$ ns, and a reduced $\chi^2 = 1.98$. For laser light scattered off a rotating ground glass, $\beta_{RGG} = 0.869 \pm 0.009$, $\tau_{RGG} = 164 \pm 1$ ns, and a reduced $\chi^2 = 2.00$.

III. ~~TEST FOR SIEGERT RELATION VIOLATION USING INTERFEROMETRIC~~ INTERFEROMETRIC PHOTON CORRELATIONS

The setup to measure interferometric photon correlations $g^{(2X)}(\tau)$ is shown in Fig. 3. Light from the source under test is sent through an asymmetric Mach-Zehnder interferometer. The propagation delay Δ between the two arms of the interferometer was introduced using single mode optical fibres. In order to clearly resolve features in $g^{(2X)}(\tau)$, the length of optical fibres used introduced a propagation delay at least ~~10~~ 4 times longer than τ_c for the respective light sources. Photoevents were detected at the output ports of the interferometer, also using actively quenched silicon single photon avalanche photodiodes. To extract $g^{(2X)}(\tau)$, the detected photoevents were timestamped and processed similar to how second-order photon correlation were extracted in Sec. III.

The respective light fields at the output ports of inter-

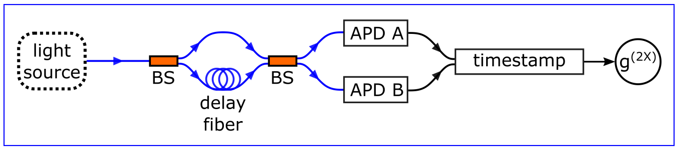

FIG. 3. ~~Interferometric~~ Experimental setup for measuring interferometric photon correlations ~~for mercury vapor lamp (blue)~~ $g^{(2X)}$. The propagation delay in the interferometer introduced about 2.22 μs , for testing laser light scattered off ~~a~~ the rotating ground glass ~~(red). The solid lines show the predicted $g^{(2X)}(\tau)$ extrapolated from the measured $g^{(2)}(\tau)$, assuming that the~~ and about 10 ns propagation delay for testing light ~~source emits thermal light~~ from the mecury vapor lamp. (BS: Beamsplitter, APD: Single photon avalanche photodetectors)

ferometer A, B are

$$E_{A,B}(t) = \frac{E(t) \pm E(t+\Delta)}{\sqrt{2}}, \tag{4}$$

where $E(t)$ is the input light field into the interferometer, and the sign difference is a result of a relative π phase acquired by one of the fields at the beamsplitter [30].

Photoevents are detected at the output ports of the interferometer and timestamped. The interferometric photon correlation $g^{(2X)}(\tau)$ is computed from the ~~photoevents~~ timestamped events

$$\begin{aligned} g^{(2X)}(\tau) =& \frac{\langle E_A^*(t+\tau)E_B^*(t)E_B(t)E_A(t+\tau)\rangle}{\langle E_A^*(t)E_A(t)\rangle\langle E_B^*(t)E_B(t)\rangle} \\ =& \frac{\langle \hat{n}_A(t+\tau)\hat{n}_B(t)\rangle}{\langle \hat{n}_A(t)\rangle\langle \hat{n}_B(t)\rangle}, \end{aligned} \tag{5}$$

where $\langle \ldots \rangle$ takes the ensemble average over the variable t, **$\hat{n}_{A,B}(t)$ is the number of photons detected by the respective photodetectors at time t,** and τ is the detection time difference between ~~photoevents detected at photodetector A and B~~ timestamped events.

Upon expansion of Eqn. 5 using Eqn. 4, it can be shown that ~~,~~ the non-zero terms of $g^{(2X)}(\tau)$ can be written as

$$\begin{aligned} g^{(2X)}(\tau) =& \\ =& \frac{1}{4}\, g^{(2)}(\tau+\Delta) + \frac{1}{4}\, g^{(2)}(\tau-\Delta) \\ &+ \frac{1}{2}[g^{(2)}(\tau) - |g^{(1)}(\tau)|^2], \end{aligned} \tag{6}$$

where $|g^{(1)}|$ is the interferometeric visibility, and $g^{(2)}$ is the standard second-order photon correlation [11, 31].

For a light source exhiting photon "bunching" $g^{(2)}(0) > 1$, a "bunching" feature at a same timescale τ_c but at 1/4 amplitude would appear at $g^{(2X)}(\tau = \pm\Delta)$. In the interval of $\tau \in [-\tau_c, \tau_c]$, a light source obeying the Siegert relation would result in the $[g^{(2)}(\tau) - |g^{(1)}(\tau)|^2] = 1$, resulting in $g^{(2X)}(\tau) = 1$. In contrast, pseudothermal light sources that ~~violates~~ deviates from the Siegert relation, would result in $g^{(2X)}(\tau) \neq 1$, for $\tau \in [-\tau_c, \tau_c]$.

IV. IDENTIFYING PSEUDOTHERMAL LIGHT

Using the setup shown in Fig. 3, ~~bottom,~~ we extract the interferometric photon correlations $g^{(2X)}(\tau)$ of light from the mercury vapor lamp, and laser light scattered off a rotating ground glass~~.~~

, shown in Fig. 4 Asssuming that Siegert relation holds, we predict $g^{(2X)}(\tau)$ of the two light sources under test, using the fitted parameters of β and τ_c extracted earlier. The predicted $g^{(2X)}(\tau)$ are compared with $g^{(2X)}(\tau)$ extracted from measurements.

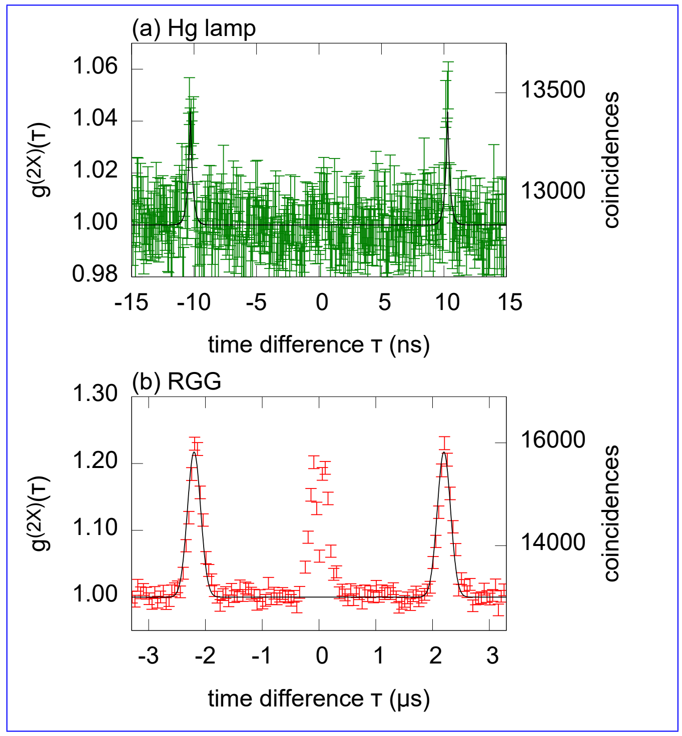

FIG. 4. Interferometric photon correlations for (a) mercury vapor lamp, (b) laser light scattered off a rotating ground glass. The solid lines show the predicted $g^{(2X)}(\tau)$ extrapolated from the measured $g^{(2)}(\tau)$, assuming that the light source emits thermal light.

For light emitted by the mercury vapor lamp, ~~$g^{(2X)}(\tau)$ extracted from measurements is in agreement with prediction, and~~ $g^{(2X)}(\tau \approx 0) = 1$ shows that it obeys the Siegert relation~~. This also suggests that the light from the mercury vapor lamp may be thermal in nature~~, as expected of thermal light. The asymmetry between the height of the two peaks at $g^{(2X)}(\tau = \pm\Delta)$ is attributed to an unequal splitting ratio of the beamsplitter recombining the two paths in the Mach-Zehnder interferometer.

For laser light scattered off the rotating ground glass, ~~$g^{(2X)}(\tau)$ extracted from measurements deviates from prediction around zero time difference, and exhibits a non-constant feature around zero time difference. The non-constant feature around zero time difference~~

$g^{(2X)}(\tau \approx 0) \neq 1$ indicates a deviation from the Siegert relation and therefore a pseudothermal light source. Instead, $g^{(2X)}(\tau \approx 0)$ consists of a ~~"anti-bunching" dip and "bunching" feature~~ dip and peak each with a distinct characteristic timescale. The charactersistic timescale of the ~~"anti-bunching"~~ dip is associated with the coherence time of the laser emitting coherent light, while the ~~"bunching"~~ peak feature suggests amplitude modulation of the laser [11, 22]. ~~This non-constant feature around zero time difference shows that the Siegert relation is violated and disqualifies the light source as a thermal light.~~

V. CONCLUSION

In summary, we performed experiments to extract interferometric photon correlations $g^{(2X)}(\tau)$ ~~on two light sources conventionally used to generate light that exhibits photon bunching. These two light sources are~~ of a commonly used thermal light source, a mercury vapor lamp, and a pseudothermal light source, laser light scattered off a rotating ground glass. ~~From their respective $g^{(2X)}(\tau)$~~Using this technique, we found from $g^{(2X)}(\tau)$ that laser light scattered off a rotating ground glass ~~violates Siegert relation , and hence does not exhibit properties of thermal light~~ deviates from Siegert relation despite exhibiting photon bunching and hence a pseudothermal light source. On the contrary, light from the mercury vapor lamp obeys Siegert relation suggesting thermal light. ~~We advocate the method of testing Siegert relation violation using interferometric photon correlations, to further classify light sources which exhibit photon bunching but violates Siegert relation as pseudothermal light.~~

Apart from positively identifying pseudothermal light, a null identification of pseudothermal light using the technique presented here increases the confidence that a source emits thermal light than the observation of photon bunching alone. The is crucial in applications with results relying on the assumption of a thermal light source. For example, the phase randmoness in thermal light is used in range sensing [32, 33] and optical coherence tomography [34], or inferring spectral lineshape [18] or spectral broadening mechanisms [16] from the photon correlations of thermal light.

This technique may also be used to identify laser signatures falsely identified as a thermal light source exhibiting photon bunching. Applicable scenarios would be in identifying laser signatures from extraterrestial signals [35], technosignatures [36] and astrophysical lasers [37] , with its amplitude modulated by scattering media, such as the atmosphere and interstellar dust, along its line of sight.

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