

Semiconductor photon Bose-Einstein condensate as a practical light source for range finding

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We report the measurement of thermal photon statistics from a semiconductor photon Bose-Einstein condensate operating just above the condensation threshold. We identify a regime where coherent, single-mode emission occurs while still demonstrating significant photon bunching. Taking advantage of the photon bunching, along with the continuous-wave operation and high photon flux, we demonstrate optical range sensing using a photon Bose-Einstein condensate. We characterize the precision of the range measurement and analyze the dependence on the condensate's pump power and resulting coherence properties.

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Condensates of light have often been suggested as novel light sources [1] with high spatial coherence [2], low threshold [3], and thermal photon statistics [4,5]. However, limitations in operation mean they have not been practical. Exciton-polariton condensates typically operate at cryogenic temperatures in order to stabilize the low binding energy of excitons in inorganic semiconductors [3] while condensates based on organic dyes are susceptible to triplet state shelving and degradation if not excited using a pulsed laser [6]. The recent experimental realization of semiconductor-based room-temperature photon Bose-Einstein condensates (BECs) now points to a technologically viable system, capable of continuous-wave operation with reduced operating complexity, increased light output, and longer device lifetime [7,8].

In this work we use the thermal statistics of a semiconductor photon BEC operated just above the condensation threshold to perform range sensing. Unlike conventional optical ranging techniques, which assess photon time of flight directly [9,10] or rely on controlled variation of the amplitude or frequency of photons [11], here we use the Hanbury Brown–Twiss (HBT) effect to determine the time delay between two detectors [12]. This requires a thermal or pseudo-thermal “bunched” light source, where the peak in second-order intensity correlations reveals the time delay and distance [13]. This approach benefits from being

less sensitive to phase noise and having no ambiguity range due to pulse repetition or phase wrapping. Unfortunately, the coherence time of most thermal light sources, such as LEDs, is too short to measure (subpicosecond) using an HBT interferometer. Ranging with thermal light from LEDs has been possible with spectral filtering to achieve detectable coherence times [14], but this requires precise filtering and can lead to poor system efficiency. Operating such a system just below laser threshold ensures sufficient light emission without the instability of laser emission near threshold. Alternatively, pseudo-thermal lasers, produced when coherent laser light passes a rotating ground glass diffuser [13,15], are efficient and bright, but have limited precision due to long (of microsecond order) coherence times. The stable, single-mode, and coherent emission with thermal statistics from a photon BEC at threshold offers a compromise on both efficiency and precision with reduced system complexity. In the present scheme, the relevant coherence time sets the width of the $g^{(2)}(\tau)$ bunching feature, and therefore the timing precision, rather than the maximum measurable range. Here we use the light produced directly and without modification for range sensing.

We begin by detailing the cavity structure and experimental setup, and characterize the thermal character of the photon BEC emission through the second-order coherence function, $g^{(2)}(\tau)$. Next, we demonstrate the basic ranging principle by using the peak in the $g^{(2)}(\tau)$ measurement to determine relative time of flight, and distance, between the two detectors of the HBT interferometer. We also show the system's capability for detecting two objects at different positions in a single measurement. We finish by assessing how the measurement and system parameters of the photon BEC affect the precision and identify the optimal parameter regime.

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The open semiconductor microcavity that we use to create the BEC is shown in Fig. 1(a). Full details of BEC operation and sample fabrication are detailed in Ref. [7]. The cavity is formed by a spherical mirror and a planar half-cavity, with the latter comprising a mirror and a single InGaAs quantum well. The curved mirror is a commercial half-inch Bragg mirror (Layertec) with a radius of curvature of 0.1 m and reflectivity of at least 99.99%, and has been ground to a diameter of 1 mm. The planar half-cavity consists of a 32-repeat GaAs/AlAs distributed Bragg reflector, with a reflectivity of at least 99.95%, on top of which there is a single InGaAs quantum well, with a peak absorption of 1% at the quantum confined bandgap near 925 nm.

For all measurements in this work the cavity is operating with the 14th longitudinal mode tuned to 950 nm. The cavity length is maintained using a piezoelectric crystal tuned using feedback from optical interference fringes from illumination with a 830-nm laser diode, imaged on a camera (CCD).

We excite the photon BEC using a 785-nm laser through the pass-band of the curved mirror. The laser is focused using a near-infrared objective lens (20× Plan Apochromat, Mitutoyo). This is primarily absorbed by the bulk GaAs with generated electron-hole pairs migrating to the InGaAs quantum well, where they recombine to emit photons into the cavity mode near 950 nm. Electrical injection of photon BECs is also possible with monolithic vertical-cavity surface emitting laser type devices, but requires careful tuning of system parameters as discussed in Ref. [8]. Repeated absorption and emission events within the cavity allow the light to reach thermal equilibrium [16–18]. As the pump intensity increases so does the photon density inside the cavity. Above the critical density a phase change occurs from a thermalized photon gas to a Bose-Einstein condensate, marked by a massive coherent occupation of the lowest energy state of the system, the fundamental mode of the cavity [6]. Figure 1(c) shows the unfiltered input-output light curve for this device, fit with a multimode laser model [7], clearly showing the increase in output intensity upon condensation. The single-mode component of the model is plotted to show the change in population of the BEC.

The optical setup used for measurements is shown in Fig. 1(b). The emission is collimated by an objective lens (10× Plan Apochromat, Mitutoyo) and sent through a 950-nm long-pass filter to reduce background spontaneous emission reaching the detectors. The emission then passes through a modified Hanbury Brown–Twiss interferometer to two avalanche photodiodes (APDs—ID100, ID Quantique). APD1 is placed immediately after a 10 : 90 beam splitter while APD2 is after a Michelson interferometer with a variable delay stage (DDS600, Thorlabs). All measurements except those in Fig. 4(4-f) have one arm of the interferometer blocked. Both detectors

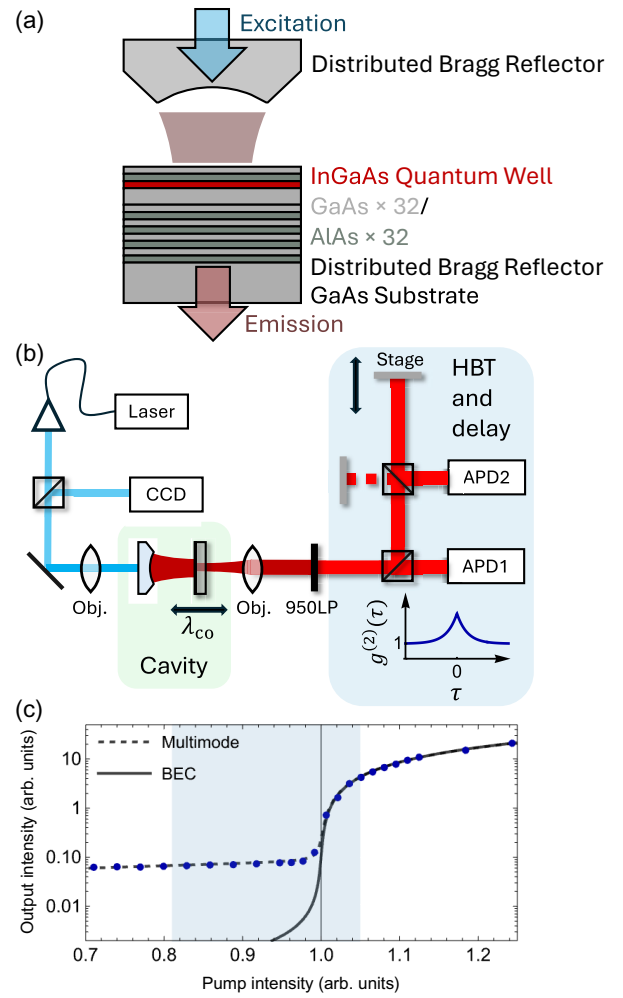


FIG. 1. Cavity and experimental setup. (a) Schematic diagram of the open semiconductor microcavity. (b) Schematic diagram of the experimental setup. A fibre-coupled laser is used to excite the semiconductor in the cavity through an objective lens (Obj.). A CCD camera (CCD) is used to monitor cavity length by imaging an interference pattern from a broadband LED. Emission (red line) is collimated by an objective lens (Obj.), sent through a 950-nm long-pass filter (950LP) and sent to the Hanbury Brown–Twiss (HBT) interferometer, highlighted in the blue box. The first avalanche photodiode (APD1) starts the coincidence timer, and the second (APD2) stops the timer. The second avalanche photodiode is placed after a Michelson interferometer with a variable delay stage (STAGE). The second arm, indicated with a dashed line, is blocked unless otherwise stated. (c) Input-output curve for the photon BEC. Data (points) are from power measurements fit with a multimode rate equation model (dashed line), shown with the single-mode component of the model (solid line) [7]. The vertical line is $P = P_c$ and the shaded region represents the region of interest for this work.

have 900-nm long-pass filters to reduce detection events from room light. A timing card (HydraHarp 400, Picoquant) is used to record time intervals between subsequent detection events on APD1 and APD2, which are then displayed as a histogram. Range-finding measurements use

neutral-density filters to reduce APD count rates to below 10^6 s^{-1} , with photon statistics collected over 30 s.

Typically a coherent light source has Poissonian intensity fluctuations and therefore constant $g^{(2)}(\tau) = 1$. A typical thermal light source instead shows bunching and $g^{(2)}(\tau = 0) = 2$. Condensates of light, despite being coherent light sources, also demonstrate thermal statistics at low condensate fractions due to their relatively large excitation reservoirs [19], with a transition from thermal to Poissonian statistics occurring only with increasing condensate fraction. This has been widely studied in exciton-polariton condensates [20] and dye-based photon condensates [5], and here we present the first study of this in a semiconductor-based photon BEC.

Figures 2(a), 2(b), 2(c) show the $g^{(2)}(\tau)$ measurement at increasing pump powers $P = 0.83P_c$, P_c , and $1.05P_c$, respectively. P_c is the critical pump power, or pump power with the greatest increase in output intensity, as shown by the vertical line in Fig. 1(c). We note that the condensation begins to occur at P just below P_c , and there can be a few hundred photons in the condensate at $P = P_c$ [17]. The data are fit with

$$g^{(2)}(\tau) = 1 + ae^{-|\tau-\tau_0|/\tau_l}, \quad (1)$$

where a is a bunching amplitude, τ_0 is the time delay between detectors, and τ_l is the width of the bunching peak. The height can be expressed as

$$a = \frac{\bar{n}^2}{(\bar{n} + b)^2} \left(\frac{\Delta n}{\bar{n}^2} - 1 \right), \quad (2)$$

where $\bar{n}$ is the mean photon number of the BEC mode, b represents all other detection events (photons in higher-order modes, background, dark counts), and Δn is the

fluctuation in photon number of the BEC mode. The first term characterizes the reduction due to uncorrelated detections and the second represents the inherent bunching of the BEC light [5,17,20].

The background light and dark count components of b are independent of excitation power, while the component due to emission into higher-order modes varies nonlinearly. Initially, it grows linearly within the excitation power but saturates when condensation and gain clamping occur. We note that while emission into higher-order cavity modes will also have thermal statistics, only coincidences from photons that are coherent with each other show bunching in the $g^{(2)}(\tau)$ measurement [14,21]. Δn can be related to the effective reservoir size of the condensate and depends on the number of excitations in the system, the carrier density, and the spectral overlap of the BEC mode with the thermalization medium, in this case the quantum well [4].

While $g^{(2)}(\tau = 0)$ should equal 2 before condensation occurs, we measure a significantly lower value of 1.11. The 950-nm long-pass filter does not filter all emission from higher-order transverse modes, meaning b is large relative to $\bar{n}$. As we increase the pump power $g^{(2)}(\tau = 0)$ initially increases, as $\bar{n}$ increases and b is effectively constant. This can be seen in Figs. 2(b) and 2(c), and the trend in Fig. 2(d). However, as pump power and $\bar{n}$ further increase, gain clamping occurs and the system enters the canonical regime. Eventually $\bar{n}^2 \gg \Delta n$, and Poissonian intensity fluctuations are reached with $g^{(2)}(\tau = 0) \rightarrow 1$, as shown in Fig. 2(d), and we limit our analysis to before this point. The elevated $g^{(2)}(0) > 1$ region for range measurements thus extends over $1.05 > P/P_c > 0.8$. The maximum height of $g^{(2)}(0)$ could be increased by further filtering, spectral and polarization, to isolate the ground state mode of the cavity.

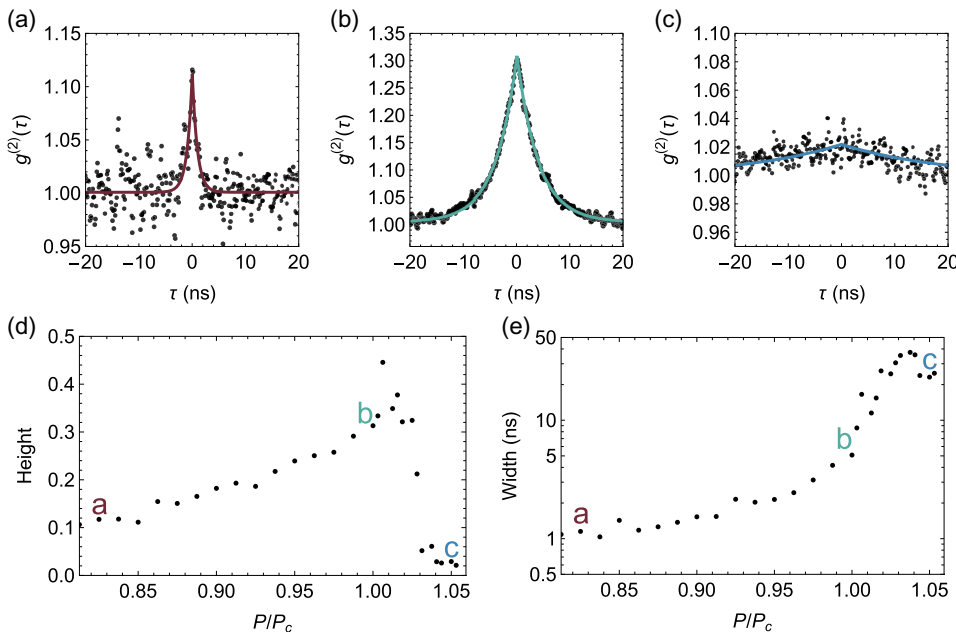


FIG. 2. The height and width of the second-order correlation function $g^{(2)}(\tau)$ as a function of pump intensity. (a)–(c) $g^{(2)}(\tau)$ measurements at $P/P_c = 0.83$, 1 , and 1.05 , respectively. Data (points) are fit with the exponential decay shown in Eq. (1) (line). Labels in (d),(e) indicate these measurements. (d) Height of the $g^{(2)}(\tau)$ as a function of power, where the Poissonian baseline value of 1 is subtracted. (e) Width of the $g^{(2)}(\tau)$ as a function of power.

This is, however, unnecessary for the use case highlighted here, and we opt for an experimentally simple implementation. We also note that aside from the intensity fluctuations that are the focus of this work, the device is otherwise stable and remains single-mode in the threshold region.

Additionally, we see the $g^{(2)}(\tau)$ function initially broadens with increasing power, before plateauing and then subsequently falling as shown in Fig. 2(e). If we assume a modified Siegert relationship holds for this region,

$$g^{(2)}(\tau) = 1 + a |g^{(1)}(\tau)|^2, \quad (3)$$

where $g^{(1)}(\tau)$ is the first-order coherence function, the broadening is due to the increasing coherence of the condensate above the critical intensity. We note studies that show this modified Siegert relationship holds near threshold for $g^{(2)}(0) > 1.1$ for laser devices in the weak coupling regime [22,23]. Using Eq. (3), we see that the coherence time is twice the width of the bunching feature, reaching over 70 ns as the condensate forms. Further investigation is required to determine if the coherence begins to fall after this point, in line with both theoretical and experimental studies on photon BECs and exciton-polariton condensates [20,24], or if instead the Siegert relationship no longer holds at higher photon numbers [19].

We use the bunching feature in $g^{(2)}(\tau)$ to determine the relative path length differences between two detectors. Figure 3(a) shows two $g^{(2)}(\tau)$ measurements taken with approximately 1 m of additional optical delay in one of the arms, showing a clear shift in the bunching peak. These measurements were taken with $P \approx P_c$, where $g^{(2)}(0) \approx 1.3$. The central location of the $g^{(2)}(\tau)$ bunching peak can be tracked through fitting with Eq. (1), where the shift in the center of the feature is determined by τ_0 , the delay between the detectors. Accounting for the zero delay offset, the time delay reveals the distance between detectors.

To test the effectiveness of this ranging approach we used a translation stage to shift a mirror on a delay stage up to 0.6 m, corresponding to 1.2 m of optical delay, and use Eq. (1) to determine the distance at each mirror position. Figure 3(b) shows the correspondence between actual and measured mirror positions, which works well over the full delay range. The deviation is shown in Fig. 3(c), with all measurements falling within 5 mm of the actual delay. The magnitude of the error is independent of the measured distance.

As a proof of principle measurement we demonstrate how this technique can measure relative distance between two objects simultaneously; in effect, depth imaging. We unblock the second arm on the Michelson interferometer and send the BEC emission to two mirrors. A $g^{(2)}(\tau)$ measurement is then performed, with an example shown in Fig. 3(d) for long time delay. Two bunching features are clearly visible, corresponding to the two possible paths. For this

measurement we reduced power to $P \approx 0.92P_c$ to allow the two peaks to be better visually distinguished.

The $g^{(2)}(\tau)$ features can then be fit in order to extract the difference in time of flight for the two paths, and therefore relative distance. Figure 3(e) shows the actual and measured distance between the two mirrors, while Fig. 3(f) shows the deviation. The results are generally similar to those shown in Figs. 3(b) and 3(c) for a single distance measurement, albeit with larger errors due to fitting two bunching features and lower count rates. Notably, if the width of the bunching feature is well known, distances of around 2 cm can be measured, corresponding to flight times shorter than the width. This method does not give access to any spatial information, however this can be achieved by either using an APD array or raster-scanning the imaging beam [25]. Combining a spatial method with this multitarget range finding should increase the effective resolution of the image, beneficial when considering the difficulties in achieving high spatial resolution conventionally.

We now move on to looking at how system and measurement parameters affect the precision and uncertainty of distance measurement. We begin by looking at the relationship between measured distance, integration time, and uncertainty in Fig. 4(a). We compare the error magnitude for 0 m (blue) and 0.6 m (red) distances and see no significant difference, as expected for range finding on specular targets over short distances [14]. We discuss longer range measurement below. For our attenuated count rates, we find that integration times beyond 80 s offer diminishing returns in measurement precision. Depending on desired accuracy, integration for less than 20 s can achieve promising results.

As the height and width of the $g^{(2)}(\tau)$ measurement are directly dependent on power, we now investigate the optimal regime for maximizing precision in the measurement. The precision in the τ_0 value for the data shown in Fig. 2 is shown in Fig. 4(b). We initially see that the error decreases with pump power, likely due to the increase in count rate over the integration period, before rapidly increasing again. The solid line is the power where the $g^{(2)}(\tau = 0)$ height plateaus. At higher excitation powers the BEC emission statistics cross over from thermal to Poissonian, and while the total emission gets brighter, a decreasing number of coincidence counts contribute to the bunching feature, reducing the relevant signal for range finding. The bunching feature width also significantly increases, spreading these coincidences over a larger area. Fewer coincidence counts contributing to a broader feature explains this decrease in precision. There is a significant power range ($0.95 \leq P/P_c \leq 1$) where the error is reasonably low, giving a good tolerance to variance in pump power and cavity length, which affects P_c [7].

The APDs and timing card combination used have timing resolution of the order of 100 ps; however, the width

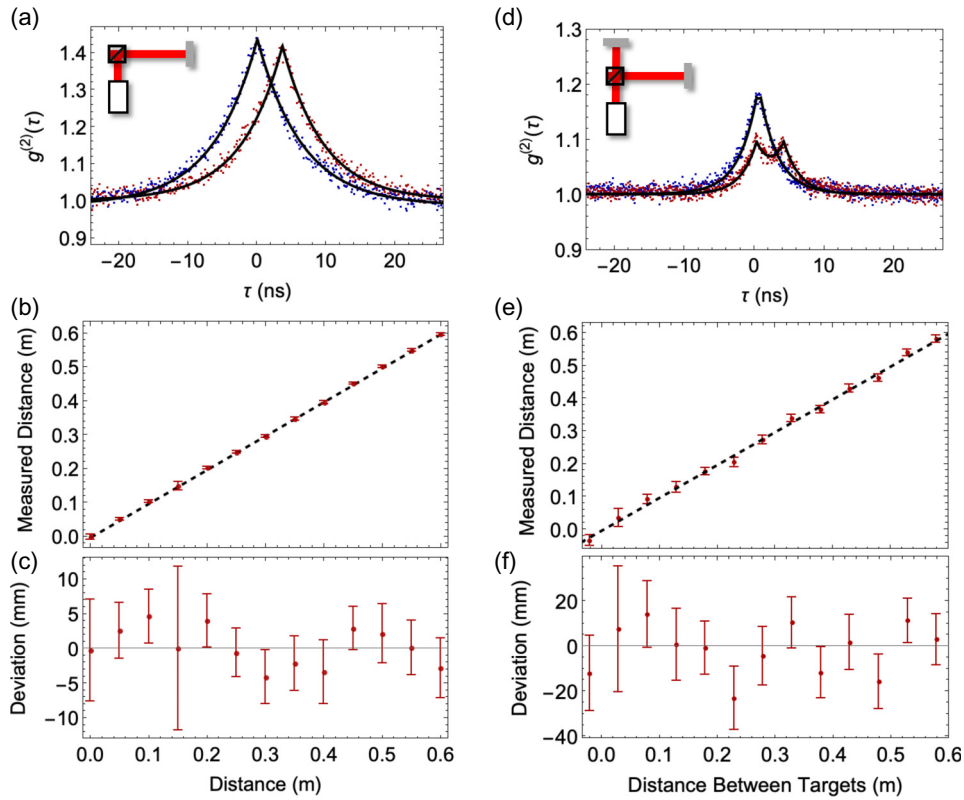


FIG. 3. Distance measurement using the thermal statistics of the BEC. (a) Data (points) from two $g^{(2)}(\tau)$ measurements differing by approximately 1 m of optical delay, showing a clear shift in bunching feature. Data are fit with Eq. (1) (lines). (b) Measured distance (points) as a function of optical path delay. The dashed line is $x = y$. (c) Deviation from actual distance (points) as a function of distance. (d) Data (points) from two $g^{(2)}(\tau)$ measurements where one arm of the HBT interferometer has two paths differing by approximately 0.1 m (blue) and 1 m (red) of optical delay. The 0.1 m measurement looks like a single broadened peak, and the 1 m measurement shows two clear bunching features. Data are fit with Eq. (1) (line), modified to have two peaks. (e) Measured distance (points) as a function of actual distance, expressed as distance between objects. The dashed line is $x = y$. (f) Deviation from actual distance (points) as a function of distance.

of the $g^{(2)}(\tau)$ feature is significantly broader than this. In Fig. 4(c) we investigate the relationship between timing resolution and the accuracy and precision of the distance measurement. We take the mean value of measurements for $0.9 < P/P_c < 1$, which have a width of approximately 2.2 ns. The resolution is changed by binning the original data taken with 128 ps timing resolution. There is no significant reduction in precision until the timing resolution exceeds the bunching feature width. Using higher pump powers to measure a broader bunching feature could further relax the timing precision required; however, this is limited by the rapidly falling $g^{(2)}(\tau = 0)$ value. This could be addressed by moving to using a shorter cavity with better overlap between the fundamental mode and the quantum well emission and absorption spectra, which would allow for thermal fluctuations to be seen at higher powers [4].

Finally, we consider the brightness and spectral density of our system [14]. When optimized for precision the total photon flux is in the region of $5 \times 10^{11} \text{ s}^{-1}$. Spectral measurements give a spectrometer-limited linewidth value

of 0.05 nm; however, if we use the modified Siegert relation this would give a linewidth of 0.1 pm. This gives a spectral density of 1×10^{13} to 5×10^{15} photons/second/nm. If we instead operate at the maximum coherence value, values of $> 1 \times 10^{16}$ photons/second/nm can be achieved. The BEC flux can also be increased through either increasing the reservoir size [4,19], or simply increasing the radius of curvature of the curved mirror, as for a fixed BEC intensity and P/P_c the count rate scales linearly with radius of curvature. For example, with a 1 m radius of curvature mirror these values can be increased by a factor of 10.

To investigate the BEC's suitability for practical sensing scenarios involving long distances and noncooperative targets, we extend our measurements to investigate the effects of attenuation and diffuse scattering. The measurements in Figs. 3 and 4(a) were performed with attenuation to reduce count rates to ensure reliable APD performance [15]. With our 1-mm-diameter output beam this corresponds to the loss in intensity due to the divergence expected over 10 m. Repeating these measurements with a factor of

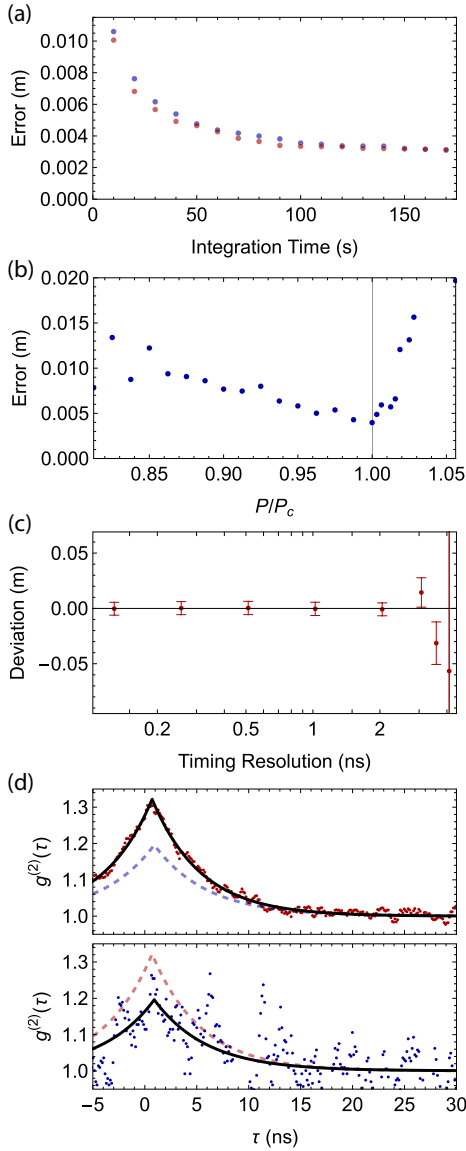


FIG. 4. Dependence of error in distance measurement on system parameters. (a) Error magnitude as a function of integration time (points) for no (blue) and 0.6 m (red) delay for $P = P_c$. Both tend to the same value, showing measurement error to be independent of distance. (b) Error magnitude as a function of P/P_c for an integration time of 30 s. (c) Average deviation and error magnitude for distance measurement as a function of timing resolution for $0.9 < P/P_c \leq 1$. Timing resolution is reduced through rebinning data. (d) Comparison between $g^{(2)}(\tau)$ measurements with a mirror (top) and paper (bottom) target. Data (points) are fit with Eq. (1) (solid lines). The fit from the other target is shown for reference (dashed lines).

1200 attenuation (45 m of divergence) shows an increase in the average distance error to around 20 mm, in line with extrapolating the behavior seen in Fig. 4(a). Used as is, the BEC can range over moderate distances; however, replacing the current objective for a cheaper long-focal-length lens would increase beam diameter, extending the

Rayleigh range and therefore potential ranging distance. Using beam expansion optics, such as a telescope, this distance could be increased to many kilometers [14,26].

To test performance against a diffuse scatterer we replace the mirror with a piece of white paper. To accommodate the nondirectional Lambertian scattering the collection optics were modified to use a parabolic mirror with a central aperture for excitation, and integration time was increased to 120 s. Figure 4(d) shows a comparison between the $g^{(2)}(\tau)$ measurements performed on a mirror and the paper target at a distance of 0.3 m. Both measurements agree within 2 cm; however, the significantly reduced count rate on the paper target resulted in a larger uncertainty compared to the mirror target, increasing from 3 mm to 30 mm. Additionally, the reduction in signal means the detector dark count rates (approximately 3 kcnt/s) become a meaningful contribution, reducing the measured $g^{(2)}(0)$ value. While this currently limits the maximum measurable distance for diffuse targets, these measurements confirm that the semiconductor photon BEC source provides sufficient flux to perform ranging on non-cooperative objects, with performance limited by radiometric flux and collection efficiency rather than source physics.

In conclusion, we have demonstrated the application of a room-temperature, continuous-wave semiconductor photon Bose-Einstein condensate as a light source for time-of-flight range sensing. By characterizing the above-threshold thermal photon statistics, we established that the second-order coherence bunching peak, $g^{(2)}(\tau)$, provides a robust feature for determining optical delay. We measure distances up to 0.6 m with a precision of approximately 5 mm, and critically, we identified the optimal pump power regime where measurement uncertainty is minimized by balancing photon flux against the coherence characteristics of the condensate.

Beyond the specific application of range sensing, this work serves as a broader demonstration that continuous-wave, room-temperature semiconductor photon BECs have now achieved the brightness and stability required to be considered practical light sources. This achievement bridges the gap between fundamental studies of macroscopic quantum states and practical metrology. While photon BECs have previously been explored for their unique properties, our results establish a clear pathway toward their use in real-world applications such as LiDAR or depth imaging. Furthermore, our proof-of-principle demonstration of simultaneous multidistance measurement highlights the potential for this method to be extended to full three-dimensional imaging.

We acknowledge that the current demonstration has limitations. While we have demonstrated the feasibility of ranging against noncooperative targets, the precision becomes limited by the radiometric loss associated with Lambertian scattering. Future work should therefore focus

on several key areas. Optimizing the microcavity design by increasing the quantum well overlap with the cavity mode and operating the device nearer the quantum well bandgap as suggested by theory [19] could significantly expand the operational power range where thermal statistics are prominent. Using a mirror with a larger radius of curvature will also increase photon flux for a given P/P_c . While optical power is inherently limited by the need to maintain thermal statistics, for eye-safe applications [27] there is a limit on usable power. Following this, improving focusing and collection optics, and exploring parallel detection schemes would be the logical next steps toward realizing a complete, single-photon sensitive imaging system based on a photon BEC.

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Data availability. The data that support the findings of this article are openly available [28].

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